ISSN 0386-5878
PWRI Technical Note No. 4077

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Guidelines for Landslide Prevention Technologies (Draft)

September 2007

Landslide Research Team
Erosion and Sediment Control Research Group
Public Works Research Institute (PWRI)
(Independent Administrative Institution)

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Overview

Landslide phenomena present varying behaviors depending on the features of the environment, such as the topography, geology, and geological structure, making it difficult to predict their development. Therefore, when implementing landslide prevention measures, it is required to take flexible and effective measures by adequately grasping the characteristics of individual landslides.

In order to prevent landslide disasters, it is necessary to implement emergency surveys and inspections/monitoring after construction, in addition to carrying out general surveys, planning, design, and construction. This PWRI technical note provides standard methodologies and key points to be used for the preparation of landslide prevention plans.

Keywords: landslides, disasters, landslide prevention plans

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Chapter 1 General

1.1 Purpose and Scope of the Guidelines

These guidelines for landslide prevention technologies (hereinafter referred to as the “Guidelines”) provide standard methodologies and the points to be noted when implementing surveys, planning, survey and risk management standard for emergency situations, design, inspection and monitoring of landslide slopes after works, and maintenance of the functions of landslide prevention facilities, in order to prevent landslide disasters.

Landsides as used in these Guidelines refer to a sliding or moving phenomenon of part of land due to groundwater, etc.

The scope of these Guidelines will be revised as needed with the improvement of technologies, etc.

Comments

Landslide phenomena vary according to the features of the environment, such as the topography, geology, and geological structure. Therefore, before implementing planning, surveys, etc., it is necessary to make an investigation in order to determine the actual characteristics of the landslide site and to adopt effective measures, by referring to the guidelines presented here.

If new information is obtained from a continued survey, then it may be necessary to revise a plan or a survey process. Also, an additional survey or plan may be required if the landslide movement changes. In the case of slopes where intermittent sliding movement is occurring, it must be kept in mind that analysis on incoming information should be performed swiftly and adequate measures, etc. should be taken incorporating the obtained results.

1.2 Application of the Guidelines

Landslides are natural phenomena that occur deep in the ground, and hence the prediction of all their behaviors is impossible. Therefore, when implementing a survey, planning, or construction works, it is important to respond as necessary in view of the actual landslide conditions.

For that reason, the present Guidelines need not be applied when doing so would produce an irrational result.

Also, if there is a better methodology that can achieve an intended objective sufficiently, adopting it should not be precluded.

1.3 Organization of the Guidelines

These Guidelines provide standard methodologies and the points to be noted in each stage by organizing the contents into six chapters: surveys; planning; survey and risk management standard for emergency situations; design; inspection and monitoring of landslide slopes after work; and maintenance of the functions of landslide prevention facilities.

Actual landslide prevention measures should be advanced by considering the entire process of a given landslide prevention project from survey to maintenance by referring to these Guidelines, while keeping in mind the fact that that a limited landslide survey cannot capture landslide movement and its characteristics fully.

Chapter 4 is provided as a separate chapter to cover emergency surveys, because landslides that are heavily sliding or very likely to slide should be treated by emergency surveys and measures first before moving onto the normal survey and planning stages.

Comments

These Guidelines are organized as shown in Fig. 1-1.

A series of topics, from survey for landslide prevention measures to the maintenance of facilities after construction work, are presented in Chapters 2 and 3 and Chapters 5 through 7. Also, Chapter 4 is specifically provided to address the situation requiring immediate responses against landslides that are currently sliding or very likely to slide. Matters related to the survey and risk management standard in emergency situations are described in this chapter.

Since the landslide prevention surveys are limited, landslide prevention measures are started before fully determining the landslide movement and its characteristics. Therefore, additional construction work may be required as the monitoring results become available during and after construction. For that reason, the contents of these Guidelines do not proceed from Chapter 1 to Chapter 7 sequentially, but may go back to previous chapters to deepen knowledge on landslide movement.

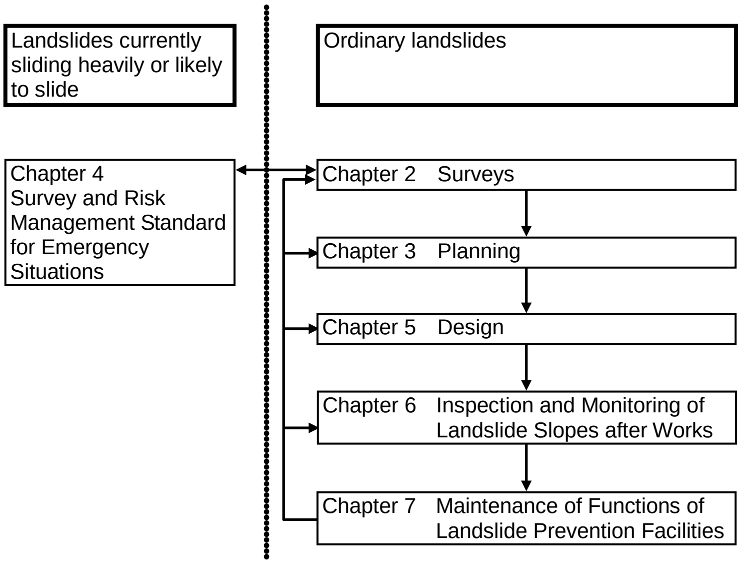


Fig. 1-1 Organization of the Guidelines

Chapter 2 Surveys

2.1 General

Landslide surveys are conducted with the aim of formulating a landslide prevention plan. Surveys are conducted by dividing them into preliminary surveys, rough surveys, and detailed surveys, as needed.

A landslide prevention plan is formulated to protect the lives and properties of people, public facilities, etc. from disasters due to landslides. It is equivalent to the landslide prevention plan set forth in the "Technical Criteria for River Works."

Comments

An outline of a preliminary survey, rough survey, and detailed survey conducted in landslide surveys and their relationship are shown in Fig. 2-1. Analysis is performed based on the results of these surveys.

When prevention works are urgently needed, the minimum necessary surveys, such as a slip surface survey and a groundwater survey, are sometimes performed in advance by site reconnaissance to identify the scope of the landslide and movement conditions to determine the scale of the necessary works.

Also, valuable information can be obtained during and after the prevention works. They include wall conditions that are observable during excavation for a drainage well and the drainage conditions that are known from the installed groundwater drain. As can be seen, it is effective to carry out landslide survey-cum-prevention works when prevention works are urgently required or when clarifying the landslide occurrence and movement mechanisms is likely to take a long time.

A basic survey (hereinafter referred to as the "basic survey") based on the Law Concerning the Promotion of Sediment-related Disaster Prevention in Sediment-related Disaster Hazard Area (Sediment-related Disaster Prevention Law) is a wide-ranging survey conducted every five years. It is different from a preliminary survey, rough survey, and detailed survey mentioned here in terms of the target range and timing. However, as the scope of the former and latter surveys overlap to some extent, their results should be used to supplement each other as described in Fig. 2-1.

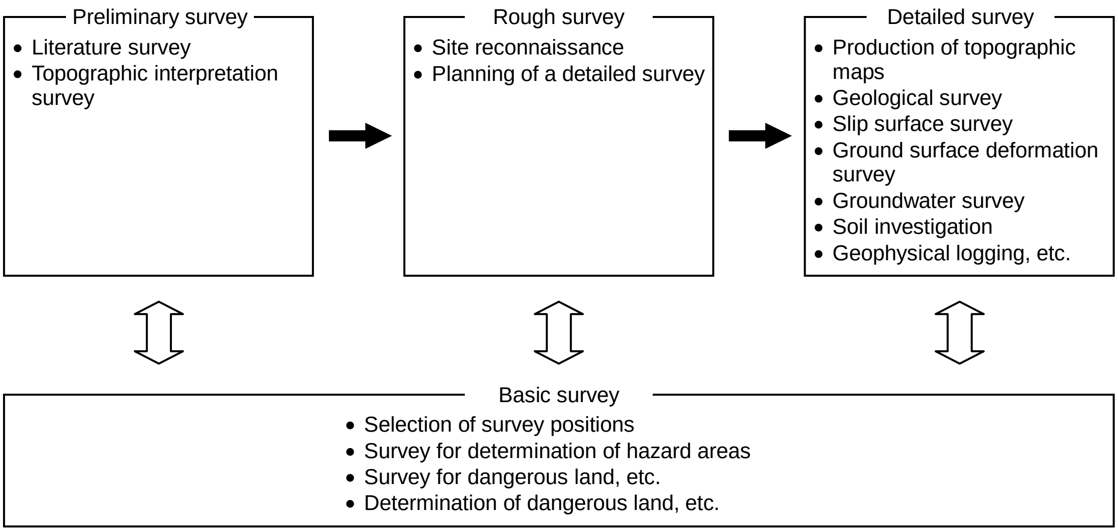


Fig. 2-1 Outline of landslide surveys added to 1)

2.2 Preliminary Surveys

2.2.1 Outline and purpose of preliminary surveys

Preliminary surveys are conducted to identify the outline of distribution, geology, and groundwater conditions of landslide sites, and take in a wide area.

Preliminary surveys are performed by a literature survey and a topographic interpretation survey.

2.2.2 Literature survey

A literature survey is carried out to collect information on the topography, geology, weather, past landslide history, and landslide occurrences in the surrounding area. Its aim is to determine the landslide characteristics.

Comments

Landslides are often triggered in areas having specific topography and geology. Also, a similar type of landslide tends to occur in areas having similar topography and geology (see Appendix 1.1). Accordingly, information on the topography, geology, weather conditions, past landslide history, and landslide occurrences in the surrounding area, which is obtained through a literature survey, gives valuable clues for finding the characteristics of landslide occurrence and movement in the given area.

In the literature survey, collect the following materials and extract information on the topography, geology, landslide occurrences in the surrounding area, and weather conditions at the time the landslides occur.

(1) Materials related to ground conditions such as topography and geology

- 1) Topographic maps
- 2) Aerial photographs
- 3) Geological maps
- 4) Topographic classification maps, land condition maps
- 5) Others (existing soil and geotechnical investigation reports, etc.)

(2) Materials related to past disaster history and landslide occurrences in the surrounding areas

- 1) Existing construction logs, disaster survey reports, soil (geotechnical) investigation reports
- 2) Research papers and reports of academic societies, etc.
- 3) Materials on settlement distributions, land use conditions, etc.
- 4) Topographical documents, newspapers
- 5) Others (interviews with local people)

(3) Materials related to weather conditions

- 1) Monthly weather reports
- 2) Observation records at various observatories

2.2.3 Topographic interpretation survey

A topographic interpretation survey is performed to examine the landslide topography and the characteristics of its geological structure using aerial photographs and topographic maps, etc. with a view to identifying the topographical and geological characteristics over a wide area.

Comments

Landslide topographies (see Appendix 1.3) and geological weak lines, etc. as shown in Fig. 2-2 should be interpreted using topographical maps, aerial photographs, etc. A topographic interpretation survey is a very effective means of identifying the landslide distribution over a wide area, which is not identifiable by site reconnaissance.

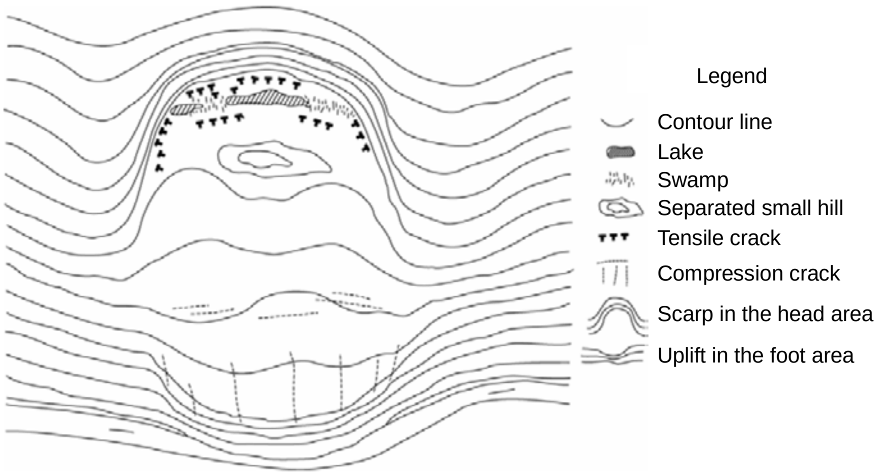


Fig. 2-2 Schematic representation of landslide topography[2)]

A landslide topography formed by repeated landslide movements is one of the topographies that is easy to interpret. But, as the pyroclastic flow deposit at the foot of a lava plateau and a river terrace are occasionally misinterpreted as a landslide topography, it is necessary to conduct a site reconnaissance and confirm the topography on site. Also, a rockslide that is difficult to interpret from a topographic map because of small displacement is discernible from the presence of a weak line in the geological structure.

As the maps for topographic interpretation, 1/25,000 scale topographic maps prepared by the Geographical Survey Institute (GSI) are available for any area in Japan, and they are relatively easy to obtain. Also, these days, a 3D representation using a digital map is in practical use, which is effective for a rough survey over a wide area. Furthermore, 1/10,000-scale topographic maps are being prepared by municipalities. For the mountainous areas, basic forest maps (1/5,000) are available.

Extract landslide topographies by paying attention to the geology and the geological structure. When performing topographic interpretation, pay particular attention to the following areas where the landslide occurrence is rather frequent.

(1) Geology

1) Mudstone and tuff of the Neogene formation

2) Crystalline schist (green schist, black schist) and clay slate distributed along the crush zone

3) Greenstone

4) Serpentine

5) Areas composed of volcanic altered rocks such as solfataric clay, etc.

(2) Geological structure (see Appendix 1.1)

1) Areas around the fault accompanying a crush zone and areas along the geological tectonic line

2) Areas on the dip slope

3) Areas around the anticlinal and synclinal axes of the fold composed of sandstone, mudstone, etc. of the Neogene formation

4) Areas around the boundary of igneous rock and intrusive rock

5) Areas having cap rocks (basalt, andesite, pyroclastic materials, etc.)

For topographic interpretation, extract landslide topographies by focusing on the following areas and features.

(3) Topography

1) Areas on the V-valley slope that entrenches an eroded flat plane

2) Buried valley areas and areas where thick collapsed deposits exist

3) Areas categorized as water-collecting topographies, such as a topography having a small depression on the hillside and a small rise at the foot of the slope, a topography having an extruded river, etc., or a topography in which a mountain stream disappears

4) Areas at the scouring-prone slope made of landslide-susceptible rock or areas on both sides of the slope if the scouring-prone slope is made of hard rock

5) Areas located at a bend in a river where the raised position is being eroded

6) Areas having a small or large scale terraced paddy field

(4) Microtopography

1) Contour lines are disturbed. The contour line interval is narrow at the upper slope, wide at the middle slope, and again narrow at the foot of the slope.

2) A horseshoe-shaped or quadrangular scarp exists at the upper slope and a gentle-sloped flat area at the middle slope. A separated small hill may exist in some cases.

3) Depressions, subsidence, fissures, etc. exist. A strip-like subsidence may exist in a mountainous area or at the mountaintop.

4) Ponds, bogs, and swamps exist in a certain uniform layout.

5) The flanks of a landslide have a valley-like topography or fissures.

6) The ridge behind the landslide often has subsidence.

7) Areas at the foot of a steep slope have uplifts or extrusions.

8) Areas where a sharp bend in a road or a railroad or the displacement of a structure is observed

9) Areas having an abnormal bend in a valley or a river or areas where the river becomes narrow

2.3 Rough Surveys

2.3.1 Outline and purpose of rough surveys

Rough surveys are conducted to assess the needs of emergency measures. If they are found necessary, make an emergency response plan. Also, the range, scale, and movement of landslides should be investigated with the aim of preparing a detailed survey plan to conduct a survey efficiently.

Basically, rough surveys should be executed through site reconnaissance.

2.3.2 Site reconnaissance

Site reconnaissance is conducted to formulate a detailed survey plan or an emergency response plan based on the results of a preliminary survey. The landslide occurrence and movement mechanisms and their effects should be roughly determined.

Site reconnaissance should be carried out with particular attention to the following items: (i) estimation of the landslide range and range of danger, (ii) geological properties and geological structure, (iii) estimation of the geological structure from micro- and macro-topographies, (iv) estimation of the groundwater distribution, (v) estimation of the movement mode, (vi) estimation of secondary causes, (vii) prediction of future landslide movements, and (viii) prediction of possible damage.

Comments

The following are points to note when conducting site reconnaissance.

(1) Estimation of the landslide range and range of danger

Using topographic maps, observe topographies of the landslide site and surrounding areas at a distance from a high position on the opposite bank, etc. Based on the observation results and signs of landslide movement such as fissures, uplifts, etc., estimate the landslide activity range, possible future landslide range, possible damage range, objects to be protected, etc.

(2) Geological survey (geological properties and structure)

The characteristics of old and new landslide movements can be estimated from the investigations of the kind and particle size of the materials that constitute a landslide mass, the quality and shape of the gravel and other rock materials, and the color of clay, etc. These investigation results are also effective for estimating the quality of the bedrock and landslide mass.

The characteristics of the geological structure of the landslide can be estimated by investigating the bedrock at the outcrop near the landslide site and by surmising a rough stratigraph, strike and dip in the bedrock. If a fault or a crush zone exists in the surrounding ground, it is important to investigate if they are related to a landslide or not by tracking their distributions.

(3) Topographic survey (estimation of the geological structure from micro- and macro-topographies)

In the topographic survey, estimate the geological structure and confirm landslide topography (see Appendix 1.3) mainly through the observations of micro- and macro-topographies.

(4) Estimation of the groundwater distribution

Conduct an investigation of the ponds, bogs, swamps, and spring water in and around the landslide site. It is possible to infer if their water comes from shallow groundwater or deep groundwater by conducting an examination of the relationship between the rainfall and the water level in ponds and bogs and between the rainfall and spring water volume for the spring water.

(5) Estimation of the movement mode (from various signs)

Estimate the movement mode and direction of the landslide by investigating the microtopographies, the main cracks, the side cracks, and the end cracks; deformation of structures such as roads, houses, stone walls; and abnormalities in vegetation, such as the crooking of tree trunks.

(6) Estimation of secondary causes

Estimate secondary causes of the landslide by examining the weather conditions, the movement mode, etc. at the time of landslide occurrence (see Appendix 1.2).

The following are typical secondary causes, but careful investigation is necessary because landslides are triggered not by a single but by multiple secondary causes.

1) Erosion at the foot of the landslide by a river, etc.
2) Persistent rainfall or snowmelt
3) Heavy rain due to typhoons, etc.
4) Cut at the landslide foot, fill at the landslide head
5) Improper drainage of surface water and groundwater
6) Ponding (in the case of landslides around reservoirs)
    a) Initial ponding (increase in the water level)
    b) Abrupt decrease in the water level
7) Earthquakes, volcanic activities

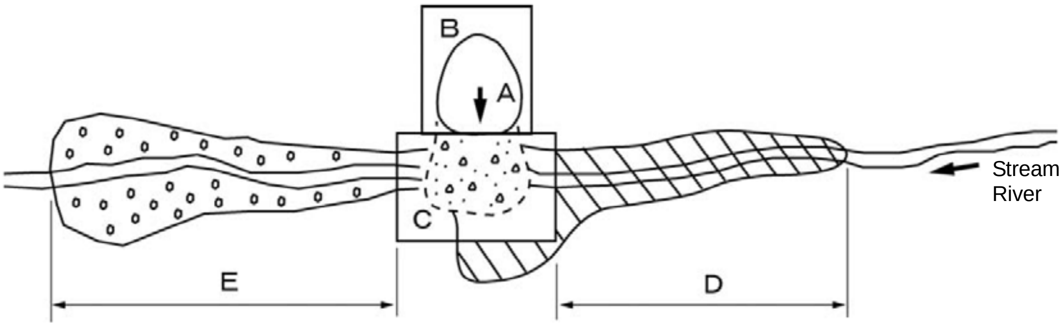
(7) Prediction of future landslide movements

It is very difficult to predict future landslide movements from reconnaissance only, but sliding is highly likely if the bedrock or weathered rock landslide has a nearly uniformly inclined slip surface. If the location of the landslide foot is higher than the riverbed, the possibility of collapse is rather high.

(8) Prediction of a damage area and a damage level in relation to the activation of landslide movement

If landslide activation is anticipated from the abovementioned surveys, it is necessary to predict the possible damage area and take necessary measures (establishment of a warning and evacuation system, etc.) for that area quickly. Caution must be taken regarding the expansion of landslide toward the upper slope area in particular by carefully examining the topography around the landslide. In the case of landslides that resemble a ship’s hull or a chair, there is the possibility of a secondary landslide at the foot of the landslide. It must be kept in mind that these types of landslides tend to activate under the influence of rainfall, etc. because their scale is usually small due to a thin landslide mass.

It is also required to predict the possibility of debris flowing and its impact range when the landslide occurs, the possibility of landslide dam formation, and the possible damage range when a landslide dam bursts (see Fig. 2-3).



A: Landslide block
B: Slope having the same primary causes as A
C: Range of reach of moving mass
D: Ponding area outside the potential landslide area
E: Flooding area downstream of C

A + B: Potential landslide site
A + B + C: Potential landslide area
A + B + C + D + E: Potential landslide damage area

Fig. 2-3 Example of a potential landslide damage area[3)]

(9) Preparation for emergency responses

If the landslide occurrence and movement mechanisms are roughly determined and landslide activation or sliding is predicted from the reconnaissance results, it is necessary to start preparations for the adoption of a landslide monitoring system, a warning and evacuation system, emergency measures, etc. Also, formulate an emergency survey plan if necessary, which includes the placement of devices that can monitor landslide behaviors in real time.

Table Appendix-1 is useful for the rough estimation of a landslide occurrence mechanism (primary and secondary causes) and a landslide movement mechanism (planar range, movement type, blocks, moving direction, moving speed, etc.)

2.4 Detailed Surveys

2.4.1 Outline and purpose of detailed surveys

Detailed surveys are carried out to confirm the results of the preliminary survey and rough survey and to clarify the landslide occurrence and movement mechanisms.

The following detailed surveys can be conducted depending on the purpose: (i) topographic survey, (ii) geological survey, (iii) slip surface survey, (iv) ground surface deformation survey, (v) groundwater survey, (vi) soil tests, etc.

Comments

To formulate a detailed survey plan, it is necessary to divide the landslide site into several movement blocks and establish survey lines in each of them. This is because analysis is normally performed block by block.

Survey items and survey contents to be investigated are shown in Table 2-1. Before starting an investigation, it is necessary to estimate the possible results in advance based on the results of preliminary and rough surveys and to carefully consider if those investigations are really necessary or not. The results obtained will be used as the basic data for clarifying the landslide mechanism. Before preparing a detailed survey plan, it is important to examine what kind of analysis will be performed on the obtained data.

Table 2-1 presents only representative survey items and survey details. They will vary depending on the past survey history, the need for emergency responses, etc. and they should be determined in view of the landslide conditions.

Table 2-1 Survey items and survey details

		Survey item						
		Topographic survey	Geological survey	Slip surface survey	Ground surface deformation survey	Groundwater survey	Soil tests	Environmental survey
Survey detail	1) Landslide type based on topography, geology, etc. (See Table Appendix 1)	○	○					
	2) Weak zone in the geological structure	○	○					
	3) Dividing of movement block and range of reach of each block	○			○			
	4) Movement of each block			○	○			
	5) Area and volume of landslide mass	○		○				
	6) Form and position of slip surface		○	○				
	7) Groundwater distribution and flow conditions					○		
	8) Physical property constants and others		○				○	
	9) Natural environment of landslide site	○						○

1) Dividing of the movement block

A landslide prevention plan is prepared targeting an individual movement block that moves as a mass. Hence analysis is normally performed block by block. To formulate a detailed survey plan, it is necessary to divide the movement block into several blocks based on the results of the preliminary survey and site reconnaissance.

The movement block must be divided by taking into account the topography, geology, possible damage, etc. Blocks are determined by microtopography and movement conditions, and one block should consist of a slope with one head or a slope circled by tensile cracks.

The dividing of the movement block mentioned here is intended for the formulation of a landslide prevention plan. Therefore, it is sometimes better to divide into large blocks since small blocks may complicate planning of the prevention plan. The divided blocks need to be reviewed and changed based on the results of detailed surveys.

2) Placement of survey lines

The survey lines are basic lines used for the determination of actual geological survey positions, groundwater survey positions, etc., and they are placed block by block. If the area of the landslide is wide, multiple survey lines may be placed.

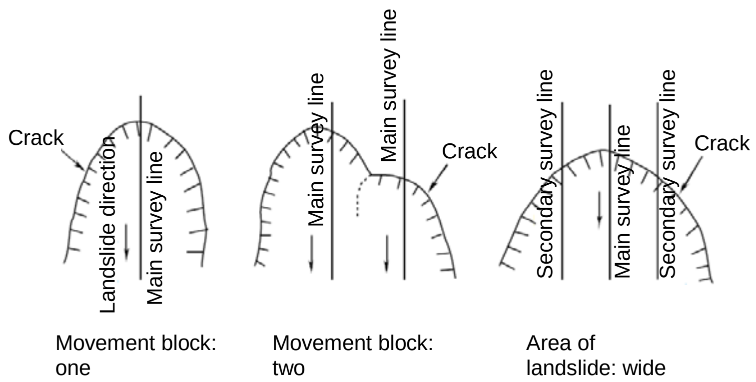


Fig. 2-4 Placement of survey lines[1)]

Primary survey lines should be placed in a position and in a direction that makes it possible to observe the geology, geological structure, groundwater distribution, ground surface deformation, slip surface, etc. in the movement block, and that are considered appropriate for the formulation of a basic plan and a basic design. The cross sections of the primary survey line are used for 2D stability analyses. Therefore, the primary survey lines should be placed in a direction parallel to the landslide movement and in a position that will not result in insufficient response measures. If the direction of landslide movement between the upper and lower slopes differs, a bent survey line can be placed.

Secondary survey lines are placed when supplementary survey lines are needed to investigate the traverse or planar conditions of the geological structure, groundwater distribution, etc. In principle, secondary survey lines are laid in parallel to the primary survey lines. If the area of the block is wide, 100 meters or more, it is advisable to place multiple secondary survey lines on both sides of the primary survey line at intervals of about 50 meters.

2.4.2 Topographic survey

A topographic survey is conducted to prepare topographic maps that are used as basic materials for landslide prevention measures.

The features that become necessary for surveying and implementation of measures should be described in the topographic map. Topographic maps should be produced to an accuracy and in a range that allows the movement block to be divided. Furthermore, topographic maps with a wide coverage, including the topography around the landslide site and positions of past landslide sites, should be prepared if necessary.

Comments

The features that are necessary for surveying and implementation of measures should be described in the topographic map. The topographic map should be prepared to an accuracy and in a range that allows the movement block to be divided. The map scale should be about 1/500 when the length of the landslide is less than 200 meters. When the length of the landslide is 200 meters or more, the scale should be about 1/1,000 – 1/3,000 for the map of the entire landslide site and about 1/500 for the map of part of the landslide site. If the landslide site is particularly wide, prepare an entire site map at a scale smaller than the abovementioned scale and, in addition, prepare topographic maps of individual blocks and the surrounding area. The features to be indicated on the map include houses, roads, various structures, rivers (including small streams), collapsed sites, bogs, spring water positions, swamps, fissures, scarps, paddy fields, dry fields, etc.

It is advisable to prepare topographic maps with a wide coverage including past landslide sites in the vicinity, so that the topography around the target landslide site and upper slope conditions can be understood.

The produced topographic maps will be utilized as basic maps for future landslide prevention, from survey to planning. Therefore, their range and accuracy should be carefully determined. It must be noted that topographic maps prepared from aerial photographs, etc. may not fully represent the true topographies. In recent years, a laser profiler is used for the production of topographic maps and this makes it easy to interpret microtopographies.

2.4.3 Geological survey

A geological survey is conducted to find geological conditions, soil quality, slip surface conditions, etc.

In principle, geological surveys should be performed by boring. Elastic wave exploration, electrical prospecting, and radioactive prospecting should be conducted where necessary.

Comments

In a geological survey, the following items need to be identified:

(1) Distribution of fragile layers and a slip surface that may be related to landslide deformation

(2) Areas of resistance and layers having a large bearing capacity that will resist or control landslide movement.

A geological survey is mainly performed by boring. In some cases, elastic wave exploration is also adopted to cover a wide area. Based on the results of a geological survey, it is necessary to conduct site reconnaissance again to verify the geological structure and geology of the landslide site and to infer the depth and the shape of the slip surface.

1) Bore survey

A bore survey is carried out to identify the slip surface, geology, and geological structure of the landslide by collecting samples directly from the ground in order of depth. In the bore survey, in principle, samples are collected throughout the entire length of the bore. The borehole diameter should be carefully determined since the holes are utilized for subsequent surveys.

(1) Slip surface survey (investigation by pipe strain gage, borehole inclinometer, vertical extensometer; observation of borehole walls)

(2) Groundwater survey (observation of groundwater level, groundwater tracking, measurement of pore water pressure, measurement of ground temperature, pumping test, groundwater prospecting, other logging)

(1) Number and length of bores

In principle, four or more bores should be drilled, which consist of three or more bores within the movement block that are drilled at intervals of 30 – 50 meters along the primary survey lines in the direction of landslide movement, and one or more bores in the upper slope area outside the movement block. If the landslide block is small, two or more bores should be drilled at the most appropriate positions for investigating the geology of the landslide site. Similar bores should also be drilled at intervals of 50 – 100 m along the secondary survey lines. Furthermore, if faults or crush zones are distributed in the bedrock, if the geological structure is complicated, or if the slip surface shape is complex, additional supplementary bores should be drilled. The depth of one bore should be sufficient to confirm the conditions of the bedrock. To avoid the possibility that the rock mass within the landslide mass is mistaken for bedrock, it is desirable to drill at least one bore deep into the ground.

When the thickness of the landslide block cannot be estimated, determine the length of one bore to about 1/3 of the width of the landslide block in principle. Adjust the length as the bore advances and its results are obtained.

Figure 2-5 shows an example of the layout of survey lines and bores at a landslide site that is constituted of multiple blocks. In the case of small-scale landslides, bores are often drilled along the primary survey lines only. In the case of large-scale landslides, detailed surveys will not be complete within a short period such as one year, but continue for a long period by conducting analysis based on the bore results and revising the detailed survey plan. Therefore, bores are not necessarily made in the original positions specified in the initial plan. It is important that the bore positions be determined to be useful to the production of sectional drawings, longitudinal drawings, slip surface contours, water table contours, etc.

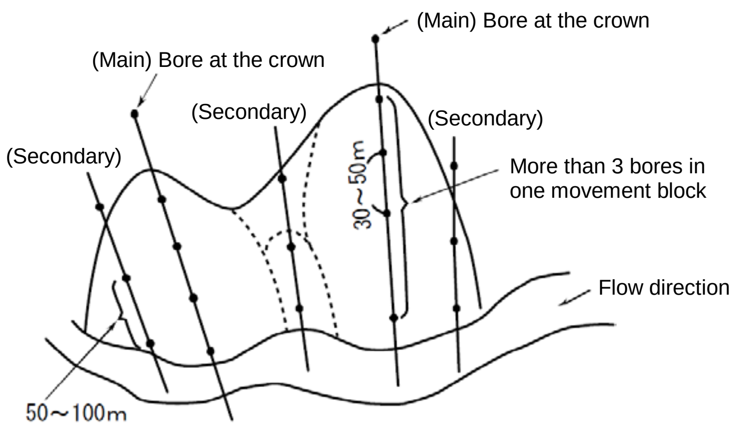


Fig. 2-5 Layout of bores along the survey lines in each block[4) with partial revision]

(2) Summarizing the results

The results of a bore survey should be summarized in the borehole log in relation to observations on various items that are necessary to investigate the geology, soil quality, and the slip surface of the landslide site.

The main items to be described in the borehole log are the geology and soil quality observed from core samples, conditions during drilling, water level in the borehole during drilling and at the final stage (see Fig. 2-30), and core sampling rate. Observation results from the bedrock survey, such as the weathering level, crack angle, angles of bedding plane and the schistosity plane, extent of cracking, etc. should also be described together with their vertical distribution. Observations of the geology, soil quality, and the slip surface should be performed by experienced engineers. Take color photographs of core samples as records of the slip surface conditions and the properties of the landslide mass. Take the photographs by attaching a standard three- or five-color tone plate so that the colors of the samples are correctly evaluated. Fig. 2-6 shows an example of a borehole log.

The results of the bore survey should be summarized according to the "Geological Materials Summary Manual (Draft)" [5] and compiled into a database. The borehole log format can be produced by referring to the "Bore Log Production Manual for Landslide Surveys (Draft)."[6]

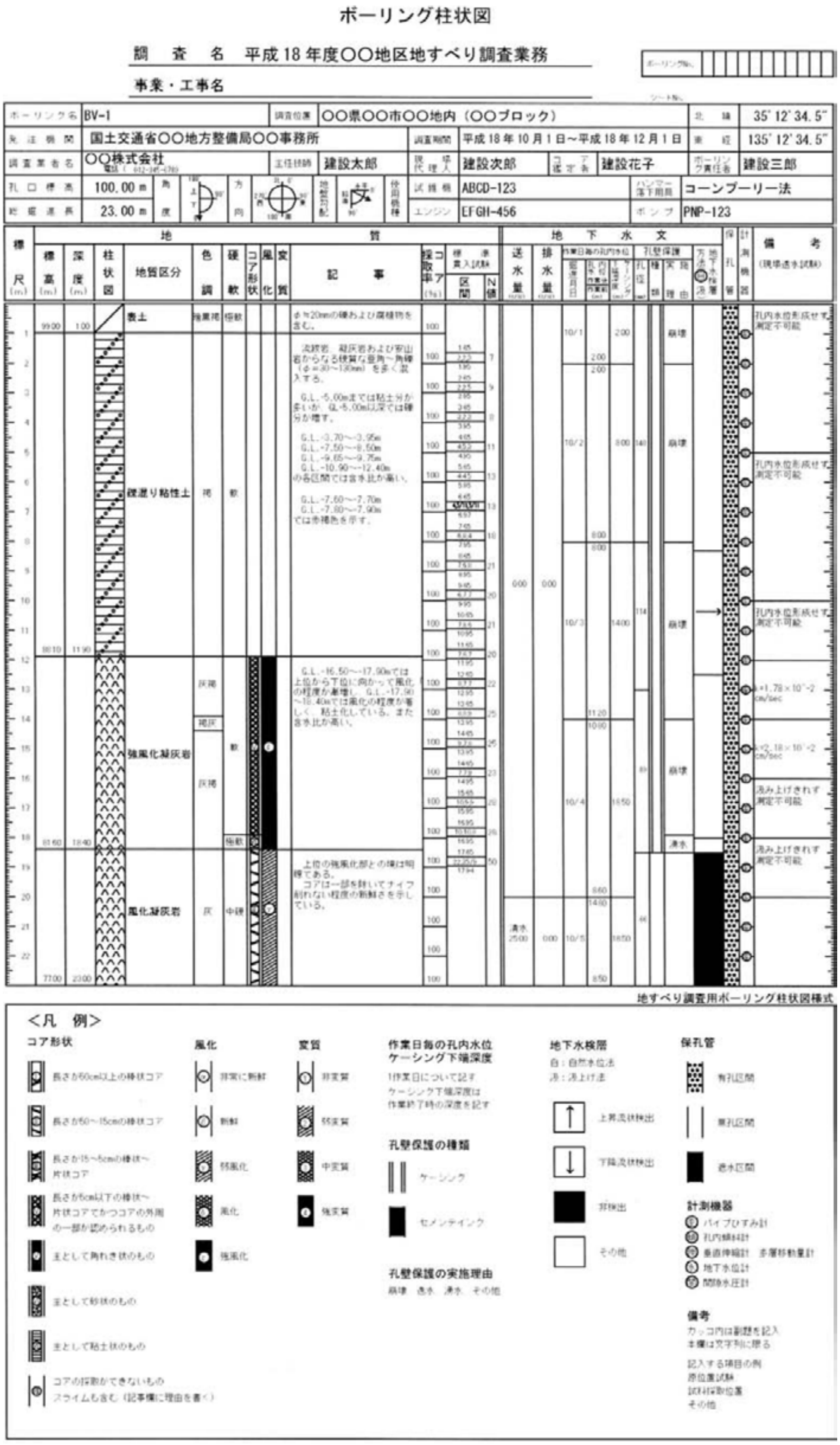


Fig. 2-6　Example of a borehole log[added to 6)]

(3) Surveys using boreholes

As the bore advances, the various tests shown in Table 2-2 are performed using the borehole walls to which casings are not yet applied (the bare borehole section).

Tests shown in Table 2-2 are utilized for the quantitative evaluation of ground characteristics of the landslide site. They are also utilized for the design of restraint works, infiltration flow analysis, and stress-strain analysis (FEM, etc.).

Table 2-2 Tests performed in the borehole[7] with partial revision

In-situ tests using the ground at the bottom of the borehole	Dynamic in-situ tests	Standard penetration test, large-scale penetration test, (N vane test)
	Static in-situ tests	Deep loading test, Vane test, (Ring shear test)
In-situ tests using the base of the borehole wall	Static in-situ tests	Borehole horizontal loading test, (self-propulsion type dynamic pressure meter test), (borehole shear test, skin friction test, borehole cone penetration test)
	Slip surface tests	Measurements by a pipe strain gauge, a borehole inclinometer, a vertical extensometer, a wire multilayer movement meter
Other in-situ tests		(Subsurface stress test, propulsion resistance measurement sounding)
Observation of borehole walls		Borehole camera
Geophysical logging	Velocity logging	P wave logging, PS logging
	Electrical logging	Resistivity logging, spontaneous-potential well logging
	Radioactive logging	Spontaneous radioactive logging, density logging, neutron logging
	Others	Borehole diameter logging, temperature logging, geotomography, measurement of borehole bend
Groundwater survey	Measurement of water level and water pressure	Measurement of borehole water level, measurement of pore water pressure
	In-situ permeability test	Auger method, tube method, piezometer method
	Pumping test	Single well method, observation well method
	Bedrock groundwater test	Spring water pressure test (JFT), Lugeon test
	Others	Groundwater logging, water quality survey, flow direction and flow velocity test

2) Elastic wave exploration

An elastic wave exploration is carried out to identify the distribution characteristics of formations by measuring the propagation velocity of an elastic wave in the formation. This method is particularly useful when surmising the distribution of formations in a very large landslide site. However, the elastic wave exploration cannot detect a weak layer sandwiched by formations because it is designed to work based on the assumption that formations become hard in order starting from the ground surface.

The following methods are available as elastic wave exploration.

(1) Refraction method

(2) Shallow reflection method

(3) Microtremor method

It is known that the following relationship exists between elastic wave velocity and geology.

(1) The faster the elastic wave velocity, the larger the compressive strength. This tendency is

particularly conspicuous in the same kind of rocks.

(2) If the rock weathers, the elastic wave velocity becomes slow. The more severe the weathering, the slower the elastic wave velocity.

(3) The more severe the fracture level, the slower the elastic wave velocity.

(4) The lower the solidification level, the slower the elastic wave velocity.

3) Natural radioactivity prospecting

Rocks that occur naturally in the ground contain radioactive elements such as uranium, tritium, etc. As these elements break down, inert gases such as radon and thoron are generated. These inert gases are also radioactive elements, but they dissipate above the ground by passing through the underground faults and crack zones. Therefore, by measuring those emitted radioactive elements at the ground surface, we can infer from the presence of large amounts of these elements that a fault or a crush zone is likely to exist in the ground below.

4) Electrical prospecting

There are two electrical prospecting methods. One is the resistivity method and the other is the natural potential method. The former method involves applying an electric current to the ground artificially and measuring the potential that changes due to the changes in the electrical characteristics of the ground. The latter method involves measuring the natural potential that exists in the ground.

In landslide surveys, the resistivity method is normally adopted. However, it is difficult to find the conditions of formations from the results of electrical prospecting only, because the electrical characteristics change due to the changes in the formation and due to the presence or absence of water even in the same formation. Therefore, the results of electrical prospecting must be evaluated by comparing with the results of bore survey, etc.

2.4.4 Slip surface survey

> A slip surface survey is performed to identify the position of a slip surface.
>
> The position of a slip surface should be determined by evaluating the results of a bore survey and the results of measurements using gauges (pipe strain gauge, borehole inclinometer, vertical extensometer, wire type multilayer movement meter, creep well, etc.) comprehensively.

Comments

A slip surface survey can be conducted by a bore survey and measurements using gauges. For the measurements using gauges, those such as a pipe strain gauge, borehole inclinometer, vertical extensometer, wire type multilayer movement meter, creep well, etc. can be used. The position of a slip surface should be evaluated in a comprehensive manner based on the results of these geological and gauge surveys. It is desirable not to use the borehole for a slip surface survey using gauges for the monitoring of groundwater, because the measurement accuracy is sometimes impaired by improper filling around the monitoring pipe.

1) Evaluation by a bore survey

In the geological survey, the following method is normally used for the evaluation of a slip surface.

(1) Evaluation during drilling

In the region where the landslide movement is active, the position of a slip surface may be identified from a bend in the borehole during drilling, resistance at the same depth that is felt every time a bore is drilled, the sampling of a half-moon core, etc.

(2) Evaluation by observing bore cores

The position of a slip surface can also be surmised by observing bore cores. Carefully observe the color tone, shape and extent of cracking, the wreathing level, clayey layer, etc. of the cores and evaluate the slip surface position comprehensively.

The area around the slip surface is often fractured due to displacement. Occasionally, the slickenside, streak, or wooden pieces around the slip surface are contained in the core. Pay attention to this kind of condition in the core.

Figure 2-7 shows the vertical configuration of a landslide mass. The slip surface tends to be argilliferous and dark-colored, with little permeability. In contrast, the moving layer is often brown-colored with large permeability. However, it must be kept in mind that these features will vary depending on the groundwater distribution and the position inside the landslide mass (head area, foot area, etc.)

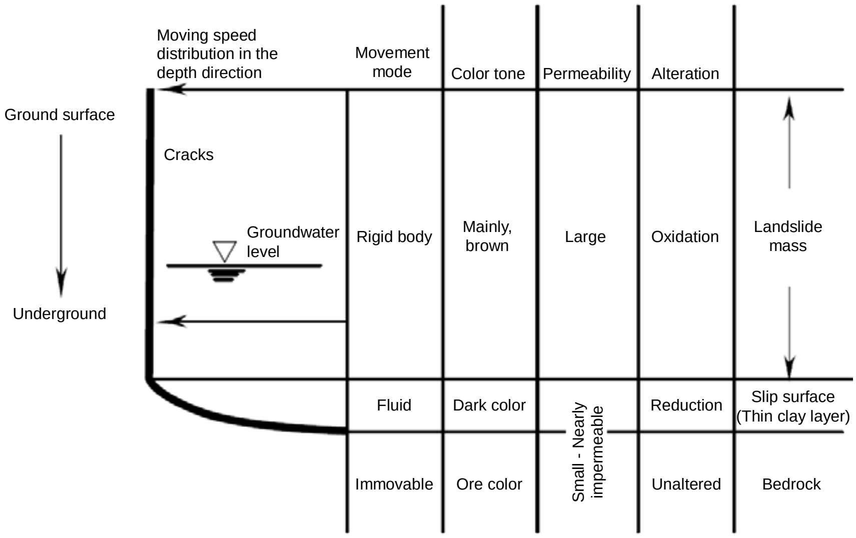


Fig. 2-7 Configuration of a landslide slope[8)] with partial revision

The following should be noted when evaluating the slip surface from observation of the cores[9)].

1) Presence of a weak clay layer
2) Beneath the colluvial deposit
3) Weathered rock on upper side of the bedrock
4) Boundary between different types of rocks
5) Presence of a weak seam or a crushed area in the bedrock
6) Presence of a disturbed sedimentation structure in the sedimentary rock
7) Correlation between the scale and mode of a landslide and the depth of a slip surface

If the results of an observation of the borehole walls (wall photos, projected diagram, etc.) are available, they should be utilized for evaluating the slip surface in the same manner as with the cores.

2) Evaluation by a short pipe

Insert a short pipe for searching for a slip surface into the borehole and try to pull it up after a certain period. The pipe will stop at the position where the borehole has been bent. If a similar kind of pipe is put into the borehole from above, the pipe will stop at the same position, indicating the presence of a slip surface.

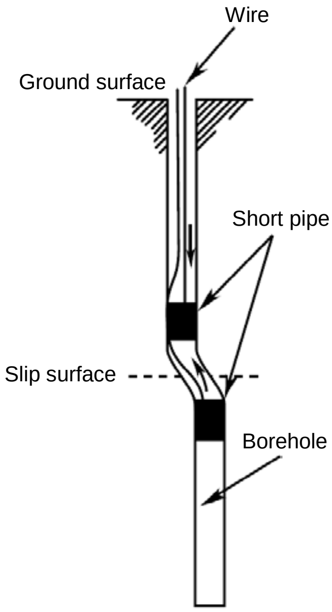


Fig. 2-8 Evaluation of a slip surface using a short pipe[8) with partial revision]

3) Evaluation by a pipe strain gauge

A pipe strain gauge can measure the bend over the entire length of the borehole, but its service life is one to two years. To measure the strain, one pair (two pieces) or two pairs of gauges are attached to the external surface of every PVC pipe for insertion (usually one meter each) at positions 180° apart. The gauge direction should be the same as the landslide direction in principle, but if the landslide direction is unknown, four gauges should be attached at one position of the pipe in the form of a right-angled cross.

After the pipe strain gauges are placed in the borehole, the void between borehole walls and the pipe should be filled completely using cement liquid, etc. (recently, an acrylic-based chemical solution is effectively used as a polymerization agent for this purpose). The measurement interval of the gauges is basically once in seven days, but it can be varied depending on the movement of the landslide.

