Manual for Landslide Hazard Zonation Mapping / Yellow and Red Zone Mapping
(Total Impact Zone Map)

Project for Capacity Strengthening on Development of Non-Structural Measures for Landslide Risk Reduction in Sri Lanka

October, 2022

National Building Research Organisation
(NBRO)

Japan International Cooperation Agency
(JICA)

Democratic Socialist Republic of Sri Lanka

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Preface

Landslide is a major geological hazard, which poses serious threat to life and property in hilly regions of Sri Lanka. Having been designated as the national focal point for landslide risk management in the country, the National Building Research Organisation (NBRO) has taken enormous efforts in landslide risk reduction through multiple measures including but not limited to landslide susceptibility mapping.

Under Landslide Hazard Zonation Mapping Project, NBRO has so far produced landslide susceptibility maps for all landslide prone areas of the country. However, hazard levels in these maps are only an indication of the likelihood of initiation of a landslide at a particular location and therefore only applicable to identify landside rupture zones excepting any paths of debris transport or zone of deposition. Yet, most disastrous landslides in Sri Lanka have been induced by intense rainfall as sudden events with, long run-out distances and rapid run-out velocities, due to their unexpected nature, leaves no time for people living in downstream impact zones to safely evacuate. Hence, development of landslide hazard zonation maps demarcating all impact zones is essential for reducing the risk of sediment disasters in Sri Lanka in the future.

Intended as a step towards the mentioned exertion, this manual was developed under project “SABO”, a technical cooperation project for capacity strengthening of development of non-structural measures for landslide risk reduction in Sri Lanka which was undertaken by the Japan International Cooperation Agency (JICA) conjointly with NBRO in 2022. Each manual in the project has been developed drawing on Japanese expertise and referencing to Japanese guidelines, “Guideline and Explanation for Hazard Mapping for Sediment Disaster” and “Guidelines for Basic Investigation of Risk Assessment”.

The content here provides an approach for risk identification through landslide hazard zonation, which will be especially useful to landslide risk reduction practitioners in Sri Lanka. Readers are most welcomed to make wide use of this manual by understanding, learning and replicating the techniques in their respective department/organizations to create hazard maps in the future.

Last but not least, it should be pointed out that this document is the outcome of extensive desk and field studies done by JICA and NBRO officials. While appreciating their hard work in bringing out this publication, it is expected that the users of this manual will find their efforts worthwhile and commendable.

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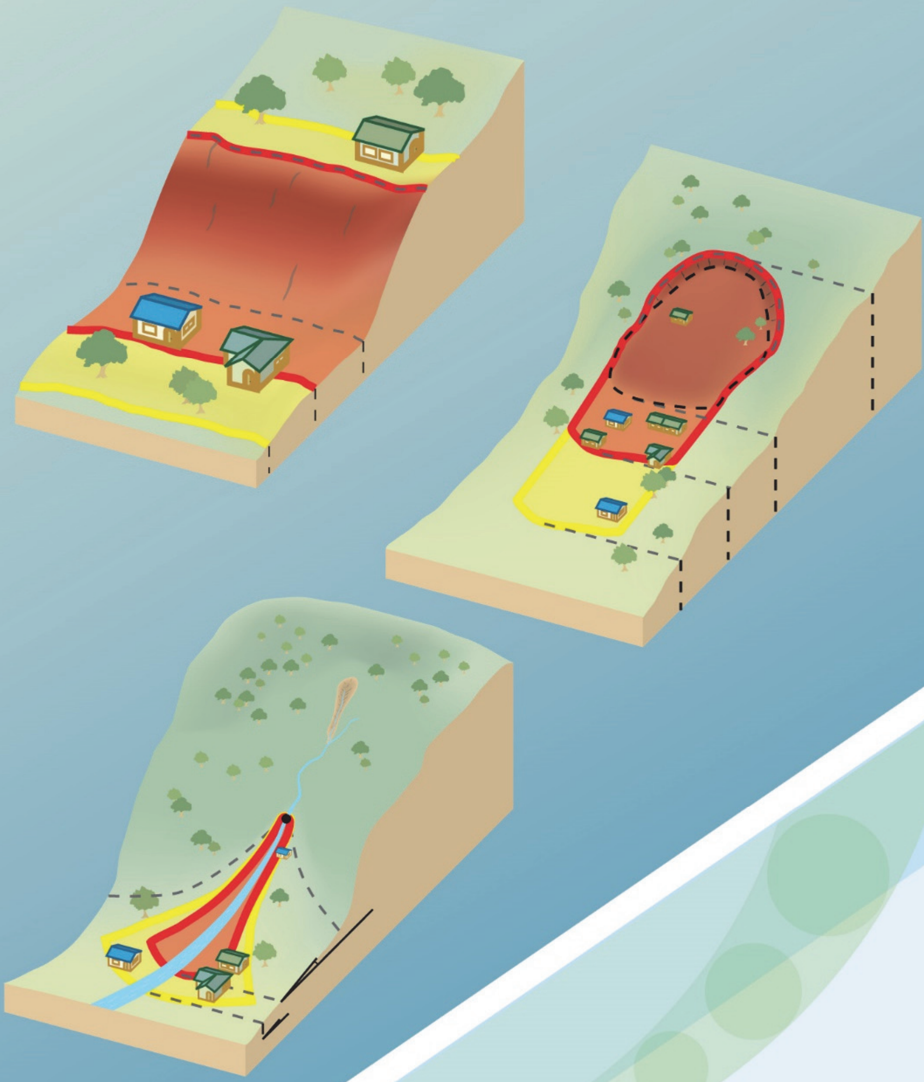
List of Abbreviation