The values used for analysis should be those that are taken one week after the placement of the gauges in principle. Summarize the measurement results in the cumulative chart and evaluate the slip surface based on the criteria shown in Table 2-3. Even though the measured values show significant strain, a depth that has no cumulative trend cannot not be deemed a slip surface. Conversely, even though the measured strain is small, a depth showing a cumulative trend is probably a slip surface and it needs continuous monitoring.

Figure 2-9 gives an example of cumulative strains versus time, taken from the deepest position.

Table 2-3 Landslide evaluation criteria based on the strain measurement using a pipe strain gauge[2) with partial revision]

Type of strain variation	Cumulative strain (μ/month)	Mode of strain variation		Slip surface presence - topologically/ geologically possible or not	Overall evaluation	
		Cumulative trend	State		Landslide evaluation	Sliding possibility
Type A	More than 5,000	Significant	Cumulative	Yes	Definite	Very active bedrock – landslide with colluvial deposit
Type B	More than 1,000	Less significant	Cumulative	Yes	Fairly definite	Landslide with rather slow creep
Type C	More than 100	Slight	Cumulative Intermittent Disturbance Recurrence	Yes	Latent	Presence of a slip surface not confirmed. Continuous observation necessary
Type D	More than 1,000 (short period)	None	Intermittent Disturbance Recurrence	No	Abnormal	No slip surface exists. Attributable to factors other than a landslide.

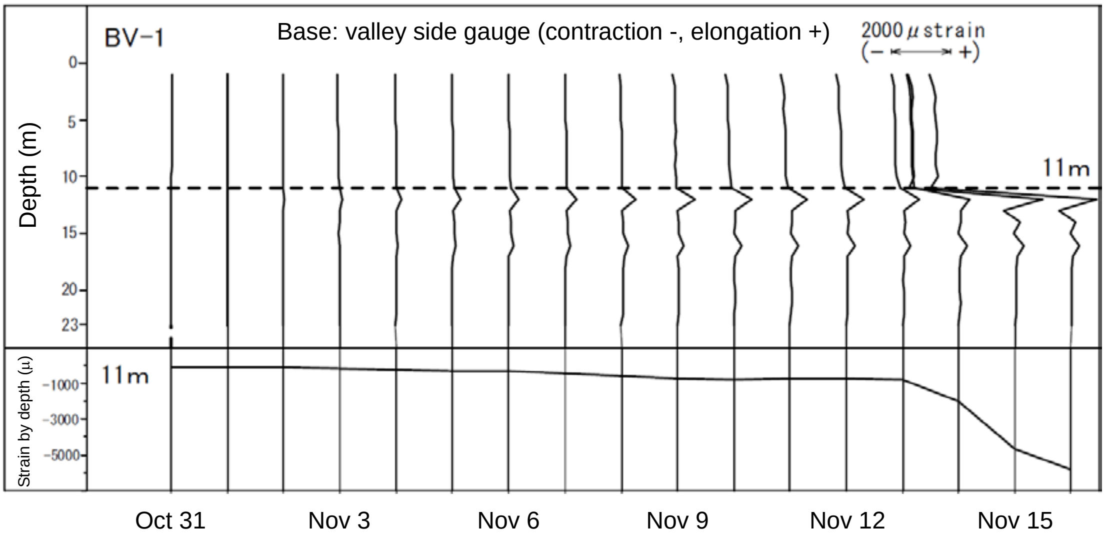


Fig. 2-9 Example of cumulative strain obtained by a pipe strain gauge

4) Evaluation by a borehole inclinometer

A borehole inclinometer is used to measure the inclination angle of a guide pipe that is inserted into the borehole to measure the inclination, by moving the inclinometer upward and downward along the guide pipe. It can follow the changes in the pipe shape due to the bend of the borehole almost continuously. However, its drawback is that the insertion of the device becomes impossible if the borehole bend is significant. Figures 2-10 and 2-11 give an outline of an insertion-type borehole inclinometer and an example of measurement results using that inclinometer, respectively.

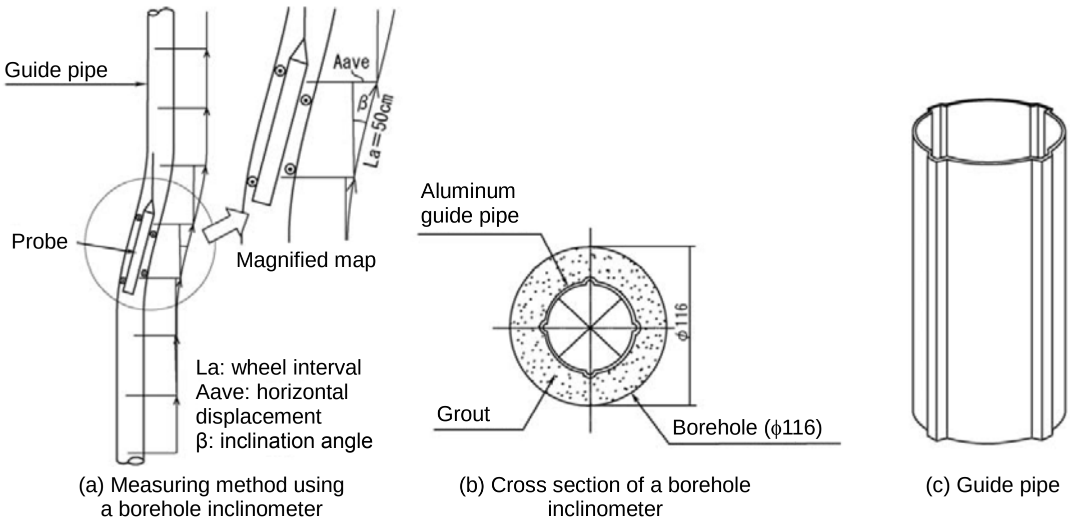


Fig. 2-10 Outline of an insertion-type borehole inclinometer[added to 10)]

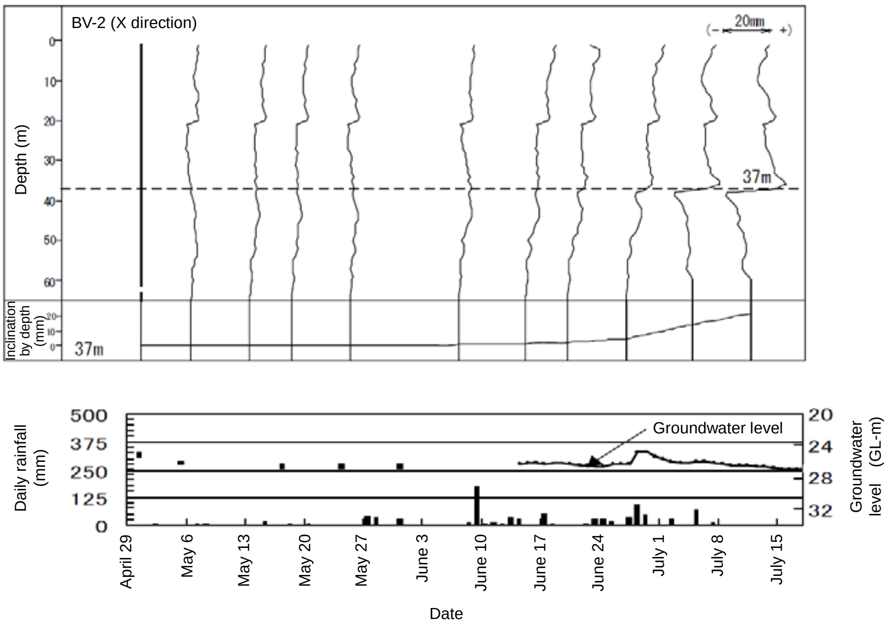


Fig. 2-11 Example of cumulative inclinations measured by a borehole inclinometer

The measurement results are expressed by the integral of the inclination amount from the borehole bottom. The position having a significant bend and cumulative strains is deemed to be the slip surface. Before starting measurement, the sensor area should be placed inside the ground having a small temperature change for a certain time to avoid the possible effect of temperatures.

A fixed borehole inclinometer, which is fixed at a depth in the slip surface, is also used to measure inclination and deformation. A typical example of installing this type of inclinometer is shown in Fig. 2-12.

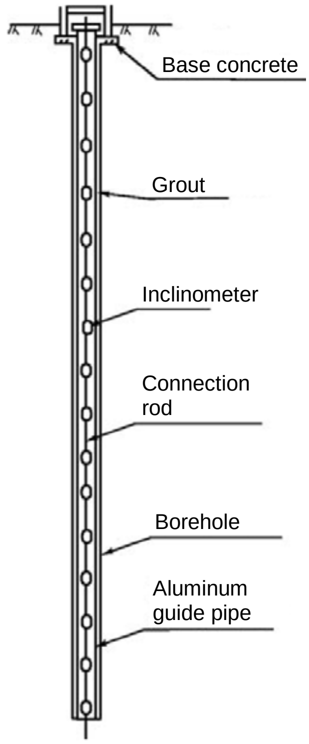
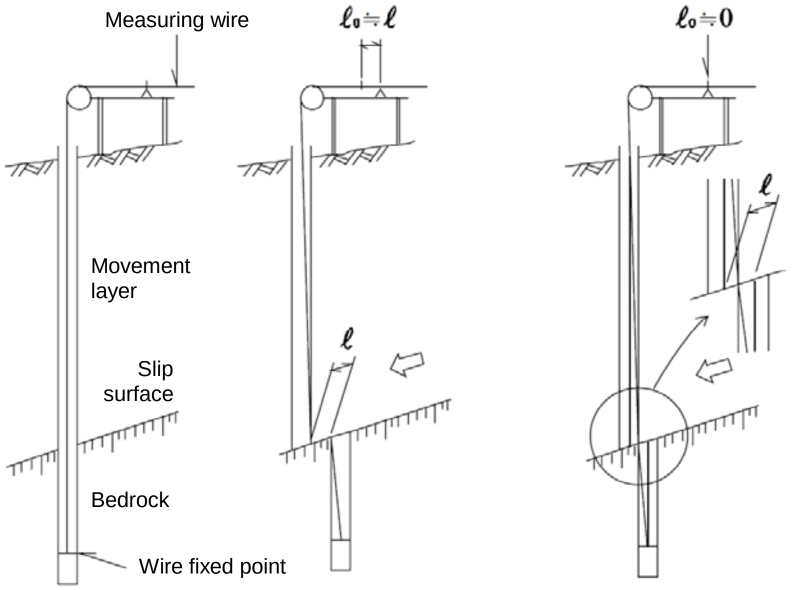


Fig. 2-12 View of a fixed borehole inclinometer[10) with partial revision]

5) Evaluation by a vertical extensometer

In this method, one or two ground extensometers used for the measurement of landslide displacement are inserted into the borehole in the vertical direction to measure the displacement in the upper and lower layers sandwiching the slip surface directly. The tip of the wire is fixed at the borehole bottom and the wire is extended up to above the ground so that the amount the wire extends and contracts can be measured by the device installed on the ground. A compression tendency is sometimes observed in the measurement at the head area of the landslide due to ground subsidence. Fig. 2-13 gives an outline of this process. When the measurement of ground surface deformation is difficult due to the accumulation of snow, a vertical extensometer may be used as an alternative to a ground extensometer.



(a) Slippage at the slip surface and wiring length (b) Initial insensitivity area

Fig. 2-13 Outline of a vertical extensometer[10)]

6) Evaluation using a wire multilayer movement meter

A wire multilayer movement meter is used to measure a slip surface when the depth of the slip surface is unknown, when many slip surfaces exist, or when large displacement is observed. According to this measuring method, wires are fixed at arbitrary multiple depths in the PVC pipe that is placed in the vertical direction in the landslide mass. The wires are extended up to above the ground and the degree of their expansion and contraction is measured. A stainless steel measuring scale and a pulley is set up on the measuring stand, 1.0 meter high, 0.5 meters wide, and 0.5 meters long, installed on the ground. The wires that extend from each depth pass through the measuring stand pulled by a weight or a spring having a certain tension, which enables direct measurement of wire elongation at each depth (Fig. 2-14). The measurement results are described in a time-series cumulative diagram, with the date on the abscissa and the cumulative expansion/contraction amount at depths on the ordinate, and are used to determine the position of the slip surface.

Fig. 2-15 depicts the structure of the aboveground portion of a wire multilayer movement meter.

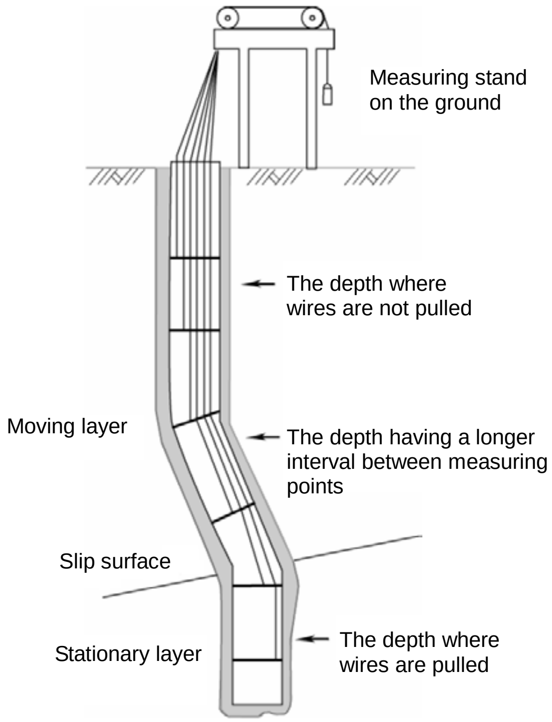


Fig. 2-14 Outline of a wire multilayer movement meter[11)]

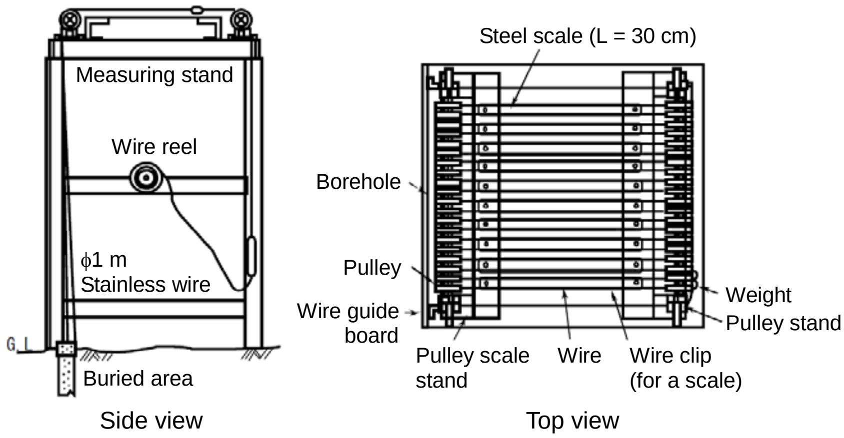


Fig. 2-15 The measuring system of a wire multilayer movement meter[11)]

7) Evaluation using a creep well

If a liner plate well is dug up to the depth of the bedrock at the landslide site and bolts in the vertical direction are released after construction, the well will have a form in which a number of liner plate rings, each 10 – 50 cm high, are stacked vertically. If the slip surface exists at some depth along the rings, the rings will move at that depth, making it possible to locate the position of the slip surface and the amount of movement. Use of a creep well also makes it possible to collect undisturbed samples used for the observations of slip surface conditions and soil tests. Fig. 2-16 gives an outline of this measuring method.

When constructing a creep well, observe the excavated surfaces (walls) and record their conditions using photographs and projected diagrams. Collect samples for soil tests where necessary. It is also effective to use a creep well for groundwater surveys, such as a pumping test.

The diameter of the creep well should be equivalent to that of a drainage well to ensure the safety of the work inside the well.

The creep well can be used as a groundwater drain after the end of the investigation.

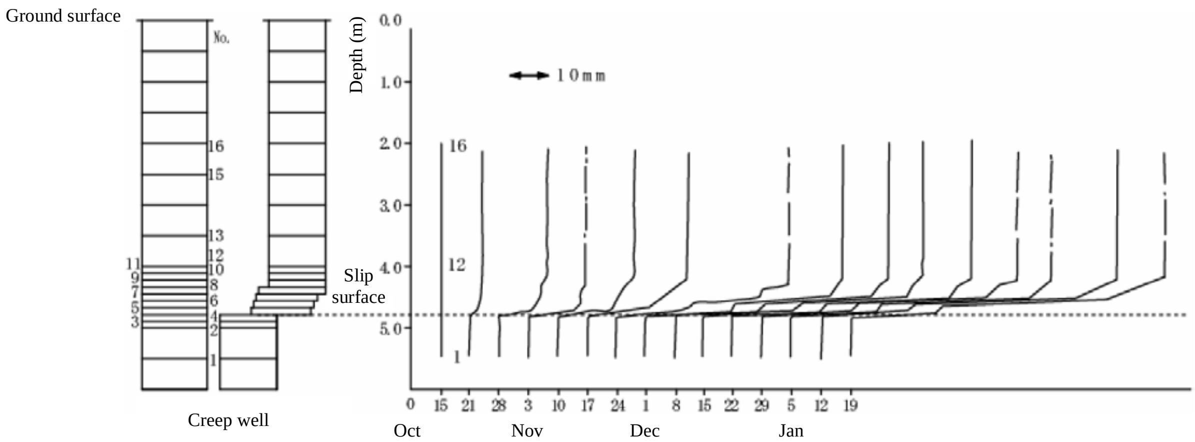


Fig. 2-16 Outline of a creep well[10)]

8) Features of measuring devices

Table 2-4 shows the performance of the measuring devices presented so far. In the slip surface survey, the position of the slip surface (depth) and the displacement amount are measured. The column “measurement interval” below the column “position of slip surface (depth)” shows the minimum measurement interval. The column “measurement range” below the same column shows the maximum depth that is actually measureable. The column “displacement at the slip surface” gives the measurement accuracy and a maximum measurement range. These values are all standard values and they vary depending on the devices. Before installing the devices at the site, their specifications need to be confirmed. Although the general performance of each device is presented in Table 2-4, it must be kept in mind that devices having high accuracy and a large measurement range are not necessarily good devices. For slip surface surveys, it is important that measuring devices suitable for site conditions be selected by taking into account such factors as the feasibility of continuous measurement, ease of installation, durability, the effects of accumulated snow, etc., and that continuous monitoring be conducted.

Table 2-4 Features of measuring devices

	Measurement items			
	Position of slip surface (depth)		Displacement at the slip surface	
	Measurement interval	Measurement range	Accuracy	Measurement range
Pipe strain gauge	1.0 m	Approx. 50 m	(Measureable indirectly)	
Borehole inclinometer	0.5 m	Approx. 50 m	1.0 mm	Approx. 10 cm
Vertical extensometer	(Not measureable)			Approx. 200 cm
Wire type multilayer movement meter	1.0 m	Approx. 30 m		Approx. 200 cm
Creep well	0.1 – 0.5 m	Approx. 20 m	10.0 mm	Approx. 100 cm

2.4.5 Ground surface deformation survey

A ground surface deformation survey is conducted as part of a detailed survey to measure the deformations occurring on the ground surface, such as cracks, subsidence, uplift, etc. using a ground extensometer, ground inclinometer, surface survey, GPS survey, etc. with a view to elucidating the landslide occurrence and movement mechanisms.

Comments

The following methods are generally adopted for the ground surface deformation survey. The purposes of these methods are provided in Fig. 2-17.

(1) Use of a ground extensometer

(2) Use of a ground inclinometer

(3) Surveying

1) Surface surveying

2) GPS surveying

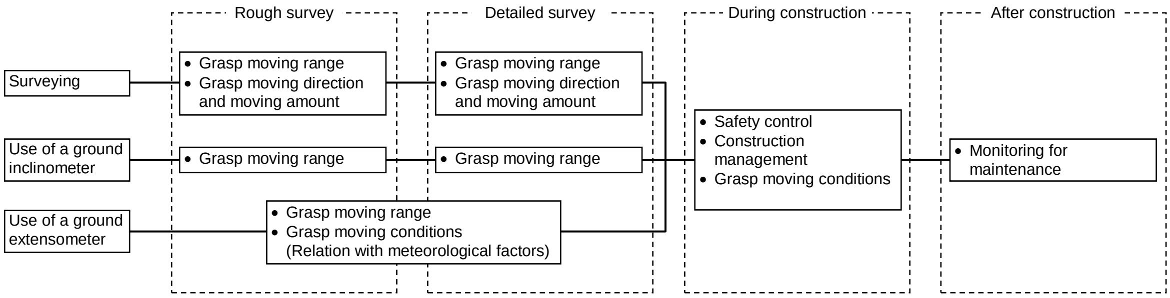


Fig. 2-17 Purposes and methods of a ground surface deformation survey

The purpose of a ground surface deformation survey varies depending on the stages – during rough survey, during detailed survey, during construction, and after construction. The purpose particularly differs between the detailed survey stage and the post-construction stage. During the detailed survey, the main purpose is to grasp the landslide mechanism, but it changes to the maintenance of a landslide site and prevention works after construction.

1) Survey using a ground extensometer

A ground extensometer is a device for measuring the ground expansion in a section having cracks and unevenness due to landslide movement. Ground extensometers should be placed in the landslide movement direction along the survey lines as far as possible. The observation values from these devices are automatically recorded continuously. Like the case of a ground inclinometer discussed below, it is desirable to conduct observations under various weather conditions, such as snowmelt, during the rainy season and during a typhoon, for a period of one year or more, so that the characteristics of the landslide movement under those conditions can be determined.

Figure 2-18 depicts the method for installing a ground extensometer. The stake that fixes the invar wire should have sufficient cross section to fix the wire firmly and should be driven into the ground one meter or more. The intervals at which the ground extensometer is installed should be about 15 meters or less as a rule. The invar wire should be protected by a PVC pipe, etc. to minimize expansion due to temperature changes or contact with plants. Caution should be taken to prevent the invar wire from contacting with the protective pipe. When the top area of a landslide is unknown or when the overall moving conditions have not been determined, ground extensometers can be installed continuously along the main survey lines.

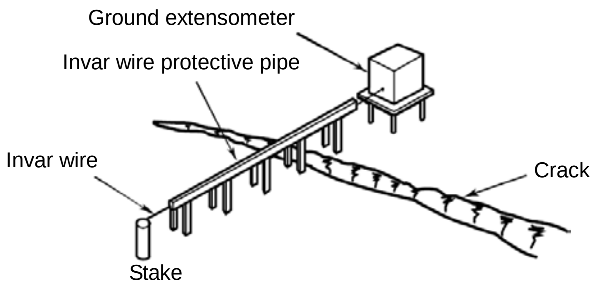


Fig. 2-18 Installation example of ground extensometer installation[1)]

The survey results should be summarized in a chart, with cumulative ground expansion on the ordinate and the date on the abscissa, in a manner that facilitates comparison with the groundwater level or precipitation. Figure 2-19 shows an example of the summarized results. It is also effective to summarize the data in a way that enables a comparison with the evaluation criteria shown in Table 2-5.

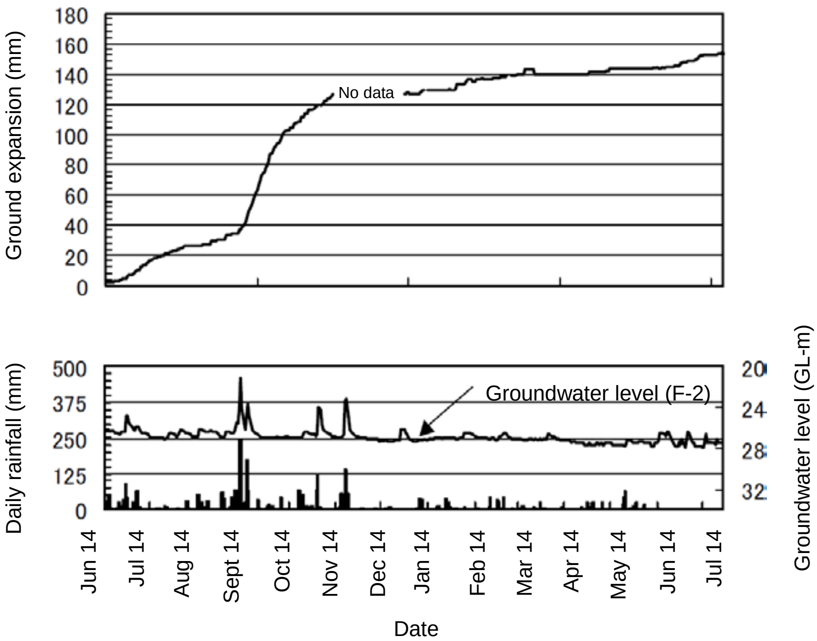


Fig. 2-19 Example of a summary of the measurement results using a ground extensometer

Table 2-5 Landslide evaluation criteria based on the measurement results using a ground extensometer[2) with partial revision]

Type of displacement variation	Daily displacement (mm)	Cumulative displacement (mm/month)	Cumulative trend in the same direction	Overall evaluation	
				Landslide evaluation	Activity level, etc.
Type A	More than 1	More than 10	Significant	Definite	Actively moving, surface and deep slides
Type B	0.1 – 1	2 – 10	Less significant	Almost definite	Slowly moving, clayey and collusive slides
Type C	0.02 – 0.1	0.5 – 2	Slight	Latent	Continuous monitoring necessary
Type D	More than 0.1	None (Intermittent displacement)	None	Abnormal	Local ground deformation, others

2) Survey using a ground inclinometer

A ground inclinometer is installed not only within the landslide site but also on the upper slope of the moving block along the main survey line in order to investigate the possibility of landslide expansion. A ground inclinometer is also installed on both sides of the moving block if necessary. To produce a base for setting a ground inclinometer, excavate to a depth of about 20 cm, construct a concrete block as shown in Fig. 2-20, place a glass plate over the upper surface of the block and make it level. Cover the block with a wooden box to encase the device. Inclinometers are available in various types, such as the water tube type, the servo type, and the differential transformer type. In the case of the water tube type, measurements are made by placing two inclinometers orthogonally in the N-S and E-W directions, with the main axis (the axis having a diagraph) aligned on the N and E sides.

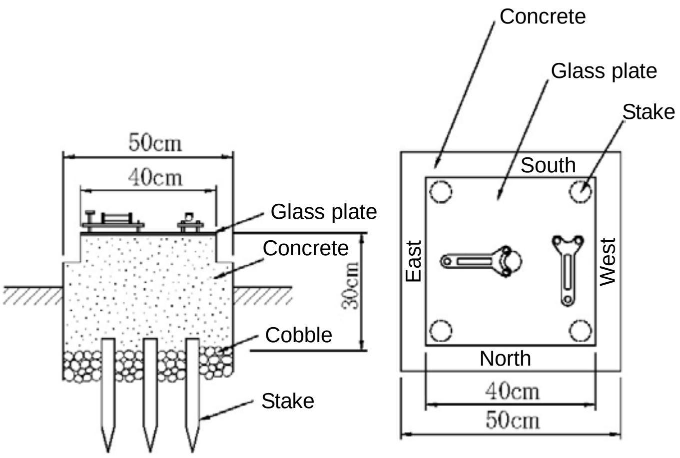


Fig. 2-20 Installation example of a ground inclinometer[added to 12)]

The survey results should be summarized in a chart, with the cumulative inclination or daily inclination on the ordinate and the date on the abscissa, in a manner that facilitates comparison with the groundwater level or precipitation. Then calculate the cumulative inclination speed and daily mean inclination. Figure 2-21 shows an example of summarizing the measurement results. The landslide occurrence is mainly dictated by the cumulative inclination,. and the landslide activity level is dependent on the variation in the inclination. Evaluate the landslide movement based on the evaluation criteria shown in Table 2-6.

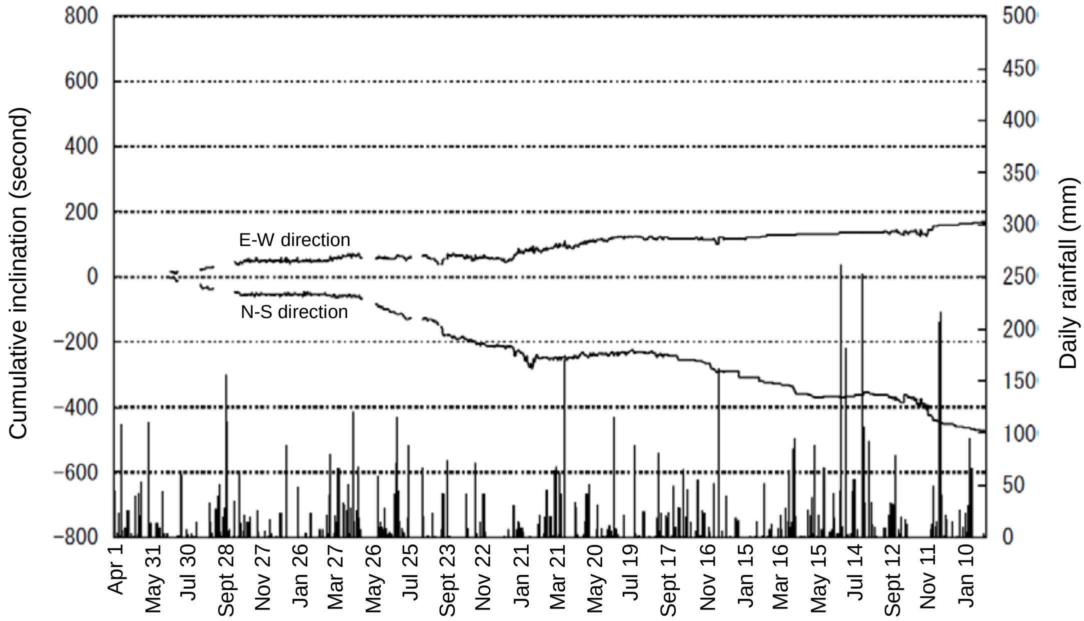


Fig. 2-21 Ground inclination measured using a ground inclinometer

Table 2-6 Landslide evaluation criteria based on the measurement results using a ground inclinometer 2) with partial revision

Type of inclination variation	Daily mean inclination (sec)	Cumulative inclination (sec/month)	Cumulative trend	Correlation between moving direction vs. topography	Overall evaluation	
					Landslide evaluation	Activity level, etc.
Type A	More than 5	More than 100	Significant	Yes	Definite	Actively moving
Type B	1 – 5	20 – 100	Less significant	Yes	Almost definite	Slowly moving
Type C	Less than 1	Less than 20	Slight	Yes	Latent	Continuous monitoring necessary
Type D	More than 3	None (Intermittent)	None	No	Abnormal	Local ground deformation, others

3) Surface survey

A surface survey is performed mainly when the direction of landslide movement is unclear or when the movement is significant.

A surface survey includes a cross-sectional visual survey from a fixed point located outside the landslide site, a movable pile survey, aerial triangulation, aerial photogrammetry, etc.

Figure 2-22 shows the results of a movable pile survey. The distribution of landslide movement and the moving direction are known from this figure.

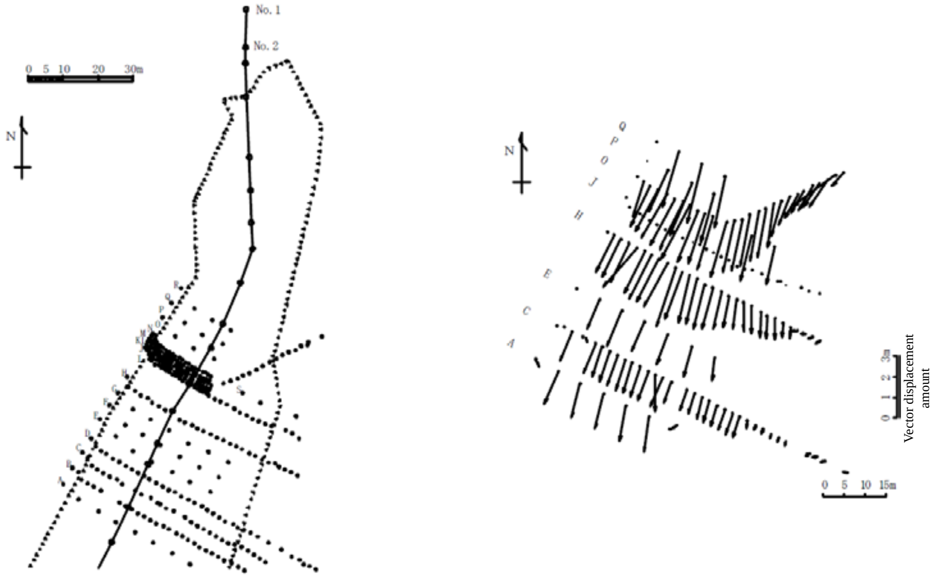


Fig. 2-22 Results of a movable pile survey[1)]

4) GPS survey

A GPS survey is conducted mainly when the direction of landslide movement is unclear, when a movement survey is necessary over a large landslide site, etc.

A GPS survey is based on the system that automatically measures the 3D coordinates of observation points using multiple artificial satellites. As shown in Fig. 2-23, this survey method consists of three areas: the space, the user, and the control. Its advantages are that visibility is not needed between observation points, meteorological conditions have little impact, night observations are feasible, and continuous observations for extended periods are possible. The measurement error is about ±5 to ±10 mm, although it depends on the number of artificial satellites. The measurement accuracy decreases when the number of artificial satellites is small and when the visibility in the sky is poor. Even though the measurement error in each time is considerable, GPS surveying can provide a trend owing to continuous observations.

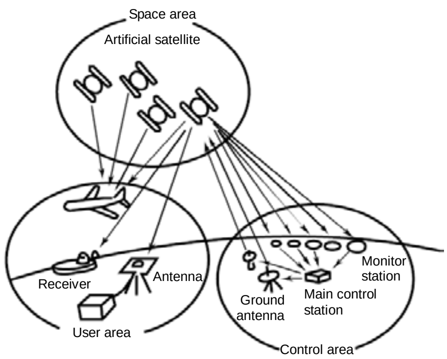


Fig. 2-23 Concept of the GPS survey[13)]

5) Surveys using other measuring devices

(1) Survey using an optical fiber sensor

An optical fiber itself can function as a sensor because the properties of light (intensity, frequency, and wavelength) that passes through an optical fiber change due to the effects of temperature, strain, bending, etc. An optical fiber sensor is appropriate for field measurements since it does not need a power source and can withstand lightning and electromagnetic waves. For these reasons, its application to slope monitoring is being studied. As an alternative to electric measuring devices, various optical fiber devices, such as displacement meters, inclinometers, water gauges, compasses, and thermometers are already put into practical use. In the field of landslide measurement, optical fiber devices such as ground extensometers, ground inclinometers, pipe strain gauges and water pressure gauges are being developed. Also, by taking advantage of multiple-point measurement using only one optical fiber line, a system is being applied to a large landslide site to identify the planar landslide activity.[14)]

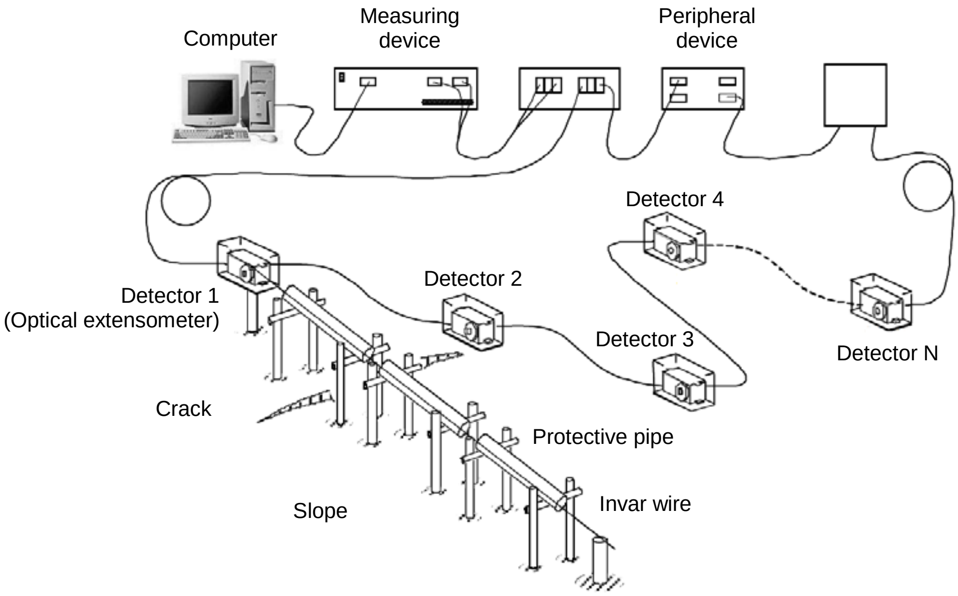


Fig. 2-24 Observation by a ground displacement gauge utilizing an optical fiber[15)]

(2) Survey using a laser scanner

A surface 3D laser scanner is being put into practical use for observation of the dynamic state when entry into a landslide site is dangerous or when producing a topographic map following a landslide.

The measuring principle is basically the same as that of optical wave survey methods, such as a total station. A surface 3D laser scanner can perform high-speed scanning in excess of several thousand points per second by changing the laser direction by rotating a mirror in the device. The obtained data is utilized to produce topographic maps or to calculate the amount of movement as the difference from some reference point.

A non-prism optical wave survey by placing targets is also effective for the observation of landslide movement.

It must be noted that measurement errors from these measurements can be several centimeters per 100 meters in some cases.

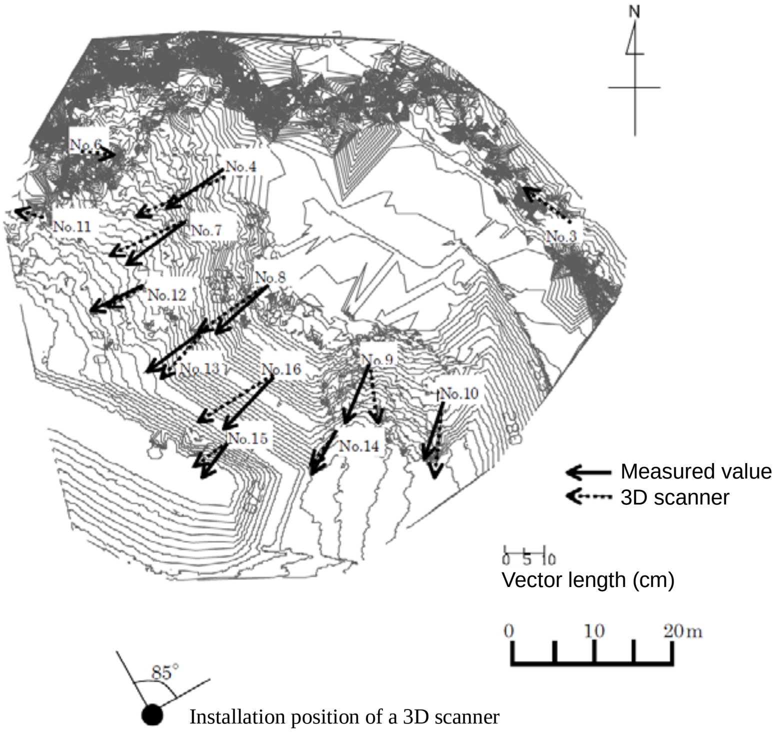


Fig. 2-25 Example of measurement using a laser scanner[16)]

2.4.6 Groundwater survey

A groundwater survey is conducted to find the route by which groundwater is supplied to the landslide site, the groundwater distribution and the flow in the landslide site, the pore water pressure acting on the slip surface, etc. with a view to obtaining basic materials for slope stability analyses and for preventive works.

Appropriate groundwater survey methods should be selected considering the purpose, such as monitoring the groundwater level, monitoring the pore water pressure, measurement of water level fluctuations during drilling, groundwater logging, groundwater temperature logging, measurement of the flow direction and velocity in the borehole, groundwater tracking, electrical prospecting, earth temperature prospecting, water quality prospecting, and simple pumping test.

Comments

A range of groundwater survey methods is available, as shown in Table. 2-7. Appropriate methods should be selected in accordance with the purpose of the survey.

Table 2-7 Purposes and methods of groundwater survey[1) with partial revision]

Purpose	Method
Estimation of pore water pressure acting on the slip surface	Measurement of pore water pressure, measurement of groundwater level
Examination of correlation, etc. between rainfall and groundwater fluctuations in the natural ground	Measurement of pore water pressure, measurement of groundwater level
Examination of a groundwater flow layer in the natural ground	Groundwater logging, simple pumping test
Examination of a groundwater flow route in the natural ground	Groundwater tracking, water quality analysis
Examination of the groundwater distribution in the natural ground	Electrical prospecting, earth temperature prospecting, water temperature survey, water quality analysis
Estimation of permeability in the natural ground	Permeability test, simple pumping test

1) Survey of pore water pressure

(1) Monitoring of groundwater level

The groundwater level is monitored to find the correlation between rainfall and groundwater fluctuations and to estimate pore water pressure acting on the slip surface through the measurement of the groundwater level in the borehole. Monitoring should be carried out continuously in the boreholes along the main survey line.

An automatic water level gauge is used for the continuous measurement of the groundwater level. Two types of automatic water level gauges are available: the float type (Fig. 2-26) and the water pressure type (Fig. 2-27).

The float-type automatic water level gauge may not follow the changes in the groundwater level well if there is friction between the float and the borehole walls, if the balance between the weight and the float is poor, or if there is substantial friction in the device. Particular care must be taken to maintain the mechanism that monitors the water surface because the speed of groundwater fluctuation is slower than that of a river, etc. If a weight and a float are put into the same borehole, it can increase friction. It is necessary, therefore, to dig a separate borehole next to the borehole for a float and put a weight in the second borehole.

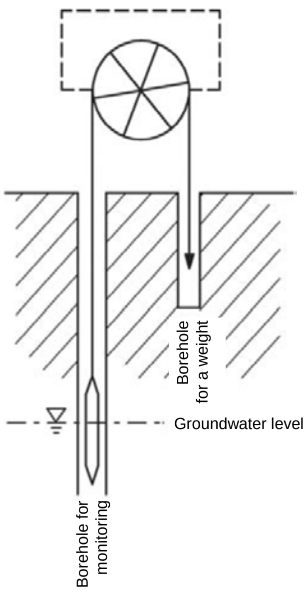


Fig. 2-26 Float type water gauge[13)]

The water pressure-type automatic water level gauge is inserted to a depth that is close to the bottom of the borehole, and electric signals from the gauge are sent to the recorder above the ground via a cable. However, this method also has problems, such as the accumulation of soil at the bottom of the borehole and aging of the gauge. Therefore, regular inspection is required.

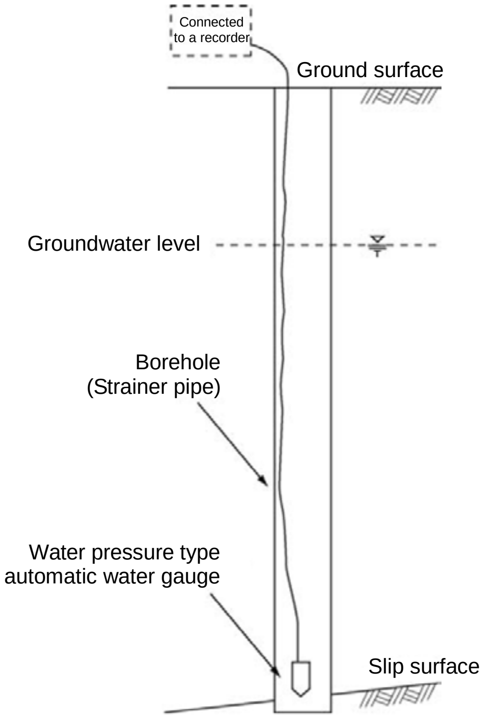


Fig. 2-27 Water pressure-type automatic water gauge

As a simple alternative, a sensing pin-type water level gauge is available. This gauge has an electric contact at the tip of the scale. If it reaches the water surface, it forms an electric circuit and passes an electric current. It is possible to measure the correct depth of the groundwater surface, that is, when the water surface is reached, by measuring the current using an ammeter or by using a lamp that is turned on.

When drilling the borehole, it is necessary to record the presence of spring water, the escape of muddy water, the color of bore circulation water, etc. in addition to the water level, since there is the possibility of penetrating through multiple groundwater zones. Monitoring of the groundwater needs to be continuous for a long period after drilling to keep track of the groundwater level.

A full strainer pipe and a partial strainer pipe are available for groundwater monitoring. When multiple groundwater zones exist, monitoring using a full strainer pipe may not capture the correct groundwater level, so the use of a partial strainer pipe is desirable.

The results of groundwater monitoring should be summarized in a chart that allows comparison with the rainfall and the ground surface deformation on that day. In this way they can be used as basic material for investigating the correlation with the landslide movement and for studying landslide prevention works.

(2) Measurement of pore water pressure

There are two methods for measuring pore water pressure around the slip surface. One is direct measurement using a pore water pressure gauge and the other is measurement using a groundwater level measurement pipe with holes only around the lower end of the pipe near the slip surface (a partial strainer pipe). Whichever method is adopted, it is important to determine the conditions of the slip surface and the flow layer in advance.

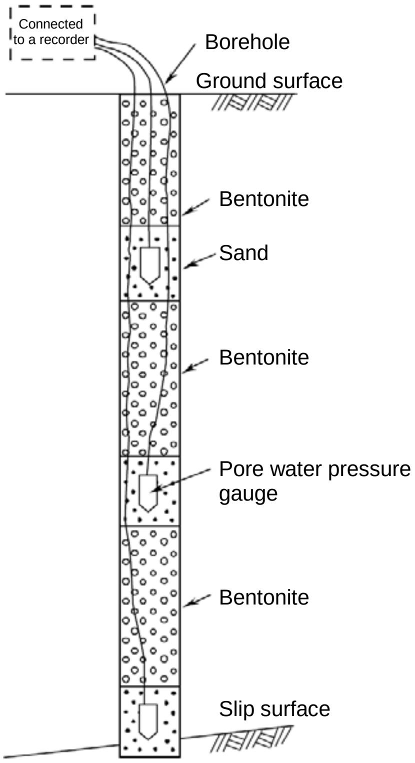


Fig. 2-28　Burial-type pore water pressure gauge (for measurement at multiple depths)

If the hydrological conditions of groundwater in the landslide site are complicated, it is necessary to measure the pore water pressure in the confined groundwater zone at multiple depths (Fig. 2-28).

Figure 2-29 shows an example of measuring pore water pressure.

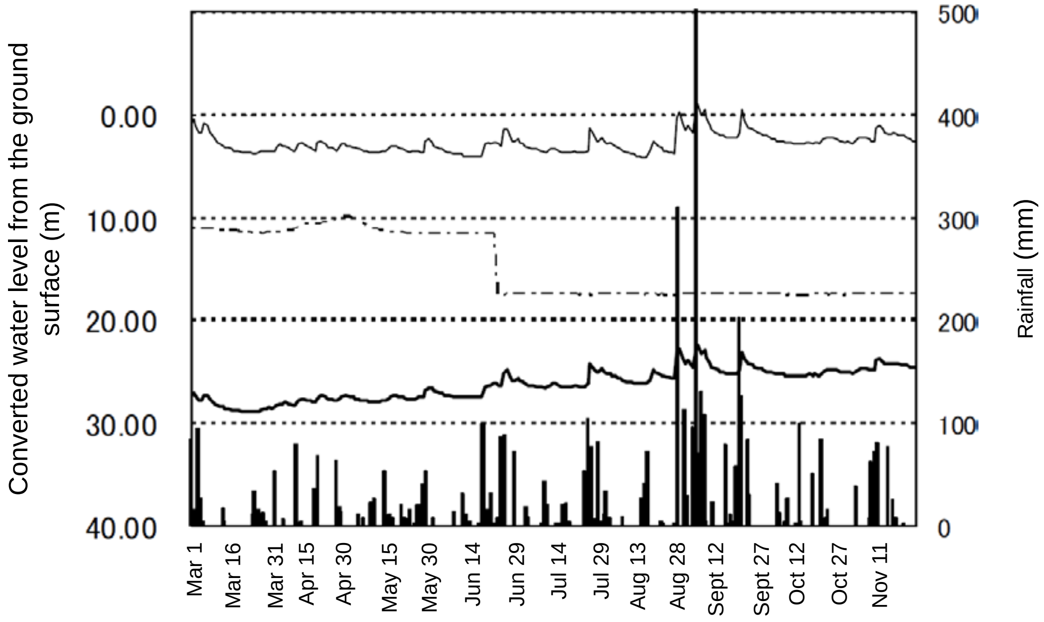


Fig. 2-29　Measurement example of pore water pressure

2) Survey of groundwater distribution

Surveys (1) – (5) are available as surveys that use boreholes and surveys (6) – (9) as surveys focusing on the planar area.

(1) Water level fluctuation during boring

When a bore survey is conducted at the landslide site, a casing is often inserted to the bore depth because of the possibility of wall collapse or extrusion. Therefore, data of groundwater conditions are obtainable only at the tip of bore as it advances. From the water level fluctuations thus obtained, it is possible to evaluate the hydrological conditions of the groundwater.

It is possible to evaluate the presence of a confined groundwater zone, a permeable layer, a water leakage layer, etc. by analyzing the water level difference at various casing insertion depths or before and after bore advancement. Figure 2-30 shows an example of summarizing the water level fluctuation during boring. According to this figure, the groundwater level on Oct. 5 before the start of bore work was higher than that on Oct. 4 at the end of bore work. From this, it is inferred that the groundwater zone is distributed around the depth of 4.00 to 7.00 meters.

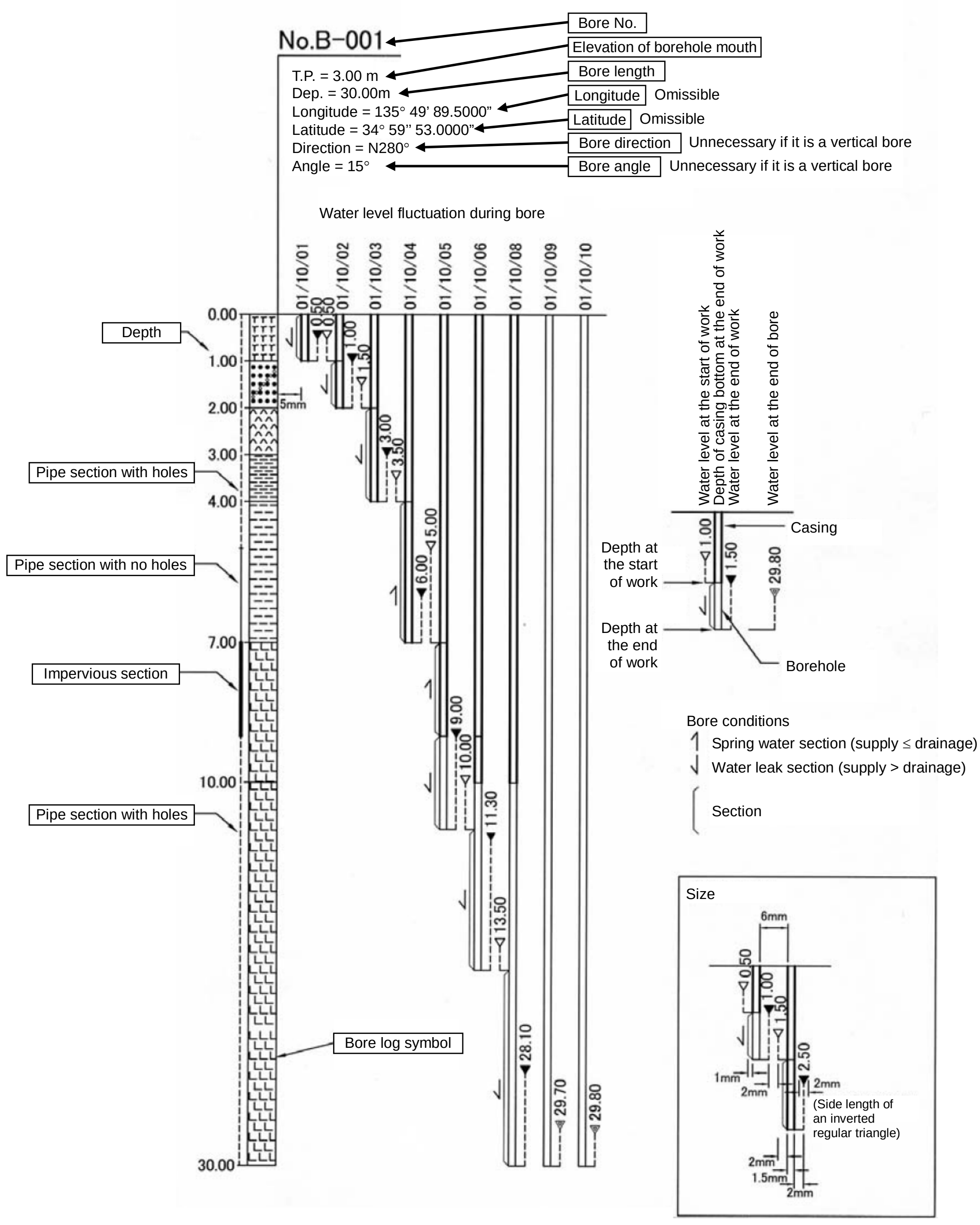


Fig. 2-30 Example of recording the water level fluctuation during boring[6)] with partial revision

(2) Groundwater logging

Groundwater logging refers to survey and analysis performed to investigate the position and condition of the groundwater flow layer around the borehole by utilizing borehole water.

To identify a groundwater flow layer, measure the electrical resistivity of borehole water first and then inject an electrolytic substance such as salt into the borehole uniformly at a rate that would produce electrical resistivity roughly 1/10 of that of the borehole water. The electrical resistivity of saline water increases at the surface of groundwater flow due to dilution by the water. Therefore, the presence of a groundwater flow layer can be identified by measuring the changes in electrical resistivity with time. There are two types of measuring devices: a multi-pole type in which an electrode is placed every 25 cm of the cord and a single pole type in which an electrode is attached at the tip of the cord only. Insert either of them into the borehole and inject salt after the electrode becomes stationary. Then measure the electrical resistivity of the borehole water at intervals of 10, 20, 30, 60 minutes, etc.

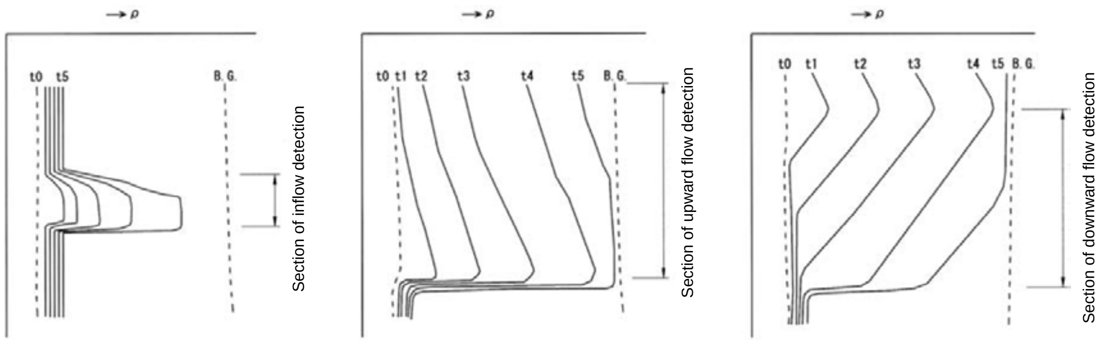
If the borehole penetrates through the impermeable layer, the real groundwater level and the flow layer may not be detectable because the water level will descend below the slip surface. If this is anticipated, groundwater logging can be performed at each stage of bore advancement. It is also possible to find the flow layer, which is latent under natural conditions, by artificially changing the water level in the borehole.

The obtained electrical resistivity over time should be summarized in a geological log in a manner that allows a comparison with reference values, such as the resistivity immediately after or 10 minutes after the injection of the salt. These results are used to examine the position of a groundwater flow layer and the correlation with other layers. If the obtained results are described in a geological profile, the groundwater flow route becomes much clearer. The results of groundwater logging are evaluated as “inflow detected,” “upward flow detected,” “downward flow detected,” “not detected,” or “others” based on Table 2-8 and Fig. 2-31. Figure 2-32 shows an example of the evaluation results of groundwater logging. The presence of a groundwater flow layer must be evaluated comprehensively based not only on the groundwater logging results but also water level fluctuations during boring and the properties of bore cores.

The method of electrical resistivity by conversion of salt is normally used for surveying a groundwater flow layer, but the use of dissolved oxygen has also been put into practical application.[17] The measuring methods using a conductance meter or an optical fiber as the sensor are also proposed.[18]

Table 2-8 Evaluation criteria for the results of groundwater logging[6]

Results of groundwater logging	Symbol	Remarks
Inflow detected	→	Section where the groundwater inflow is observed, as shown in Fig. 2-31 (a).
Upward flow detected	↑	Section where the changes shown in Fig. 2-31 (b) are observed.
Downward flow detected	↓	Section where the changes shown in Fig. 2-31 (c) are observed.
Not detected	■	Section where virtually no change is found in resistivity.
Others		Sections other than “inflow detected,” “upward flow detected,” “downward flow detected,” and “not detected.”



a) Inflow detected b) Upward flow detected c) Downward flow detected

Fig. 2-31 Evaluation of the results of groundwater logging[6]

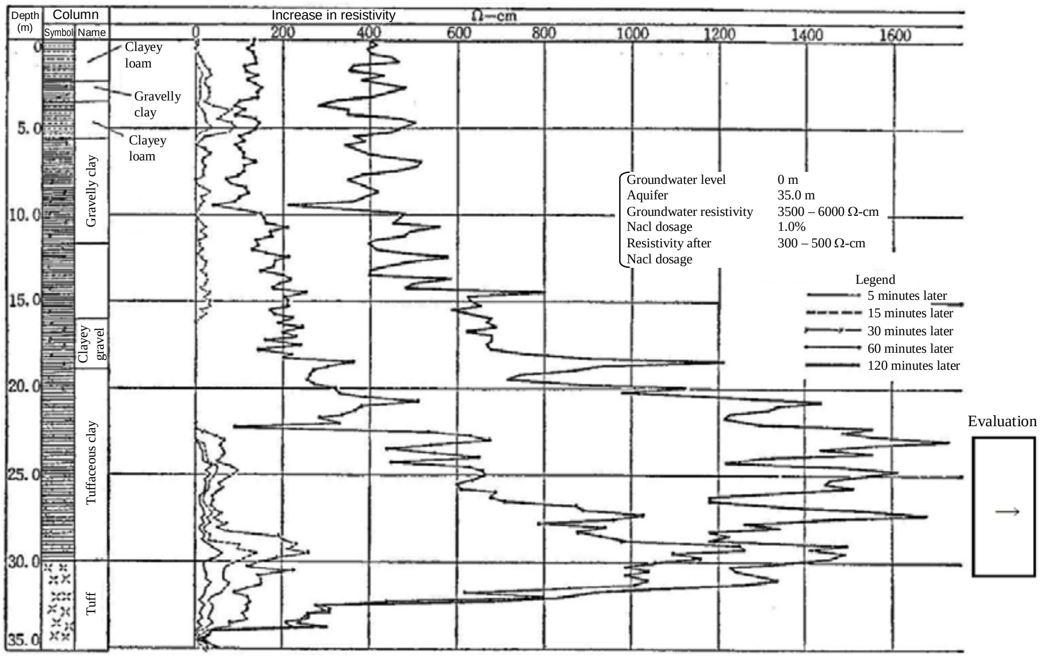


Fig. 2-32 Results of groundwater logging[2)]

(3) Simple pumping test

A simple pumping test is carried out to obtain the coefficient of permeability of the groundwater flow layer and the ground that uses borehole water.

To conduct a test, create a bare borehole section at intervals of three to five meters during boring, pump up the borehole water using a pump or a simple water sampler until the water level in the borehole reaches a certain level, and estimate the pumped-up volume. After reaching that level, stop pumping and obtain a curve that represents the time versus the water level recovery relationship. The coefficient of permeability at each depth is derived from this recovery curve.

A coefficient of permeability of the ground plays an important role in the groundwater analysis. Even when good results are not obtained from groundwater logging, a simple pumping test may provide good results. Therefore, it is desirable to perform this test.

(4) Groundwater temperature logging

Groundwater temperature logging is performed to investigate and analyze the position and the conditions of the groundwater flow layer by replacing borehole water with hot water and examining temperature changes due to the inflow of groundwater.

A sensor and measuring system that can measure at multiple measuring points has been developed, making it possible to perform quick measurement and analysis.

Figure 2-33 gives an outline of a multipoint temperature logging system.

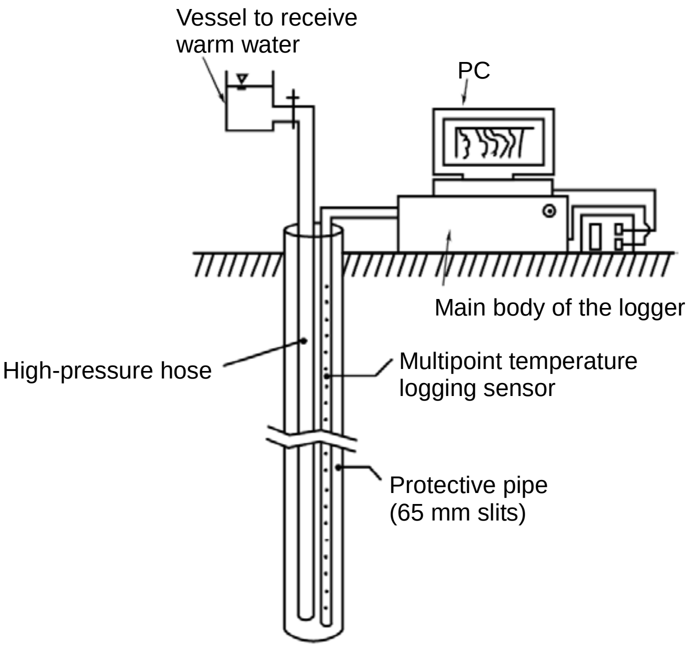


Fig. 2-33 Outline of a multipoint temperature logging system[19)]

(5) Measurement of flow direction and flow velocity within the borehole

The following methods have been proposed as methods for investigating the flow direction and flow velocity of groundwater: (i) direct measurement using a flow direction/velocity meter fitted with a propeller, (ii) survey of flow direction and velocity by visually tracking foreign matters (tracers) in the groundwater using a borehole camera, and (iii) mechanical measurement of various tracer substances.[20)] Of these methods, Method (iii) is normally adopted because the measurement by (i) and (ii) is difficult due to the disturbance of water flow when the velocity is low.

(6) Groundwater tracking survey

Groundwater tracking is performed to find the flow route (flow direction) by putting a tracer, such as water soluble pigment, salt, or inorganic chemicals, into the groundwater via a survey borehole, etc. and by detecting it in the spring water, borehole, well, stream, etc. Detection is made by comparing with the background values at each sampling position that are determined in advance.

The upper slope should be selected as the tracer dosing position. To ensure that the tracer flows out, a large volume of water should be injected and tracer infiltration facilitated with the impact of water head. Water sampling should be made at as many positions as possible over the entire area, such as boreholes, spring water, wells, streams, etc. In the case of a borehole, the tracer may be slow to spread, slow to reach the groundwater flow layer, or be lost due to dilution if a permeable layer exists below the water surface. Therefore, it is desirable to sample water at the position of the permeable layer by referring to the results of groundwater logging. For sampling, use a water sampler that can take water at any depth. Water sampling should be made 0.5, 1, 2, 4 and 8 hours after dosing the tracer on the first day and once a day on the second day or later for at least 20 days. Then, by plotting the detection results and detection time of the tracer at each sampling position on the chart, the flow route of groundwater will be found. Use non-hazardous substances as the tracer. Measure the background concentration of the tracer for use once a day for at least a week before the start of groundwater tracking. Only values that exceed a certain background value are evaluated as “tracer detected” (see Fig. 2-34).

Groundwater tracking can also be used to estimate the coefficient of permeability from the distance between the tracer injection borehole and the water sampling borehole and the detection time. The obtained coefficient of permeability is basic material for use in the design of groundwater drainage works.

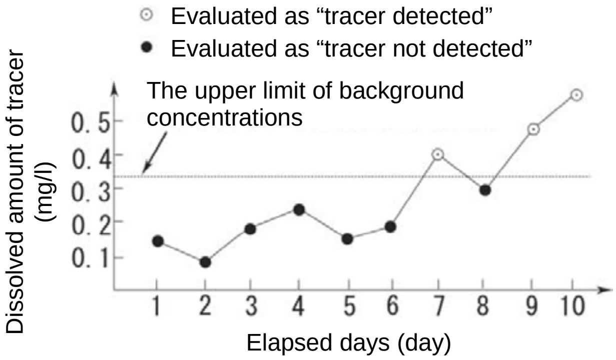


Fig. 2-34 Results of tracer detection[1)]

(7) Electrical prospecting

Electrical prospecting is often performed to find the conditions of groundwater distribution over a wide area. The resistivity method is normally adopted.

The resistivity of the ground varies according to the composition of rock and soil, the porosity associated with crush zones and cracks, degree of saturation, resistivity of groundwater and the content of clay minerals related to weathering and alteration, etc. Therefore, the characteristics of the landslide mass may be clarified to some extent if electrical prospecting is performed.

(8) Earth temperature prospecting

If spring water temperatures and the temperatures of drainage water from the drainage bore are measured at the landslide site for a long period, it is known that they are stable all the year round with only ±2°C variation. In contrast, the ground surface temperatures at a depth of one meter vary greatly, as much as ±10 – 13°C. This means that there is a temperature difference between the ground surface and the subsurface area where the groundwater flows. Earth temperature prospecting aims to identify the position of a groundwater artery by tracking such a temperature difference.

For the measurement of ground surface temperatures at a depth of one meter, insert a thermistor thermometer into the ground at the bottom of the hole drilled by an iron rod, and measure the temperature 5 – 10 minutes later when the thermometer has adapted to the surrounding ground.

(9) Water quality survey

A water quality survey is conducted to find the flow route of groundwater and the relationship between surface water and groundwater by classifying groundwater at the landslide site according to the quality of land water and by examining its quality. In general, the groundwater is classified into two types: shallow groundwater that comes out a short time after the rainwater has seeped into the ground, and deep groundwater that is retained in the ground for a long time.

Shallow groundwater, which is retained in the ground for a short time, is similar to the land water in terms of water quality composition. Shallow groundwater is mainly observed at the landslide site and collapsed site having a thin moving layer, at the foot of a large-scale landslide, or at the cut slope of a road. Deep groundwater can be classified into two types: the type that flows along the cracks, faults, and crush zones in the bedrock and the type that flows along the surface topography of the bedrock. The latter type of deep groundwater has properties between those of the shallow groundwater and the former type of deep groundwater, and we can consider it as the mixture of those two types of groundwater.

For the groundwater survey, collect water samples, about one liter, at each outcrop of groundwater (spring water, well, borehole, pond, swamp, stream, etc.) in and around the landslide site. Then conduct water quality tests on them and infer the flow route of groundwater based on the obtained results. General measurement items include water temperature, pH, EC, BOD, HCO_3, Cl, SO_4, SiO_2, Ca, Mg, Na, K, etc. Water quality tests are usually conducted in accordance with the rules of the water quality survey specifications, which are based on the National Land Survey Act.

2.4.7 Soil test

A soil test is performed to estimate a slip surface strength or a ground strength that is necessary for the design of prevention works.

For the estimation of a slip surface strength, a soil test or a rock test suitable for the purpose should be performed, such as a box shear test, a triaxial compression test, and a ring shear test.

To estimate the ground strength, which is necessary for the design of prevention works, a borehole horizontal load test, a standard penetration test, etc. should be performed.

Comments

Bore cores are often used as test specimens, but it is also advisable to conduct a test when the outcrop of a slip surface is exposed at the landslide scarp or foot or when it is exposed during the construction of a drainage well or a drainage tunnel.

There are different types of shear strength: peak strength, fully softened strength, and residual strength. Research is ongoing to determine which of these shear strengths should be used for landslide stability analysis. Therefore, the so-called back-calculation method is often adopted, as mentioned below in 3.2.2.1 “Soil strength constants.” The evaluation of the effectiveness of groundwater drainage works varies greatly depending on the soil strength constant. Therefore, shear strength constants obtained from soil tests are normally used as reference values only.

To estimate the ground strength, which is necessary for the design of prevention works, a borehole horizontal load test, a standard penetration test, etc. that can provide a coefficient of ground reaction are usable.

1) Physical test

A physical test is carried out to investigate the physical properties of the soil. In the landslide survey, physical tests such as a water content test, a particle size analysis, a liquid and plastic limit test, a wet density test, etc. are conducted mainly focusing on the slip surface.

A physical test can produce results in a shorter time than a mechanical test. Therefore, it may be possible to identify a slip surface from the comparison of the soil bore log and the physical property values in the depth direction, which are obtained by a bore core test.

2) Box shear test

In the box shear test on the slip surface clay, a specimen is set in the shear box which is separable into upper and lower parts, and one of the parts is horizontally moved while a vertical stress is applied from above in order to shear the specimen. If this test is conducted on multiple specimens under different consolidation stresses, strength constants c and ϕ can be obtained. The cyclic box shear test equipment for obtaining a residual strength has been developed and put into commercial use.

3) Triaxial compression test

The specimen for a triaxial compression test is cylindrical-shaped, 3.5 to 5.0 cm in diameter and 8.0 to 12.5 cm in height. This test is designed to obtain shear strength indirectly by the application of compression. It is also possible to control the pore water pressure and the stress acting on the specimen. The disadvantage of this test is that the height of the specimen can be compressed by only about 15% and the residual strength is not measureable.

4) Ring shear test

The specimen for a ring shear test of slip surface clay is ring-shaped and hollow in the center. The specimen size is usually 6.0 to 10.0 cm in inside diameter, 10.0 to 20.0 cm in outside diameter, and 1.0 to 2.0 cm in height. The feature of this test is that an infinite shear displacement can be induced since the shear propagates in the circumferential direction of the ring. Therefore, it is said that this test accurately reproduces the strength characteristics (residual strength) of slip surface clay that has sustained a large displacement.

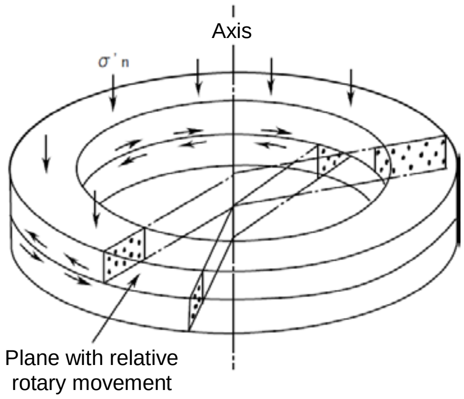


Fig. 2-35 Ring shear test equipment[21)]

5) Selection of test equipment by the type and strength of samples

Table 2-9 shows the selection of test equipment that varies according to the type and strength of the samples.

The peak strength is usually obtained by a triaxial compression test using undisturbed samples, but it can also be obtained by a cyclic box shear test and a ring shear test. The fully softened strength is often obtained by a triaxial compression test using slurry samples, but it can also be obtained by a cyclic box shear test and a ring shear test using slurry samples or undisturbed samples. The residual strength cannot be obtained by a triaxial compression test, so it should be obtained by a cyclic box shear test or a ring shear test. Samples containing slip surface clay can reproduce the actual strength of the slip surface rather realistically. The problem is that it is difficult to set it on the test equipment.

Test methods should be selected in view of the activity level of landslide and other factors.

Table 2-9 Selection of test equipment by the type and strength of samples[22, 23]

Sample \ Strength	Peak strength	Fully softened strength	Residual strength	Shear test method
Undisturbed	○, $\overline{CU}$	×	×	Triaxial compression
	△, *CD*, III	△, *CD*, II	○, *CD*, I	Cyclic box shear
	△, *CD*, III	△, *CD*, II	○, *CD*, I	Ring shear
Slurry	×	○, $\overline{CU}$	×	Triaxial compression
	×	△, *CD*, III	○, *CD*, I	Cyclic box shear
	×	△, *CD*, III	○, *CD*, I	Ring shear
Precut	×	×	×	Triaxial compression
	×	×	○, *CD*, II	Cyclic box shear
	×	×	○, *CD*, II	Ring shear
Slip surface included	△, $\overline{CU}$, or *CD*			Triaxial compression
	○, *CD*, II			Cyclic box shear
	○, *CD*, II			Ring shear

Measured strength
○: usable
△: usable in some cases
×: not usable

Test conditions
$\overline{CU}$: consolidated undrained (measurement of pore water pressure)
CD: consolidated drained

Shear displacement
I: very large
II: large
III: not large

2.5 Analysis

Based on the results of preliminary, rough, and detailed surveys, examination should be made on the landslide occurrence and movement mechanisms, including the primary and secondary causes of landslides, the range and scale of landslide blocks, the shape and position of slip surfaces, groundwater conditions, etc. A landslide block diagram and a landslide sectional diagram should be produced using the obtained results.

Comments

In the analysis process, perform analysis on the landslide mechanism using the results of the surveys shown in Table 2-10 and prepare a landslide block diagram and a landslide sectional diagram.

Table 2-10 Analysis items and surveys used

Analysis item		Preliminary survey	Site reconnaissance	Topographic map production	Geological survey	Slip surface survey	Ground surface deformation survey	Groundwater survey	Soil test
Production of a landslide block diagram									
	Landslide block diagram	○	○	○			○		
	Land use, structures, etc.	○	○						
	Features of landslide topography		○	○					
	Survey positions and results				○	○	○	○	
	Slip surface contour map		○	○	○	○	○		
Production of a landslide sectional diagram									
	Geological profile	○	○		○				
	Distribution of groundwater level		○					○	
	Land use, structures, etc.	○	○						
	Features of landslide cross section		○	○	○	○			
	Survey positions and results				○	○	○	○	
Analysis of landslide mechanism		○	○	○	○	○	○	○	○

1) Analysis of landslide mechanism

To identify the landslide mechanism and reflect it in the landslide prevention plan, the landslide survey results should be analyzed comprehensively, with a focus on the primary and secondary causes of the landslide, the range and scale of landslide blocks, the shape and position of slip surfaces, and the groundwater conditions. Utilizing the results, a landslide block diagram and a landslide sectional diagram should be produced and the concept for the formulation of a prevention plan described. The survey results should be attached to these materials.

(1) Primary causes of a landslide

In general, landslide sites have various primary causes susceptible to a landside. Even though landslides are seemingly triggered by the artificial secondary causes shown below, the underlying causes are largely natural. Primary causes include topography, geology (soil property), geological structure, groundwater conditions, etc.

(2) Secondary causes of a landslide

If areas having the above-mentioned primary causes are exposed to natural phenomena, such as earthquakes, flooding due to heavy rain, rain during the rainy season, snowmelt, and other changes in natural conditions (scouring due to river at the foot of landslide, changes in the surface water and groundwater routes at the landslide site, blockage of channels, etc.), landslides may be induced by these secondary causes.

In the meantime, if a fill slope or a cut slope is constructed at the head (head loading) or at the foot (reduction in resistance) of a landslide-prone slope, respectively, or if a slope is submerged under water in areas having these primary causes, landslides may be triggered under the effect of those artificial causes. Landslide may also be triggered by alterations in the action of hot springs due to volcanic gas, etc. in volcanic areas.

(3) Range and scale of landslide blocks

Determine the entire landslide range primarily based on the results of the ground surface deformation survey and divide it into several blocks by considering their movement mode. The correlation between rainfall and the moving direction and moving conditions of the landslide should be examined. The area of those blocks and their soil volume should also be examined.

Also, based on the examination results, the future moving possibility and the moving range of those bocks should be examined.

(4) Shape and position of slip surfaces

Primarily based on the results of a slip surface survey, the relationship between the shape and position (depth) of slip surfaces and their geology and geological structure should be examined.

(5) Groundwater

Primarily based on the results of a groundwater survey, the relationship between the sliding movement of the landslide and the groundwater distribution, changes in the groundwater level, the flow direction of the groundwater, water quality classification, etc. should be examined.

2) Landslide block diagram

A landslide block diagram, with movement blocks described on the topographic map (Fig. 2-36), should be used for analysis as basic material.

To produce a landslide block diagram, draw landslide blocks identified from preliminary, rough, and detailed surveys on the topographic map using dashed lines, etc. Also, draw the range of potential landslides inferred from the measurements by a ground inclinometer, etc. using dashed lines. Prepare a slip surface contour map indicating the distribution of the slip surface if necessary.

Describe the prevention works and their primary attributes as well after the prevention plan is prepared.

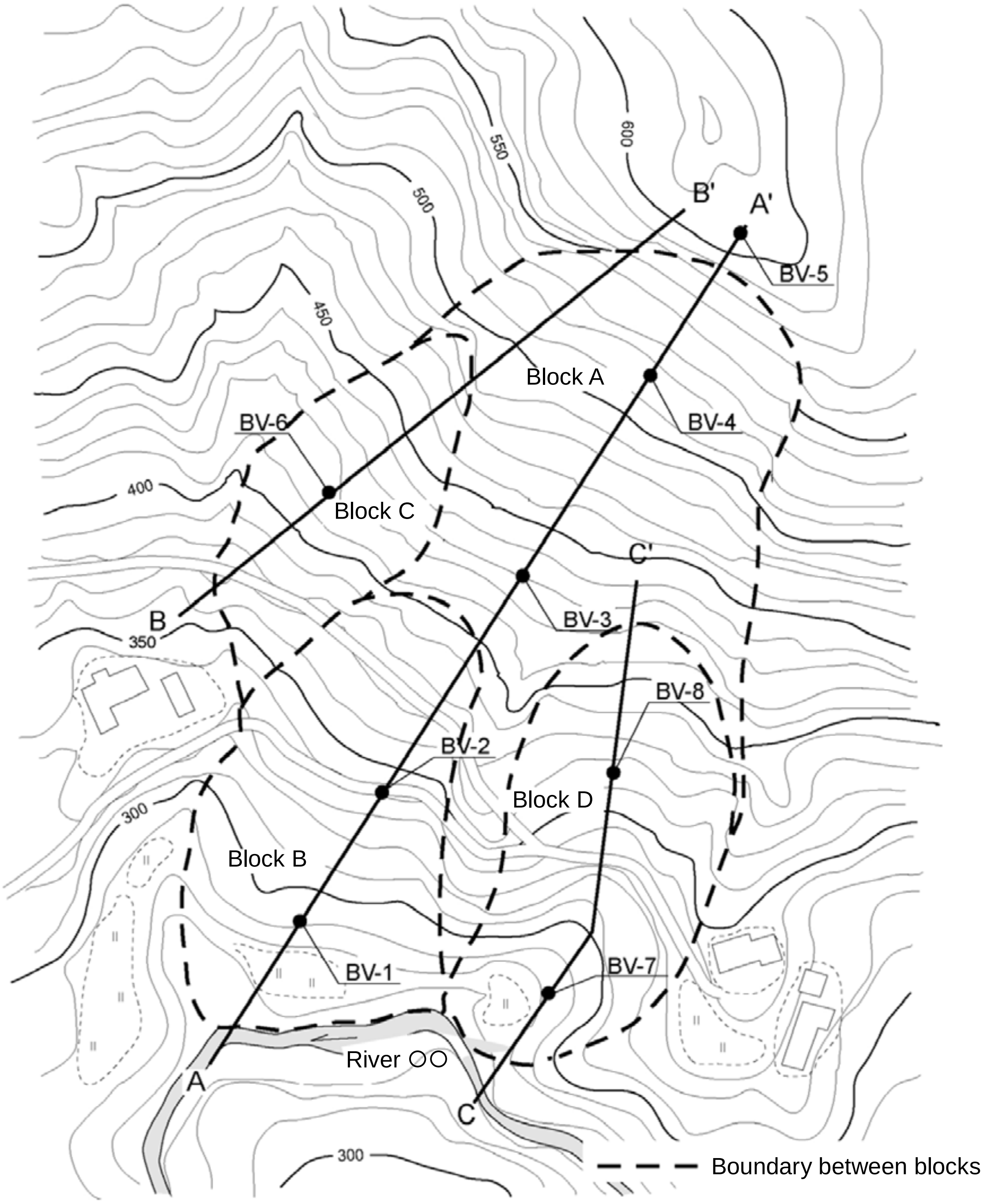


Fig. 2-36 Example of a landslide block diagram

3) Landside sectional diagram

A landslide sectional diagram is produced by describing the survey results on a geological profile.

To produce a landslide sectional diagram, prepare a geological profile along the main survey line first, which is basically in the same direction as the landslide movement direction, then describe the positions of a potential slip surface, groundwater level, crack positions, etc. on that profile. Describe those features on the geological profile after carefully examining the results of the bore survey and other surveys. Produce a landslide sectional diagram along the secondary survey line and traverse survey line if necessary.

If the sectional shape before the landslide is known, describe it on the landslide sectional diagram. Also, describe the position of aquifers found from a groundwater logging and the maximum and minimum groundwater levels taken from each borehole. The landslide sectional diagram should be produced along the survey line at a scale of about 1/200 or 1/500 (the same scale for both the vertical and horizontal directions). The following features should be described on the diagram: bend points of ground surface inclination, cracks, unevenness, ponds and bogs, depressions, plateaus, survey bore positions, positions of various measuring devices, surface soil, horizon and inclination of the bedrock, distinction between bedrock and colluvial deposit, soil quality, distribution of faults and crush zones, etc. (Fig. 2-27).

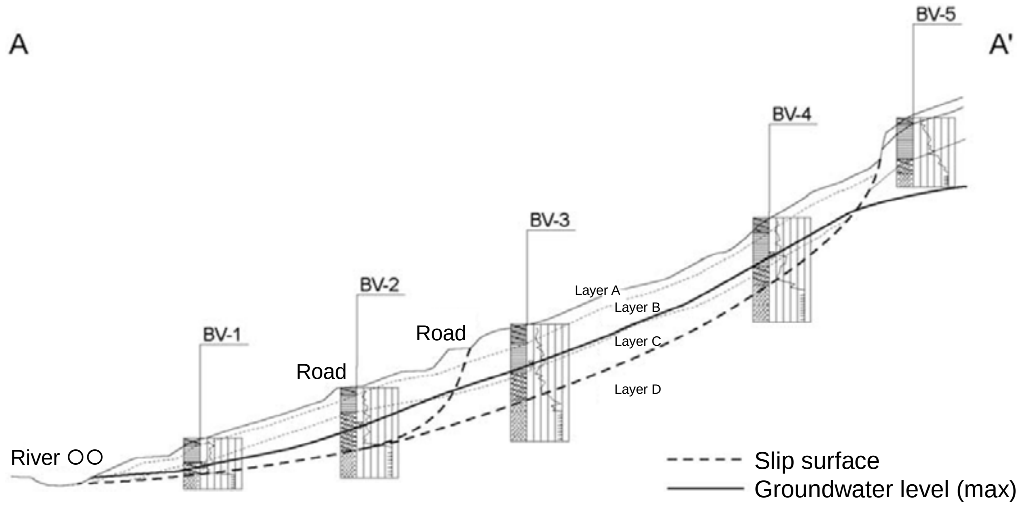


Fig. 2-37 Example of a landslide sectional diagram along the main survey line

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Chapter 3 Planning

3.1 Landslide Prevention Plan

3.1.1 General

A landslide prevention plan should be prepared so that it is a comprehensive plan consisting of structural measures, such as the installation of landslide prevention facilities, and nonstructural measures, such as the establishment of a warning and evacuation system, based on the results of landslide surveys.

The landslide prevention plan should be consistent with the surrounding environment, related laws and regulations, local improvement plans, etc.

Comments

The landslides that are targeted by landslide prevention works are usually large scale landslides composed of multiple movement blocks, with construction taking many years. On the other hand, there are many houses, public facilities, etc. on landslide-prone slopes, so it is essential to implement non-structural measures, such as warning and evacuation systems when the landslide is activated. Therefore, a landslide prevention plan should be prepared with consideration to the implementation of non-structural measures as well so that a warning and evacuation system is always in place.

A landslide prevention plan should be prepared to an appropriate scale and content by considering landslide conditions (topography, geology, scale, movement, etc.), the importance of the structures to be protected, the urgency and effectiveness of protection works, etc., in addition to the results of surveys and analyses conducted in advance.

A landslide prevention plan should be consistent with the surrounding environment, related laws and regulations, local improvement plans, etc.

3.1.2 Determination of structures to be protected

The structures to be protected under the landslide prevention plan should be determined considering the scale of the target landslide and its occurrence and movement mechanisms.

Damage types covered by the landslide prevention plan are:

(i) Loss of human life, damage to houses, roads, paddy fields and dry fields, and damage to public facilities located on the landslide slope

(ii) Loss of human life, damage to houses, roads, paddy fields and dry fields, and damage to public facilities located downstream of the landslide slope

(iii) Inundation above the landslide dam

(iv) Damage due to the flow of debris and flooding downstream due to the collapse of the landslide dam

Comments

Landslide phenomena develop slowly in most cases, but some landslides move or slide abruptly. Therefore, it is necessary to determine the possible landslide movement range and the damage range by referring to the past landslide cases, etc. near the target site (see 2.3.2 (8)).

The importance of structures to be protected varies according to the frequency of use and the availability of alternative facilities, etc. In the case of roads, the importance varies according to the traffic volume and availability of alternative routes. Landslides tend to occur in mountainous areas, so even alternative routes often take much time to reach.

3.1.3 Establishment of a proposed safety factor

In the landslide prevention plan, proposed safety factors (P.Fs) should be determined for individual landslide blocks.

In the case of general landslide prevention works, assume the current safety factor as 0.95 – 1.00 according to current sliding conditions, then determine the proposed safety factor to 1.10 – 1.20 by taking into account the landslide occurrence and movement mechanisms, importance of objects to be protected, possible damage level, etc.

Even for emergency responses that are taken to ensure safety for the time being, the proposed safety factor should be set at 1.05 or more.

It must be noted that the proposed safety factor indicated here is a value for determining the scale of landslide prevention works, and not the value indicating the stability of the slope after the works.

Comments

The proposed safety factor indicated above has been determined based on past landslide cases involving cut slopes and fill slopes and empirical design safety factors that have been adopted for landslide prevention works in Japan. For example, there was a case where a landslide became active due to a decrease in safety factor by 5 – 10% when the safety factor before the landslide was assumed to be 1.00 [1)]. Other considerations involved were that the slip surface strength decreases as the landslide movement develops, and that the permeability increases due to the collapse of soil mass as the landslide movement develops. Here, it must be noted that the proposed safety factor mentioned above is an empirical value that is based on the soil strength constants that are obtained by back-calculation (see 3.2.2.1) using a simple safety analysis method.

3.1.4 Warning and evacuation measures

As warning and evacuation measures against landslides, the management standard (see 4.3) that provides a reference for taking measures should be established by considering landslide occurrence and movement mechanisms. Also, monitoring equipment, such as a ground extensometer and a ground inclinometer, should be installed and an adequate communication system to relevant organizations established.

Comments

To prevent damage due to a landslide, it is necessary to implement warning and evacuation measures to prevent human casualties, in addition to the execution of landslide prevention works. Since landslides move slowly compared with collapses, warning and evacuation measures are usually taken based on the slope conditions and movement amounts collected by monitoring equipment. In other words, it is desirable to take warning and evacuation measures based on the monitoring results of landslide movement. Landslide movement varies by topography, geology, shape of the slip surface, etc., so a warning and evacuation standard should be established in accordance with the movement characteristics of the landslide by referring to survey and analysis results and past landslide cases in the vicinity. Furthermore, to help those measures, monitoring equipment that can collect data immediately, such as a ground extensometer and a ground inclinometer, should be installed. In addition, an adequate communication system to relevant organizations should be set in place. When implementing warning and evacuation measures, the following points must be enforced.

(1) The target range of warning and evacuation must be determined.

- Monitoring system on landslide movement
- Landslide range and range of reach

(2) Warning and evacuation timing must be defined.

- Establishment of warning and evacuation control values

(3) A warning and evacuation information communication system must be established.

3.1.5 Environmental considerations

Landslide prevention works will inevitably cause some impact on the environment in order to achieve the necessary disaster prevention benefits, but efforts should be taken to reduce that impact as much as possible.

Comments

Because activated landslide movement has an impact on the slope environment, it is necessary to stop that movement in terms of slope environment preservation, etc. Landslide prevention works can prevent the landslide mass from falling and preserve the habitats of plants and animals on the landslide slope, but they may totally change the slope environment in some cases. For example, large-scale earth removal and embankment loading will remove vegetation distributed on the slope. Also, groundwater drains may have an impact on the aquatic plants, etc. by changing the groundwater conditions and eliminating swamps and bogs at the landslide site.

It is unavoidable to have some impact on the environment if landslide prevention facilities are installed to obtain necessary disaster prevention benefits, but that impact must be minimized as much as possible. Concurrently, the type of planning, installation method, and structure that can facilitate the restoration of the natural environment should be adopted. Also, the shape and layout of disaster prevention facilities should be determined with consideration for aesthetics and the ecosystem.

The following environmental considerations must be taken in the two broad categories of the environment that may be affected by the installation of landslide prevention facilities: 1) the natural environment and aesthetics, and 2) the living environment. These considerations must be taken appropriately at every stage of survey, construction, and maintenance.

(1) Natural environment and aesthetics

- Large-scale earth removal and embankment loading can change the slope environment drastically. Therefore, when selecting the work type, consider the restoration of the natural environment and the promotion of greening.
- In the case of restraint works on the slope, promote early greening in consideration of the natural environment and aesthetics.
- Take sufficient care for environmental impact during landslide prevention works, such as tree cutting and generation of muddy water.

(2) Living environment

- It must be noted that landslide sites, particularly those in mountainous areas, are often an important habitat.
- The landslide site often has a plenty of groundwater that the local people use. Since groundwater drains may have an impact on this water, sufficient prior survey is essential.
- On the other hand, groundwater drains may open up new forms of water usage for local people, such as agricultural water, snow-removal water, and potable water. Carefully examine the possibility of groundwater usage and the local demand for water. [2)]

3.2 Landslide Prevention Facility Layout Plan

3.2.1 General

A landslide prevention facility layout plan should be prepared to prevent landslide disasters based on the landslide prevention plan (see 3.1) and by considering the landslide scale, occurrence and movement mechanisms, importance of objects to be protected, possible disaster level, etc.

It is not always possible to get a full picture of the landslide from advance surveys. Therefore, the layout plan should be revised as new information is obtained.

It is also necessary to confirm that the intended effect of landslide prevention works is attained during and after construction, and revise the plan if necessary.

Comments

In the landslide prevention facility layout plan, the construction method, construction position, and the number of facilities, the construction sequence, etc. should be determined based on the landslide prevention plan (see 3.1) and by considering the landslide scale, occurrence and movement mechanisms, importance of objects to be protected, possible disaster level, and the characteristics of each construction method, with a view to preventing landslide disasters.

A landslide often consists of multiple blocks that move in an interrelated manner. Therefore, the layout of prevention facilities should be planned to improve the stability of individual blocks firstly by determining the range of blocks, correlation of blocks and their stability, priority of measures of individual blocks in terms of the position and importance of objects to be protected, etc.; and then to improve the stability of the entire target landslide site based on the landslide prevention plan. A full picture of the landslide may not be able to be obtained from advance surveys. Therefore, it may be necessary to revise the plan depending on subsequent surveys.