NBRO	National Building Research Organisation
JICA	Japan International Cooperation Agency
LHZ	Landslide Hazard Zonation
UNISDR	
LHZM	Landslide Hazard Zonation Map
API	Aerial Photograph Interpretation
LIDAR	Light Detection and Ranging



Chapter 1
Introduction

This chapter describes the objective and scope of the manual and the general process of landslide hazard zoning

CHAPTER 1

INTRODUCTION

1.1 Necessity of Landslide Total Impact Zone Mapping

Like in many other countries, in Sri Lanka landslides have become frequent major natural hazard, especially in the mountainous and hilly areas of the central highland. Landslides have caused major socioeconomic impacts on peoples, their homes and properties, and lifelines, such as highways, railways, and communications systems. Likewise, landslides in Sri Lanka have presented great problems in development and land use planning.

Landslide hazard mapping or zonation is an initial and important step towards landslide hazard and risk management. Varnes (1984) defines the term "zonation" as "the progress of division of land surface into areas and ranking of these areas according to the degree if actual or potential hazard from landslides or other mass movements." Following a landslide hazard mapping program implemented from 1990 to 1996, NBRO in 1995 developed a model for regional level landslide susceptibility evaluation (Manual on Landslide Hazard Zonation, 1995). The model, using statistical method and expert knowledge, was developed considering six major landslide causative terrain factors, namely, a) Bedrock geology and geological structures, b) Soil type and thickness (colluvium and residual soil), c) Slope angle and category, d) Hydrology and drainage, e) Land use and management, and f) landform. The model identifies spatial distribution of landslide hazard and produces landslide hazard zonation (LHZ) maps with a scale of 10,000. The landslide hazard areas in the existing LHZ maps are divided, in terms of susceptibility to land sliding, into five levels as a) Landslides are most likely to occur (Brown color), b) Landslides are to be expected (Orange color), c) Modest level of landslide hazard exists (Yellow color), d) Landslides not likely to occur (Green), and e) Inaccessible slope or not mapped area (Gray color), in addition to areas on which landslides have occurred in the past (Red color).

The existing LHZ maps have been effectively used in the establishment of landslide early warning, in the regional assessment for the suitability of lands for development planning, and in the identification and prioritization of potential landslide areas for mitigation. However, because the existing LHZ maps neither identify different types of landslides nor consider the flow path and depositional area of various types of landslides, they cannot be used to properly assess the risk of the entire impact zone, different types of landslides. In addition, recently as development expands into unstable hill slope areas under the pressures of increasing population and urbanization, human activities such as excavation of slopes for road cuts and building sites, etc. have significantly increased not only the susceptibility of hilly areas to landsliding but also largely put people and their properties at extreme risk. Therefore, identification of different types of landslides and subsequent assessment of total impact zone of a landslide are increasingly becoming important in landslide hazard evaluation and risk reduction.