It is necessary to confirm that the intended effect is duly realized during and after construction. It is desirable to evaluate the effectiveness of the works in terms of landslide phenomena, such as displacement. However, special caution must be taken regarding the evaluation after the end of landslide phenomena because landslide phenomena are usually slow and may be activated intermittently due to abnormal weather conditions, such as heavy rain, persistent rain, snowmelt, etc. Concerning evaluation after the construction, make arrangements to continue monitoring for some years if necessary and confirm that abnormal behavior attributable to a landslide does not recur.

3.2.2 Slope stability analysis

In the landslide prevention facility layout plan, slope stability analysis should be performed on the cross section along the moving direction of movement of each landslide block, and based on the obtained results, the method and scale of the landslide prevention works should be determined to ensure the proposed safety factor.

Comments

There are two kinds of stability analysis methods: the limit equilibrium method that treats stability in terms of the limit equilibrium of stress, and the stress analysis method that takes into account the stress-strain relationship of the soil.

The split method (slice method) is well-known as an example of the limit equilibrium method, and depending on the assumptions, such as the interslice force, a simple method (Fellenius method), the Bishop method, the Janbu method and the Morgenstern-Price method, etc. are proposed.[3), 4)] Also, 2D stability analysis that uses a cross section along the main survey line and 3D stability analysis that deals with the entire landslide block are proposed. As the 3D stability analysis method, the Hovland method [5)] and 3D simple Janbu method[6)], etc. are proposed. In addition, a simple 3D analysis method [7)] is proposed, which adds a weight that varies according to the width between cross sections to the stability analysis of 2D cross sections along multiple survey lines.

Stress analysis methods include methods such as the finite element method, discrete element method, rigid spring model method, etc. They differ in their treatment of discontinuous planes of the landslide.[8)]

It is desirable to adopt an appropriate analysis method from the above in consideration of the characteristics of the landslide site (planar shape, slip surface shape, moving conditions, etc.). To date, a simple 2D analysis method has often been adopted, and the proposed safety factor is also determined based on this method.

The simple method is introduced below.

The simple method uses a similar type of equation with the so-called Fellenius method or Swedish slice method. The simple method is originally intended for arc landslides and derives a safety factor from the ratio between the rotation moment and the resistance moment at the rotation center of the arc landslide. However, this equation has also been used for non-arc landslides considering only the balance of forces.

$$FS = \frac{\sum(N-U)\cdot tan\phi' + c'\sum l}{\sum T} \quad \text{… (Equation 3-1)}$$

Where,

Fs: safety factor

N: normal force by gravity of slice (kN/m) $= W \cdot \cos\theta$

T: tangential force by gravity of slice (kN/m) $= W \cdot \sin\theta$

U: pore water pressure acting on slice (kN/m)

I: slip surface length of slice (m)

c': cohesion of slip surface (kN/m^2)

ϕ': internal friction angle of slip surface (°)

W: weight of slice (kN/m)

θ: inclination angle at the slice area of the slip surface (°)

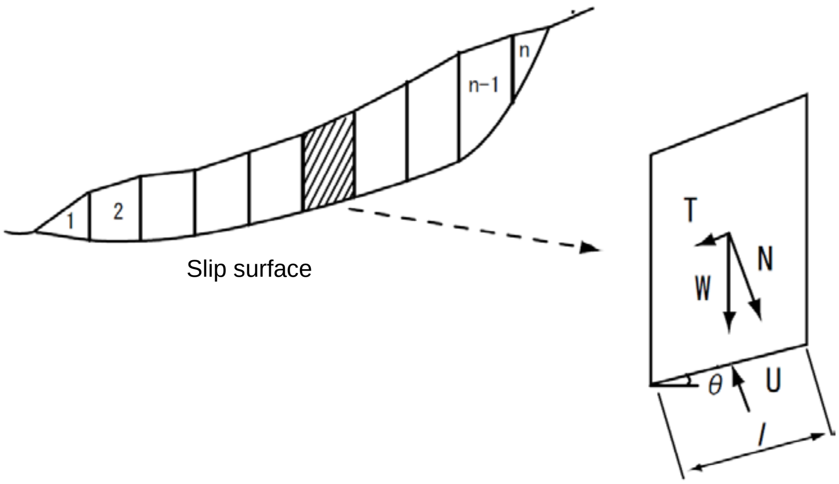

Fig. 3-1 Schematic representation of the simple method

3.2.2.1 Soil strength constants

Soil strength constants (cohesion of slip surface: c', internal friction angle of slip surface: ϕ') used for slope stability analysis should be determined by the most appropriate method in view of the landslide mode and soil conditions, such as a soil test on clay samples taken from the slip surface or back-calculation by estimating the current safety factor from landslide conditions.

Comments

Two methods are available for determining soil strength constants: (i) soil test on the clay samples taken from the slip surface, and (ii) back-calculation of soil strength constants by estimating the current safety factor from landslide conditions (back-calculation method).

In the case of stability calculation using a simple method, cohesion (c') and internal friction angle (ϕ') can be obtained by the procedures (1) – (3) below if the slip surface depth, unit weight, and pore water pressure have been found from detailed surveys.

(1) Determination of current safety factor

The current safety factor should be determined in view of current moving conditions (see 3.1.3).

(2) Estimation of cohesion (c')

Cohesion (c') is often estimated by a soil test or by referring to Table 3-1 which is established for the maximum layer thicknesses of the landslide mass. When the maximum vertical layer thickness is more than 25 m, c' is assumed to be 25 kN/m^2. However, its adequacy must be examined carefully by evaluating not only the value of c', but also the value of ϕ' comprehensively. Separate examination is necessary for the value of c' when the vertical layer thickness is less than 5 meters.

(3) Back calculation of internal friction angle (ϕ')

The internal friction angle (ϕ') can be obtained by back calculation by substituting the values obtained in (1) and (2) into the stability analysis equation (equation 3-1).

Then substitute cohesion (c') and internal friction angle (ϕ') obtained from procedures (1) through (3) into the stability analysis equation, and examine the content of landslide prevention works that will be required to achieve the proposed safety factor.

The value 18kN/m^3 is normally used as the unit weight of a soil mass. But if it is a highly porous layer containing a large amount of *shirasu* or boulders or a layer exposed to hydrothermal alteration, it is desirable to determine the unit weight by conducting a soil test.

Table 3-1 Maximum vertical layer thickness and cohesion

Maximum vertical layer thickness of landslide mass (m)	Cohesion c' (kN/m^2)
5	5
10	10
15	15
20	20
25	25

3.2.2.2 Pore water pressure

The pore water pressure used for slope stability analysis should be the value measured by the most appropriate method for measuring pore water pressure at the slip surface.

It is desirable to measure pore water pressure using a direct or indirect pore water pressure gauge. But if it is not possible, the groundwater level in the borehole can be used as an alternative.

Comments

The measured groundwater level in the borehole can be incorrect if a full hole strainer is used when multiple aquifers exist. If the soil around the strainer has low permeability, the groundwater level fluctuates with a time lag. Therefore, it is desirable to measure pore water pressure using a direct or indirect water pressure gauge.

However, if it is not possible to measure pore water pressure using those gauges, the measured groundwater level in the borehole can be used as an alternative. In this case, it is still necessary to install a partial hole strainer in the groundwater monitoring boreholes at positions appropriate for the hydrogeological structure of the landslide, so that groundwater fluctuations acting on the slip surface can be measured even though multiple groundwater zones are distributed or there is a layer of muddy water.

When sufficient monitoring data cannot be obtained in cases such as immediately after a disaster, prevention works should be planned based on stability analysis using groundwater level fluctuations during boring or the monitoring results in a short period. When sufficient monitoring data becomes available, the prevention plan should be revised as appropriate.

Normally, stability analysis is performed using the maximum groundwater level obtained from monitoring. However, if the groundwater level at the time of sliding is known, that groundwater level can be used for back-calculation to derive soil strength constants.

In the Fellenius method, $(N - U) < 0$ can occur if the slip surface is steep. In that case, $(N - U) = 0$ should be used in the calculations.

3.2.3 Selection of landslide prevention works

A landslide prevention facility layout plan should be planned to adopt control works and restraint works, either individually or in combination, based on the landslide prevention plan and by considering the landslide scale, occurrence and movement mechanisms, importance of structures to be protected, possible damage level, economy of the works, etc.

The following points must be noted when selecting the works to be performed.

1) Control works and restraint works should be rationally combined in view of their features and placed at adequate locations.
2) If landslide movement is actively continuing, restraint works should not be introduced in principle before control works, but introduced after the landslide movement is reduced or arrested by control works.
3) The total cost, including construction and maintenance, should be taken into account.

Comments

The landslide prevention works are roughly divided into control works and restraint works by the difference in prevention functions.

Control works … works aimed at arresting or mitigating landslide movement by improving the balance between sliding force and resistive force by improving the natural conditions at the landslide site, such as topography and groundwater conditions.

Restraint works … works aimed at arresting part of or all of the landslide movement by applying structural resistance.

Figure 3-2 shows the classification of landslide prevention works that have been adopted generally.

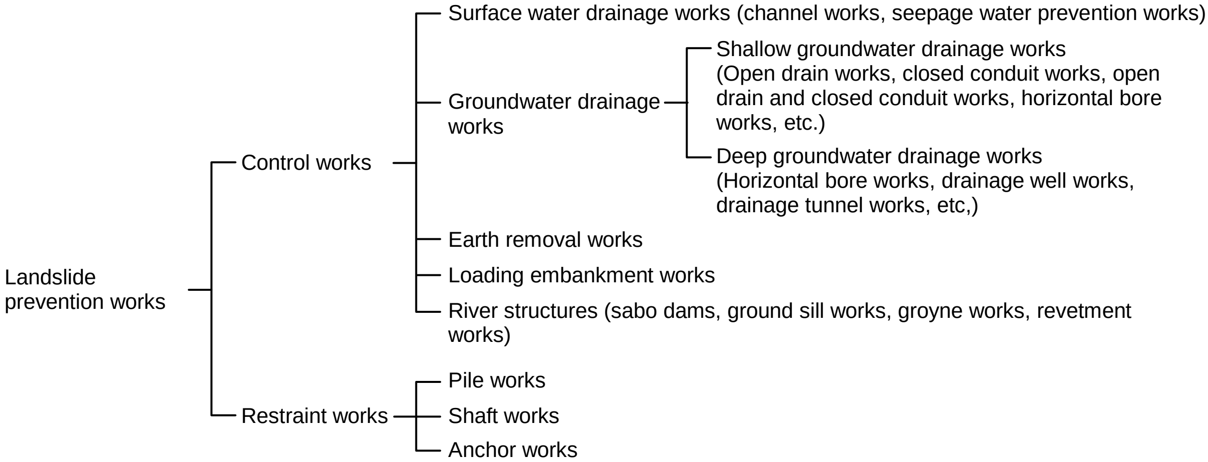

Fig. 3-2　Classification of landslide prevention works

Appropriate landslide prevention works should be selected by carefully considering various factors, including primary and secondary causes, particularly the relationship between rainfall (snowmelt) and groundwater and landslide movement, topography, and geology; landslide scale; movement mode; moving speed; objects to be protected; economy (total cost including construction and maintenance costs); priority, etc. Prevention works should be planned in principle after the characteristics of the target landslide have been clarified through detailed surveys.

Although it is not possible to discuss the planning process of landslide prevention works uniformly as landslide characteristics vary according to the site, general notes for planning are presented below, by placing a particular focus on secondary causes of landslide, reduction in the sliding force and addition of resistive force, landslide movement conditions, landslide scale, construction position of prevention works, etc.

1) Secondary causes of landslide (removal of secondary causes)

In general, removing the secondary causes of a landslide is the most effective prevention measure.

It is no exaggeration to say that secondary causes of many naturally occurring landslides are an increase in the amount of groundwater due to heavy rain, persistent rain, snowmelt, etc. Therefore, surface water drains and groundwater drains are important works to be considered first.

On the other hand, when secondary causes are artificial activities, restoration to the former state is effective particularly in the case of an emergency response. For example, if a cut slope or a fill slope is a secondary cause, restoration to the former state in order to remove that impact as much as possible is an effective measure.

2) Reduction in sliding force, addition of resistive force

Typical works for reducing the sliding force of landslide (the denominator of the stability analysis equation) is earth removal conducted at the landslide head area. It can provide an immediate effect, but careful examination must be made in advance to confirm that neither an unstable slope nor another landslide block exists at the upper part of the slope from which earth is removed.

On the other hand, typical works that can add resistive force (the numerator of the stability analysis equation) are embankment loading and pile construction. The former, which is an effective measure, is constructed at the foot of landslide. Anchors are also often adopted.

3) Moving conditions of the landslide

If the landslide is moving quickly, it is impossible to construct restraint works. Even if they are constructed, they may be damaged. Therefore, artificial secondary causes such as a cut slope or a fill slope should be removed first and then control works such as surface water drains and groundwater drains (e.g. horizontal bores) should be constructed. After the speed of the landslide is reduced by these works, restraint works should be introduced as appropriate.

4) Landslide scale

Regarding the groundwater drains in the case of small landslides, it is not difficult to drill a horizontal bore penetrating the slip surface from the ground surface. However, as the landslide scale increases, the bore length becomes longer and the water drainage efficiency around the slip surface decreases. In this case, drainage wells and drainage tunnels, etc. become promising alternatives that are efficient and economical.

In the case of restraint works, the construction of piles becomes difficult as the landslide scale increases, and anchors and shafts become promising alternatives.

5) Position of constructing prevention works

It is effective to construct groundwater drains and surface water drains at the landslide head area where many cracks and voids exist, as it is a tensile zone. Groundwater drains are also constructed at the head area to prevent inflow of groundwater from outside the landslide site. Earth removal is also conducted at the head area.

In contrast, loading the embankment and restraint works are appropriate for the landslide foot area, which is a compression zone.

3.2.4 Planning of control works

Control works should be planned so they are laid out rationally as a combination of the following works to improve the balance between the sliding force and resistive force by improving the conditions of topography, groundwater, etc. at the landslide site, and concurrently considering the total cost, including maintenance.

Comments

The following types of works can be adopted as control works.

- Drainage of surface water: channels, seepage water prevention
- Drainage of shallow groundwater (groundwater flowing in the layer near the surface):
  closed conduits, open drains and closed conduits, horizontal bores
- Drainage of deep groundwater (groundwater at the deep area near the slip surface):
  horizontal bores, drainage wells, drainage tunnels
- Removal of soil mass at the landslide head area: earth removal
- Placement of soil mass having good permeability at the landslide foot area: loading the embankment

- Protection of riverbanks and stabilization of the landslide foot area: erosion control works by river structures, etc.

1) Surface water drains

Surface water drains are constructed to prevent seepage of rainfall and re-seepage of water from spring water positions, bogs, channels, etc. in order to control an increase in groundwater. Surface water drains include channels and seepage water prevention. Works that can be constructed quickly should be chosen in consideration of landslide conditions. Channels should be planned to suit the topography of the landslide site and should be of a scale that needs no large-scale earthworks. Channels to prevent surface water from flowing into the landslide site should be constructed at a stable peripheral area away from cracks and scarps.

The effectiveness of surface water drains cannot presently be quantified, but it is desirable that they form part of landslide prevention. They are particularly effective when rainfall and landslide movement are closely interrelated.

(1) Channels

Channels are constructed to collect rainwater within the landslide site quickly and to drain it away from the site, or to prevent water from flowing into the landslide site.

Channels are classified into collection channels and drainage channels.

(i) Collection channels

Collection channels are usually constructed in the traverse direction of the slope to collect rainfall and surface water quickly. Channels are constructed to relatively wide and shallow and connected to drainage channels.

(ii) Drainage channels

The cross section of drainage channels should be determined by a runoff calculation because they are used to discharge collected water away from the site quickly. Channels are constructed in locations that have a valley topography. Girdles are placed at intervals of 20 to 30 meters along the channel in principle, and a groundsill and a catch basin are installed at the end of the drainage channel or at the junction of the channels.

(2) Seepage prevention works

Seepage prevention works involve covering cracks with clay, cement, plastic sheeting, etc. To prevent water leaking from bogs, channels, etc., an impermeable cover can be applied, the bog can be cut, or the channels can be rerouted or improved.

2) Groundwater drains

The purpose of groundwater drains is to remove groundwater that flows into, seeps into, or is distributed in the landslide site in order to reduce the pore water pressure (groundwater level) in the landslide mass. Groundwater drains are classified into shallow groundwater drains to handle the groundwater flowing in the layer near the surface, and deep groundwater drains to handle deep groundwater near the slip surface.

The design groundwater level varies by the type of prevention works and topography, geology, and groundwater conditions at the landslide site. The groundwater level must therefore be examined and determined by referring to the groundwater level analysis results, past groundwater reduction results at similar locations, etc. When these reference materials cannot be obtained, the following values may be used as a reference. However, it must be noted that the values presented here are empirical values when groundwater drainage facilities are adequately placed at the landslide site, and they should be assumed as the maximum groundwater level reduction that can be expected. Hence, continuous monitoring must be made after the construction and if the expected groundwater level reduction is not achieved, the works must be reexamined and additional works applied if necessary.

Horizontal bore	3 m
Drainage well	5 m
Drainage tunnel	8 m

(1) Shallow groundwater drains

(i) Closed conduits

Closed conduits are installed to remove groundwater distributed in shallows areas of ground and rainwater that seeps into the ground from the ground surface. These works are particularly recommended when the objective is to remove abundant groundwater in the layer of soil that has a small permeability coefficient. Groundwater to a depth of two meters can be removed.

(ii) Open drains and closed conduits

Open drains and closed conduits are installed to prevent inflow and the seepage of surface water and to remove groundwater that has seeped from the surface into shallow ground. Shallow groundwater is water that has seeped from the surface, so a combined structure of closed conduits and surface water channels should be constructed at valleys and depressions on the slope.

(iii) Horizontal bores

Horizontal bores are the structures for removing shallow groundwater that cannot be removed by open drains or closed conduits, etc. The bores are constructed when topographically feasible. It is desirable to determine the diameter, length, angle, etc. of the horizontal bores based on the results of groundwater analysis, but their tip intervals are generally 5 to 10 meters. They are constructed intensively in areas that have abundant groundwater.

(2) Deep groundwater drains

(i) Horizontal bores

Horizontal bores that are constructed to remove deep groundwater remove the groundwater distributed around the slip surface and groundwater along the faults and crush zones. These bores should be planned toward the aquifer after confirming the presence of deep groundwater in the landslide block, the groundwater level, etc. The tip intervals of bores are generally 5 to 10 meters. They are often planned to create a 5- to 10-meter overbreak penetrating through the potential slip surface.

(ii) Drainage wells

Drainage wells are constructed to remove deep groundwater. They are planned particularly when the intention is to collect deep groundwater intensively or when the length of the horizontal bores exceed 50 meters.

Drainage wells are constructed when no spring water is expected from the well walls but when a large volume of water is expected from the groundwater artery by drainage bore.

The position of the drainage well should be at least two meters shallower than the slip surface to ensure the stability of an open caisson and drainage bore in the case of an active landslide site. If the landslide site is not active, the caisson foundation of the drainage well can be constructed in the stable ground penetrating through the slip surface.

The position and scale of the drainage well should be determined by considering the water collection effect, construction safety and maintenance, etc. In particular, the position and construction method of the drainage well should be determined in a way that allows natural drainage of water from the well to the ground surface. If direct drainage of the water from the well to the ground surface is impossible, construction of a relay well should be planned. In either case, drainage bores should be constructed at positions that do not cross landslide blocks in principle so that they will not be cut by a landslide.

Drainage wells are constructed when intensive groundwater drainage is necessitated at the landslide site where groundwater is distributed in a layered or folded form. If the groundwater distribution is multilayered, more than two layered bores in the vertical direction are required.

If the geology is poor and spring water is abundant, construction of the drainage well is difficult and other construction methods should be adopted. Also, at positions where there is active deformation, the caisson may sustain strain due to increased side pressure, which may result in a failure. It is advisable to avoid such a position in consideration of maintenance after the construction as well as the prevention of disasters during construction. Therefore, determine the position of the drainage well in principle by examining the geological conditions and the bedrock through survey bores.

When multiple drainage wells are constructed, determine their number and positions by considering the length of the drainage bores, the scope of possible impact of groundwater reduction due to those wells, and the groundwater conditions at the site.

(iii) Drainage tunnels

Drainage tunnels are planned when it is difficult to remove deep groundwater by drainage wells or horizontal bores.

Drainage tunnels are constructed with the aim of removing deep groundwater around the slip surface by water collection bores from inside the tunnel. Drainage tunnels are roughly classified into bottom drainage tunnels, which are constructed below the slip surface, and peripheral drainage tunnels which are constructed in the peripheral area of the landslide. Tunnels should not be constructed within the landslide mass in principle, and they should be located more than twice the diameter of the drainage tunnel from the slip surface.

Water collection bores should be bored toward the upper or horizontal direction from the bore space in the tunnel.

3) Earth removal

Earth removal is conducted to reduce the sliding force of the landslide by removing a soil mass from the head area. Before planning earth removal, it is necessary to conduct sufficient surveys and examinations so as not to create a potential landslide at the upper slope. If a potential landslide is found to exit at the upper slope, earth removal should not be adopted.

The volume of earth removal should be determined by stability calculation by correctly estimating the landslide scale and the slip surface position. After earth removal is competed, restoration of the natural environment should be facilitated by introducing vegetation to the slope and the excavated earth.

Where earth removal is to be carried out on a steep slope or in an area where there is a large displacement and it is dangerous for workers to enter the site, the introduction of unmanned construction technologies should be studied.

The disadvantage of earth removal is that a considerable time may be required for the purchase of land, in addition to the cost necessary for the removing and treating sediment and maintenance of the cut slope. On the other hand, its advantage is that it is free from the problems of functional deterioration, unlike horizontal bores, drainage wells and groundwater drains, which tend to suffer from slime adhering to the water collection and drainage boreholes. Therefore, earth removal should be adopted actively if it is found favorable in terms of ease of construction, sediment treatment, necessary land, functional deterioration risks, and total cost, including maintenance.

4) Embankment loading

Embankment loading is performed to increase the resistive force against the sliding force by banking a soil mass having good permeability at the foot of the landslide. This work should be planned for the landslide foot after confirming that a new landslide would not be triggered at the embankment area or on the slope around it. The embankment position is often the bed of a river or a stream, so relocation of a river channel or revetment may be required in some cases.

Embankment loading is often planned as a combination with earth removal since this combination is effective. It is also desirable to combine it with groundwater drains as preparation for a possible increase in groundwater level at the back of the embankment.

The volume of embankment should be determined by stability calculation. After the work is completed, greening should be introduced to facilitate recovery of the natural environment and aesthetics. Also, a construction method that can secure the safety of workers should be adopted, as mentioned earlier for earth removal.

5) Erosion control using river structures, etc.

Erosion control using river structures, etc. are planned to protect river banks and stabilize the landslide foot area when riverbed degradation and river bank erosion due to flowing water undermine the stability of the landslide mass and may induce a landslide as a secondary cause.

River structures that are constructed to prevent landslides are sabo dams, groundsills, revetments, and groynes, etc. Redirection of a river may be planned in some cases.

If sabo dams or ground sills are constructed in a river or a stream immediately below the landslide site, collapse and erosion at the landslide foot area may be prevented by sedimentation, an effect similar to that of embankment loading.

Sabo dams and groundsills should be constructed on stable bedrock at a position immediately below the landslide site not affected by the landslide. If the construction of a group of sabo dams or groundsills is planned for the landslide site, similar structures may also be planned for the position immediately below the site not affected by the landslide in some cases.

3.2.5 Planning of restraint works

Restraint works should be planned so they are adequately laid out, as a single work or a rational combination of the following works, in order to arrest part of or all of the landslide movement by adding the resistive force of the structure and concurrently considering the total cost, including maintenance.

Comments

There are two types of restraint works:

- Directly resist the sliding force of the landslide mass utilizing the shear resistance or flexural resistance of steel piles, reinforced concrete, etc.: piles, shafts
- Stabilize the slope utilizing the tensile strength of tendons (steel materials, etc.): anchors

1) Piles

Piles are constructed to directly resist the sliding force of the landslide mass by adding the shear resistance or flexural resistance by driving steel pipes, etc. up to the immovable soil mass penetrating through the slip surface.

In ordinary pile works, multiple steel pipes are arranged linearly in the direction perpendicular to the moving direction of the landslide to make them resist the sliding force as a unified single body. This means that if more than 1 mm/day deformation is occurring or likely to occur due to the active landslide movement, the expected effects will not be attained unless all the piles are constructed at the same time in order to avoid discrete movements of piles. Therefore, piles should be constructed after confirming that the landslide movement is largely arrested by the application of emergency measures or control works.

In principle, piles should be constructed at a position below the center of the landslide block and at a position having strong bedrock that can anchor the piles and provide ground support.

2) Shafts

Shafts are intended to provide resistance against the sliding force of the landslide through the use of a shaft that is constructed by casting reinforced concrete in it. Shafts are planned when the proposed safety factor (P.Fs) cannot be attained by pile works due to large sliding force, although the foundation ground is favorable.

To construct shafts, a vertical shaft, 2.5 to 6.5 meters in diameter, is excavated to the immovable soil mass. Reinforced concrete is cast in it to make it behave like a large pile. Shafts are constructed when large bore machines cannot be used due to the ground conditions or when bending piles cannot resist the sliding force of the landslide. Caution should be taken to ensure safety during the excavation of the vertical shaft. Also, to enable sufficient drainage during the excavation, the presence of groundwater or spring water should be carefully surveyed and examined in advance.

3) Anchors

Anchors are constructed to stabilize the slope by utilizing the tensile strength of tendons (steel, etc.), which are inserted into the immovable ground from the slope and anchored at the bedrock. Anchors to prevent landslides are available in two types: one is the type that increases shear resistance by increasing the normal stress acting on the slip surface by the anchors (tightening effect); the other is the type to restrain a landslide mass from falling by using the tensile force of the anchors in the tangential direction of the slip surface (restraining effect). Anchors should be placed at positions that optimize the restraining effect or the tightening effect.

Anchors are works aimed at stabilizing a landslide by anchoring high strength steel materials into the ground as tension members, transferring the load acting at the head of the tension members to the ground, and unifying those grouped reaction structures with the natural ground as a single consolidated body. Anchors should be planned when the landslide site is steep and piles and shafts cannot provide sufficient ground reaction, or when a quick effect is needed due to an emergency.

3.3 Safety Measures for Construction Work

Landslide deformation should be monitored during the construction work by using a ground extensometer, etc. in accordance with the conditions of the sliding movement. Safety measures for construction work should be examined and implemented, which include the establishment of a safety management standard based on the deformation, rainfall, etc. and the introduction of unmanned construction technologies for earth removal and embankment loading.

References

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7) Lambe, T.W. & Whitman, R.V.: *Soil Mechanics*, John Wiley & Sons, Inc., p. 570, 1969.

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Chapter 4 Survey and Risk Management Standard for Emergency Situations

4.1 General

When deformations due to a landslide are found on natural and artificial slopes, the following responses should be taken.

(i) Confirmation of the deformation range and direction of landslide movement

(ii) Measurement of movement, displacement, etc.

(iii) Estimation of occurrence mechanism (primary and secondary causes)

(iv) Prediction of the behavior of landslide mass

(v) Investigation of expansion possibility

(vi) Estimation of the impact range

(vii) Establishment of risk management control values

Comments

Here we present technologies that are useful for risk management when deformations are generated on the slope due to a landslide.

When required in terms of risk management, a warning and evacuation or other measures are directed based on the Disaster Prevention Basic Measures Law and the Law Concerning the Promotion of Sediment-related Disaster Prevention in Sediment-related Disaster Hazard Area (Sediment-related Disaster Prevention Law).

Items (i) through (vii) above are listed broadly in order of time, but they should be conducted simultaneously in the event of an emergency.

In particular, (vi) and (vii) are related to human lives, so responses that are quick and erring on the side of safety are essential.

Emergency surveys and urgent measures at the site should be executed by ensuring the safety of workers.

4.2 Emergency Surveys

4.2.1 Site survey

A site survey should be carried out to confirm the deformation range and to measure the movement, displacement, etc.

The confirmation of the deformation range should be conducted over a range larger than the range where deformation is observed.

Measurements of movement, displacement, etc. should be performed at appropriate intervals in view of the sliding conditions using a ground extensometer, etc. Alternative measuring methods should be considered in advance in preparation for when the displacement increases significantly or when the site is not accessible due to increased danger.

Comments

1) Confirmation of the deformation range

If deformations are found on the slope, it is necessary to first confirm the deformation range and the direction of landslide movement. Correct and detailed surveys are important because the following examinations are made based on the obtained results: (iii) estimation of occurrence mechanism (primary and secondary causes), (iv) prediction of the behavior of landslide mass, and (v) investigation of expansion possibility. An adequate survey should be performed not only in the deformation range but also behind the slope and on adjacent slopes so that a large-scale landslide encompassing the deformation range will not be overlooked. Utmost priority should be given to the safety of workers when conducing surveys.

Attention should be paid to the following points during the survey:

(1) Topography

Look over the macro-topography to find the distribution of the existing landslide and collapse sites. Then check the micro-topography in the deformation range to help determine the landslide range.

It is better to examine the macro-topography, etc. in the surrounding area in advance using topographic maps and then observe a broad view of the entire slope that sustained deformation from the opposite bank or from the sky.

(2) Geology and geological structure

Obtain geological maps and survey the geology and the geological structure at the outcrop in order to estimate the landslide range and the properties of the moving mass.

(3) Distribution of deformations of structures and the slope

It is easy to find deformations of structures, but the deformations of the slope (natural ground) are not so easily found. If it is a sudden movement, some sort of deformation should be present on the slope (natural ground). So, conduct a detailed survey and find the deformation range that will help determine the landslide range.

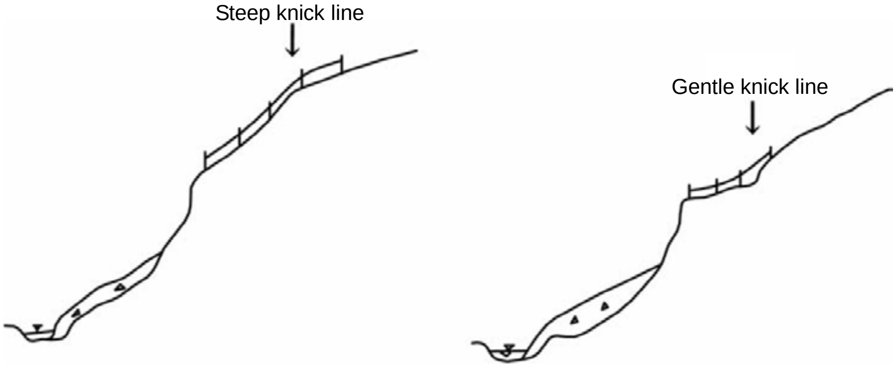
Conduct a detailed survey of the upper part of the collapse and the flanks of the slope since they are often unstable. It is also important to examine the relationship between the collapse at the landslide foot and the topography at the upper slope because the collapse might have been induced by the landslide activity.

(4) Spring water

The landslide site often has abundant spring water. If the slip surface is an impermeable layer, spring water often comes out at the outcrop of the slip surface around the landslide foot area. Surveying the spring water positions will help identify the landslide range.

2) Measurement of movement, displacement, etc.

If deformation of the ground surface is not so noticeable, it is necessary to confirm the moving range by measuring the tensile and compressive displacements using a ground extensometer, etc. Normally, a ground extensometer is extended from the moving mass to the immovable ground crossing the tensile crack. However, when the deformation range at the landslide head is not found or when the moving range is anticipated to expand, a ground extensometer needs to be extended to the upper slope. In that case, multiple ground extensometers should be installed sequentially using steep and gentle knick lines as a reference, as shown in Fig. 4-1.



(a) Schematic of a steep knick line (b) Schematic of a gentle knick line

Fig. 4-1 Installation range of a ground extensometer[1)]

A ground extensometer is a device used to measure the slope deformation to confirm the moving range as well as for other purposes, such as (iv) prediction of the behavior of the landslide mass, (vii) establishment of risk management control values, planning of emergency works, application to warning and evacuation, and reference for safety management during construction work.

It is desirable to use a ground extensometer that can set the measurement interval to a short time, 10 minutes or so, in view of the sliding conditions. If fitted with an alarm, it can be effectively utilized for swift warning and evacuation. Adopt an automatic extensometer so that data can be collected even when entry into the slope area is restricted.

As a note concerning installation, it may be necessary to select an extensometer that can obtain a reaction force using a spring, etc. if large displacement is anticipated that may make measurement impossible. Also, monitoring using survey equipment should be considered as a preparation for the time when the device fails or the landslide site becomes inaccessible due to increased danger.

For monitoring using survey equipment, optical wave- or laser light-type high-precision rangefinders are available. They are designed to irradiate optical waves or laser light at the target and estimate the distance from the time taken for reflected light to return. In the case of an optical wave rangefinder, a high level of accuracy is possible because a reflection prism is set up. But if the target site is a cliff or the landslide movement is quick, setting of a reflection prism is difficult. For such a dangerous slope, a non-prism survey that irradiates laser light directly at the target is effective. However, this device has the disadvantage that night measurement is very difficult. Because a prism is not set up on the slope, the same point is not measureable and the collimation error becomes significant.

To overcome this difficulty, the Landslide Research Team of the Public Works Research Institute has developed a new technology called RE-MO-TE^2 (Remote 2: Remote Monitoring Technology 2) through joint research with the private sector. It is technology that makes it possible to place measuring targets safely from a distant position and to measure the landslide behavior of a dangerous slope to which entry is restricted at high accuracy.

In the RE-MO-TE^2 technology, a capsule containing a retroreflective paint is attached to the tip of a crossbow and it is shot at the slope. A strike accuracy of ±50 cm from a position 300 meters away was confirmed through experiment. Because a series of operations are performed from a distant position, it is possible to execute monitoring safely. The RE-MO-TE^2 technology manual is presented in Appendix 4.

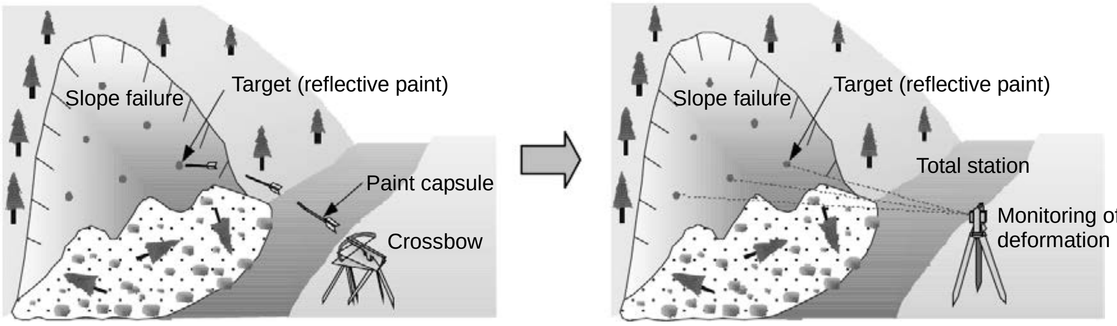


Fig. 4-2 Outline of the RE-MO-TE^2 technology that can set targets from a distant position

A simple measuring method when cracks are generated on the ground is the measurement of deformations (horizontal and vertical displacements) utilizing a horizontal wooden bar called *nukiita* (Fig. 4-3). Another simple method is measuring the distance between two pins installed on both sides of a crack. These methods are usually adopted as an emergency measure before bringing in advanced measuring devices or when measurements should be made at multiple positions. Deformation is also measured utilizing moving stakes (visibility survey, optical wave distance measurement). Monitoring of slopes and river conditions by a CCTV camera is also effective.

It is important to select monitoring positions that can measure movements correctly. Also, in terms of confirming the landslide range and moving conditions, it is desirable to collect as much data as possible. If measuring devices such as a ground extensometer, a borehole inclinometer or a vertical extensometer have already been installed, install additional devices when deformation has expanded or new cracks have appeared.

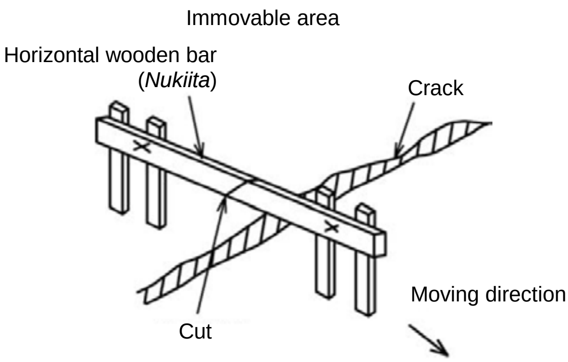


Fig. 4-3 Measurement using a horizontal wooden bar (*Nukiita*)[1)]

4.2.2 Prediction of landslide movement

Based on estimating the landslide occurrence mechanism (primary and secondary causes) and predicting the behavior of landslide mass, it is recommended that the possibility of expansion be investigated and the impact range be estimated.

Comments

1) Estimation of landslide occurrence mechanism (primary and secondary causes)

Estimation of the landslide occurrence mechanism (primary and secondary causes) is extremely important for predicting future landslide movements. Find primary causes such as the topography, geology, and geological structure of the slope, and investigate the possibility of further movement. In addition, identify the secondary causes that moved the slope and examine them in an effort to establishing a warning and evacuation system and implementation of emergency responses. Attention should be paid to the following items:

(1) Topography

(2) Geology and geological structure

(3) Rainfall (groundwater) conditions

(4) Artificial activities (cut slope, fill slopes, etc.)

Of these items, (1) and (2) are associated with the primary causes of a landslide. Although finding primary causes is important, they are not necessarily found, particularly during the period immediately after the disaster.

Items (3) and (4) are related to the secondary causes of a landslide. Secondary causes consist of natural causes, such as rainfall, snowmelt, erosion at the landslide foot and earthquakes, as well as artificial causes such as cut slopes, fill slopes, and the construction of reservoirs. Identifying secondary causes is very important because the works that remove secondary causes or related factors are effective for emergency measures in particular.

2) Prediction of the behavior of the moving mass

Predict the future behavior of the moving mass from the landslide deformation and topographic conditions.

In general, the larger the plasticity of the ground, the longer the time from the generation of cracks to the sliding of the mass. Also, sliding is not so easily triggered if the slip surface is shaped like an arc the bottom off a ship and the toe is uplifted. In contrast, if the toe of the slip surface is open-ended or small in scale, sliding is highly likely, particularly under the influence of rain.

In terms of landslide deformations and topographic conditions, the landslide mass tends to show the following tendency as the future behavior.

(1) The landslide after sliding

The stability of the moving mass is relatively high after sliding.

The upper slope tends to become unstable because the relative height of the scarp is generally high.

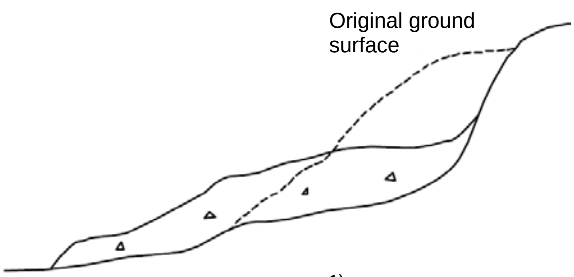


Fig. 4-4[1)]

(2) When the landslide foot is uplifted.

It is inferred that the slip surface is nearly horizontal or inversely sloped. Therefore, the movement will gradually stop as the sliding amount increases because the foot of the sliding mass acts as a resistive body.

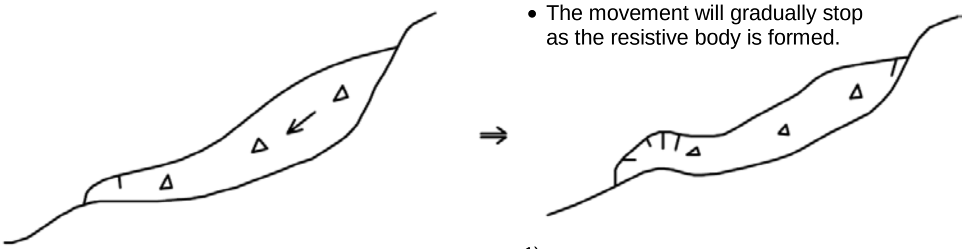


Fig. 4-5[1)]

(3) When the landslide foot is gentle.

The movement will gradually stop for the same reason as (2).

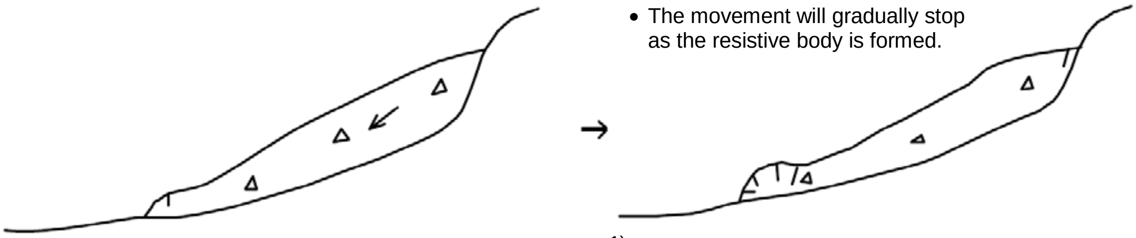


Fig. 4-6[1)]

(4) When the landslide foot is steep.

The movement will not stop easily because the collapse at the landslide foot will continue and the formation of a resistive body is difficult.

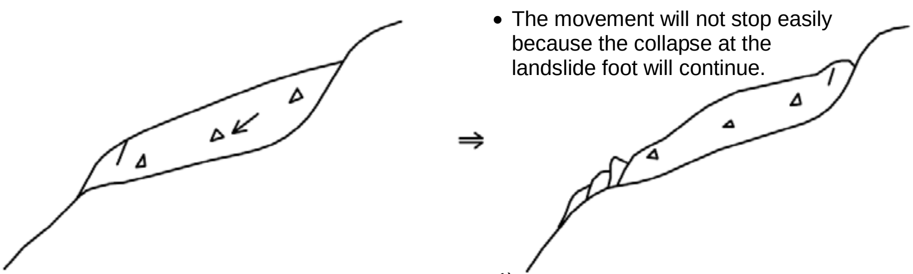


Fig. 4-7[1)]

However, it must be noted that all these descriptions show a general tendency. Careful evaluation must be made by taking site peculiarities into account. Caution must be taken particularly at a position having abundant groundwater because the soil mass may turn into a debris flow.

The moving speed of the soil mass tends to increase abruptly immediately before sliding. Therefore, if the moving speed is continuously monitored, the sliding timing is predictable in some cases. If tensile cracks are found on the slope, measure the elongation of the uppermost crack and then calculate the sliding timing or continue monitoring by fitting an alarm.

Typically, two methods can be used to predict the timing that the slope slides by measuring the moving speed by installing a ground extensometer across the crack (tensile crack). One is the creep failure prediction method proposed by Saito[2)], and the other is the prediction method utilizing the reciprocals of the moving speed, which is proposed by Fukuzono.[3)] It is desirable to predict the sliding timing if it is a landslide that has a significant social impact. However, we must bear in mind that precise prediction is possible only in very limited cases.

The following is an example of sliding prediction that was carried out based on the monitoring results using a ground extensometer installed in the landslide head area. In this landslide, the displacement began to increase from around May and a slide occurred at around 0:15 on August 10 due to repeated typhoons.

Figures 4-8 through 4-10 show the results of sliding prediction obtained by Saito's equation and Fukuzono's equation. Comparing the results of these methods, an appropriate method having good applicability to each landslide site should be selected.

It is necessary to shorten the interval of sliding prediction in accordance with the development of the sliding conditions.

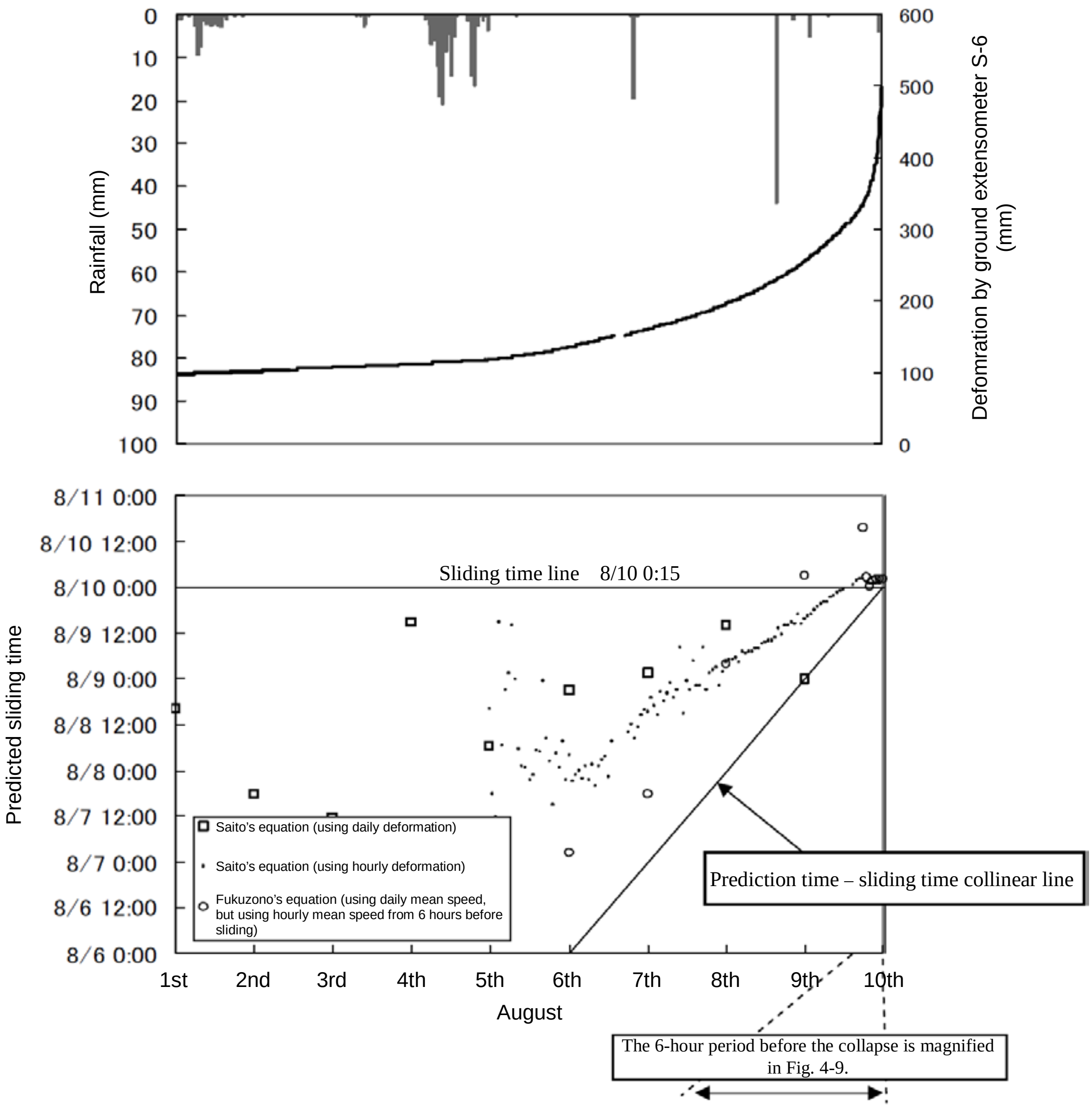


Fig. 4-8 Sliding prediction by Saito's and Fukuzono's equations (Aug. 1 – 10)

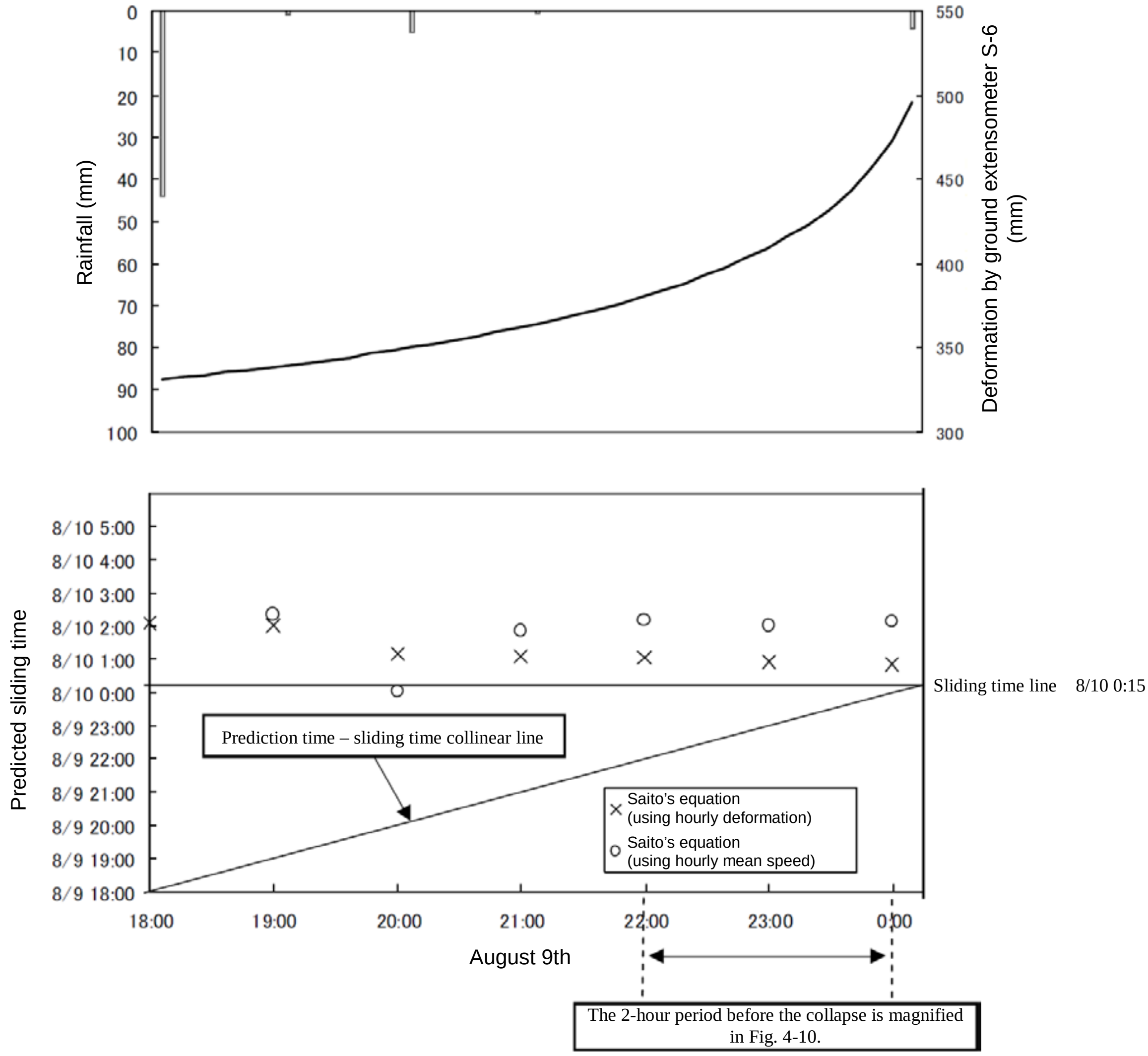


Fig. 4-9 Sliding prediction by Saito's and Fukuzono's equations six hours before sliding (predicted from hourly deformation)

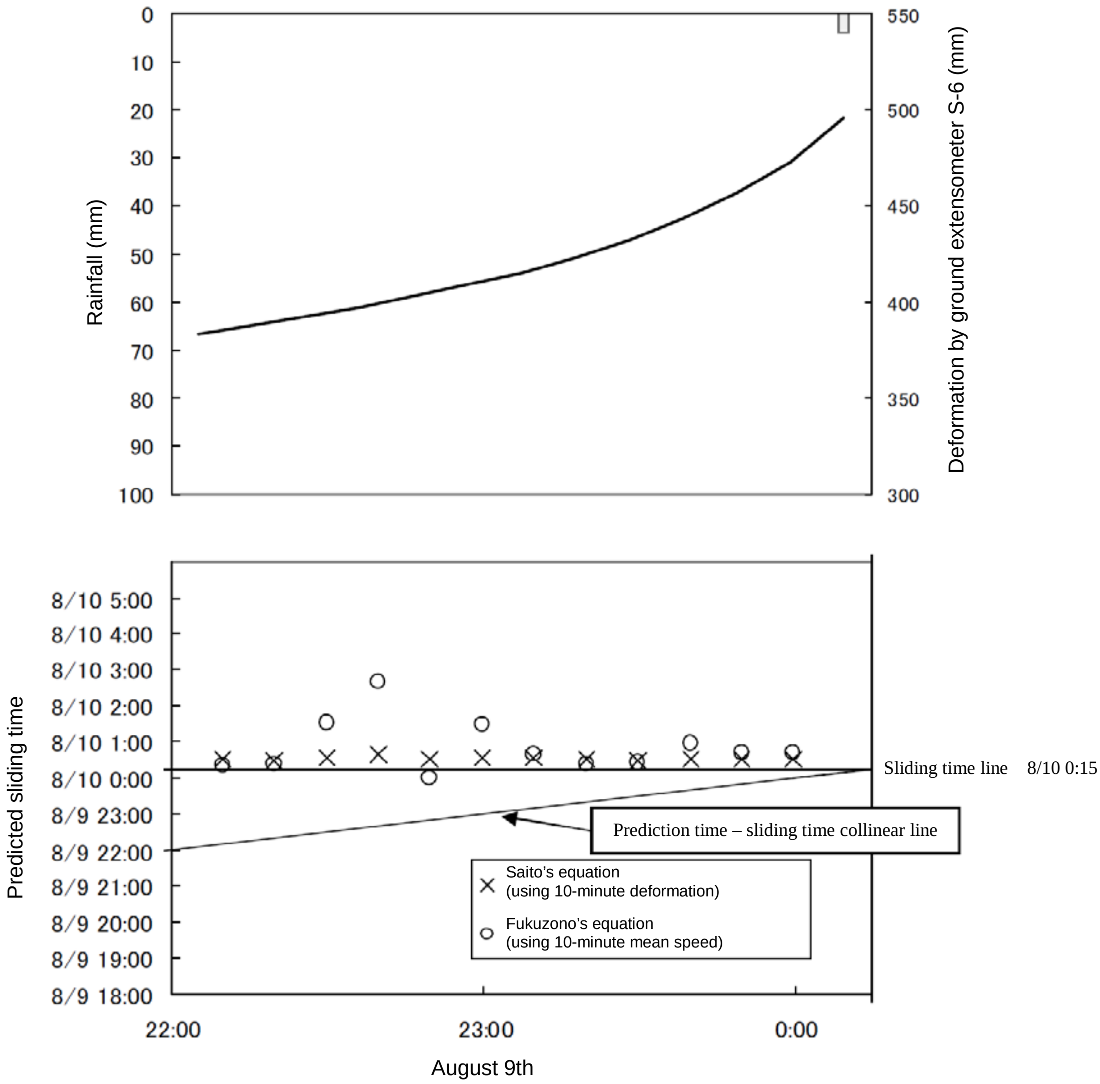


Fig. 4-10 Sliding prediction by Saito's and Fukuzono's equations two hours before sliding (predicted from 10-minute deformation)

[Reference: explanations of each prediction method]

(i) Fukuzono's prediction method using reciprocals of the moving speed

From experimental results, Fukuzono found that the moving speed of the surface and the acceleration have a linear relationship on a double logarithmic chart. Then, by placing the time on the abscissa and the reciprocals of the moving speed on the ordinate, he predicted that the intersection of the abscissa and the straight line estimated from the reciprocals of the moving speed is the time when failure will occur. Figure 4-11 shows the results obtained by applying Fukuzono's prediction method using reciprocals of the moving speed to the monitoring results in Fig. 4-8. In Fig. 4-11, the time at which the straight line estimated from the reciprocals of the moving speed intersects with the abscissa is the predicted sliding time.

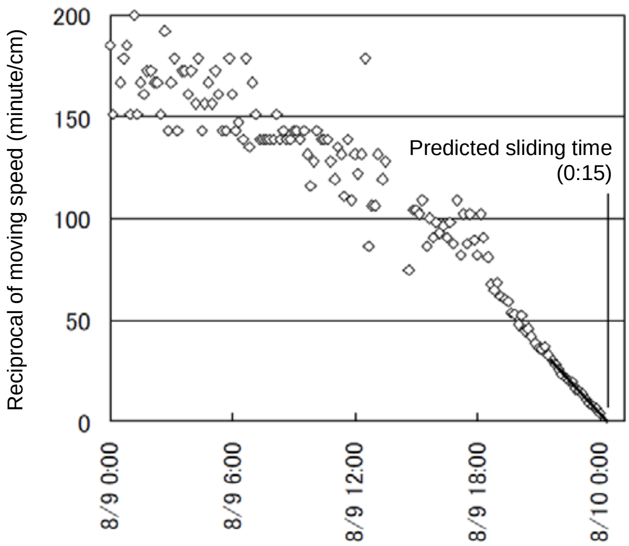


Fig. 4-11 Prediction of sliding time using reciprocals of moving speed, proposed by Fukuzono

(ii) Saito's prediction method

Saito[4)] found a relationship between the strain speed and the time of slope failure, as shown in Fig. 4-12, from field measurements and experiments. The ordinate in the figure shows the time (minutes) before the failure and the abscissa the strain speed.

Saito derived the following equation as a rough equation for failure prediction from the secondary creep. It is shown that the creep failure time can be used as the allowance before the real failure.

$Log\ 10\ tr = 2.33 - 0.916 \cdot Log\ 10\ \dot{\varepsilon} \pm 0.59$ . . . (Equation 4-1)

tr: creep failure time

$\dot{\varepsilon}$: strain speed (10^{-4}/minute)

The strain speed between two piles placed at two positions can be obtained from the following equation.

$\dot{\varepsilon} = (\Delta l / l) / \Delta t$ . . . (Equation 4-2)

l: distance between piles (mm)

Δl: displacement at *Δt* (mm)

Δt: time necessary for the displacement of *Δl* (minute)

The strain speed can be obtained from Equation 4-2 using the displacement from an extensometer, and the predicted sliding time from Equation 4-1.

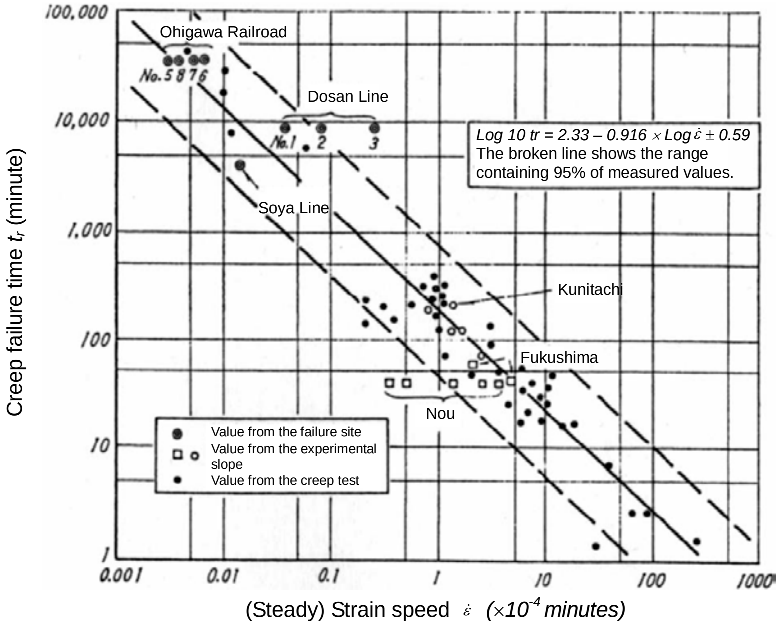


Fig. 4-12 Measurement results of slope failure [2)]

(iii) Prediction method in the tertiary creep area

Saito[4)] also proposed a prediction method in the tertiary creep area.

3) Investigation of the possibility of expansion

It is necessary to investigate the possibility of landslide expansion sufficiently because it can cause severe damage. Identify the possible range of landslide expansion by taking the following points into account, and install measuring devices such as a ground extensometer where appropriate.

(1) Topography

Presence of landslide topography, distribution of steep and gentle knick lines, distribution of ridges and valleys, topography at the landslide foot

(2) Geology and geological structure

Distribution of faults, dip-slope structure, etc.

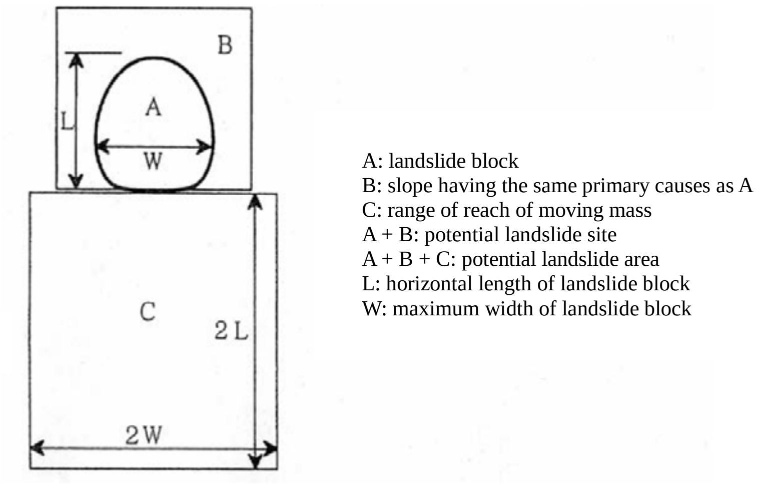
(3) Others

Distribution of deformations, type of deformations (cracks, uplifts, etc.), changes in displacement, distribution of spring water, vegetation conditions

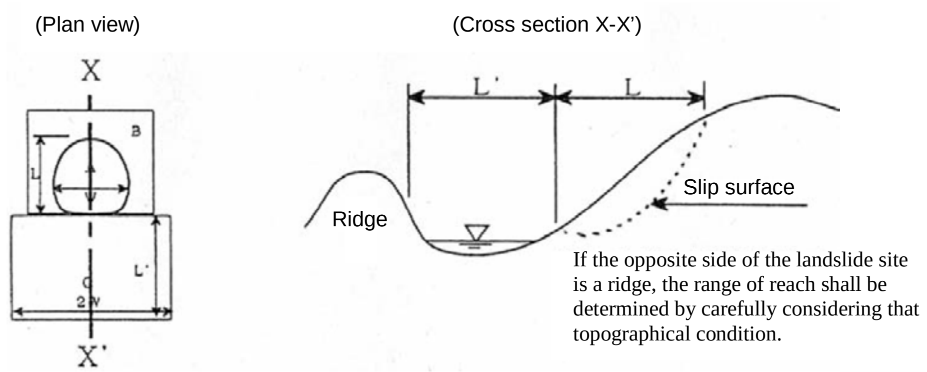
4) Estimation of the impact range

If the possible moving range has been found, it is necessary to infer the possible range that the landslide mass will reach. In the case of past disasters, it is said that 95% of landslides reached up to twice the length and width of the landslide from the landslide tip.[5)] Therefore, as a basic rule for warning and evacuation, it is desirable to establish a range twice the length and width of the landslide from the landslide tip as the possible impact range, as shown in Fig. 4-13.

However, not all landslide phenomena stay within this range. Therefore, the possible impact range should be determined carefully by considering the topography below the site, the characteristics of the landslide movement, etc. and by referring to past disasters around the target landslide. Also, if there is the possibility of landslide dam formation, it is necessary to estimate the possible impact range in areas both downstream and upstream of the landslide dam as the basic material for adequate warning and evacuation (see 2.3.2 (8)).



(a) Range of the potential landslide area



(b) Case where the range of reach of a landslide mass is restricted by topographical conditions

Fig. 4-13 Range of reach of a landslide mass[6)]

4.3 Establishment of Risk Management Control Values for Emergency Situations

As a reference for enforcing a warning and evacuation system as landslide activities develop, risk management control values should be established based on the measured values from ground extensometers (displacement), etc.

Comments

Tables 4-1 through 4-3 show examples of existing risk management control values. Although it is not possible to define control values uniformly as they vary depending on the movement characteristics and impact range of individual landslides, they are normally determined as “caution” if the movement amount by ground extensometers is in the order of 1 mm/day, “warning” if in the order of 10 mm/day, and “evacuation” or “entry restricted” if in the order of several tens of mm/hour.[7)] When enforcing a warning and evacuation system, it is important to consider not only the measured individual displacements but also cumulative displacements. Some landslides can increase their moving speed abruptly, so the control values should be carefully determined by referring to past disaster cases in the vicinity, etc.

When cancelling the warning and evacuation system, do not simply apply control values. Strive to make a safe side judgment. For example, confirm prudently that a certain level of safety has been secured by emergency responses or that no further deformations have been generated.

Table 4-1 List of management control values[added to 7)]

(a) Designated landslide area, etc.

Land slide name	Management control values by ground extensometer				Other management control values	Remarks
	Caution	Warning	Evacuation	Entry prohibited		
A-1		4 mm/h or 20 mm/D			Rainfall	Reconnaissance taken when exceeding control values
A-2	1 mm/D	10 mm/D	2 mm/h*2h 4 mm/h	10 mm/h Expert	Ground extensometer (ref. value), Pipe strain gauge (ref. value)	
A-3	1 mm/D	10 mm/D	4 mm/h*2h	10 mm/h Expert	Ground extensometer (ref. value), Pipe strain gauge (ref. value)	
A-4	1 mm/D	10 mm/D	2 mm/h*2h 4 mm/h	10 mm/h Expert		
A-5	1 mm/D	10 mm/D	2 mm/h*2h 4 mm/h	10 mm/h Expert	Ground extensometer (ref. value)	
A-6	1 mm/D	10 mm/D	2 mm/h*2h 4 mm/h	10 mm/h Expert	Ground extensometer (ref. value) Pipe strain gauge (ref. value)	
A-7	1 mm/ D*7D	12-17mm /D	2 mm/h*2h 4 mm/h		Control value by a wire type multilayer movement meter	
A-8	1 mm/D	10mm/D	2 mm/h*2h 4 mm/h	10 mm/h Expert		
A-9			2-4 mm/h		Rainfall	
A-10			4 mm/h		Rainfall	
A-11			1) 2mm/h 2) 4 mm/h			Below 1): embankment loading possible at the landslide foot Below 2): earth removal at the landslide head and drainage works possible 2) or above: evacuation
A-12			2 mm/h			Reconnaissance taken when exceeding control values, evacuation or traffic closure after consultation
A-13	10 mm/D	2 mm/h	4 mm/h		Rainfall	Issuance of warning when exceeding 4 mm/h
A-14			4 mm/h 20 mm/D		Rainfall	Reconnaissance and check of devices when exceeding control values, evacuation if necessary
A-15			1 mm/D		Rainfall	Control values during construction – stop work if 1 mm/D by movement meters around the caisson works

h: hour D: day M: month *Δ: duration of Δ Expert: judgment by experts

If there are two control values, initiate the response when one of them is reached.

Table 4-2 List of management control values added to 7)

(b) Reservoirs, etc.

Reservoir name	Management control values by ground extensometer		Other management control values	Remarks
	Caution	Stop of ponding		
B-1	1 mm/D*3D (tension) 0.6 mm/D*3D (compression)	3 mm/3D (Expert)	Ground inclinometer, Inspection tour	Management control values during test ponding
B-2	0.4 mm/D		Ground inclinometer, Inspection tour	As above
B-3	1.2 mm/3D	Expert	Ground inclinometer, Inspection tour (Subsurface inclinometer)	As above
B-4		2 mm/h 10 mm/D	Inspection tour	Management control values during test ponding, study of responses and measures
B-5			Ground inclinometer	Management control values during test ponding
B-6	0.4 mm/D*3D	1 mm/D Expert	Ground inclinometer, Inspection tour	As above
B-7	4 mm/h			Control value for landslides adjacent to the dam
B-8	1 mm/D	Expert	Ground inclinometer, (Subsurface displacement gauge)	Management control value during test ponding
B-9	0.4 mm/D*3D	1 mm/D	Ground inclinometer, Inspection tour	As above

h: hour D: day M: month *Δ:duration of Δ Expert: judgment by experts

If there are two reference values, initiate the response when one of them is reached.

Table 4-3 List of management control values added to 7)

(c) Roads, etc.

Road name	Management control values by ground extensometer				Other management control values	Remarks
	Caution	Warning	Prevention works	Road closure		
C-1				20 mm/D 4 mm/h 2 mm/h*2h	Inclinometer, acceleration meter, etc,	Management control value during tunnel bore: road closed when exceeding control value
C-2					Subsurface displacement gage	
C-3		3 mm/h		4 mm/h		
C-4		20 mm/D		4 mm/h	Rainfall	
C-5	0.02 mm/D 0.5 mm/M	0.1 mm/D 2 mm/M	1 mm/D 10 mm/M			
C-6	0.02 mm/D	0.1 mm/D	1 mm/D			
C-7				2 mm/h		Conduct on-site check, cancel if no abnormalities found one hour later.
C-8				2 mm/h		Conduct on-site check, cancel if no abnormalities found one hour later. Road closed at night.
C-9				2 mm/h		As above
C-10				4 mm/h		On-site check and discuss the response.
C-11				2 mm/h 10 mm/D	Rainfall	Road closed, works stopped. Road closed on the opposite bank, too, if 4 mm/h or more
C-12				10 mm/D		Management control value during work: work stopped if exceeding the control value
C-13		4 mm/D		A: 2 mm/h 10 mm/D B: 4 mm/h 20 mm/D	Rainfall	Management control value during work: if exceeding A – work at the landslide foot and subsurface work stopped. if exceeding B – all works stopped.
C-14				10 mm/D		Management control value during work: if exceeding control values – work stopped.

h: hour D: day M: month *Δ:duration of Δ Expert: judgment by experts

If there are two reference values, initiate the response when one of them is reached.

4.4 Emergency Measures

When the landslide movement becomes active and is likely to have an impact on houses or public structures, etc. around the site, emergency measures should be taken aimed at mitigating landslide movement while concurrently preparing to activate a warning and evacuation system. Even though they are intended to ensure safety for the time being, the proposed safety factor (P.Fs) should be set at 1.05 or more.

Works for emergency measures should be selected by considering the sliding conditions of the landslide and safety of the construction work.

Comments

To mitigate landslide movement, it is effective to remove the secondary causes that can trigger a landslide. However, the removal of secondary causes is not always possible because of topographic conditions or landslide movement conditions. Therefore, it is required to select works that can be applied in terms of the landslide conditions and the safety of construction work, while placing priority on the removal of secondary causes.

Emergency works that are frequently adopted include seepage prevention, horizontal bores, earth removal, and embankment loading.

The following are points to be noted when implementing emergency works.

(1) Emergency surface water drainage works

Seepage of surface water into the ground at the landslide site can be prevented using measures such as emergency drainage consisting of channels or changes to channel routes, restricting the surface water flowing into the landslide site by the installation of channels at the peripheral area of the landslide, coverage of cracks using a plastic sheeting, drainage of spring water, drainage of pond or bog water by channel excavation.

(2) Emergency groundwater drains

Horizontal drainage bores are constructed from a stable position at the flanks of the landslide or behind the scarp toward the direction below the cracks in the peripheral area. If entry into the landslide site is possible, horizontal bores at the landslide site or pump drainage from the shaft via large bores is also effective.

(3) Emergency earth removal

Before implementing emergency earth removal, it is necessary to carefully examine the stability of the slope above the area from where the earth is to be removed and the check for the presence of a potential landslide.

Introduction of unmanned construction technologies should also be considered because entering the area form where the earth is to be removed can be dangerous depending on the landslide conditions.

(4) Emergency embankment loading

There area two types of embankment loading: permanent embankment loading and temporary embankment loading, where the embankment will be removed after the installation of permanent structures. In either case, erosion control measures against flooding, etc. must be considered if the landslide foot reaches the river. In addition, embankment materials having good permeability should be used to avoid an increase in groundwater level at the back of the embankment.

Before implementing embankment loading, the introduction of unmanned construction technologies should be studied, because entering into the earth removal area can be dangerous depending on the landslide conditions.

(5) Responses to landslide dams

If there is the possibility of inundation or damage from flooding due to the formation of a landslide dam and its outburst, removal of soil mass or excavation of channels should be undertaken quickly. In that case, care must be taken to ensure that those operations will not trigger the displacement of other masses or the collapse of the upper slope above the soil mass that fell to form a landslide dam. If such movements are anticipated, install ground extensometers and undertake works by constantly monitoring their movements. Introduction of unmanned construction technologies should also be considered by taking into account the possible movement type (collapse, landslide) of the landslide mass.

If a sabo dam is located downstream of the landslide dam, it is also effective to remove part of the accumulated sediment by confirming the sediment storage capacity at the sabo dam. To ensure safety during the sediment removal work, safety measures should be taken such as the installation of debris flow sensors downstream of the landslide dam. Although it is not easy to judge the possibility of a landslide dam bursting its banks, judgment should be made based on the comprehensive evaluation of related factors, including the basin area above the landslide dam, the gradient of the riverbed, the river length blocked by the landslide dam, materials constituting the landslide dam, etc.

(6) Scale of emergency works

Based on the examinations of past landslide cases[1)], one report states that a landslide will begin to slide if the safety factor is lowered by about 5% and a moving landslide will stop if the safety factor is increased by about 5%.

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Chapter 5 Design

5.1 General

The landslide prevention facilities should be designed to have adequate functions and safety based on the landslide prevention facility plan.

When designing landslide prevention facilities, sufficient examination should be made, including the adoption of durable materials to maintain facility functions for a long time and the prevention of a reduction in safety factor due to aging. At the same time, consider the total cost, including the initial construction costs as well as the maintenance costs.

Also, the design should be revised on an as-needed basis based on data from the construction stage so that an intended results will be achieved.

5.2 Design of Control Works

5.2.1 Surface water drains

When designing surface water drains, it is necessary to consider factors such as the adoption of a flexible structure to retain functionality even with some deformation and the ease of repair.

Comments

1) Channels

Channels consist of structures that collect the water, which are arranged in the form of branches at depressions in the landslide slope, and drains that drain the collected water. They should be arranged as shown in Fig. 5-1. Also, measures should be taken to prevent surface water from flowing into the landslide block from outside the block as appropriate.

The following points should be noted when designing channels.

(1) The channels should be excavated to enable the collection of surface water on the slope and to prevent re-seepage of water at depressions (Fig. 5-2). The channel route should be selected to minimize excavation of the landslide surface.

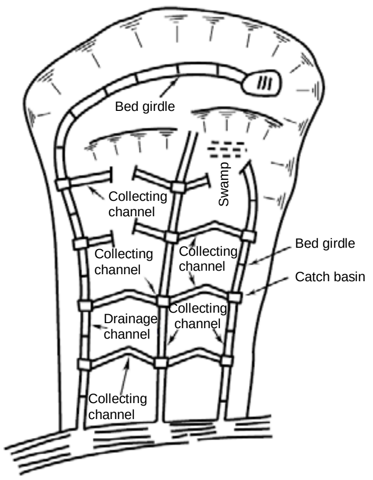


Fig. 5-1 Network of surface drainage channels

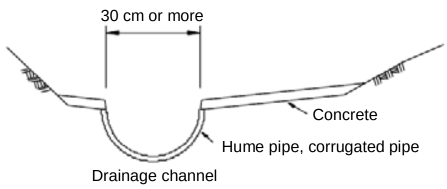


Fig. 5-2 Surface drainage channel

(2) The collection channels and small-scale drainage channels should be as wide and shallow as possible, at least 30 cm, for easy maintenance.

(3) Channels should be lined to prevent re-seepage of flowing water. A catch basin should be installed at the junction with branch channels, at the position of channel crooking, and at the position where the channel inclination bends. The shoulders of channels should be covered with concrete or asphalt to guide surface water into the channel.

(4) The cross section of the main channel should be determined from the designed maximum flow rate. The channel should be designed so that the probability of the rainfall exceeding the capacity of the channel is about 1/50. It is also necessary to include an allowance of at least 20% in the channel cross section by considering a possible decrease in the cross section due to the accumulation of sediment, etc.

(5) When designing a catch basin on an inclined slope, the basin size should be determined using Equation 5-1 by considering the gradient, flow volume, and overflow depth (Fig. 5-3).

$L = k\,(h_1 + t)$ . . . (Equation 5-1)

L: inside width of catch basin (m)

k: 2.5 – 3.0

t: water depth of the upper channel (m)

h_1: head between the beds of upper and lower channels (m)

h_2: water cushion of catch basin (m)
(0.2 – 0.5 m)

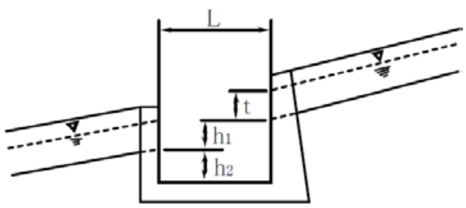


Fig. 5-3 Side view of a catch basin

(6) Basically, channels constructed in locations where there is a high groundwater level should consist of an open drain and closed conduit, combined with buried conduits.

(7) Figure 5-4 is a drawing of a typical catch basin and channels on an incline. The catch basin and channels on the incline should be installed at intervals of 20 to 50 meters.

(8) The channels are constructed from reinforced concrete U-shaped gutters, semicircular hume pipes, corrugated pipes, or plastic pipes. If channel deformation is anticipated due to a landslide or ground behavior, material that accommodate the ground movement should be selected, such as flexible pipes.

(9) When weeds are very likely to fall into the channel, it is effective to cover the adjacent one meter of area on both sides of the channel using concrete etc. to help prevent them from falling in.

(10) Regular inspection and repair are required because ground uplift or subsidence associated with landslide movement can expand or damage channel joints and cause water to leak.

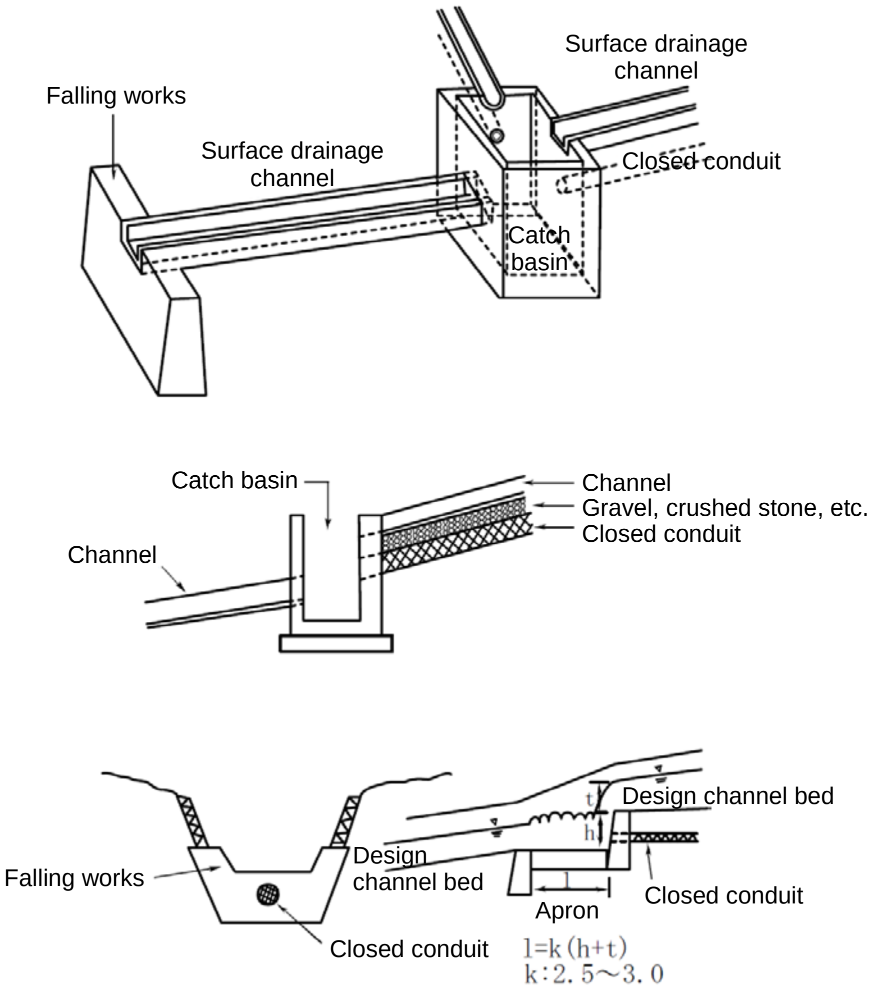


Fig. 5-4　Typical catch basin and channel on an incline

2) Seepage prevention

The following work is generally conducted to prevent seepage:

(1) Filling

The cracks are filled with clay or concrete. This is suitable in an emergency.

(2) Coverage by plastic sheets

The cracks are covered with plastic sheets. This is suitable in an emergency.

(3) Water leakage prevention

When water leaks from the bog, the bottom should be covered with an impermeable material such as asphalt.

5.2.2 Groundwater drains

When designing groundwater drains, it is necessary to consider the groundwater level, the landslide conditions, the safety of facilities in terms of slope stability, ease of maintenance, etc.

Comments

1) Shallow groundwater drains

1-1) Closed conduits

The following points should be noted when designing closed conduits.

(1) Determine the positions of closed conduits by considering the soil properties and groundwater conditions.

(2) The linear length of one conduit should be about 20 meters. Install catch basins to prevent blockage in the channels and re-seepage of the groundwater. Guide collected water to the surface drainage channels.

(3) The depth of the closed conduit should be about two meters. Lay a waterproof sheet at the bottom of the conduit to prevent water leakage. Also, place suction prevention material around the conduit to prevent the suctioning of sediment (Fig. 5-5).

(4) Place filter materials around the conduit to facilitate the collection of shallow groundwater (Fig. 5-5).

(5) If intending to collect surface water as well, fill the conduits with cobbles or crushed stones up to the ground surface.

(6) Closed conduits should be resistant to a certain level of ground deformation, so gabions or perforated pipes are usually employed for closed conduits. If the slope inclination is steep, fasten the conduit using a pile, etc. as shown in Fig. 5-6.

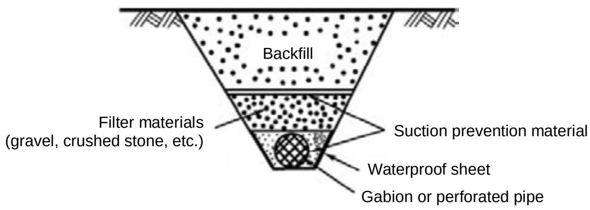


Fig. 5-5 Closed conduit

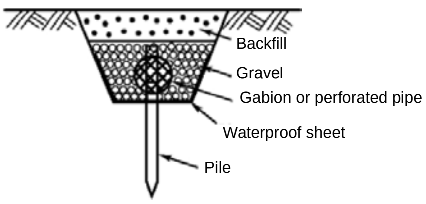


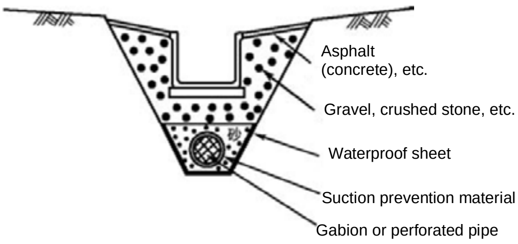
Fig. 5-6 Gabion conduit

1-2) Open drains and closed conduits

The following points should be noted when designing open drains and closed conduits (Fig. 5-7).

If one open drain/closed conduit is very long, the collected water may re-seep into the ground. Therefore, the length should be determined in view of the conditions at the site.

The collected water is usually drained into surface channels utilizing catch basins or channels on the incline, which are installed at intervals of about 20 meters, as shown in Fig. 5-8.



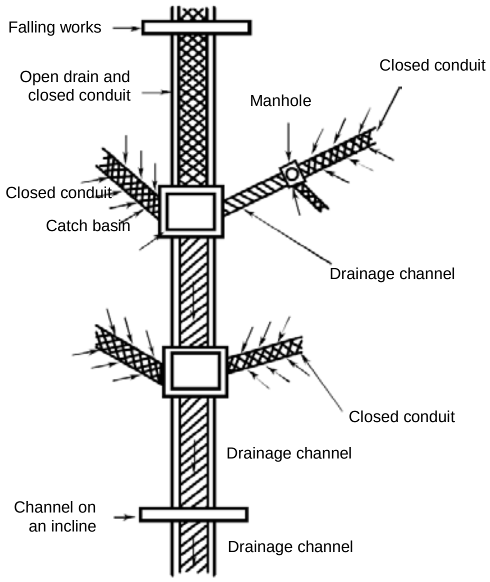


Fig. 5-7 Open drain and closed conduit

Fig. 5-8 Drainage of collected groundwater

1-3) Horizontal bores

Figure 5-9 depicts the concept of a horizontal bore. As shown in the figure, horizontal bores should be constructed by considering the position of a groundwater flow layer based on the groundwater logging.

(1) The following points must be noted when designing horizontal bores.

In general, horizontal bores should be constructed at the position where shallow groundwater is concentrated. Bores should be driven toward a radial or parallel direction at tip intervals of 5 to 10 meters (Fig. 5-10). Also, they should be planned to have a 5- to 10-meter overbreak penetrating through the slip surface.

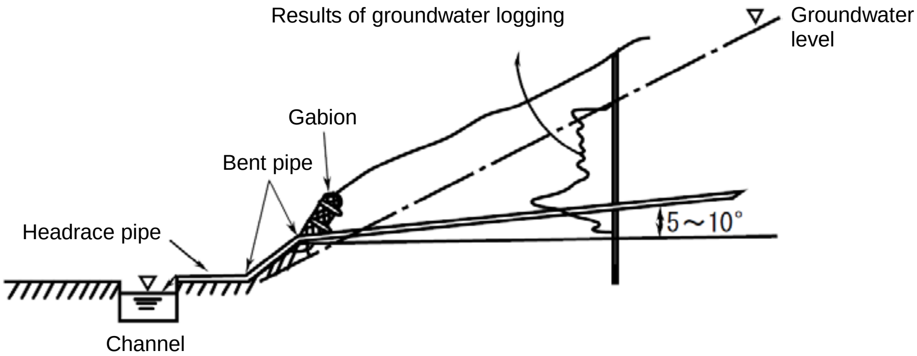


Fig. 5-9 Horizontal bore

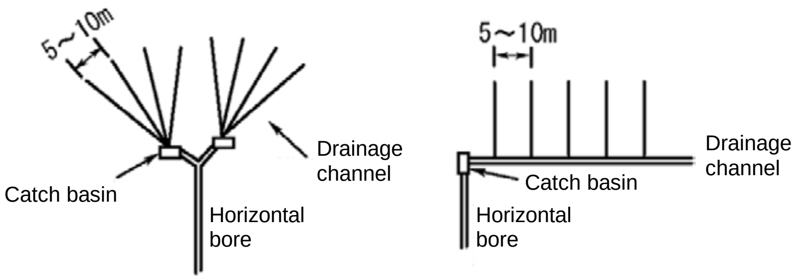


Fig. 5-10　Layout of horizontal bore

(2) Guide the collected groundwater to the catch basin or channel so that it is quickly discharged from the landslide site.

(3) Place the bore mouth in stable ground and protect it to prevent its collapse due to drainage water (Fig. 5-11).

(4) The bore elevation angle should be roughly 5° to 10° with a bore diameter of 66 mm or more to enable the natural flow of collected groundwater.

(5) Increase the bore diameter if the soil on the landslide slope is clayey with a small coefficient of permeability.

(6) Use a pipe with an inside diameter of 40 mm or more to collect the water. For the aquifer section, use a strainer pipe with either holes or slits. The water collection pipes should be connected with a socket joint or butt joint, and the joint length should normally be about 1.5 times the inside diameter of the pipe. Figure 5-12 shows an example of a strainer with holes.

(7) Check the drainage volume from the horizontal bores regularly. If the volume is reduced due to clogging or suchlike, clear the borehole (see 5.4.1).

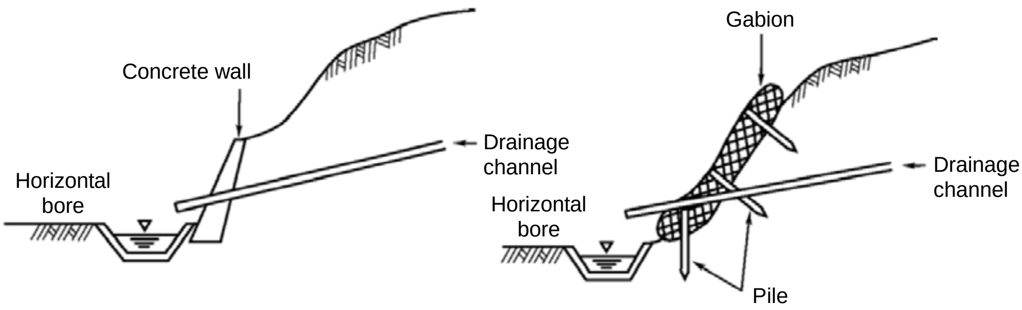


Fig. 5-11　Work to protect the mouth of horizontal bore

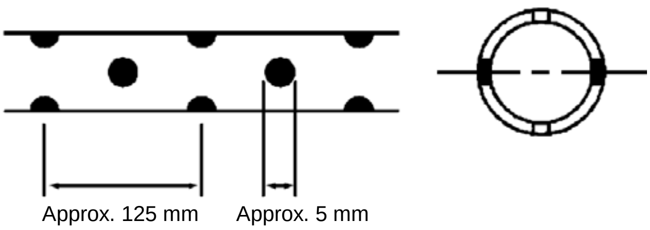


Fig. 5-12　Example of a strainer for water collection pipes

2) Deep groundwater drains

2-1) Horizontal bores

The design considerations are the same as those mentioned in 1-3) above. However, the following points must be noted with regard to the drainage of deep groundwater.

(1) The length of a horizontal bore used for the drainage of groundwater in the aquifer should be about 50 meters and the final bore diameter should be 66 mm or more.

(2) The bore angle should be 5° to 10° in the upward direction toward the aquifer in principle. The bore direction should be determined carefully so that the bore does not bend. Care is also needed to prevent the leakage of collected groundwater from collection pipes.

(3) When the objective is to drain confined groundwater, the bore is driven obliquely downward in some cases to enable the groundwater to discharge spontaneously.

2-2) Drainage wells

The drainage well should be constructed in relatively stable ground in which well construction is easy. The water collection pipes should be laid from the well toward the aquifer (Fig. 5-13). Therefore, the well position should be determined by examining the geology and the ground conditions by conducting an exploratory bore.

When the groundwater is distributed over a wide area and two or more drainage wells are constructed, their layout should be determined appropriately by considering the bore length for groundwater collection, the range of possible reduction in groundwater level due to the wells, and the reserve of groundwater, etc. In drainage wells, groundwater is collected predominantly from collection pipes and collection from the well walls is not anticipated.

Construction of a drainage well is a good opportunity to directly observe the geology and soil structure of the landslide slope and the position and conditions of the slip surface. Collection of undisturbed samples is also possible. Therefore, it is advisable to utilize this opportunity not just for well construction but also for various surveys.

The landslide mass is often heavily weathered and fragile, so caution should be taken to ensure safety when excavating a drainage well or when driving a bore inside the well.