1.2 Objective of the Manual

The objectives of this manual are to provide a standard method or protocol for developing landslide hazard zoning in Sri Lanka to identify the total impact area of a landslide at a 1:2,500 or 1:5,000 scale. The manual is focused on the identification and zonation of the major types of landslides for further landslide hazard and risk management. The manual is mainly for internal use at NBRO as well as for relevant landslide hazard management organisations in Sri Lanka. Through the manual, users can quickly and consistently produce standardized landslide hazard zoning maps.

The manual has been prepared mainly based on the concept of "Landslide Hazard Yellow Zone" and "Landslide Hazard Red Zone" in Japan and the results of landslide inventory survey in Sri Lanka. The Japanese method of landslide hazard Yellow and Red Zone mapping was developed with the focus on the residents, under the Sediment Disaster Prevention Act in 2001, to prepare total impact zone maps that contain two zones, namely, landslide hazard yellow and red zones. The landslide hazard Yellow Zone is defined as an area to prone sediment disaster, while the landslide hazard Red Zone is defined as an area where a high risk of damage to buildings and threat to residents may be expected. The definition of the Yellow Zone and Red Zone is further described in Chapter 1.5.

1.3 Scope of the Manual

This manual describes the methodologies of landslide hazard zoning/ yellow and red zone mapping (total impact zone mapping) (hereafter refers as yellow and red zone mapping/maps) and reference data, mainly including three major types of landslides, such as slope failure, slide and debris flow. The manual consists of five chapters and technical notes, as shown in Figure 1.1 below.

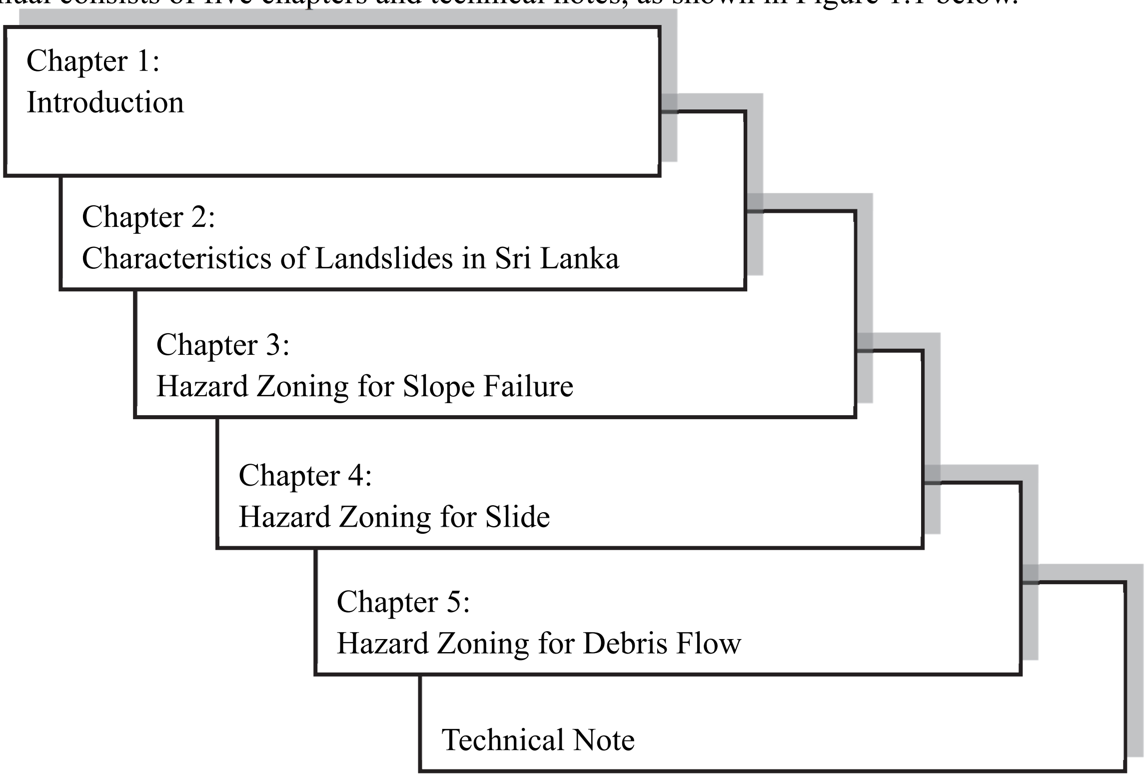


Figure 1.1 Structure of the Manual

Chapter 1, Introduction, describes the objective and scope of the manual as well as the general process of landslide hazard zoning.