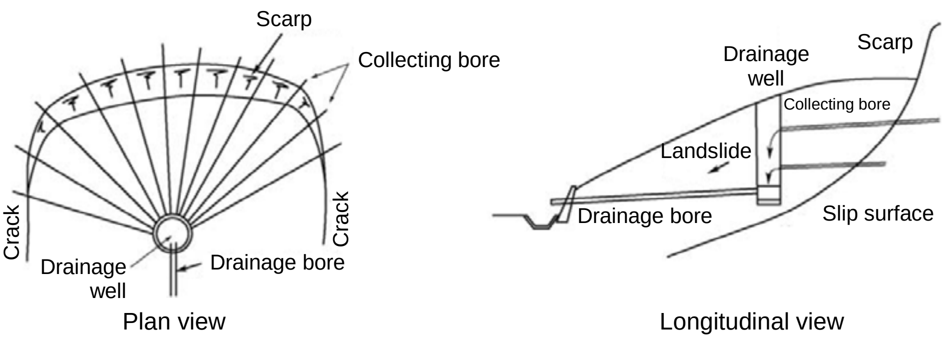


Fig. 5-13 Drainage well

(1) Depth of the drainage well

Regarding the depth of the drainage well, in principle the well bottom should be more than two meters shallower than the slip surface in the case of a moving landslide slope, and it should be buried into the bedrock for two to three meters if the landslide slope is not moving or if the well is constructed outside the landslide slope. This is because if the well bottom is buried below the slip surface in a moving landslide slope, the drainage well may be damaged at the position around the slip surface when the landslide moves. On the other hand, in the case of an unmoving landslide slope, where the slip surface depth is usually unknown and it is difficult to find a harmful aquifer, the well bottom should be buried into the bedrock to enhance the collection of water.

Also, in the case of a moving landslide slope, the construction period should be as short as possible because the construction may become difficult due to changes in the soil quality or an increase in earth pressure, etc. if the construction period is extended.

(2) Structure of the drainage well

The drainage well is cylindrically shaped and the inside diameter is typically 3.5 to 4.0 meters. However, the inside diameter can be increased if the construction of collection bores is difficult due to the ground conditions, such as if the sediment contains gravel or boulders or if there is hard rock or crushed stones, etc. In any case, caution must be taken to ensure safety during construction.

The drainage well should in principle be hollow to ease groundwater collection and the maintenance of drainage pipes. If landslide movement starts and there is a fear of well damage, put cobblestones, etc. into the well to stabilize it as an emergency measure.

Apply lining concrete, about 50 cm thick, to the bottom of the well to cut off the supply of groundwater to the landslide layer or the bedrock to suppress landslide activity.

The drainage well is normally made from steel (liner plate) or reinforced concrete, but the material should be determined by considering a variety of factors, such as the ease of transporting the material to the construction site and the total cost from construction to maintenance. Since the construction site is usually in a mountainous area, it may be difficult to transport the material using large machinery and not many materials may be used at the same place. Therefore, it is advisable to adopt materials that are lightweight and easy to assemble.

The upper end of the drainage well should be one meter above the ground surface. It should be provided with a cover, and protected by a fence to restrict entry by members of the public. Also, install steps or a ladder inside the well to facilitate maintenance, etc.

1) Design of the steel (liner plate) drainage well

Earth pressure should be the only load considered to act on the peripheral area of the drainage well. Water pressure should not be considered. The earth pressure considered should be the active earth pressure, and earth pressure that is generated by landslide movement should not be considered in principle. However, as the actual behavior of the landslide is complicated, earth pressure that is generated with the development of landslide movement can be included in the calculations as appropriate. If well deformation is anticipated, reinforce the well using lateral struts and vertical stiffeners. Also, if unsymmetrical earth pressure is anticipated, it should be considered in the design.

The member cross section (plate thickness) should be determined so that it does not prevent buckling by the following equation, using the maximum earth pressure, P_{tmax}, acting on the peripheral area of the drainage well.

$$q_A = \frac{3 \cdot E \cdot I}{f \cdot R^3} > P_{t\,max} \quad \text{. . . (Equation 5-2)}$$

q_A: allowable external pressure at the peripheral area of drainage well (kN/m^2)

E: Young's modulus (kN/m^2)

I: moment of inertia per meter depth of liner plate or corrugated plate (m^4/m)
However, the effective moment of inertia is reduced to 0.81_0 in consideration of water collection holes, bolt holes, etc. (I_0: moment of inertia when there are no water collection holes, bolt holes, etc.).

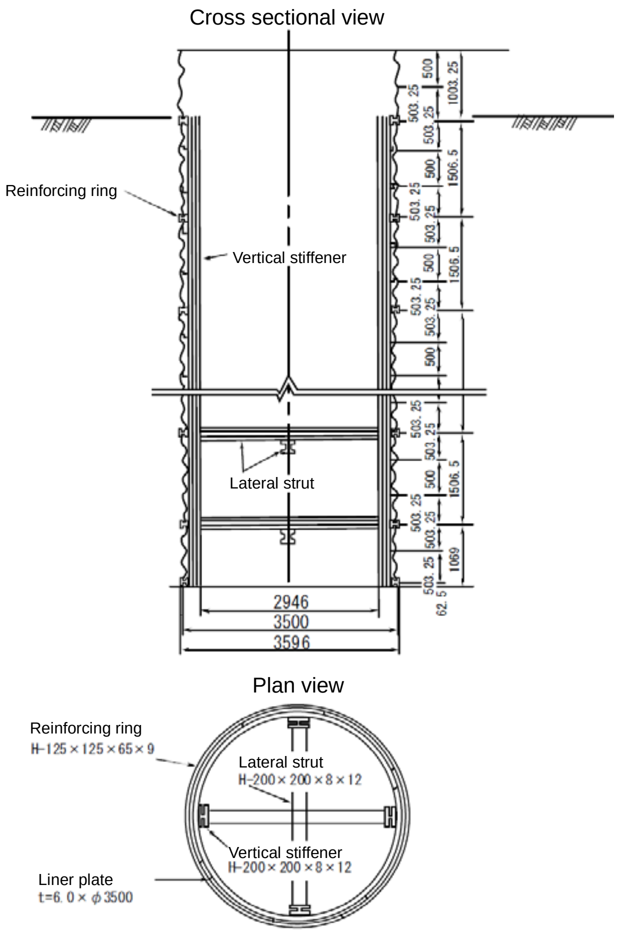
f: safety factor (1.5 – 2.0)

R: radius of drainage well (m)

P_{tmax}: maximum earth pressure acting on the peripheral area of drainage well

Equation 5-2 shows an equation for buckling per unit length of a thin-walled cylindrical well exposed to external pressure when Poisson's ratio is set to zero by considering the effect of corrugations of steel plates. If this equation is not satisfied, apply an H steel reinforcing ring to the horizontal connections of the liner plates or corrugated plates or to the inside of the well for reinforcement. The cross section and interval of a reinforcing ring should be determined by converting the interval of a reinforcing ring into unit length (Fig. 5-14).

If the design conditions such as earth pressure are clearly known, the cross section of members can be changed in accordance with the distribution of earth pressure.



Note) Use a lateral strut or a vertical stiffener as needed.

Fig. 5-14 Example of a drainage well constructed of liner plates (unit: mm)

Two equations can be used to estimate the maximum earth pressure acting on the peripheral area of the drainage well: Terzaghi's equation that takes into account the arch action of the peripheral earth, and Rankine's earth pressure equation. Generally, however, Equations 5-3 and 5-4, which consider that the earth pressure will not increase at the position more than 15 meters deep and assume a triangular distribution of earth pressure at rest, are often adopted (Fig. 5-15).

$P_h = k \cdot \gamma \cdot h$ h < 15 m . . . (Equation 5-3)

$P_h = 15 \cdot k \cdot \gamma$ h ≥ 15 m . . . (Equation 5-4)

P_h: earth pressure (kN/m^2)

k: coefficient of earth pressure at rest (0.5 regardless of whether the soil is sandy or clayey)

γ: unit weight of soil layer (kN/m^3)

h: depth from the ground surface (m)

If it is judged that the earth pressure will increase even at positions deeper than h = 15 m, Equation 5-3 may be used in some cases.

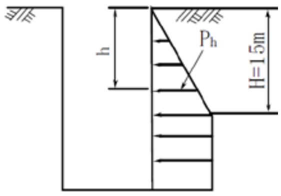


Fig. 5-15 Earth pressure acting on the peripheral area of a drainage well

2) Design of a reinforced concrete drainage well

In general, a reinforced-concrete drainage well is constructed in the following cases.

a) When the ground is a relatively homogeneous, such as sandy soil, and the drainage well easily settles down under its own weight.

b) When the ground is a sandy and is susceptible to bubbling (mud pumping) due to the presence of a large amount of groundwater.

c) When the ground is soft clayey soil susceptible to heaving (the cover layer being pushed up by the confined groundwater).

(3) Drainage bore

Water should be constantly drained from the drainage well under gravity in principle. Mechanical drainage is not desirable because groundwater drainage becomes impossible if the equipment fails. Also, it may induce a landslide and require huge costs for regular maintenance.

The length of the drainage bore is usually about 80 meters maximum. Steel piles, 80 to 100 mm in inside diameter, are normally used. When a large volume of groundwater is expected, use larger pipes or drive multiple drainage bores.

If the length of a drainage bore is very long or bore construction is difficult, construct a relay well at a position 70 to 80 meters away and connect drainage bores to it. Place the flow end of the drainage bore within the landslide block and direct the water outside the block using a channel. Protect the mouth at the flow end and the slope around it using a gabion, a retaining wall, etc.

(4) Water collection bore

The water collection bore should be constructed in one or multiple layers to the radial direction in each aquifer to drain deep groundwater as well as shallow groundwater. The length of one bore is normally 50 meters, but it can be 80 to 100 meters in some cases when the bore is driven into the bedrock penetrating through the slip surface immediately below the scarp.

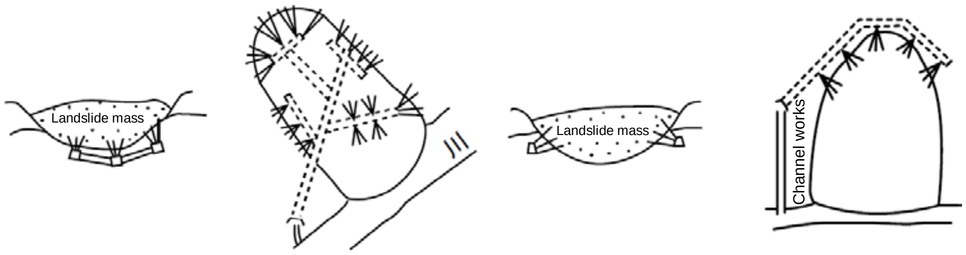
The position, direction, interval, number, etc. of water collection bores should be determined based on the results of geological and groundwater surveys. However, the direction, interval, and number of bores may be changed as the actual groundwater conditions are determined during construction. Hard PVC pipes with an inside diameter of 40 mm or more should be used as water collection pipes. They should be provided with strainers, just like the water collection pipes for horizontal bores.

2-3) Drainage tunnels

Drainage tunnels are constructed when the scale of the landslide is large, the moving layer is thick, or the landslide is moving quickly. Drainage wells cannot be an alternative in these situations because they must be very deep to collect the groundwater and the construction of the well is difficult if the landslide is moving quickly.

The drainage tunnels should not be placed in the landslide mass but placed in stable bedrock in principle (Fig. 5-16). Groundwater that has an adverse impact on the strength of the slip surface should be drained by including water collection bores from the tunnel, a drainage well, etc.

The following points must be noted when designing drainage tunnels.



(a) Drainage tunnel below the mass (b) Drainage tunnel in the peripheral area

Fig. 5-16 Drainage tunnel

(1) Position of drainage tunnels

The distance from the crown of the drainage tunnel in the bedrock to the slip surface should be twice the tunnel diameter by considering the range of possible ground loosening. Drainage tunnels should be positioned to enable groundwater to be drained from immediately below the scarp where groundwater tends to be concentrated and from both sides of the landslide by considering a distribution of groundwater arteries that have an impact on the landslide. Also, the mouths of drainage tunnels should be placed in hard ground as much as possible.

(2) Longitudinal angle of drainage tunnels

The longitudinal inclination of drainage tunnels should be lowered toward the tunnel mouth in order to drain collected groundwater under gravity. Normally, the inclination should be less than 15/1000.

(3) Cross section and structure of drainage tunnels

The cross section of a drainage tunnel can be a horseshoe, circular, semi-circular, trapezoidal or rectangular in shape (Fig. 5-17). Tunnels should be basically hollow for ease of maintenance, including maintenance of the water collection facilities, and should be covered with lining for greater durability. The tunnel cross section should be determined by considering ease of construction, ease of maintenance, and the total cost from construction to maintenance.

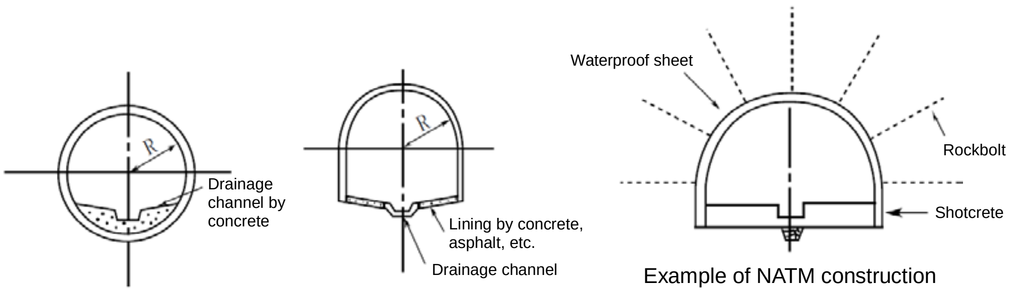


Fig. 5-17 Examples of the cross section of a drainage tunnel

Concrete, liner plates and corrugated plates, etc. are used as lining materials.

(4) Tunnels for emergency escape

If a drainage tunnel is more than 1000 meters long, it is necessary to install an inclined shaft or a vertical shaft for emergency escape to ensure safety.

(5) Water collection

Water should be collected into drainage tunnels through the use of water collection bores in principle. Water collection bores should be driven from inside the tunnel toward the aquifer in a radial configuration either in the upward or horizontal direction. The bore angle should be determined by taking into account the distance up to the aquifer, the total length of the bore, the distance across the aquifer, etc.

If the bore angle is steep, a bore space with an enlarged cross section should be constructed in the tunnel. For the length of the water collection bores and water collection pipes, refer to sections 1-3 and 2-1, “Horizontal Bores.”

(6) Drainage tunnels

The base area of the drainage tunnel should have the same structure as the channels in principle so that the groundwater collected by water collection bores does not re-seep into the ground. Even when the drainage tunnel is lined with liner plates or corrugated plates, they should not be used for the base area of the tunnel because water can leak due to a joint failure or the loosening of bolts. The base area, or the channel in the tunnel, should be constructed of concrete to ensure that the functionality of the drains is retained.

(7) Earth pressure acting on the drainage tunnel

The earth pressure acting on the drainage tunnel should be determined by considering the geology, the size of the tunnel cross section, the construction method, the type of lining, the construction period, the behavior of the natural ground, etc.

The reference values are shown in Table 5-1.

Table 5-1 Earth load acting on the tunnel supports proposed by Terzaghi[1)]

Bedrock conditions	Height of earth load	Remarks
(i) Hard and undisturbed	0	Use simple tunnel supports if rock falls and rock bursts are seen.
(ii) Hard and layered or schist-like	0 – 0.5B	Use simple tunnel supports. The load changes irregularly depending on the position.
(iii) Large mass with ordinary level of joints	0 – 0.25B	
(iv) Ordinary mass with cracks	0.25B – 0.35 (B + H_t)	No lateral pressure
(v) Very small mass with many cracks	(0.35 – 1.10) (B + H_t)	The lateral pressure is small or none.
(vi) Completely fractured but not weathered chemically	1.10 (B + H_t)	If the tunnel bottom is weak due to considerable lateral pressure or water leakage, place a through base at the tunnel bottom or use circular supports.

(1) This table shows the earth load acting on the crown of steel arch supports when the overburden is 1.5 (B + H_t) or more.
B: width of the tunnel cross section (m)
H_t: height of the tunnel cross section (m)

(2) This table assumes that the tunnel crown is below the groundwater level. If the tunnel crown is above the groundwater level permanently, the values of (iv) – (vi) can be reduced by 50%.

(8) Materials used for tunnel supports

Wooden and steel materials are used for to support the tunnel. In general, wooden materials are used when the ground is hard rock or when filling is performed a short time later, and steel materials are used for locations where the earth pressure will act or when lining is applied some time later. In recent years, the use of the NATM construction method that applies shotcrete and rockbolts is increasing.

2-4) Other works

Other works include water collection and drainage works using a large bore. Steel pipes, 300 to 600 mm in diameter and provided with slits, are used for water collection pipes for horizontal bores or drainage wells. They are also used when it is anticipated that the slits will become clogged or the water collection pipes will fracture.

5.2.3 Earth removal

Earth removal should be designed to stabilize the slope mainly around the landslide head area. Factors such as the removal volume, removal position, inclination and vertical height of the cut slope should be determined through analysis of the slope stability.

When designing the earth removal, it is necessary to carefully examine the stability of the slope above the earth removal position and the risk of a landslide, plus the adequacy of the earth removal itself, so that the stability of the upper slope will not be reduced and a landslide will not occur as a result of the work. Protecting the slope after the earth is removed should also be considered.

Comments

The following points should be noted when designing earth removal.

(1) Cut slope

Figure 5-18 shows a concept of earth removal and the resulting cut slope. The inclination and vertical height of the cut slope should be determined by examining the stability of the cut slope in advance with a focus on the geological conditions, etc. These examinations are necessary because a cut slope tends to have less stability over time and may cause a surface failure.

Normally, the inclination of the cut slope in soft rock is about 1:0.5 to 1:1.2, and a berm with a width of 1.0 to 2.0 meters is installed every 7 meters in vertical height.

In the case of sandy soil, the inclination of the cut slope is about 1:1.0 to 1:1.5 per vertical height of 5 to 10 meters, and a berm with a width of 1.0 to 2.0 meters is installed every 5 to 10 meters in vertical height.

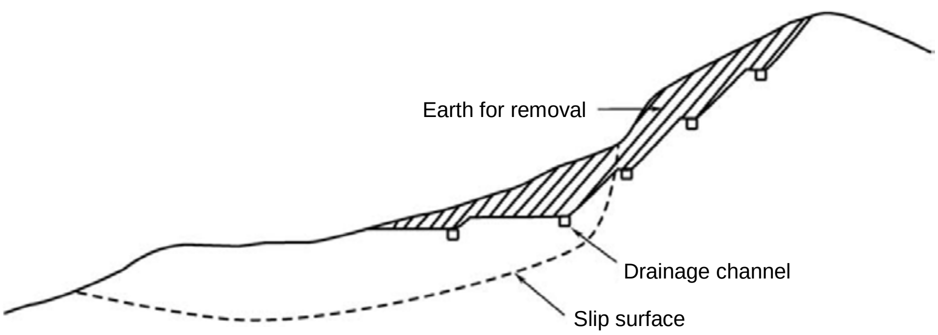


Fig. 5-18 Earth removal and the cut slope

(2) Investigation of the stability of the upper slope

When removing earth, it is necessary to investigate the stability of the upper slope and risk of a landslide at the site in advance. This is because the removal of earth tends to destabilize the upper slope and cause a landslide in some cases. If there is found to be a risk of a landslide on the upper slope, it is necessary to remove the landslide or construct a restraint. Therefore, sufficient investigations are necessary, including an investigation into the adequacy of adopting earth removal itself.

(3) Protection of the slope after earth removal

After soil has been removed, the slope soil tends to be weakened by rainfall, etc. and there may be a slope failure. Therefore, channels to collect surface water, drainage channels, and berms should be installed on the slope to improve water drainage.

Also, to prevent erosion and weathering, the slope should be protected with vegetation or structures. In the case of slopes that are not conducive to vegetation or where vegetation only is not enough to ensure stability, it is necessary to protect the slope with stonemasonry, block masonry or cribs, etc.

5.2.4 Embankment loading

Embankment loading should be designed to provide a resistive force against the sliding force of the landslide by installing an embankment at the foot of the landslide slope. The volume and position should be determined by analyzing the slope stability to provide the required resistive force.

When designing embankment loading, it is necessary to investigate the stability of the ground below the embankment based on the survey results of the foundation ground, plus groundwater treatment at the slope behind the embankment and the protection of the slope and toe of the embankment.

Comments

Figure 5-19 shows the concept of embankment loading.

Because the landslide slope is often disturbed and weak, there is the possibility of failure at the base of the embankment. Also, if the lower slope below the embankment is unstable and is at risk of sliding, a failure can be triggered. Therefore, when designing embankment loading, it is important to investigate the stability of the bedrock beneath the embankment based on the survey results of the foundation ground.

The height and slope of embankment loading should be determined by considering the embankment materials and the properties of the foundation ground. Usually, the average inclination of the embankment is 1:1.5 to 1:2.0, and a berm with a width of 1.0 to 2.0 meters is installed every 5 meters in vertical height. Channels should be provided to the berms.

Sometimes, spring water is present and horizontal bores, etc. are installed at the foot of the landslide slope, so caution should be taken not to block the bores when constructing an embankment. If a shallow groundwater aquifer is located at the position of the embankment, sufficient care must be taken to treat the groundwater behind the embankment. Otherwise, the groundwater level in the back slope will increase or the load will increase if the groundwater outlet is blocked by the embankment, leading to destabilization of the slope.

As the slope of the embankment is susceptible to collapse or scouring due to rainfall, etc., work should be done to protect the slope. It is desirable to introduce vegetation, or construct gabions or cribs, etc. to protect the slope. The use of rigid structures such as concrete masonry must be avoided as much as possible. However, in the case of slopes submerged in a ponding dam, stonemasonry or block masonry, etc. is sometimes adopted.

To protect the toe of the slope, structures such as gabions, retaining walls with reinforced concrete cribs or retaining walls with wave dissipating blocks should be used in principle. When a concrete gravity-type retaining wall is installed to protect the slope, caution must be taken so as not to cause a landslide by excavating its foundation. The embankment slope should be protected from surface erosion and provided with greening to improve the natural environment and aesthetics.

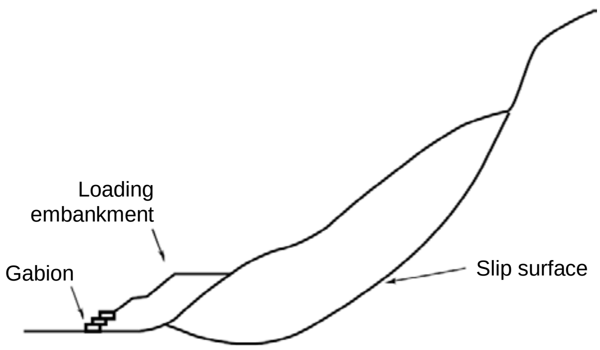


Fig. 5-19 Embankment loading

5.2.5 Erosion control using river structures

Erosion control using river structures should be designed to prevent the collapse of riverbanks due to erosion of the landslide foot by flowing water etc., and hence to prevent landslide movement.

Comments

If the foot of a landslide slope is eroded by flowing water, etc., the riverbanks may collapse and landslide movement may result. Therefore, to prevent erosion of the landslide foot, erosion control using river structures should be adopted.

If sabo dams or ground sill works are installed in the river immediately below the landslide slope, the accumulated sediment can help prevent collapse and erosion and add resistive force at the landslide foot. The following points should be noted when designing erosion control using river structures.

(1) Minimize excavation for the construction of river structures so that the stability of the landslide will not be diminished.

(2) Install a groundwater drainage facility if necessary so that the groundwater level in the landslide slope will not increase due to the installation of river structures.

(3) Adopt river structures that are flexible and safe against the effect of flowing water when installing them at the site of a moving landslide.

(4) For the landslide site that is actively moving, adopt a structure that needs no excavation or install a sabo dam at a safe downstream position in anticipation of the effects of embankment loading of the accumulated sediment.

5.3 Design of Restraining Structures

5.3.1 Piles

Piles should be designed to provide the required preventive force by considering the topography, geology, etc. of the landslide site.

When designing piles, investigation should be made of the stability of the piles against internal stress when force is applied, as well as on the prevention of passive failure in the moving layer above the piles, the failure of the foundation ground, and the extraction of soil mass between the piles.

Comments

1) Functions and classification of piles

Piles for the prevention of landslides can be classified as follows in terms of function:

(1) Flexural piles

Flexural piles are designed against the assumption that when sliding occurs, the landslide mass will be deformed and shear force and bending stress will be applied on the piles. There are two types of flexural piles: wedge piles and restraint piles.

(i) Wedge piles

These piles are designed by assuming that the sliding force of the landslide acts on the slip surface as a concentrated load, and that a shear force and a bending stress are generated when the piles move with the landslide mass and bend at above or below the slip surface.

(ii) Restraint piles

These piles are designed by assuming that the piles act like a cantilever beam when ground reaction on the side of the valley cannot be expected, and that the sliding force of the landslide acts on the piles in the moving layer as a distributed load or a concentrated load. Restraint piles are used for the foot or head area of the landslide.

(2) Shear piles

Shear piles are designed by considering only the shear force, assuming that the landslide mass will not be deformed during sliding (meaning that the bending stress will not occur in the piles) and hence the sliding force of the landslide acts on the slip surface as a concentrated load.

2) Application conditions of piles

The conditions under which piles are adopted should be examined carefully. According to past records, the thickness of a moving layer to which piles were applied is mostly within 20 meters. Other application conditions include: they should not be applied to weak ground or to a moving layer that is divided into small masses due to cracks; they must be constructed when landslide activity is dormant.

In terms of design, it must be noted that piles assume that the pile body is an elastic body, and that the ground around the piles is always expected to react except in the case of restraint piles.

When adopting shear piles, it is necessary to carefully confirm that there is no risk of bending failure with the piles. Shear piles sometimes tilt due to a shallow landslide in the slope.

3) Horizontal load-carrying capacity of piles

Piles should be designed to secure the proposed safety factor by considering the topography, geology, etc. of the landslide site.

As the equation for calculating the effect of piles, there are Hennes's equation, White's equation, PWRI equation, etc. These equations consider that the prevention effect to be obtained should be equal to the failure strength of the landslide mass around the piles when the piles are rigid bodies and have an infinite strength. But, in actuality, piles do not have an infinite strength and the stress calculated by those equations cannot be carried by only one pile. Therefore, it is necessary to estimate the required number of piles per unit width of stress, by taking into account the constructible strength of piles.

Piles are usually constructed by drilling vertical holes, inserting piles in the holes, and filling the holes with grouting. However, driver-type piles, such as steel pipe piles or steel H-beams piles, etc. are also used to prevent landslides as an emergency measure. Pile driving up to the required depth is difficult in layers containing a large amount of gravel. Also, pile driving into bedrock is very hard, and is possible only up to a limited depth. Pile driving has a negative impact as well: weathering is accelerated as the bedrock is crushed. Therefore, the adoption of driver-type piles as a permanent measure should be avoided.

To achieve the proposed safety factor, the preventive force of the pile per unit width, Pr (kN/m), can be obtained by the following equation when the simplified calculation method is used.

$$P.Fs = \frac{\sum(W \cdot cos\,\theta - U) \cdot tan\,\phi' + c' \cdot \sum l + P_r}{\sum W \cdot sin\,\theta} \quad \text{. . . (Equation 5-5)}$$

$$P_r = P.Fs \cdot \sum W \cdot sin\,\theta - \sum(W \cdot cos\,\theta - U) \cdot tan\,\phi' - c' \cdot \sum l \;. . . \quad \text{(Equation 5-6)}$$

Pr: prevention force of pile per unit width (kN/m)

P. Fs: proposed safety factor

W: weight of slice (kN/m)

U: pore water pressure acting on slice (kN/m)

I: length of slip surface of slice (m)

θ: inclination angle of slip surface of slice (°)

ϕ': internal friction angle of slip surface (°)

c': cohesion of slip surface (kN/m^2)

When control works are used in combination, the preventive force required for piles is obtained by changing *U, W,* and *I* on the right side of Equation 5-6 in accordance with the effect of each control work.

4) Position of pile installation

In principle, piles should be installed at a position that satisfies the following conditions: below the center of the landslide block where the inclination of the slip surface is relatively gentle; within the compressive range of the landslide mass; where the moving layer is relatively thick; and where a passive failure will not occur.

However, when the intended work area is limited to the upper part of the landslide block, piles may be installed in the tensile range where the inclination of the slip surface is relatively steep. In that case, it is assumed in the design that there will be no ground reaction because the soil mass on the slope below the piles will fall off.

Piles to be installed in the compressive range should be placed at the position where the back pressure can be expected sufficiently and below the boundary between $\Sigma R_i > \Sigma T_i$ (compressive range) and $\Sigma R_i < \Sigma T_i$ (tensile range) which is obtained by comparing the sliding force T_i and the resistive force R_i of each slice starting from the lowermost slice at the foot of the landslide block (Fig. 5-20).

$T_i = W_i \cdot \sin \theta_i$ . . . (Equation 5-7)

$R_i = (W_i \cdot \cos \theta_i - U_i) \cdot \tan \phi' + c' \cdot l_i$ . . . (Equation 5-8)

T_i: sliding force per slice (kN/m)

R_i: resistive force per slice (kN/m)

W_i: weight of slice (kN/m)

U_i: pore water pressure acting on slice (kN/m)

l_i: length of slip surface of slice (m)

θ_i: inclination angle of slip surface of slice (°)

ϕ': internal friction angle of slip surface (°)

c': cohesion of slip surface (kN/m^2)

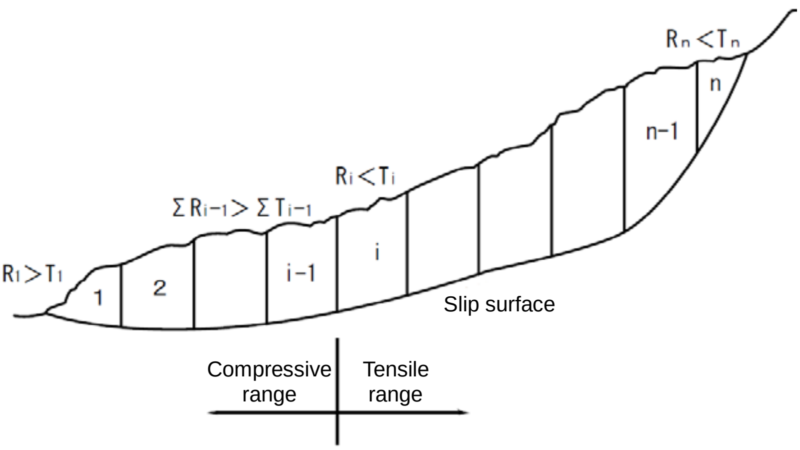


Fig. 5-20 Position of piles in the compressive range[1)]

However, the most accurate method to determine if it is a compressive range or a tensile range is to install ground extensometers sequentially on the landslide slope, from the upper portion of the slope to the lower portion, and evaluate the ground expansion at each position.

When piles are installed at the foot of the landslide, care must be taken not to cause a new landslide on the slope above the piles due to passive failure (Fig. 5-21).

For that purpose, it is necessary to satisfy *P.Fs'* (Equation 5-10) ≥ *P.Fs* (Equation 5-9).

$$P.Fs = \frac{\sum\{(W_{ab} \cdot cos\,\theta - U_{ab}) \cdot tan\,\phi' + c' \cdot l_{ab}\} + P_r}{\sum W_{ab} \cdot sin\,\theta}$$ P . . . (Equation 5-9)

P.Fs: safety factor after the installation of pile against original slip surface

P_r: Prevention force of pile per unit width (kN/m)

W_{ab}: weight of slice at slip surface *a b* (kN/m)

l_{ab}: length of slip surface of slice at slip surface *a b* (m)

U_{ab}: pore water pressure acting on slice at slip surface *a b* (kN/m)

θ: inclination angle of slip surface of slice at slip surface *a b* (°)

ϕ': internal friction angle of slip surface *a b* (°)

c': cohesion of slip surface *a b* (kN/m^2)

$$P.Fs' = \frac{\sum\{(W_{ax} \cdot cos\,\theta_{ax} - U_{ax}) \cdot tan\,\phi_{ax}' + c_{ax}' \cdot l_{ax}\} + \sum\{(W_{xy} \cdot cos\,\theta_{xy} - U_{xy}) \cdot tan\,\phi_{xy}' + c_{xy}' \cdot l_{xy}\}}{\sum W_{ax} \cdot sin\,\theta_{ax} + \sum W_{xy} \cdot sin\,\theta_{xy}}$$

. . . (Equation 5-10)

P.Fs: safety factor against assumed slip surface *a x y* after pile installation

W_{ax}: weight of slice at slip surface *a x* (kN/m)

W_{xy}: weight of slice at slip surface *xy* (kN/m)

l_{ax}: length of slip surface of slice at slip surface *a x* (m)

l_{xy}: length of slip surface of slice at slip surface *x y* (m)

U_{ax}: pore water pressure acting on slice at slip surface *a x* (kN/m)

U_{xy}: pore water pressure acting on slice at slip surface *x y* (kN/m)

θ_{ax}: inclination angle of slip surface of slice at slip surface *a x* (°)

θ_{xy}: inclination angle of slip surface of slice at slip surface *x y* (°)

c_{ax}': cohesion of slip surface *a x* (kN/m^2)

c_{xy}': cohesion of slip surface *x y* (kN/m^2)

ϕ_{ax}': internal friction angle of slip surface *a x* (°)

ϕ_{xy}': internal friction angle of slip surface *x y* (°)

$$\alpha = 45^\circ - \frac{\phi_{xy}'}{2}$$ . . . (Equation 5-11)

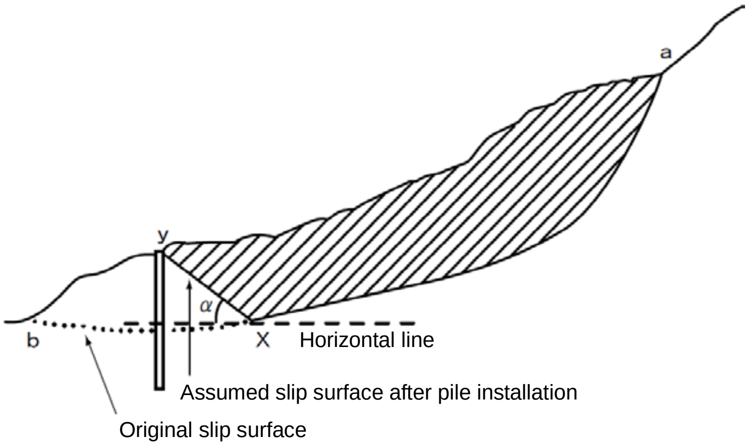


Fig. 5-21 Passive failure at the upper part of a pile[1)]

5) External forces acting on piles

In designing the piles, it is necessary to consider the bending stress and shear stress of piles in principle.[1)] When the object to be protected, such as a structure or land, is located only in the tensile range of the landslide block, piles are sometimes installed at the position closer to the object in the tensile range. In that case, the ground is not expected to react at the back of the piles and the entire sliding force from the upper slope will be applied to the piles. Therefore, those piles must be designed as restraint piles that can withstand that force.

6) Type and strength of piles

The steel materials used as piles must satisfy the design strength. The pile strength is indicated by long-term or short-term allowable stress depending on the load acting on the piles. When control works are used in combination with the piles, the short-term allowable stress should be used in principle.

Table 5-2 shows reference values of the design strength of piles. For steel materials used as steel pipe piles, see the specifications in JIS A 5525, JIS G 3444, JIS G 5201, JIS G 3106, and JIS G 3101.

Table 5-2 Design strength of piles[1) with partial revision]

Item	Short-term allowable stress (N/mm^2)		Long-term allowable stress (N/mm^2)	
	Shear	Bending	Shear	Bending
STK400 or equivalent	118	206	78	137
SM490 or equivalent	162	279	108	186

7) Pile arrangement

Piles should be arranged roughly normal to the direction of landslide movement and at equal intervals.

The pile interval should be determined considering the design conditions of the piles adopted. However, as there is the possibility of ground loosening or the soil mass being extracted due to the impact of hole drilling, depending on the soil conditions, the standard pile intervals should be as shown in Table 5-3 or broadly no more than eight times the pile diameter.

To prevent failure in the bedrock due to pile construction, intervals of at least one meter must be provided between the walls of the pile holes. If the interval between the walls of the pile holes is expected to be less than one meter by calculation, piles should be arranged in a zigzag pattern.

Table 5-3 Interval between piles[2] with partial revision

Thickness of moving layer at the pile position	Interval between piles
0 – 10 m	Less than 2.0 m
10 – 20 m	Less than 3.0 m
20 m or more	Less than 4.0 m

8) Penetration distance of piles

The distance that the piles penetrate into the ground should be determined so as not to cause the foundation to fail due to earth pressure acting on the piles. The penetration distance should be determined by considering the design conditions of the piles adopted.

It is necessary to create a unified structure for the piles and foundation ground by applying fill between the hole wall and the pile. For that purpose, insert a grout pipe between the hole wall and the pile and inject mortar to fill the cracks around the base and the space between the hole wall and the pile.

5.3.2 Shafts

Shafts should be designed to provide the required preventive force by considering the topography and geology, etc., of the landslide site.

When designing shafts, investigation should be made concerning the stability of the shafts against internal stress when the force is applied, as well as on the prevention of passive failure in the moving layer above the shaft, the failure of the foundation ground, and the extraction of soil mass between the shafts.

Comments

Shafts (Fig. 5-22) should be designed to provide the required preventive force by considering the topography and geology, etc., of the landslide site.

When designing shafts, make a sufficient investigation of the subsurface structures, such as the slip surface, and install shafts in ground that is as hard as possible.

The load to be carried by the shafts per unit width of landslide mass should be determined in the same manner as for piles.

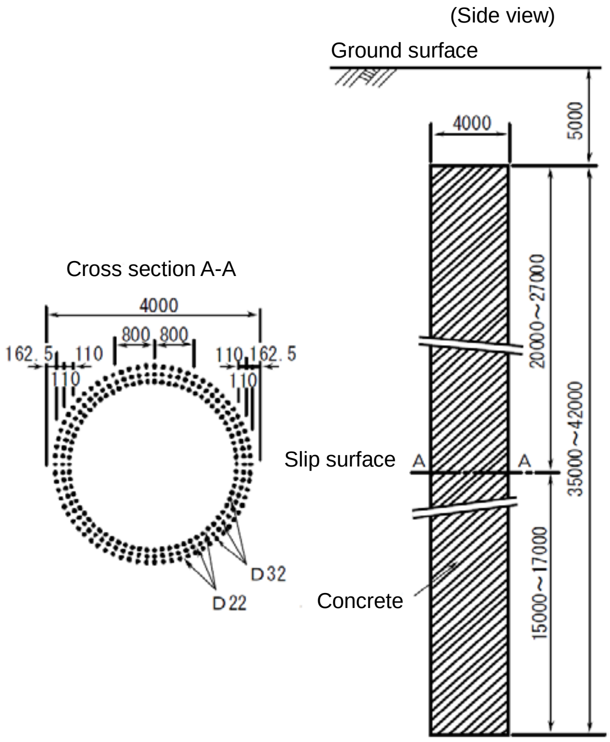


Fig. 5-22 Example of shaft (unit: mm)

Normally, the following equation is used for judging whether large-diameter structures such as shafts should be designed as the flexural pile or as the rigid pile that does not deform under load.

$\beta l \leq 2$ . . . designed as a rigid pile.

$\beta l > 2$ . . . designed as a flexural pile.

$$\beta = \sqrt[4]{\frac{K \cdot d}{4 \cdot E \cdot I}} \quad \text{. . . (Equation 5-12)}$$

K: coefficient of sub-grade reaction in the horizontal direction at the penetration ground (kN/m^3)

d: outside diameter of shaft (m)

l: penetration length of shaft from the slip surface (m)

E: elastic modulus of shaft (kN/m^2)

I: moment of inertia of shaft (m^4)

In general, reinforced concrete is used to fill the inside of the shaft.

The shaft interval is determined by dividing the preventive force of one shaft by the preventive force per unit width of landslide required to achieve the proposed design factor, but it must be an interval that does not cause the soil mass to be extracted or the foundation to fail.

5.3.3 Anchors

Anchors should be designed to provide the required preventive force by considering the topography and geology, etc., of the landslide site. They should also be designed to ensure that the anchors, the ground in which the anchors are fastened, and the anchor structures (bearing plates, etc.) are secure against the tension force applied.

Comments

(1) General

Basically, anchors consist of the following three components (Fig. 5-23).

1) Anchor head (including the reaction structure)
2) Tension area
3) Anchorage area (anchor body and the anchorage ground)

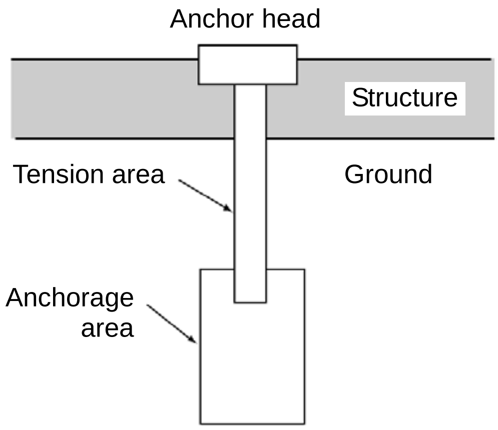


Fig. 5-23 Components of anchors

The purpose of anchors in landslide prevention is to stabilize the landslide mass by unifying it with an immovable mass, by transferring the load acting on the anchor head to the anchorage ground via the tension area.

Anchors should be designed to provide the required preventive force by considering the topography and geology, etc., of the landslide site. They should also be designed to ensure that the anchors, the ground in which the anchors are fastened, and the anchor structures (bearing plates, etc.) are secure against the tension force applied.

The various design factors associated with anchors, including the position of the anchors, the position of the anchorage ground, the layout of the anchors, the anchor angles (angle between the driving direction of the anchor and the horizontal plane) and the scale and shape of the structures, should be determined carefully by examining the topography and geology of the landslide site, the moving conditions of the landslide, etc.

Anchor can provide the following effects:

1) Tightening effects

   The tightening effect refers to the effect of increasing the shear resistance by increasing the vertical stress against the slip surface (Fig. 5-24). The tightening effect can be expected when the moving mass does not sustain significant compressive or consolidation deformation when the tension force is applied to the anchor. Therefore, it is difficult to achieve the tightening effect when the moving mass is composed of clayey or collusive soil or weathered bedrock with many cracks. It is also difficult to achieve the tightening effect when the slip surface is located in a deep position.

2) Restraining effects

The restraining effect refers to the effect that prevents a landslide mass from sliding at the slip surface by means of the force component of the anchor in the tangential direction of the slip surface (Fig. 5-24). This effect relies on the tensile resistance of steel materials, and is used for a landslide having a large sliding force or a landslide to which it is difficult use piles.

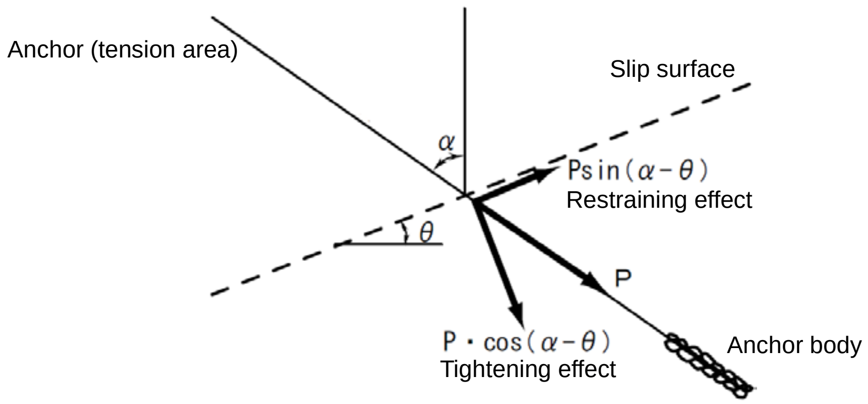


Fig. 5-24 Functions of anchors

Anchors for landslide prevention are often constructed at the foot of the landslide to provide a restraining effect. When designing anchors, it is important to select the most appropriate function by considering the anchor angle, inclination and depth of the slip surface, etc. In some cases, the engineer seeks to incorporate both of these effects into the design.

(2) Calculation of the anchor force

Two types of anchors are available to prevent landslides: (i) anchors that provide a tightening effect and (ii) anchors that provide a restraining effect. The required anchor force for each type of anchor is calculated by the following equation.

(i) Calculation of anchor force for anchors that provide a tightening

$$P.Fs = \frac{\{\sum(W \cdot cos\theta - U) + P \cdot cos(\alpha - \theta)\} tan\phi' + c' \cdot \sum l}{\sum W \cdot cos\theta} \quad \text{. . . (Equation 5-13)}$$

(ii) Calculation of anchor force for restraining-type anchor works

$$P.Fs = \frac{\sum(W \cdot cos\theta - U) \cdot tan\phi' + c' \cdot \sum l + P \cdot sin(\alpha - \theta)}{\sum W \cdot sin\theta} \quad \text{. . . (Equation 5-14)}$$

P.Fs: proposed safety factor

W: weight of slice (kN/m)

U: pore water pressure acting on slice (kN/m)

P: required anchor force (kN/m)

ϕ': internal friction angle (°)

c': cohesion (kN/m^2)

l: length of slip surface of slice (m)

θ: inclination of slip surface at the anchor position (°) (See Fig. 5-24)

α: anchor driving angle (°) (See Fig. 5-24)

(3) Layout of anchors

Anchors should be positioned considering the stability of the reaction structure, the surrounding ground and anchorage ground, and the effect on the adjacent structures. The anchor position and the direction and interval of anchors should be considered in the early stage of design.

1) Position of anchors

   In areas such as the landslide head where the slip surface is steep, the anchor angle with the slip surface becomes nearly a right angle. In this case, the anchors' restraining effect remains small and they may break due to shear force. Therefore, the anchor position should be determined with care. In principle, the landslide head area should be avoided.

2) Effect on adjacent structures

   If buried structures, tunnels, or piles are located near the anchor driving position, careful consideration is necessary to prevent those structures from being affected. The anchor driving direction should be the same as the landslide movement direction.

3) Anchor angle

   The anchor angle should be determined considering not only the mechanical advantages but also other conditions including topography, geology, and construction conditions. However, the range from -5° to + 5° from the horizontal plane should be avoided in principle due to problems related to anchor construction (residual slime, bleeding of grout materials, etc.)

4) Interval of anchors

   The interval of anchors should be determined considering the attributes of anchors, such as the design anchor force, the diameter and penetration distance of the anchors.

(4) Design of anchors

Designing of anchors, including the calculation of design anchor force and anchor length, should be conducted by referring to the "Guidelines for the Design and Construction of Ground Anchors" [3].

(5) Corrosion prevention

Basically, the anchors used in landslide prevention should be permanent anchors fully treated to prevent corrosion (Fig. 5-25). Corrosion protection for anchors should be designed by considering the corrosive environment during and after construction. Corrosion protection measures should be taken by assuming the most unfavorable corrosion conditions.

1) Corrosion prevention for the anchor body

   In general, the anchor body should be covered with a corrosion preventive material having certain thickness and strength, and the inside of the body should be filled with a grout material, etc.

2) Corrosion prevention for the tension area

   In general, the tendons should be covered with a material having certain thickness and strength, and the space between the tendon and sheath should be filled with a corrosion preventive material (rust preventive oil). In the case of anchors that need re-tensioning, a corrosion preventive material that does not confine the elongation of tendons should be selected.

3) Corrosion prevention for the anchor head

In general, the anchor head should be protected by a combination of a protective cap and a corrosion preventive material (rust preventive oil). Select an appropriate corrosion prevention measure if it is an anchor that needs re-tensioning.

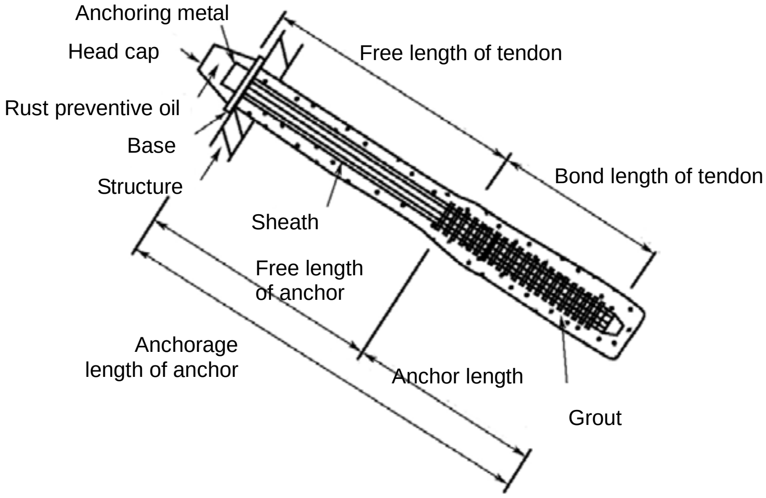


Fig. 5-25 Example of a permanent anchor

(6) Bearing plate

When using anchors to prevent landslides, a cut slope is constructed for a bearing plate. Sufficient consideration is necessary before construction of the cut slope so as not to create a landslide movement.

The bearing plate should be designed to fully resist the tension force of the anchor. The bearing plate is a structure that is installed on the slope to rigidly fasten the anchor. The bearing plate provides a reaction force and is available in two types: an independent bearing plate having various forms and a continuous bearing plate combined with a grating crib, etc. The bearing plate should be selected by considering the slope conditions, anchor attributes, ease of construction, economy, maintenance, aesthetics, etc. and designed in accordance with the slope conditions. In the case of landslides, independent bearing plates that need less slope cut are often adopted.

1) Forces acting on the bearing plate

Basically, the forces acting on the bearing plate are the design anchor force (T) and the sub-grade reaction as the reaction against it. The allowable stress for the concrete and reinforcing bars used for the baring plate should be based on the “JSCE Guidelines for Concrete: Standard Specifications for Concrete Structures (The Japan Society of Civil Engineers)”[4)].

2) Calculation of the cross-sectional force

The cross-sectional force should be calculated using a beam model in principle. Whether the sub-grade reaction should be treated as an equally distributed load and whether the anchor force treated as a concentrated load should be determined by taking into account the conditions of the ground.

3) Greening of the slope after installation of the bearing plate

The cut slope that is constructed for installation of a bearing plate should be greened to prevent erosion and to conserve the natural environment and aesthetics.

References

1) Japan River Association: Ministry of Land, Infrastructure, Transport, and Tourism Technical Criteria for River Works (Draft): *Practical Guide for Design II*, Sankaido Publishing Co., pp. 55 & 59, 1997.

2) *Design Guide for Steel Pipe Piles for Landslide Prevention*, Japan Association for Slope Disaster Management, p. 215, 2003.

3) Japan Geotechnical Society: *Guidelines for Design and Construction of Ground Anchors*, Japan Geotechnical Society, p. 219, 2001.

4) Japan Society of Civil Engineers: *JSCE Guidelines for Concrete: Standard Specifications for Concrete Structures – Structural Performance Verification*, Maruzen Co., p. 243, 2002.

Chapter 6 Inspecting and Monitoring Landslide Slopes after Conducting Work

6.1 General

Landslide occurrence and movement is a complicated mechanism and hence a sliding movement can occur on a landslide slope even after work has been conducted to prevent a landslide.

Therefore, the landslide slope should be inspected and monitored after work has been conducted to prevent a landslide in order to detect any sign that may indicate a landslide disaster in the early stages.

6.2 Inspections

Periodic inspections and a special inspection should be conducted on the landslide slope after work has been conducted to prevent a landslide.

Periodic inspections should be performed in the visually observable range roughly once a year by site reconnaissance to check for slope deformations and spring water conditions due to a landslide.

A special inspection should be carried out by visual observation after an earthquake, heavy rain, etc. in the same manner as the periodic inspections.

Comments

There are two types of inspections: periodic inspection and special inspection. Information from local people about the deformations of landslide prevention facilities, etc. plays an important role in identifying the needs of a special inspection. Landslide sites where work has been completed to prevent a landslide are usually checked by visual inspection because the monitoring devices have been removed or no longer work.

A periodic inspection should be performed in the visually observable range roughly once a year by site reconnaissance. The following items should be inspected:

1) Slope deformations due to a landslide (cracks, unevenness, deformations of restraint structures or roads)

2) Changes in spring water conditions

To facilitate an inspection for cracks, unevenness, and deformations in restraint structures and roads, it is desirable to provide an observation path paved with concrete where appropriate.

There are cases where inspection work is assigned to local people with good results.

6.3 Monitoring

In the case of landslide slopes for which work has been completed to prevent landslides, but where there are many structures to be protected, the slope stability should be monitored by installing slope-monitoring devices in and around the landslide site, in addition to performing visual inspections.

If slope deformations are found as a result of an inspection, the displacement and inclination at the ground surface should be measured and the moving conditions of the landslide immediately determined.

Comments

For the monitoring of displacement and inclination at the ground surface, a ground extensometer meter, movable piles, GPS survey, etc, should be used. Table 6-1 shows the devices used for monitoring the landslide slope.

Table 6-1 Slope monitoring using monitoring devices

	Object of monitoring	Device and method	Amount
Landslide slope	Ground surface	Ground extensometer	Displacement at ground surface Crack width
		Movable pile survey	Displacement at ground surface
		GPS survey	Displacement at ground surface
		Ground inclinometer	Ground inclination
	Sub-surface	Pipe strain gauge	Strain in the ground
		Borehole inclinometer	Displacement in the ground
		Vertical extensometer	Displacement
		Pore water gauge	Pore water pressure
		Groundwater gauge	Groundwater level
		Anchor load cell	Axial force

6.4 Record Keeping

Landslide slopes should be inspected and monitored by utilizing a slope chart, etc. that contains information such as disaster history and inspection results. Materials and records obtained from inspections and monitoring should be organized and stored in an easy-to-use manner.

6.5 Incorporation into a Landslide Prevention Plan

If factors that may lead to a landslide disaster are identified as a result of inspecting and monitoring the landslide slope, the landslide prevention plan should be reviewed and necessary landslide prevention measures incorporated.

Chapter 7 Maintenance of Functions of Landslide Prevention Facilities

7.1 General

To retain the stability of the landslide slope after work has been conducted to prevent a landslide, the functions of the completed landslide prevention facilities should be maintained.

7.2 Inspections

The landslide prevention facilities should be subject to periodic inspections and special inspections. Periodic inspections should be performed in the visually observable range roughly once a year by site reconnaissance to check for the conditions of surface drainage channels, groundwater drainage channels, slopes from which earth has been removed, embankment slopes, erosion prevention facilities such as river structures, etc. A special inspection should be performed by visual inspection after an earthquake, heavy rain, etc. in the same manner as for periodic inspections.

Comments

There are two types of inspections: periodic inspections and special inspections. A periodic inspection should be carried out in the visually observable range roughly once a year by site reconnaissance regarding the following items. A special inspection should be conducted by visual inspection after an earthquake, heavy rain, etc. in the same manner as for periodic inspections.

1) Conditions of surface drainage channels (damage such as the opening of joints and cracks, the clogging of channels due to the accumulation of sediment, failure or deformation of catch basins, the accumulation of sediment in catch basins)
2) Conditions of groundwater drainage facilities
   a) Drainage wells
      - Damage, deformation, and corrosion of drainage wells, ponding in drainage wells
      - Corrosion and clogging at the mouth of the collection pipe, water collection conditions
      - Corrosion and clogging at the mouth of the drainage pipe, water drainage conditions
      - Damage, deformation, and corrosion of ancillary facilities (cover, protective fence, steps)
      - Deformation in the peripheral area of the drainage well (collapse, cracks, depressions, etc.)
   b) Horizontal bores
      - Damage and deformation of facilities for mouth protection
      - Corrosion and clogging of the mouth of the collection pipe
   c) Drainage tunnels
      - Cracks and strain in the drainage tunnel
      - Failure, deformation, sediment accumulation in the drainage channel

- Corrosion and clogging of the mouth of the collection pipe

3) Conditions of slopes from which earth is removed and embankment slopes
   - Spring water from the slope
   - Slope failure
4) Conditions of erosion prevention facilities, such as river structures
   - Deformation of river structures
5) Anchors
   - Conditions of the anchor head (fracture, corrosion, collapse of the head chap)
   - Deformation of the anchor bearing plate (cracks, deformation)

7.3 Monitoring

In the case of landslide prevention facilities located on a landslide slope where there are many structures to be protected, monitoring should be performed to check for any decline in functionality by installing monitoring devices on the facilities, in addition to performing a visual inspection.

Comments

Table 7-1 shows the devices used for monitoring landslide prevention facilities. If slope deformations due to a landslide are found by inspection, the displacement and inclination at the ground surface should be measured and the moving conditions of the landslide immediately determined (see 6.3 Monitoring in Chapter 6).

The decline in the functionality of groundwater drainage facilities, such as drainage wells and horizontal bores, should be evaluated in terms of a decrease in the groundwater level, the extent of the decline, and the quantity of drainage from the groundwater drainage facilities. To perform this evaluation, data such as the pore water pressure, groundwater level, and the drainage quantity need to be collected.

Table 7-1 Monitoring of landslide prevention facilities using monitoring devices

Object of monitoring		Device and method	Amount
Landslide prevention facilities	Surface drainage channel	Drainage water gauge	Quantity of drainage
	Horizontal bore	As above	As above
	Drainage well	As above	As above
	Pile	Borehole inclinometer	Pile deformation
	Anchor	Center hole type load cell	Load on the bearing plate

7.4 Ancillary Facilities

The landslide prevention facilities should be provided with ancillary facilities as appropriate, such as steps, a cover, and a guard fence to the drainage well, and a door to the mouth of a drainage tunnel, for the purpose of inspections and safety.

Comments

The landslide prevention facilities should be provided with ancillary facilities as appropriate for inspections and safety.

(1) Ancillary facilities for drainage wells

The following ancillary facilities should be provided for the maintenance of drainage wells.

1) Install steps (or a ladder) inside the drainage well to provide access to the bottom of the well. Provide a landing every five meters in vertical height.
2) Provide a cover made of reinforced concrete or other material with a hatch to the drainage well to prevent people or debris from falling in.
3) Install a fence with a lockable door around the drainage well to restrict access by members of the public. The fence should be able to withstand the weight of snow if installed in a snowy region.

(2) Ancillary facilities for drainage tunnels

To prevent access by members of the public, provide a lockable door at the mouth of the drainage tunnel. If the tunnel is long, consider providing appropriate ventilation.

7.5 Record Keeping

Landslide prevention facilities should be inspected and monitored using a facility register, etc. that contains information, such as the facility layout on the slope, year of facility installation, facility configuration, etc. Materials and records obtained from inspections and monitoring should be organized and stored in an easy-to-use manner.

7.6 Evaluation of Decline in the Functionality of Landslide Prevention Facilities

The decline in the functionality of groundwater drainage facilities should be evaluated on an annual basis by comparing the relationship between the groundwater level in the effective groundwater drainage range (the range where water collection pipes are installed) and the drainage quantity from groundwater drainage facilities.

Comments

When evaluating the decline in the functionality of groundwater drainage facilities, it is useful to prepare an h-Q curve as shown in Fig. 7-1 every year and compare the drainage quantity when the groundwater level is the same. If the drainage quantity decreases, it means that the functionality of the facility has declined due to the water collection pipes becoming clogged, etc. In the case of landslide slopes where monitoring devices are not installed, any decline in the functionality of the landslide prevention facilities should be checked by visual inspection.

If it is found that there is a decline in the functionality of the facilities, maintenance for the facilities should be planned.

If sliding movement is found from monitoring, preventive measures should be taken as early as possible.

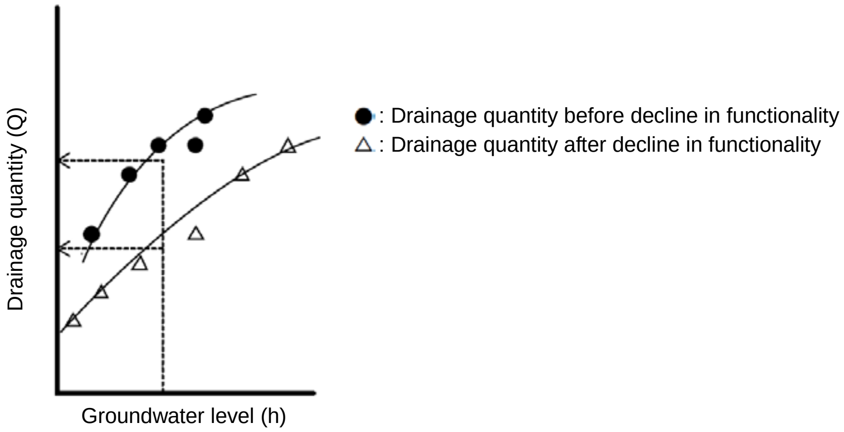


Fig. 7-1 Evaluation of the decline in functionality based on the relationship between the groundwater level (h) versus the drainage quantity (Q)

7.7 Maintenance and Repairs

If it is found necessary from the results of inspection and monitoring, plans should be made to repair the landslide prevention facilities or provide new facilities.

Comments

Existing landslide prevention facilities should be repaired and new facilities provided as appropriate. If it is found from inspections and monitoring that just repairing the existing facilities cannot prevent further landslide displacement, conduct a survey and examine the necessity of installing additional landslide prevention facilities.

1) Maintenance and repairs of control facilities

(1) Channels

Conduct inspections periodically to prevent a functional decline of channels and then perform the following repairs and maintenance.

1) To prevent clogging, remove sediment and weeds that have accumulated in the channel.
2) To prevent water leaking and water spurting from the channel, repair the damage at joints and covers.
3) Repair damage to the channel due to ground subsidence.

(2) Horizontal bores

In general, the groundwater volume collected from horizontal bores and other groundwater drainage facilities tends to decrease as time passes after installation. There are two reasons for this decrease. One is the effect of other groundwater drains and the other is the decline in the functionality of horizontal bores. The main cause of the functional decline of horizontal bores is the clogging of water collection pipes due to the adhesion of slime.

If it is found from inspection that the functionality of horizontal bores has declined or that the facilities are damaged, the following maintenance and repairs should be performed. It is advisable to erect a pole at the mouths of the horizontal bores for ease of inspection as they are easily hidden by thick vegetation.

1) If slime has adhered to the collection pipes, wash them to remove the slime.

2) If a mouth protection facility is damaged or deformed, repair it.

3) If a catch basin is damaged, deformed, or filled with sediment, etc., repair the catch basin and remove the sediment. Direct the collected groundwater into channels, etc. to discharge it from the landslide site quickly.

4) If collection pipes are seriously damaged or corroded, construct a new horizontal bore.

(3) Drainage wells

If it is found from inspection that drainage wells are functionally declined (decrease in groundwater drainage) or facilities are damaged, the following maintenance and repair should be performed. While performing maintenance and repair work inside the drainage well, oxygen and toxic gas concentrations should be constantly monitored and ventilation ensured as there is a risk of oxygen deficiency and intoxication.

1) The drainage well is made up of a caisson and reinforcing materials. The condition of the caisson is the governing factor that determines the integrity of groundwater collection function and the success of functional recovery. Therefore, if deformations, cracks, or corrosions are found on the caisson and reinforcing materials, conduct a strengthening work immediately. If strengthening is impossible, put cobbles into the caisson in order to prevent its failure and maintain its function as the drainage well.

2) If collection pipes are cut by landslide, they should be reinstalled.

3) If slime is adhered to collection pipes, wash them to remove slime.

4) If drainage pipes are cut by landslide, drain groundwater by pumping so that groundwater will not pond in the drainage well. Then, install drainage pipes again.

5) Ancillary facilities are used for the maintenance and safety of the drainage well. If deformation or corrosion is found on descending steps (or a ladder), cover, and guard fence, repair them immediately.

(4) Drainage tunnels

If the inspection reveals that the functionality of drainage tunnels has declined (decrease in the drainage of deep groundwater) or that facilities are damaged, the following maintenance and repair should be performed. While performing maintenance and repair work inside the tunnel, ensure safety by using an oxygen mask or ventilation equipment because there is a risk of oxygen deficiency and intoxication.

1) If deformation, cracking, or corrosion is found inside the drainage tunnel, conduct work to strengthen the tunnel immediately. If strengthening the tunnel is impossible, put cobbles into the tunnel to prevent it from collapsing and to ensure that the functionality of the drainage tunnel is maintained.

2) If sediment is accumulated in the drainage channel, remove it to ensure that the water is drained efficiently.

3) If slime has adhered to the collection pipes, wash them to remove the slime.

Clogging of collection pipes and the techniques for washing them are explained below.

a) Clogging of collection pipes[1)]

According to a survey of the inside of collection pipes using a compact camera, the primary cause of pipe clogging is the adhesion of slime. Slime usually starts to adhere from around the mouth of the pipe and then gradually goes to the back.

It has been found that the main component of slime is ferric oxide, and that iron bacteria exist in the slime. If the total iron content in the groundwater is 1 mg/*1* or more, slime may adhere to the collection pipe. If the total iron content in the groundwater reaches 4 mg/*1* or more, a large amount of slime will adhere to the pipe.

b) Washing of collection pipes

To restore the collection pipes to their earlier functionality, the inside of the pipe should be washed with high-pressure water at about 20 MPa.

(5) Slopes from which earth has been removed and embankment slopes

The following maintenance and repairs should be performed for slopes where earth has been removed or a loading embankment constructed.

1) If a large amount of spring water is found on the slope, install gabions and treat the spring water so that sediment at the mouth of a horizontal bore or on the slope is not washed away.
2) If movement has occurred on the slope, install a flexible and permeable facility such as a gabion on the slope to prevent the area from expanding.

(6) Erosion prevention facilities such as river structures

When river structures are found to have been deformed, take appropriate measures such as strengthening the structure to maintain the functionality.

2) Maintenance and repairs of restraint facilities

(1) Piles and shafts

If piles and shafts (caissons) are installed, it is desirable to monitor them for deformation and the displacement of the landslide layer around the piles to confirm that they are having the intended effect. Deformations in piles and shafts can be measured by a borehole inclinometer by inserting it in the guide pipe that has been installed in advance. Displacement at the head of piles and shafts can be measured by a movable pile survey.

Since landslides tend to occur during the rainy season and snowmelt season, it is advisable to conduct inspections and monitoring around those seasons.

Piles and shafts are buried structures, so they are difficult to repair. If they have been found to fail as a result of inspection and monitoring, perform safety analysis to determine if the installation of additional landslide prevention facilities is necessary or not.

(2) Anchors

It is desirable to conduct inspections and monitoring periodically to confirm that the installed anchors are continuing to produce the intended effect.

The following methods can be used to check if the installed anchors are sound or not:

1) Periodic inspection of anchor head corrosion and concrete cracks

   The anchor head needs to be protected from damage. If it is damaged, it should be repaired or other appropriate measures taken, such as driving in new anchors.

2) Measurement of the axial force of the anchor.

It is not possible to examine the conditions of the anchorage length and free length sections of an anchor because those sections are buried in the ground. Therefore, install a load cell at the anchor head and measure the axial force of the anchor. Evaluate the soundness of individual anchors based on changes in the axial force.

The monitoring frequency should be determined by taking the following conditions into account.

1) Impact on the objects to be protected
2) Strength and conditions of the anchorage ground

In general, monitoring should be conducted frequently immediately after the work has been completed and not so frequently after load changes become unnoticeable. The obtained results should be kept as maintenance records.

If the axial force of the anchors is found to have decreased from inspections and monitoring, investigation should be made if it can be corrected by repairing or reinforcing the anchors by performing slope stability analysis. Plan the construction of additional anchors, if necessary.

References

1) Hanaoka, M., Maruyama, K., and Kojima, S.: “Study of the inspection method for surface water and groundwater drainage facilities in the landslide site,” *PWRI Technical Note* No. 3967, p. 7, 2005.

Appendices

1. Causes of Landslides

Landslides tend to occur in regions having a specific geology and geological structure. A distinctive topology called "landslide topology" is formed through repeated displacements.

1.1 Primary Causes of Landslides

Figure Appendix 1 shows the distribution of landslides in Japan. Landslides are distributed throughout the country. The landslide distribution is particularly significant in the green tuff zone of the Neogene period, which is distributed along the coast on the Sea of Japan side mainly around Niigata and Nagano prefectures, and the metamorphic rock zone along the Median Tectonic Line that stretches from central Shikoku, the Kino River in the Kii Peninsula to the Tenryu River.

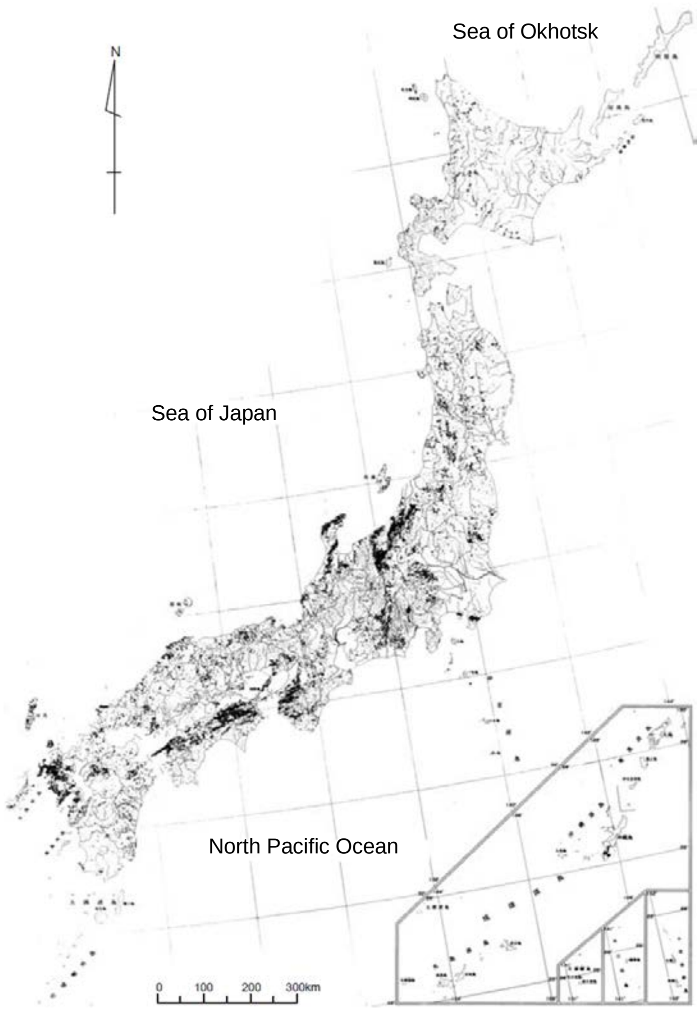


Fig. Appendix 1 Distribution of landslides[1)]

Landslides are often triggered in the zone of Neogene formations where mudstones, tuffs, etc. having low solidification are distributed and in the cataclastic and metamorphic zones. The following areas are susceptible to landslides.

(1) Area having a distribution of mudstones and tuffs from the Neogene period

(2) Area having a distribution of shales and tuffs from the Paleogene period, particularly

around the geological tectonic line

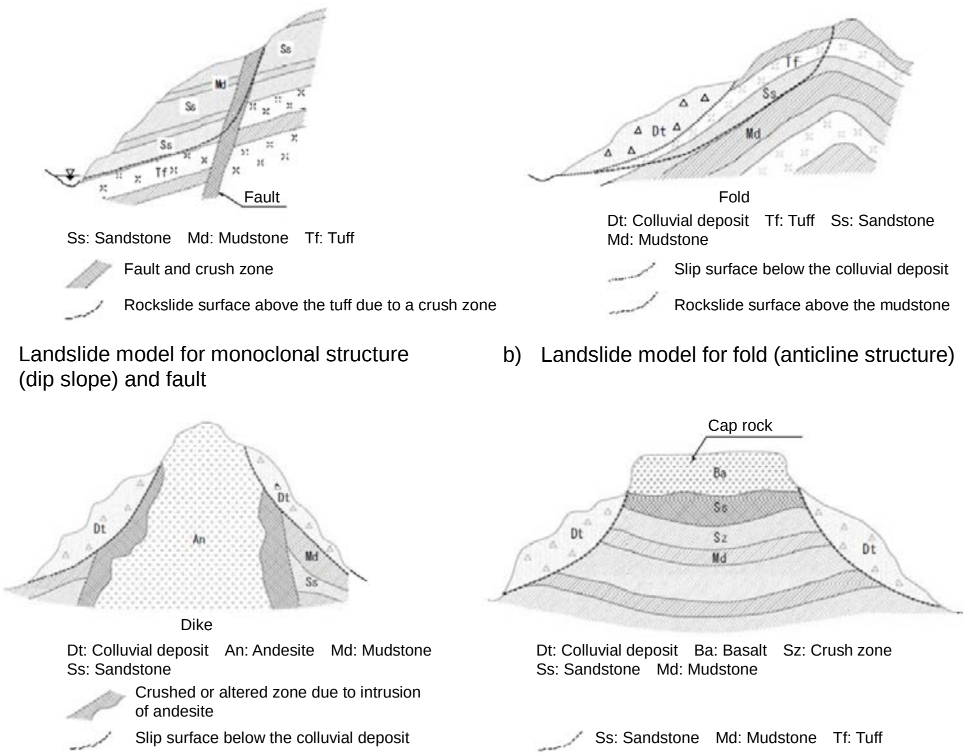
(3) Area having a distribution of Mesozoic formation, particularly the area where green and black crystalline schists are distributed, and the area around it where metamorphic shales, slates, and schalsteins are distributed.

(4) Area having a large amount of pyroclastics

(5) Area exposed to hydrothermal alteration

(6) Area subjected to tectonic cataclasis and metamorphism due to intrusive action, etc.

The geological structure susceptible to a landslide includes the area around the Median Tectonic Line, the Itoigawa-Shizuoka Tectonic Line, and the Hidaka Tectonic Line; faults (Fig. Appendix 2 (a)); crush zones; very distinct fold axes; anticline axes (Fig. Appendix 2 (b)); dome structures; intrusive structures (Fig. Appendix 2 (c); cap rocks (Fig. Appendix 2 (d)). Talus accumulation on the stratum of opposite dip can cause a landslide even though it is located on the opposite dip slope.



a) Landslide model for monoclonal structure (dip slope) and fault

b) Landslide model for fold (anticline structure)

c) Landslide model for intrusion of andesite

d) Landslide model for rice cake-shaped cap rock

Fig. Appendix 2 Landslide models for various geological structures[2)]

1.2 Secondary Causes of Landslides

The secondary causes of landslides include the following.

(1) Natural secondary causes

1) Rain-related causes (protracted periods of rain, heavy rain, snowmelt, etc.)

2) Earthquake-related causes (volcanic activity, alteration of groundwater system due to earthquakes, etc.)

Landslides attributed to 1), rain-related causes, include landslides induced by the pore water pressure at the slip surface which is increased due to the increased groundwater from seeped rainwater and snowmelt in the slope, and landslides induced by the loss of slope stability which is caused by the failure at the landslide foot due to heavy rain, etc.

Figure Appendix 3 shows the number of landslides by cause that occurred from 1995 to 2004 in each region. In the Hokuriku region where Neogene formations are distributed, the number of landslides attributed to rainfall during the rainy season, snowmelt, etc. is rather a lot. In the Shikoku region, where Mesozoic formations are distributed, the percentage of landslides due to heavy rain caused by typhoons is high.

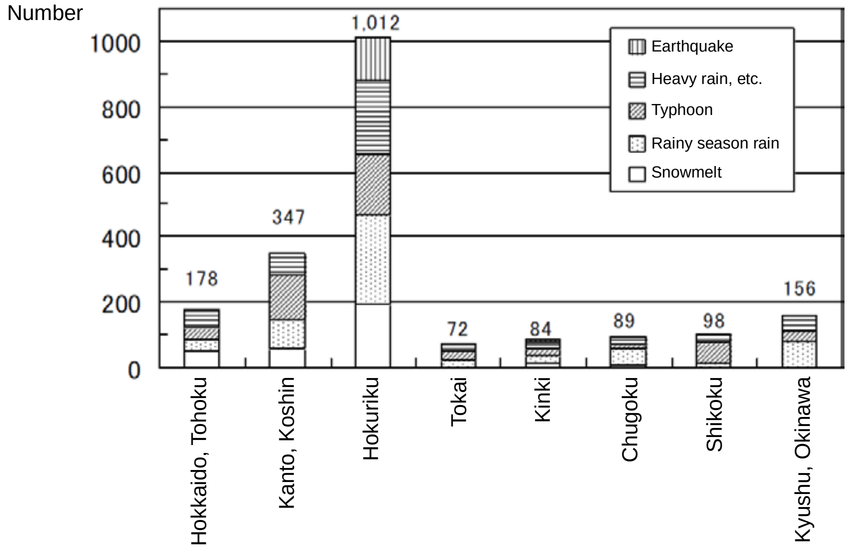


Fig. Appendix 3 Number of landslides from 1995 to 2004 by cause[3] with partial revision and added

Regarding landslides due to 2), earthquake-related causes, it is known that a huge number of large-scale collapses were caused by earthquakes. The major collapses in the past include the Nadachi collapse due to the Takada Earthquake in May 1751, the Kokuzoyama collapse due to the Zenkoji Earthquake in May 1847, and the Tobi collapse due to the Hietsu Earthquake in 1858. Also, during the Southern Hyogo Prefecture Earthquake in 1995, landslides occurred in the Nikawa and Okamoto areas. Those sites do not have the distinctive landslide topography. Although cases were reported that slight movement was observed transiently in some slope areas having the distinctive landslide topography immediately after an earthquake, the manner in which earthquake forces affect the landslide slope is not yet well understood.

It is considered that landslides and collapses due to an earthquake are primarily controlled by the magnitude of the earthquake, the distance from the epicenter, and the distance from the fault. In the case of the Mid-Niigata Prefecture Earthquake in 2004, landslides and collapses occurred mainly in the range with an estimated seismic intensity of 6 or more, particularly in the range with an intensity of high 6 values or more.[4] It has also been pointed out that locations susceptible to a landslide and collapse have a higher correlation with the maximum speed in the vertical direction than the maximum acceleration in the horizontal direction.[4]

(2) Artificial secondary causes

1) Earthworks (cut slope, filled slope, tunnel excavation, water leakage from channels, etc.)

2) Submergence of a slope under water (ponding in the dam)

Landslides due to 1), earthworks, include landslides caused by a cut slope and a filled slope, which are constructed as part of road and housing land construction. A cut slope and a filled slope change the stress distribution in the slope. A cut slope decreases the shear strength and a filled slope increases the sliding force. Also, a cut slope and a filled slope have a significant impact on the stability of stable slopes that have never experienced a landslide, inducing a first-time rockslide in some cases. Therefore, when large-scale earthworks are planned, it is necessary to conduct a detailed investigation of the target slope beforehand even though it does not have landslide topography. Landslides are also triggered by tunnel excavation. These landslides are caused by a change in the stress distribution in the slope due to ground subsidence, the formation of a groundwater flow route, and deterioration of the ground that occurs as a result of ground loosening by tunnel excavation.

Landslides due to 2), submergence of slope under water, refer to the landslides induced by water ponding after the construction of a dam. The following are considered the causes of those landslides.[5)]

a) Generation of buoyancy due to submergence of landslide mass

b) Increase in groundwater level in the landslide mass due to submergence

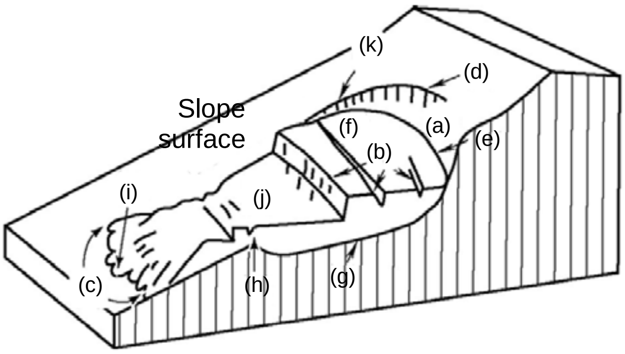
c) Generation of residual pore water pressure in the landslide mass due to an abrupt decrease in water storage level

d) Decrease in the holding load in the passive state area due to erosion and failure of shoreline.

1.3 Landslide Topography

A distinctive topography is formed through repeated landslide movements. This topography is called the landslide topography.

Figure Appendix 4 is a schematic representation of landslide topography that has a slip surface shaped like the bottom of a ship, together with the names of each position (see 1.4). Care must be taken because other similar topographies are easily mistaken for landslide topography. They include river and coastal terraces, lava plateaus, and the sites of pyroclastic flow deposits.



(a) Scarp (main crack) (b) Secondary crack (c) Toe (d) Crown
(e) Top (f) Head (g) Slip surface (h) Leg (i) Tip (j) Foot
(k) Flank

Fig. Appendix 4 Names of typical positions in a landslide [6) with partial revision]

The following are the features of landslide topography.

(1) The slope is made up of certain continuous topography, namely, a horseshoe-shaped or quadrangular steep slope at the upper slope, a trapezoidal or gentle slope below it, then a steep slope again, and an uplift or extrusion at the lower slope.

(2) On the topographic map, the contour intervals of ordinary hillside slopes are roughly uniform and parallel. However, in the case of landslide topography, distinctive contour

intervals are observed. It consists of very narrow intervals in the upper area (scarp), wide intervals in the middle area (head area), and narrow intervals again in the foot area (see Fig. Appendix 6 (c)).

(3) Ground surfaces at the head and foot areas are disturbed due to landslide movement and often dotted with small convexes and concaves. Depressions, ponds, bogs, etc. are distributed below the scarp and the head area due to ground subsidence.

(4) Both flanks of a landslide site are often like a valley due to disturbance by landslide movement. Convexes and concaves exist in places.

(5) Valleys and rivers are abnormally crooked and the river is narrow.

Figure Appendix 5 shows the planar forms of landslide topography. There are four planar forms of landslide topography: horseshoe-shaped, quadrangular, valley-shaped, and bottleneck.

The horseshoe-shaped landslide topography is said to account for over 40% of all the landslide topographies in Japan. This type of topography is formed when the soil layer in the middle of the slope is thicker than the soil layers on both flanks.[7)]

The quadrangular landslide topography is formed when the soil layer in the middle of the slope is as thick as the soil layers on both flanks. This type of topography is said to account for about 10% to 15% of all the landslide topographies.[7)]

The valley-shaped landslide topography is formed when the slope above a horseshoe-shaped or quadrangular landslide area sustains a landslide for the second or third time. In general, this type of topography appears only after the slope is subjected to repeated landslides, and the slip surface is located at a shallow position.[6)]

The bottleneck landslide topography is formed when a landslide occurs in a basin-like slope. It often has a relatively hard rock at the lower slope area.[7)]

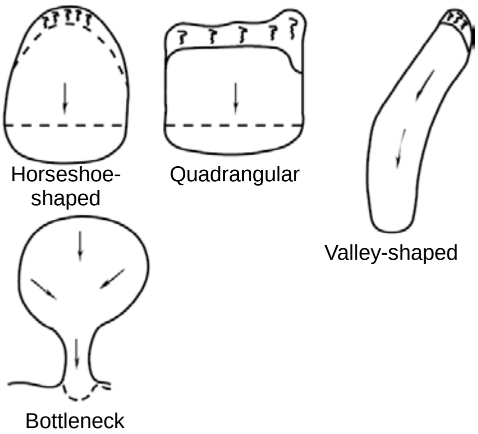


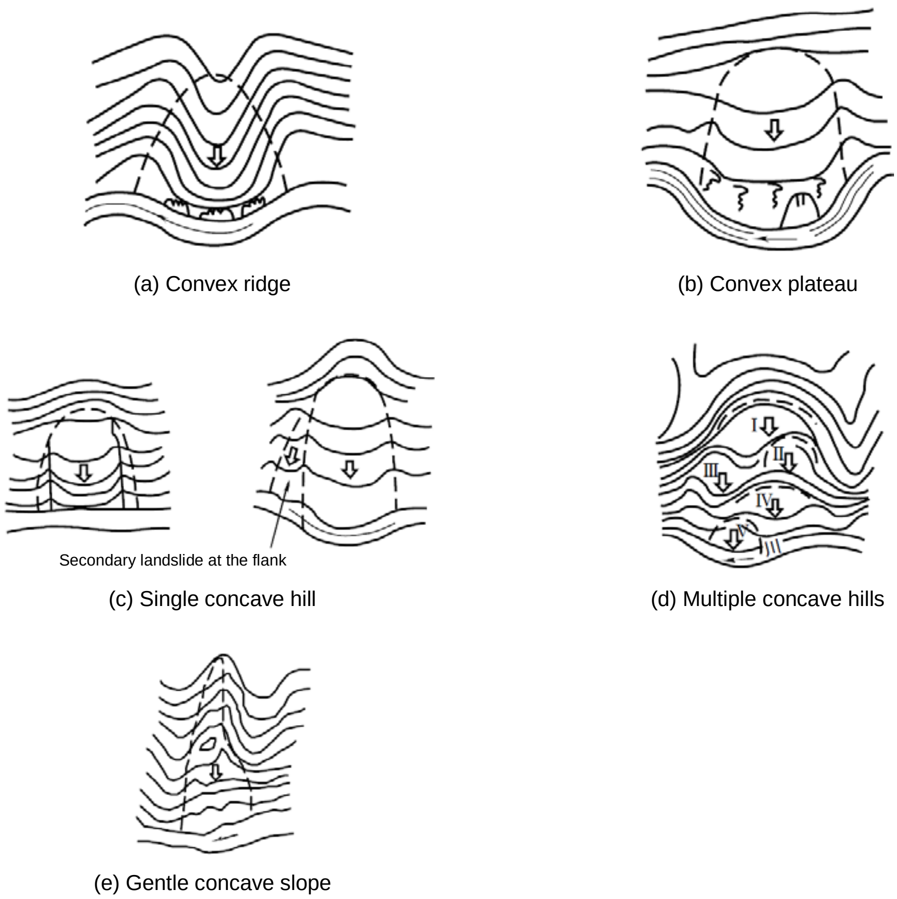
Fig. Appendix 5 Planar forms of landslide topography[7)]

Whether a site has a distinctive landslide topography or not is a valuable information source for knowing the past movement history and for predicting the future movement of a given landslide. The landslide topography is evident in the case of landslides that moved several months or several years ago. However, the topography of landslides that occurred several decades or hundreds of years ago is often unclear due to subsequent slope erosion. Also, the scars remain for a long time if the landslide movement was significant. But if the landslide movement was small, the scars quickly become indiscernible due to erosion.

As time passes after a landslide stops movement, the landslide topography gradually loses its features, with the scarp becoming gentle and the plateau scarred by erosion. The landslide topography also changes itself through repeated movements, sometimes with a new landslide occurring at the slope above the crown. If the crown recedes toward the upper slope and reaches the ridge, the ridge looks low all of a sudden compared with the peripheral area.

As the movement becomes large and its frequency increases, the landslide topography turns into an extensive gentle slope, making it difficult to recognize the head of the landslide. Figure Appendix 6 shows landslide topographies classified by their development stage.[6)]

In general, landslide topographies having a large scale and large movement are discernible from 1/10,000 scale topographic maps, but if the landslide scale is small, they are not identifiable even from 1/3,000 – 1/1,000 scale maps. Some may be discernible by oblique air photos, site reconnaissance, etc.



Landslides develop in order from (a) to (e)

Fig. Appendix 6 Landslide topographies classified by the development stage[6)]

1.4 Forms of Slip Surface

Slip surfaces on the landslide slope present varying longitudinal forms depending on the types of soil and rock involved: a linear polygonal curve in the case of landslides occurring in fresh rock; a rounded polygonal curve at the bend if the moving layer is composed of weathered rock; and a smooth curve or arc-shape if the moving layer is made up of gravelly sediment or clay. Schematically, the forms of slip surface are classified into the following types.

(1) Chair-type slip surface

Figure Appendix 7 (a) shows the form of a chair-type slip surface. If the landslide ground is rock or has properties similar to it, the slip surface becomes polygonal-curved as shown in (i). If the ground is gravelly sediment or clayey soil, the slip surface becomes curved as shown in (ii).

(2) Slip surface resembling the hull of a ship

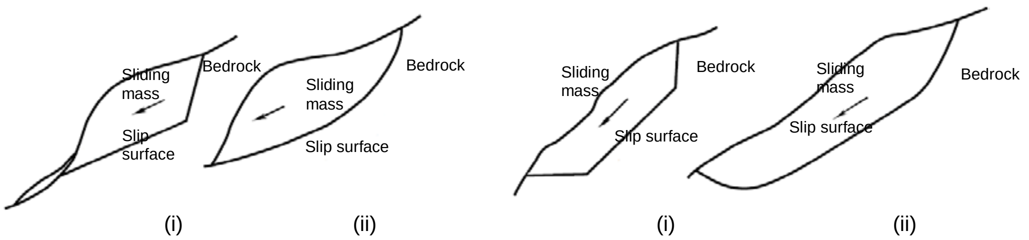
Figure Appendix 7 (b) depicts the form of a slip surface that resembles the hull of a ship. Uplift due to compression is observed at the lower area of the landslide slope. If the moving layer has a property close to rock, the slip surface resembles the hull of a ship as given in (i). But if the moving layer is made up of sediment, the slip surface is formed by two curves plus one straight line as shown in (ii).

(3) Stepped slip surface

Figure Appendix 7 (c) describes the form of a stepped slip surface. This type of slip surface is created when the upper slope is destabilized after the occurrence of a landslide at a slip surface that resembles the hull of a ship or a chair-type slip surface and the new slip surface is connected to the existing slip surface at the lower slope, taking a step-like form. A step-type slip surface does not occur when a landslide occurs for the first time. The landslide topography at the slope surface also resembles steps.

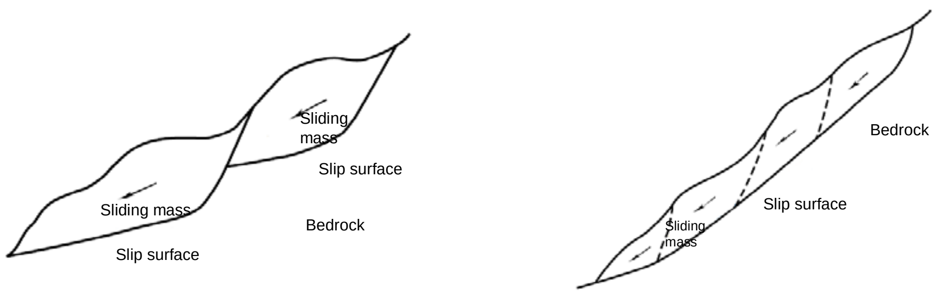
(4) Layered slip surface

Figure Appendix 7 (d) shows the form of a layered slip surface. This type of slip surface is created when a new landslide in the upper slope occurs at a slip surface that continues with a slip surface of a landslide that occurred in the lower slope. Although the formed slip surface is smoothly curved, the ground surface topography has considerable unevenness and height difference. This type of slip surface is does not occur when a landslide occurs for the first time. It occurs after repeated movements.



(a) Chair-type slip surface

(b) Slip surface resembling ship's hull



(c) Stepped slip surface

(d) Layered slip surface

Figure Appendix 7 Typical forms of slip surface[6)]

Figure Appendix 8 gives the distribution of W/D, which is the ratio between the landslide width (W) and the slip surface depth (D). The W/D value is distributed mainly in the range of 5.0 to 6.0 and the mean is about 7.