Chapter 2, Characteristics of Landslides in Sri Lanka, summaries the distribution, characteristics and classification of landslides in Sri Lanka.

Chapter 3, Hazard Zoning for Slope Failure, Chapter 4, Hazard Zoning for Slide, and Chapter 5, Hazard Zoning for Debris Flow, provide the methodologies of landslide total impact zone mapping for each major type of landslides, respectively, such as slope failure, slide and debris flow.

Finally, two technical notes are attached. Technical Note 1, Hazard Zoning Methodology for Slope Failure, which was prepared by reference to Japanese criteria, similar to Chapter 3, describes an alternative method for hazard zoning for slope failure as a reference. Technical Note 2, Aerial Photograph Interpretation of Landslides, provides reference for Chapter 5.

In addition, the manual should be used together with the Manual on 1:10,000 scale Landslide Hazard Zonation (1995) to select target areas for further hazard zoning to map the total impact area.

The manual is useful to experts or organizations concerned with landslides when developing landslide total impact zone maps. This hazard map is contribute to land use planning and development regulation.

The target phenomena in the manual are Landslides, which are technically viable to identify the hazard area. Deep-seated landslides, rock slope failures, collapses of mountain body or huge-scale mass movement with far exceed assumptions are exempt from the manual because it is extremely difficult to identify and predict accurately the hazard area due to the phenomena.

1.4 Key Definitions

Landslide:

"Landslide" is collectively defined as the movement of a mass of rock, debris, or earth down a slope. In the manual, landslide is synonymous with sediment disaster.

Landslide Hazard:

"Landslide hazard" is defined as the probability of the occurrence of a landslide event in a given area in a specific time frame.

Disaster Risk:

"Disaster risk" is defined as the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, and capacity. Disaster Risk equation is defined as follows where the risk of a disaster increases as the frequency or severity of hazards increases, vulnerability increases and capacity to cope is decreased.

$$\text{Disaster Risk} = \frac{\text{Hazard} \times \text{Vulnerability}}{\text{Capacity}}$$

Vulnerability:

The characteristics are determined by physical, social, economic and environmental factors or processes that increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards. (UNISDR Terminology, 2017).

Landslide Hazard Yellow Zone:

"Landslide Hazard Yellow Zone" is defined as the area that is susceptible to landslide and is called as "Yellow Zone" for brevity. The resistance capacity of normal residential buildings in Yellow Zone is expected to be larger than the force acting on residential buildings due to the moving debris and earth from landslides, thereby causing partial or less damage to the residential buildings in the Yellow Zone, and consequently posing a lower risk to the residents in the Yellow Zone (Figure 1.2).

Landslide Hazard Red Zone:

"Landslide Hazard Red Zone" is defined as the area where there is a high risk of damage to buildings and threat to people due to a landslide, and is called as "Red Zone" for brevity. The force acting on residential buildings due to the moving debris and earth from landslides in the Red Zone is expected to be larger than the resistance capacity of normal residential buildings. Therefore, normal residential buildings in the Red Zone would be completely destroyed by the moving debris and earth of landslides, consequently having an even higher risk to the residents in the Red Zone (Figure 1.2).