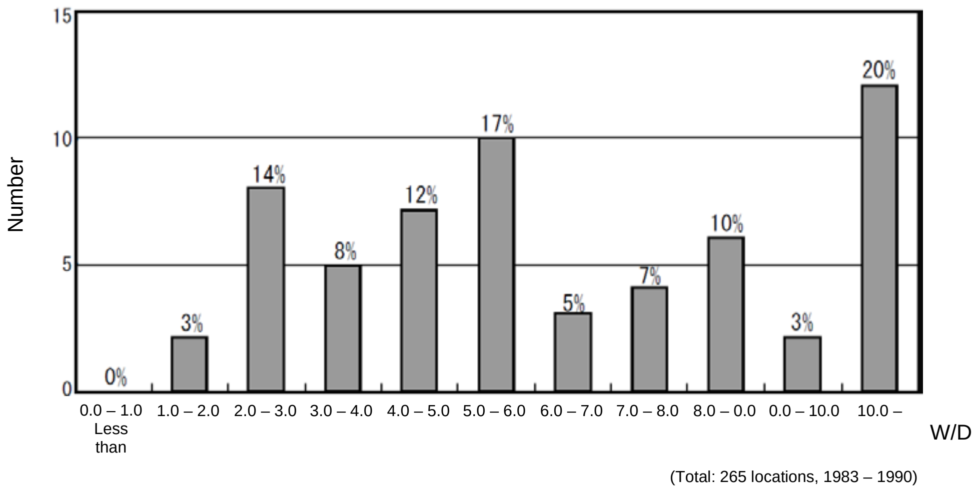


Fig. Appendix 8　Relationship between landslide width and slip surface depth (W/D)[8)]

1.5　Configuration of Slip Surface

Figure Appendix 9 shows the development stage of a slip surface that is obtained from a shear test using clay specimens. A slip surface is formed in stages from stage (i) to stage (iii), creating continuous shear cracks consistently. Therefore, it is considered that a slip surface exists as a shear zone in landslides that have occurred for the first time and then gradually grown into a plane as the extent of movement increases.

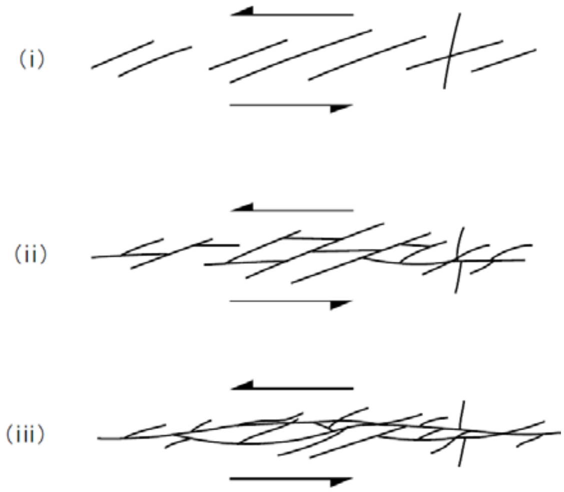


Fig. Appendix 9　Development stage of slip surface [9) with partial revision]

2. Groundwater at the Landslide Site

(1) Groundwater distribution and flow route at the landslide site

At the landslide site, a swamp or bog, etc. sometimes exists at the landslide head and spring water is observed at the landslide foot even though surface water does not flow down from the upper slope. This phenomenon is attributable to inhomogeneous permeability of the landslide mass and the non-uniform supply of groundwater. It is not easy to find the inflow route of groundwater into the landslide site accurately because the permeability of the landslide mass is not homogeneous.[10)] However, a large volume of groundwater tends to converge at the head and flanks of the landslide mass.

(2) Groundwater and landslide movement

It is a well-known fact that landslides often occur during heavy rain or snowmelt. The major cause of these landslides is an increase in the groundwater level on the slope.

Figure Appendix 10 shows the correlation between daily movement and groundwater level at the Takisaka landslide site (Fukushima Prefecture). It is a large-scale landslide that occurred in the green tuff area of the Neogene Period. It is seen that daily movement tends to increase as the groundwater level goes up. If a correlation chart between the groundwater level and landslide movement like the current one is produced, it can be used in the investigation of groundwater level that needs to be reduced by groundwater drains, such as drainage wells, to prevent landslides.

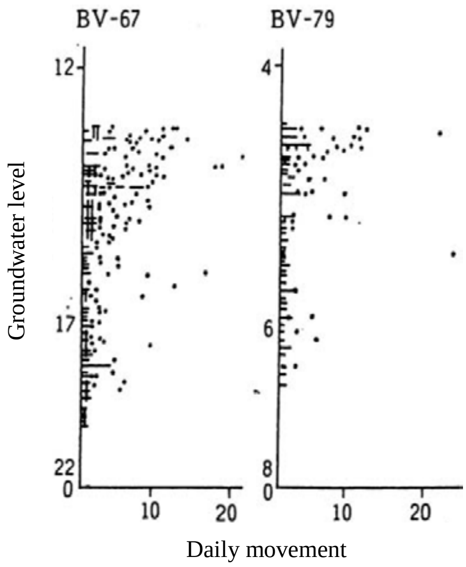


Fig. Appendix 10 Relationship between daily movement and groundwater level[7)]

3. Classification of Landslides

In Japan, attempts have been made over the past few decades to classify landslides according to various criteria.

Koide classified landslides as follows with a focus on the regularity of landslide geology and its distribution.[11] His classification is widely used.

(1) Tertiary formation landslide

(2) Crush zone landslide

(3) Solfataric landslide

Watari also classified landslides as follows in terms of materials that make up the landslide mass. [6]

Rockslide

(1) Rockslide

(2) Weathered rock landslide

(3) Colluvial soil landslide

(4) Cohesive soil landslide

Table Appendix 1 shows a list of landslide classifications and landslide features proposed by Watari. This table covers topography, geology, movement, typical preventive measures, main causes, etc. of each landslide type. The major characteristic of his classification is that he presented landslide preventive measures for each type of landslide.

If Watari's landslide classification in Table Appendix 1 is used, we can get a rough picture about the movement characteristics, such as movement speed and movement continuity, primary causes, typical preventive measures, etc.

Table Appendix 1 (1) Classification of landslides proposed by Watari[6] with partial revision

Classification / Feature	Rockslide	Weathered rock landslide	Colluvial soil landslide	Cohesive soil landslide
Planar form	Horseshoe-shaped, quadrangular	Horseshoe-shaped, quadrangular	Horseshoe-shaped, quadrangular, valley-shaped, bottleneck	Valley-shaped, bottleneck
Microtopogaphy	Convex ridge	Convex plateau	Concave plateau with multiple hills, single concave hill	Concave gradual slope
Form of slip surface	Chair-type, resembling the hull of a ship	Chair-type, resembling the hull of a ship	Stepped, layered	Stepped, layered
Main properties of landslide mass (head area)	Rock mass, weak weathered rock	Weathered rock (many cracks)	Sediment containing large gravel and ordinary gravel	Gravelly sediment
Main properties of landslide mass (foot area)	Weathered rock	Sediment containing large gravel	Gravelly sediment, Partly clayey	Clay or gravelly clay
Moving speed	2 cm/day or more	About 1.0 to 2.0 cm/day	0.5 to 1.0 cm/day	Less than 0.5 cm/day
Movement continuity	Short time, abrupt	Intermittent to some extent (once every several tens or several hundreds of years)	Intermittent (once in 5 to 20 years)	Intermittent (once in 1 to 5 years)
Sliding form	Planar sliding (chair-type)	Planar sliding (The head and foot are slightly arc-formed)	Arc and linear, the foot is fluidized	The head is arc-formed, but other areas are mostly fluidized
Block	One block in most cases	Secondary landslide at the foot and flanks	2 to 3 blocks, with division of the head area	Divided into many blocks and move in an interrelated manner
Prediction	Very difficult to predict. Careful reconnaissance and detailed survey necessary.	Predictable using 1/3,000 – 1/5,000 topographic maps. Aeral photos also usable.	Discernible using 1/5,000 – 1/10,000 topographic maps. Interviews with local people useful.	Predictable from interviews with local people. Very easily discernible.
General slope form	Usually a plateau exists, but not clear. Often seen on the convex slope. Sliding starts from the saddle position.	A clear drop, a band-like depression, and a plateau exists. Largely concave but the main part is convex.	A scarp is formed, below which concaves such as bogs and swamps exist. Several small hills remain at the head. Often seen on the concave slope.	Largely uniform gentle valley type slope. Unclear plateau exists at the head.

Table Appendix 1 (2) Classification of landslides proposed by Watari [6] with partial revision

Classification / Feature	Rockslide	Weathered rock landslide	Colluvial soil landslide	Cohesive soil landslide
Average safety factor for slope stability, its relationship with artificial activities	Mostly, *Fs*>1.10, a certain level of cut slope or fill slope is possible, if provisional.	*Fs* = 1.05 – 1.10, About 5% decrease in safety factor is possible, if provisional.	*Fs* = 1.03 – 1.05, Stable even with about 3% decrease in safety factor, if provisional.	A cut slope and a fill slope are impossible. Movement will be triggered even with a slight earth work.
Typical preventive measures	Deep groundwater drains, earth removal, restraint work	Deep groundwater drains, earth removal, surface water drains, restraint work	Deep groundwater drains at the head, surface water drains, river structures	Drainage wells at the head, shallow groundwater drains at the foot, surface water drains, river structures
Effect of preventive measures	Immediate stabilizing effect	Immediate effect, but risk of causing a landslide under abnormal weather conditions	Produce an effect 1 to 3 years after construction. Stabilization of the foot is difficult.	Produce an effect slowly, usually several years after construction. Complete stabilization is impossible.
Main causes	Large-scale earthwork, submergence of part of the slope under water, earthquakes, heavy rain	Heavy rain, abnormal snowmelt, breaking of riverbanks, earthquakes, mid-scale earthwork, others	Abnormal continuous rain, snowmelt, typhoons, heavy rain, earthwork, etc.	Continuous rain, snowmelt, river erosion, snow accumulation, small-scale earthwork
Main geology and geological structure	Susceptible to the effect of faults and crush zones	Distributed widely in the crystalline schist zone and Neogene formation. Prone to the effect of faults and crush zones	Distributed widely in the crystalline schist zone and Neogene formation	Most widely distributed in the Neogene formation, but partly seen in tectonic lines such as the Mikabo crush zone.

4. Introduction to RE-MO-TE^2 (Remote 2) Technology

This section outlines RE-MO-TE^2 (Remote Monitoring Technology 2) for measuring slope displacements from remote positions. This technology was developed as part of joint research between the Public Works Research Institute (PWRI) and the private sector. The explanations given below are extracted from of the *RE-MO-TE^2 Measurement Manual*[13)]. Refer to the manual for details of this technology.

4.1 Outline and Purpose of RE-MO-TE^2

4.1.1 Outline of RE-MO-TE^2

RE-MO-TE^2 (Remote Monitoring Technology 2) is a technology that monitors slope displacements at high accuracy by firing paint capsules onto the collapsed slope at the landslide foot from a remote position using a crossbow and measuring the targets on the slope from a non-prism total station.

Comments

One of the methods for monitoring the slope from a remote position is to conduct measurements using a non-prism total station. However, as an ordinary non-prism total station does not use targets, it is impossible to focus on the same point and collimation errors are very likely. To overcome this difficulty, RE-MO-TE^2 technology was developed. Its concept is presented in Fig. Appendix 11. This technology is aimed at improving the measurement accuracy of displacements by firing targets at the slope and measuring them from a remote position.

The features of this technology are as follows:

(i) Survey targets can be set up for a collapse-prone slope from a remote position and the non-prism total station can be used to measure those targets. A series of operations, from the installation of targets to measurement, can be executed safely at the position that is remote from the slope.

(ii) Retro-reflective paint containing fine glass beads is used as the target. Therefore, the position of the target can be located by measuring the reflection intensity of a laser, which makes it possible to conduct the measurements at night.

(iii) The target in the form of a paint capsule is attached to the tip of an arrow. The arrow is then fired at the slope using a crossbow. The paint adheres to the slope when the capsule fractures on impact with the slope.

(iv) When aiming the crossbow, the operator measures the diagonal distance from the firing position to the target position and its sight angle, and the angle of elevation is estimated utilizing a quick chart. The horizontal angle is adjusted using a level attached to the crossbow. Both the elevation angle and horizontal angle are controlled from the firing frame.

(v) A strike accuracy of ±50 cm from a position 300 meters away was verified through experiment.

(vi) The measurement accuracy of the non-prism total station will improve because it can now focus on the target set up on the slope.

This measuring technology has been developed as part of a joint effort of PWRI and three private companies. A patent for measuring technology of ground displacements at collapsed sites in landslide areas has been applied for.

Members of the joint research team

- Public Works Research Institute (PWRI)
- Kowa Company, Ltd.
- Pasco Corporation
- Radic Consultant Co., Ltd.

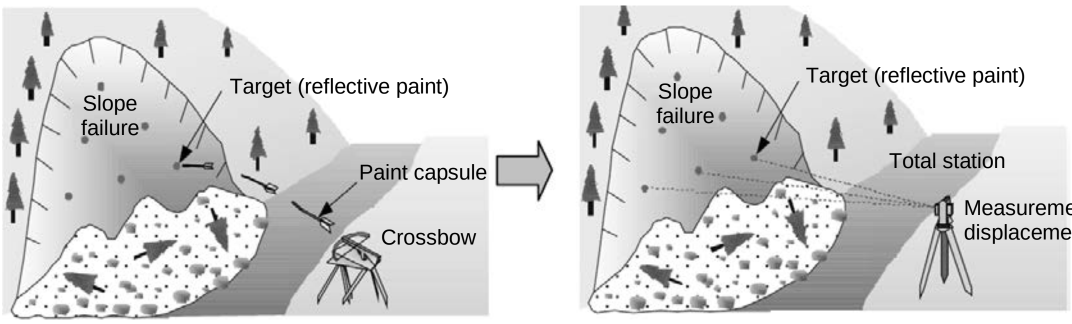


Fig. Appendix 11 Concept of RE-MO-TE^2 [12)]

4.1.2 Purpose of RE-MO-TE^2

The RE-MO-TE^2 technology aims to monitor ground displacements from a remote position quickly without the need for personnel to enter the dangerous slope. The objective is to utilize the obtained results for safety operations, such as rescues, removal of collapsed soil, emergency work at the collapsed slope, etc.

Comments

Part of collapsed soil that accumulates at the landslide foot has the effect of restraining the landslide mass at the back and restricting the scope of the collapse. However, it needs to be removed in some cases as an emergency measure, for example, in the case of rescue, to provide traffic routes, and to remove a river blockage. As it is dangerous for personnel to enter the slopes even for the purposes of surveying and monitoring due to the risk of a secondary disaster, it is necessary to adopt a method that enables displacement to be measured safely from a remote position.

4.2 Application Conditions

4.2.1 Target slope

The target slope when using a crossbow should be exposed rock, etc. at the landslide foot, in the back slope, etc. The measuring position should be selected by considering the monitoring purpose and monitoring period.

Target positions used for the measurement of slope displacements should be placed at positions where displacements appear at an early stage and the position that is dangerous if a deformation occurs. It is also desirable to select a rock as the target because the paint will adhere easily to it and not be washed away so easily.

Comments

The prerequisite for performing the measurement is that paint adheres securely to the target slope. The paint capsule is designed to break open and disperse paint on impact with the target slope. Therefore, the position where the arrow pierces the ground or the ground falls due to impact are not suitable. Also, if an arrow hits a position where there is sediment, low-solidified rock, or weathered rock, the paint may not adhere to them. Furthermore, a position that consists of boulders that can fall and a position that may be removed as part of emergency work are not suitable, particularly when long-term monitoring is planned.

This measurement technology is designed to capture slope displacements by changes in the diagonal distance between the target and the measuring device. Therefore, target positions and the installation position of a measuring device should be determined by considering the deformation direction of the slope. If the distance to the target exceeds 100 meters, target positions are difficult to find. Therefore, it is desirable to set up targets at a conspicuous position on the slope that can be fond easily.

4.2.2 Measuring position

When firing targets and conducting measurements, sufficient caution should be taken to ensure the safety of workers so as not to cause a secondary disaster.

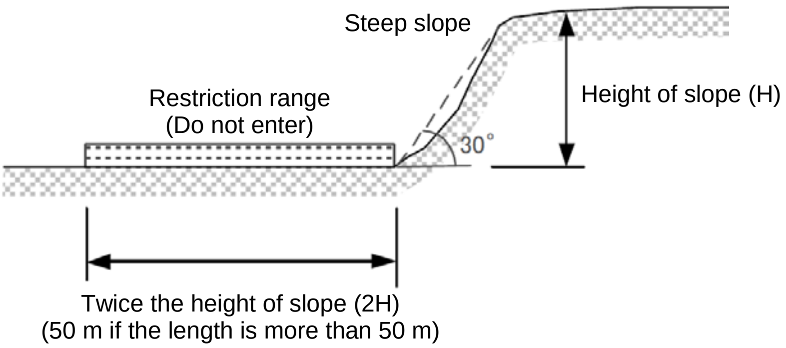
Comments

In selecting a crossbow firing position and a monitoring position, the following range where entry is restricted should be avoided as a rule. If it is necessary for somebody to enter this range, such as to fire the crossbow, he or she must not initiate work without securing an evacuation route and carrying a radio communication device for constant communication with staff located outside the range.

However, an area that the sediment will never reach in view of the site topography can be excluded from this restriction.

(1) Restriction range at the steep slope area (see Fig. Appendix 12)

In steep slope areas (with a gradient of 30 degrees or more and a vertical height of 5 meters or more) at risk of failure, the restriction range is within the longitudinal length twice the vertical height of the slope (50 meters if the length exceeds 50 meters) from the lower end of the slope and within the width formed by an angle of 30° from the lower end of the slope on both sides.



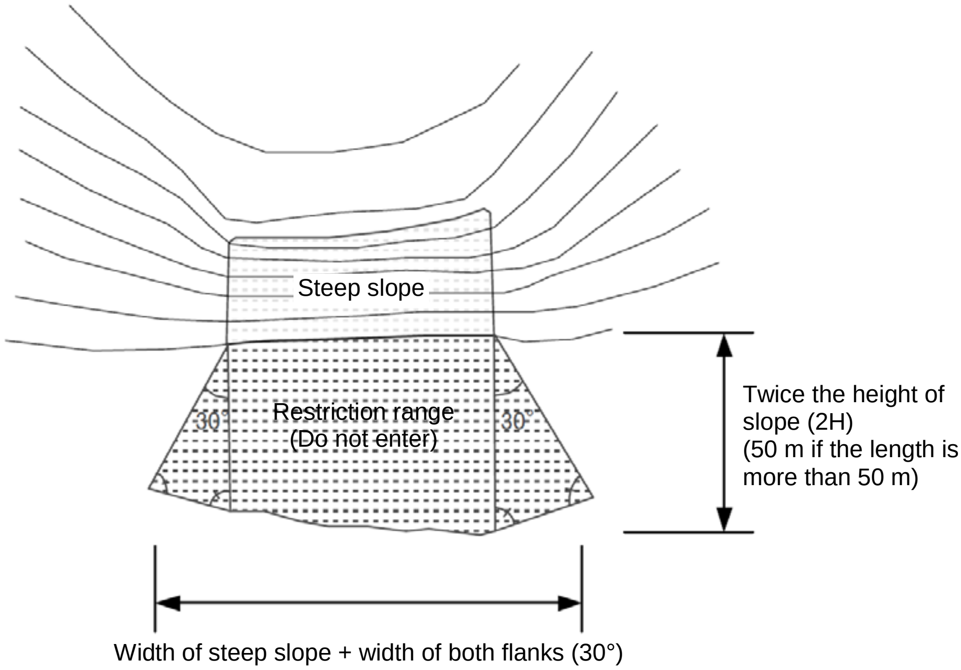


Fig. Appendix 12　Restriction range at a steep slope area

(2) Restriction range at the landslide area (See Fig. Appendix 13)

The restriction range is within 100 meters in the direction of landslide movement from the lower end of the landslide area at risk of failure.

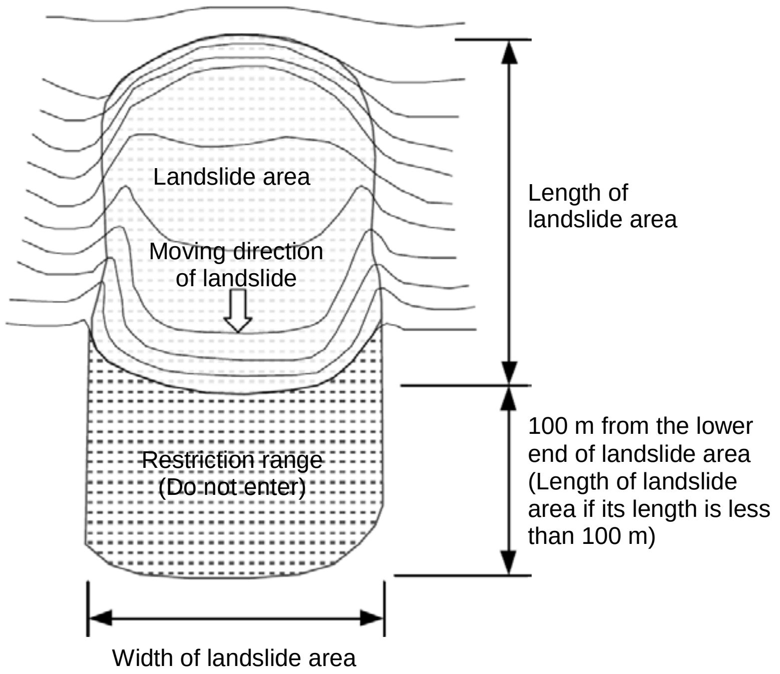


Fig. Appendix 13 Restriction range at the landslide area

Basis for the designation of a restriction range

Regarding the restriction range at the steep slope area, a restriction within 30° in the lateral direction was added to the designation criteria of a sediment-related disaster hazard area as set out in Article 2 of the Order for Enforcement (Order No. 84, March 28, 2001) of the Law Concerning the Promotion of Sediment-related Disaster Prevention in Sediment-related Disaster Hazard Area (Law No. 57, May 8, 2000) (hereinafter referred to as the “Sediment-related Disaster Prevention Law”).

Regarding the restriction range at the landslide area, if the above designation criteria that assumes a rate of 4 m/hr for a landslide is applied as it is, the derived restriction range will have a considerable safety allowance. Therefore, a length of 100 meters from the lower end of the landslide is adopted as the distance one can evacuate even after confirming the landslide movement.

(Reference: Order for Enforcement of the Sediment-related Disaster Prevention Law)

Article 2 The criteria specified by the Cabinet Order as prescribed in Paragraph 1, Article 6 of the Law should be the areas of land described in the sub-item of individual natural phenomena that can cause sediment-related disasters that are listed in the items below.

1 Steep slope failure Area of land specified below

(a) Steep slope area (Restricted to an area having a slope gradient of 30 degrees or more and a slope height of 5 meters or more. The same should apply hereinafter.)

(b) Of the areas specified below, an area sandwiched by the vertical plane formed by the upper and lower ends on the right side of (a) steep slope area and the vertical plane formed by the upper and lower ends on the left side of the same steep slope area.

(1) Area outside (a) steep slope area but located next to the upper end of that area and within a 10-meter horizontal distance from the upper end of the area.

(2) Area outside (a) a steep slope area but located next to the lower end of that area and within a distance twice the slope height from the lower end of the area (50 meters if twice the slope height is more than 50 meters) (excluding an area that debris, etc. will never reach in view of topography when a steep slope failure occurs).

2 Debris flow (omitted)

3 Landslide Area of land specified below

(a) Landslide area (Area that is currently sliding or at risk of sliding. The same applies hereinafter.)

(b) Area of land located next to (a) a landslide area and whose projection is, on the horizontal plane to which the (a) landslide area and this area are projected, equal to the trajectory which is formed when, of the projections of boundary lines at the landslide area (hereinafter referred to as “boundary line projection” in this item), the projection of the lower boundary line that lies in the sliding direction (referred to as “specific boundary line projection” in 3 (b) of the next article) and is connected to two straight lines in the direction parallel to the sliding direction (the direction to which the projection of the landslide mass moves when a landslide occurs at the landslide area. The same should apply to this item and in 3 (b) of the next article) on the same horizontal plane, is translated in the sliding direction on the horizontal plane for a distance equivalent to the length between the two straight lines which are perpendicular to the sliding direction (250 m if the distance is over 250 m) (excluding an area to which debris, etc. will never reach in view of topography when a landslide occurs).

4.3 Equipment Configuration

The equipment should consist of firing equipment and paint capsules, a device and materials for sighting and confirmation after setting, and measuring device (total station).

Comments

(1) Firing equipment and paint capsule

They should consist of the following:

(i) A crossbow

(ii) An arrow

(iii) A paint capsule

(iv) A firing frame

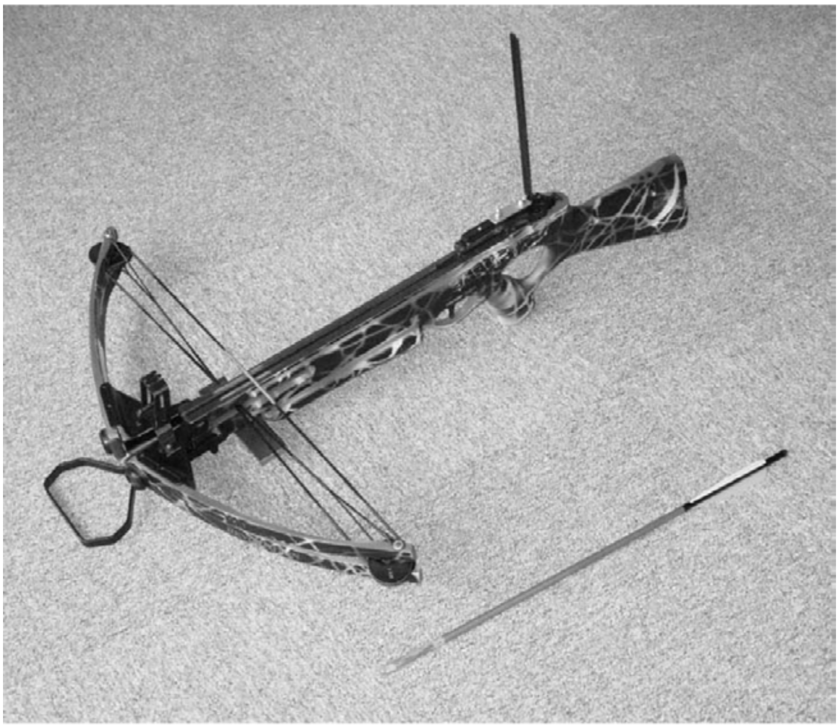
(i) Crossbow

The crossbow should be able to be used by anybody over the age of 18, without the need to hold any qualification or license. The crossbow should also require no special techniques and should be able to be easily used by a beginner.

The specification of the crossbow adopted for the current measuring technology is described below.

Product name:	Crossbow
Manufacturer:	Barnett
Model:	Revolution
Arrow power:	150 pounds (667N, 68 kg) (Catalog value)
Arrow initial speed:	104 m/s (catalog value)
Total length:	93.5 cm
Total width:	71.0 cm
Weight:	3.45 kg

An entire view of the crossbow is shown in Photograph Appendix 1.



Photograph Appendix 1　The crossbow

(ii) Arrow

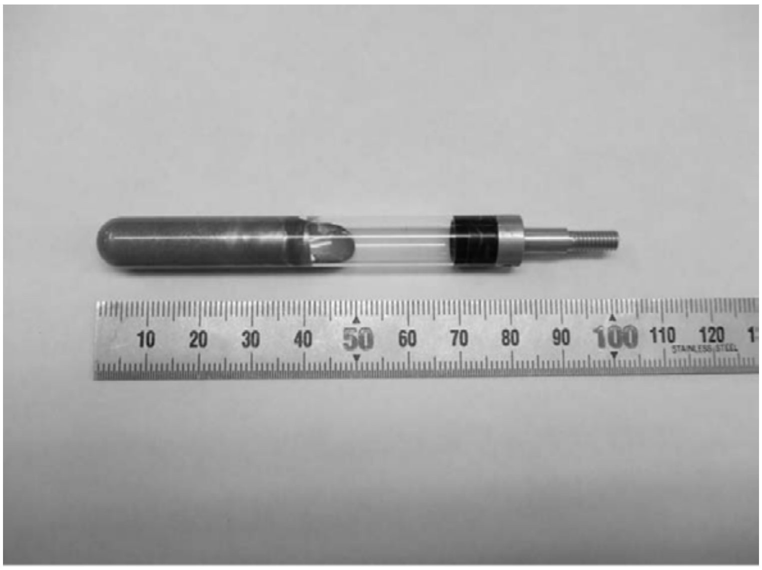
A 20 inch arrow suitable for the above crossbow should be used.

In the current measuring technology, AP050 (aluminum) manufactured by Horton is used.

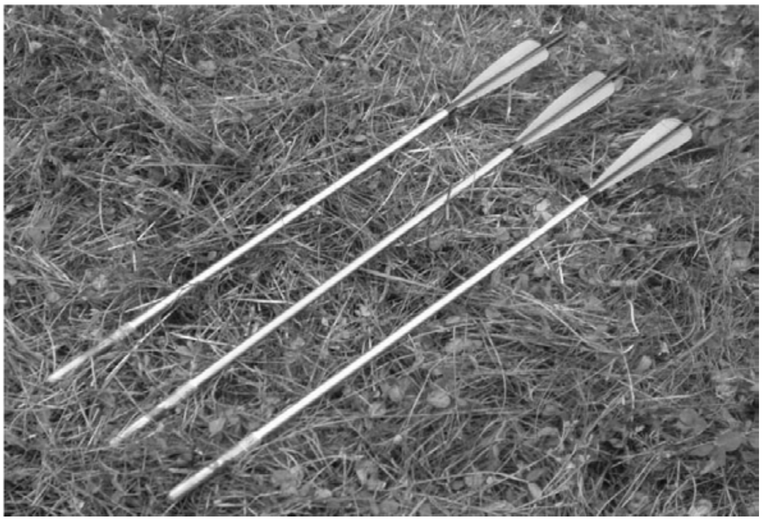
(iii) Paint capsule

The paint is encapsulated into a glass paint capsule (Photograph Appendix 2) and the capsule is attached to the tip of an arrow using a screw (Photograph Appendix 3). The capsule has a sealed structure so that the paint will not dry during storage.

Pink-colored retroreflective paint having high visibility is used. Two milliliters of paint (max. 3 ml) are put in the capsule. The retroreflectivity is the property in which reflected light returns parallel to the incident light directed at the glass beads on the paint surface.



Photograph Appendix 2　Paint capsule



Photograph Appendix 3　Paint capsule attached to the tip of an arrow

(iv) Firing frame

The firing frame is used to adjust and set the elevation angle and horizontal angle of the crossbow to take aim at the target slope, in addition to stabilizing the crossbow.

The firing frame is a dedicated frame for Revolution crossbows produced by Barnett. Its specifications are as follows:

- Frame

Material:	aluminum (A5052P)
Length:	75 cm
Width:	20 cm
Height:	40.5 cm
Weight:	26.84 kg
Vertical adjustment angle:	45°
Horizontal adjustment angle:	30°

- Tripod stand

Type:	aluminum tripod stand (TS-165T)
Head:	plane, 35 mm
Hinge:	clamp type
Extension:	max. 1660 mm, min. 1000 mm
Weight:	4.4 kg per unit
Number of stands:	2 units (total tripod weight 8.8 kg)

- Crossbow

Weight:	3.45 kg (main body)
Total weight:	frame 26.84 kg + tripod stand 8.8 kg + crossbow 3.45 kg = 39.09 kg

Photograph Appendix 4 shows the firing frame fitted with a crossbow as a complete assembly.

Photograph Appendix 4　View of the firing frame

(v) Dedicated containers

This measuring technology is intended for use in emergency situations, so the equipment and related items need to be delivered to the site quickly. For practical use, we produced dedicated containers having a size and weight that is within the limits of airfreight (there is no freight restriction on crossbows) and parcel delivery services.

The specifications of the dedicated containers are shown in Table Appendix 2.

Table Appendix-2　Specifications of the dedicated containers

Item		Crossbow	Upper frame	Lower frame	Tripod stand
Container material		Aluminum (t=1.5)	Aluminum (t=1.5)	Aluminum (t=1.5)	Aluminum (t=1.5)
Weight (kg)	Container	6.90	7.82	5.36	6.34
	Item	3.24	14.68	12.16	4.40
	Total	11.12	22.50	17.52	10.74
Size (mm)	Total length	883	823	723	1083
	Total width	503	523	303	273
	Total height	124	201	208	213
	Total length + total width + total height	1510	1547	1234	1569
Number of containers (pieces)		1	1	1	2

(2) Devices and materials for sighting and confirmation after setting

The following devices and materials should be used for the measurement of a sight angle and diagonal distance between target firing position and target setting position and for the confirmation of targets set at the slope.

(i) Angle gauge

(ii) Laser range finder

(iii) Quick chart for setting of elevation angle

(iv) Binoculars

(i) Angle gauge

Use a digital inclinometer with an accuracy of 0.1° (Photograph Appendix 5). Obtain a sight angle up to the target setting position from the target firing position. A digital inclinometer is fixed on the cylinder and the target slope is observed from the inside the cylinder with a narrowed sight, thus making it possible to reduce measurement errors (Photograph Appendix 6).

Photograph Appendix 5
Digital inclinometer

Photograph Appendix 6
Measurement using an angle gauge

(ii) Laser range finder

Measurement should be made at the target firing position in the same way as an angle gauge. Measure the distance from the target firing position to the target setting position in units of meters using a laser rangefinder (Photograph Appendix 7).

Photograph Appendix 7　Measurement of diagonal distance using a laser rangefinder

(iii) Quick chart for setting the elevation angle

Determine the crossbow firing angle from the sight angle and the diagonal distance obtained in (i) and (ii). The quick chart in Photograph Appendix 8 was prepared from calculations of the arrow trajectory and past experimental results.

Photograph Appendix 8　Estimation of an elevation angle using a quick chart

(iv) Binoculars

Binoculars are used to observe the slope conditions before and after firing the target. The targets on the slope are difficult to see with the naked eye, so check the position and condition of the adhered paint using binoculars.

(3) Measuring equipment

The non-prism total station (Photograph Appendix 9) is used as the measuring equipment. To ensure measuring accuracy, the measuring equipment must satisfy the following conditions: it must be able to measure over a long distance, it must easily register the positions of the targets, and it must have small equipment-specific errors. The equipment having the following functions is recommended based on these requirements.

(i) A distance of about 500 meters is measurable.

(ii) The laser range accuracy is 3 mm + 2 ppm (non-prism mode) or better.

(iii) The intensity of reflected light is indicated.

Photograph Appendix 9 Measurement using the total station

4.4 Preparations

<table><tr><td>As the preparations are smoothly put into effect, it is necessary to collect site information and evaluate the applicability of this measuring technology and to secure necessary equipment and workers. Confirmation of the site conditions should be made by site inspection in principle.</td></tr></table>

Comments

(1) Confirmation of site conditions

The following site information should be confirmed in advance.

(i) Geology of the target slope

Check if the target slope is composed of material that the paint can adhere to easily. The target setting position should be a position that detects the precursors of landslides and collapses. Even though the position may consist of rock mass to which paint can adhere easily, a position that cannot detect slope displacements is not appropriate as the target position.

(ii) Visibility, elevation angle, and diagonal distance between firing and setting positions of targets

The essential conditions of the target firing position are to have good visibility up to the target slope and to have no obstruction that may hamper the arrow trajectory. These conditions must be checked on site, including the selection of the target measuring position.

Also, calculate the visibility angle and a diagonal distance between those two positions and check if the target is settable or not using a quick chart. If possible, target setting positions should be selected on site and their adoptability confirmed by actual measurements using an angle gauge and a laser rangefinder.

(2) Acquisition of drawings and photographs

In the actual execution stage, work needs to be executed swiftly. For that purpose, obtain planar drawings and photographs of the target slope and determine the setting position and setting order of targets in advance. At the work site, a number of workers will undertake various tasks. So, if the setting position and setting order are communicated to them beforehand, the workers can cooperate and the work can proceed efficiently.

(3) Preparation of materials

Make arrangements to secure the necessary materials and workers so that work can be started smoothly. Confirm that the necessary materials are fully ready and load them onto a vehicle or forward to a delivery service. Include extra arrows and capsules to cover possible wastage. Also, include spare cords for the crossbow.

If a rental car is used to carry these materials to the site, select a vehicle having a large loading capacity, such as a pick-up truck or a station wagon.

4.5 Measuring Method

The measuring work for this technology can be performed without any personnel entering a dangerous slope such as a collapsed site, thereby preventing secondary disasters. The measurement targets are set up by firing them with a crossbow. Slope displacements are estimated by measuring the diagonal distance up to the target from the measuring equipment installed. A non-prism total station should be used as the measuring equipment.

Comments

The flowchart of measurement is shown in Fig. Appendix 14. The measuring method and the points to be noted are presented below.

(i) Setting of targets using a crossbow

The target setting position on the slope is determined and then a paint capsule that becomes the target is fired at the slope using a crossbow. The following are the points to be noted regarding the setting of targets.

- Select a target firing position that allows safe firing work. Also, use a quick chart or table to check if it is an acceptable position for firing in terms of distance and angle.
- The target setting position is used to monitor the slope displacement. Therefore, select a position that is likely to exhibit deformation in an early stage or a position that is highly susceptible to deformation in principle.
- Rock mass is favorable as the target setting position because the paint will adhere to it easily and not be washed away so easily.
- As the diameter of a target to be formed will be about 5 cm, it becomes difficult to see if its visibility becomes low if the distance from the measuring position is more than 100 meters. Therefore, it is desirable to set up a target at a conspicuous position.
- The position directly across the measuring position is desirable as the target setting position.
- The number of targets varies by failure scale, but five or more targets should be set up to enable planar monitoring.
- To complete setting work quickly, examine the setting position and setting order in advance and communicate it to the workers before the work starts. Arrows may not hit the slope as intended due to the wind or other effects. Therefore, to avoid wasting arrows, fire an arrow aimed at an easy-to-reach target first (for example, a position close to the location from which the arrow is fired) and find the discrepancy from the calculated trajectory as quickly as possible.

(ii) Confirmation of targets

Confirm that targets are set on the slope adequately. The main points to be noted are as follows.

- Check if the target positions are acceptable for continuous measurement over several days. If targets are placed on loose rock that may fall independently of any landslide movement or on unstable rock that will be removed in the course of emergency work, they are unsuitable.
- Confirm that the targets set on the slope can be measured from one equipment position in most cases.
- Basically, slope displacements are evaluated by changes in the diagonal distance between the target and the equipment. Therefore, confirm that targets are set at the position that can capture the slope displacements adequately in view of the possible direction of movement.

- Slope displacements may not be captured correctly if the rock surface on which a target is set is at a steep incline when seen from the equipment position. Therefore, check that targets are located right across the equipment position.
- If the number of targets is insufficient, use more targets.

(iii) Selection of the measuring position and installation of the equipment

An appropriate position should be selected as the measuring position and the measuring equipment should be installed there. The points to be noted are as follows:

- Select a position to install the equipment that affords a view of all the targets on the slope.
- The measuring distance should be roughly within 250 meters in terms of measuring accuracy.
- Ideally, the measuring equipment should be set at a position whereby the obtained changes in diagonal distance between the target and the equipment directly represent the slope displacement.
- If the above requirement is taken into account, the position directly across the slope is desirable as the measuring position. However, it must also be a position that is some distance away to ensure safety during measuring work.
- Place a point (stud) or drive a pile firmly at the equipment position so that the equipment can be installed at the same position repeatedly.
- Deploy leg piles for the tripod stand to restrain its movement during measurement.
- For measuring work, use a tripod stand for measurement, secure it firmly, and take measures to reduce the effect of sunlight, etc.

(iv) Display of reflective light intensity

When measuring the laser (prism) distance, check if the non-prism total station used is the type of equipment that displays the reflective light intensity or not..

The reflective light intensity is displayed. → go to (v).

The reflective light intensity is not displayed. → go to (vi).

(v) Confirmation of target point (by the highest reflective light intensity)

Set up the equipment at the measuring position and confirm the target point on the target from the total station. The target point should be set up at the position having the highest reflective intensity. Select a target point in accordance with the following procedures.

- Bring the center point of the target into view via the scope and measure its reflective intensity.
- By moving the target point in the horizontal and vertical directions, select a target point that has the highest reflective intensity.
- Establish the point having the highest reflective intensity as the initial value for the target points.
- If multiple points have the same level of reflective light intensity, select the one for which it is easy to place a marker.

(vi) Confirmation of target point (by visual observation)

Install the measuring equipment at the measuring position and confirm a target point on the target from the total station. The target point should be set in a conspicuous position. Select a target point as follows.

- Bring the center point of the target into view via the scope.
- If the paint is found, measure it several times using the non-prism mode and check that the values are stable.
- Also measure the area around the target point by moving the scope in the horizontal and vertical directions, and check that the selected target point is the most appropriate for monitoring.

(vii) Establishment of the base direction (horizontal angle, vertical angle, and diagonal distance)

- To ensure repeatability of measurement when the equipment is moved during continuous measurement, establish a base point (back point) and an object that give the base direction of the target point that was established as the initial value.
- Measure the horizontal angle, vertical angle, and diagonal distance using the base point (back point) and the object as a reference.

(viii) Measurement of target point (continuous monitoring)

- Measure the diagonal distance of the target point that was established as the initial value.
- Record the monitoring date and time because time-series monitoring is important data.
- Make observations of meteorological factors (weather, wind direction, wind force, temperature, air pressure) that may influence the distance measurement and correct the distance where appropriate. Record the names of the people who did the observations, note-taking, etc. as needed.
- Determine the measuring time (measurement intervals) in consultation with related organizations.

(ix) Calculation of displacements (continuous monitoring)

- Calculate the displacement based on the measurement record.
- Prepare a graph of the calculation results so that the displacement conditions can be easily evaluated.

(x) Evaluation and judgment

- Related agencies should conduct an evaluation and make a judgment based on the results of calculating the displacement through consultations.

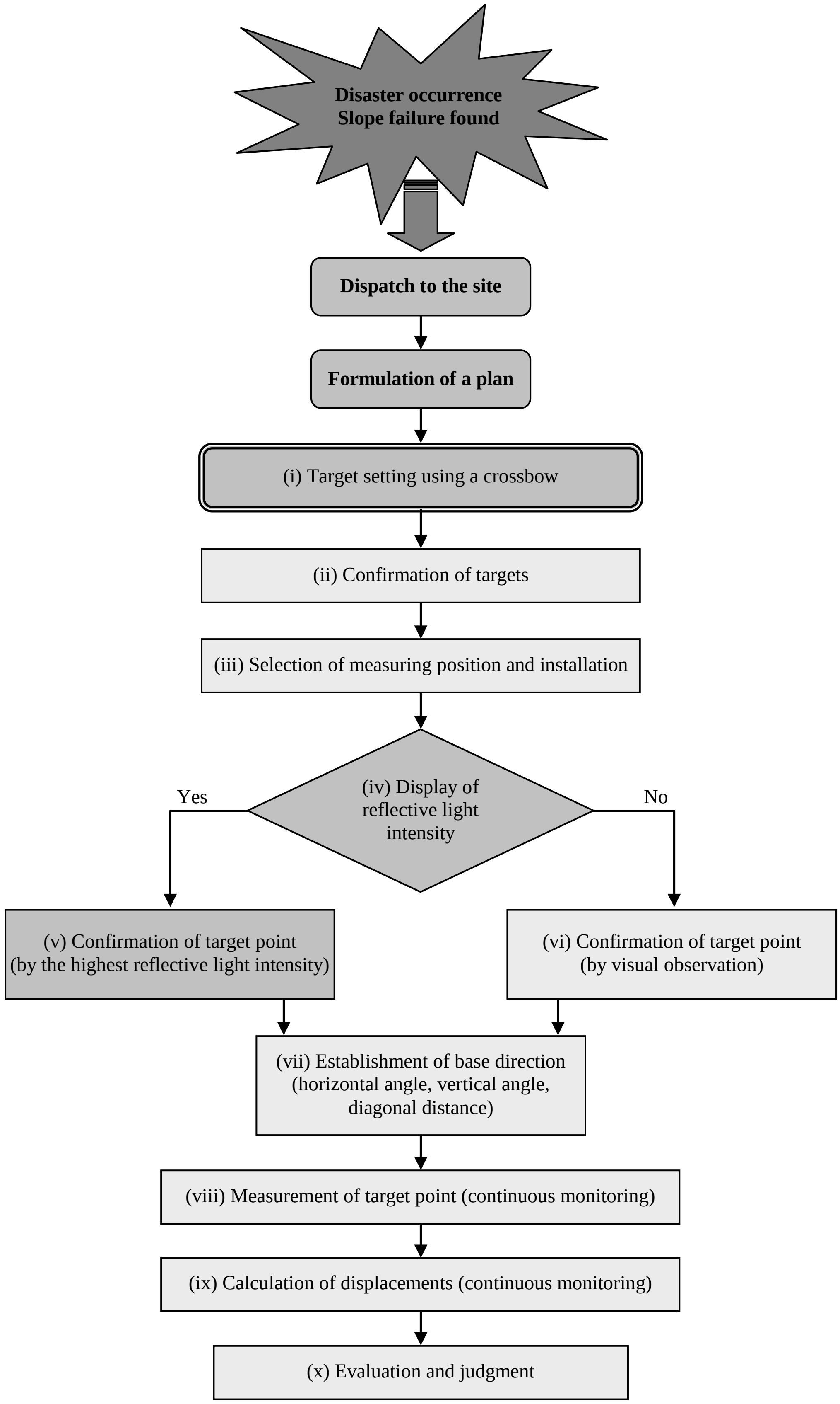


Fig. Appendix 14 Flow of RE-MO-TE^2 monitoring

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