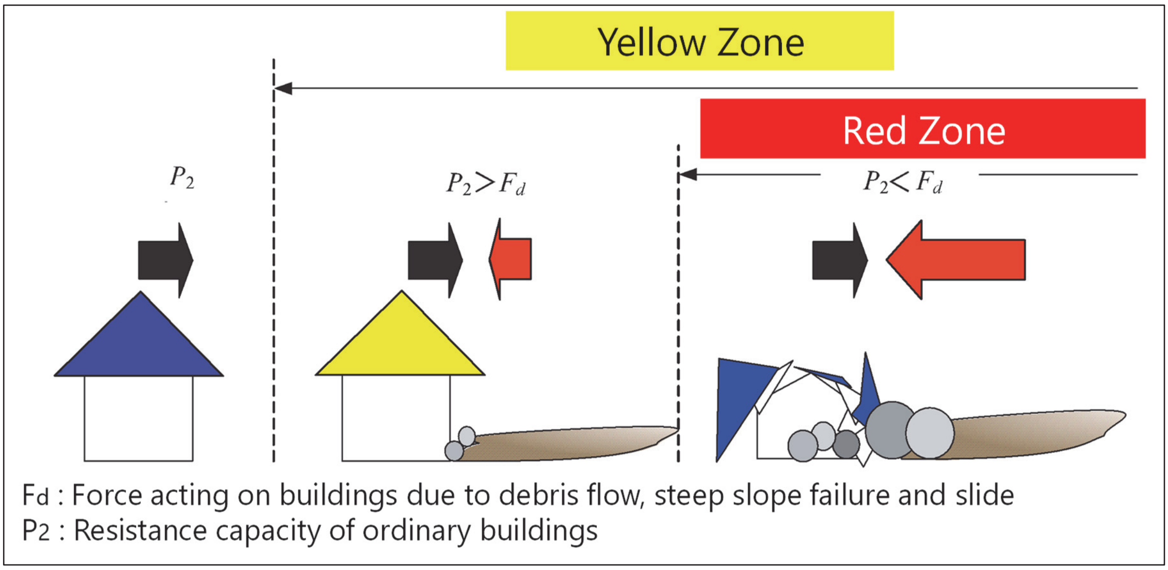


Figure 1.2 Basic Concept for Yellow Zone and Red Zone

1.5 General Process of Yellow and Red Zone Mapping

Yellow and Red zoning is conducted according to the steps shown below (Figure 1.3).

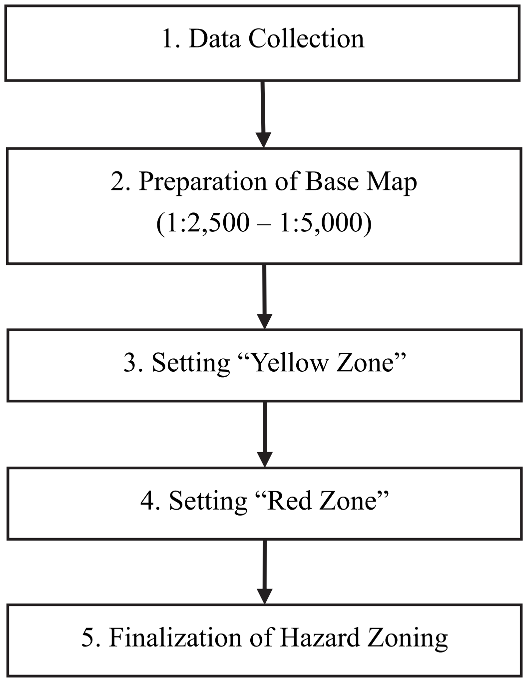


Figure 1.3 General Process of Development of Yellow and Red Zone Maps

1.6 Preparation of Yellow and Red Zoning

Relevant data such as base maps and landslides hazard area information for hazard mapping should be collected in accordance with the actual conditions at the target areas.

The following relevant data should be collected.

a. Base Map

- Digital map and Ortho data (1:2,500 or 1:5,000 scale, 1m counter interval)

b. Information on hazardous areas

- Location of residential houses and public buildings
- Past disaster records
- Location of the existing countermeasures against landslides

The accuracy of Yellow and Red zone maps to be produced depends on the resolution of base map and the quality or details of the disaster records at the target area. In addition, yellow and red zone maps to be created, shall be at map scale of 1:2,500 or 1:5,000, which allows to divide or delineate landslide areas into different hazard zones.

Chapter 2

Characteristics of Landslides in Sri Lanka

This chapter summarizes the characteristics and classification of landslides in Sri Lanka

CHAPTER 2

CHARACTERISTICS OF LANDSLIDES IN SRI LANKA

2.1 Distribution of Landslides in Sri Lanka

NBRO is compiling a landslide inventory database to better document the distribution and geologic and topographic attributes of landslides in Sri Lanka. As of 2018, the NBRO inventory database has more than 3,000 documented landslides. Out of the 14 landslide prone districts Landslides have occurred in 12 districts are shown in the Figure 2.1, and especially concentrated in Kandy, Badulla, Ratnapura and Kegalle districts, in the mountainous and hilly areas of central Sri Lanka. The distribution of landslides reflects regional geology, topography and land use and urbanization conditions.

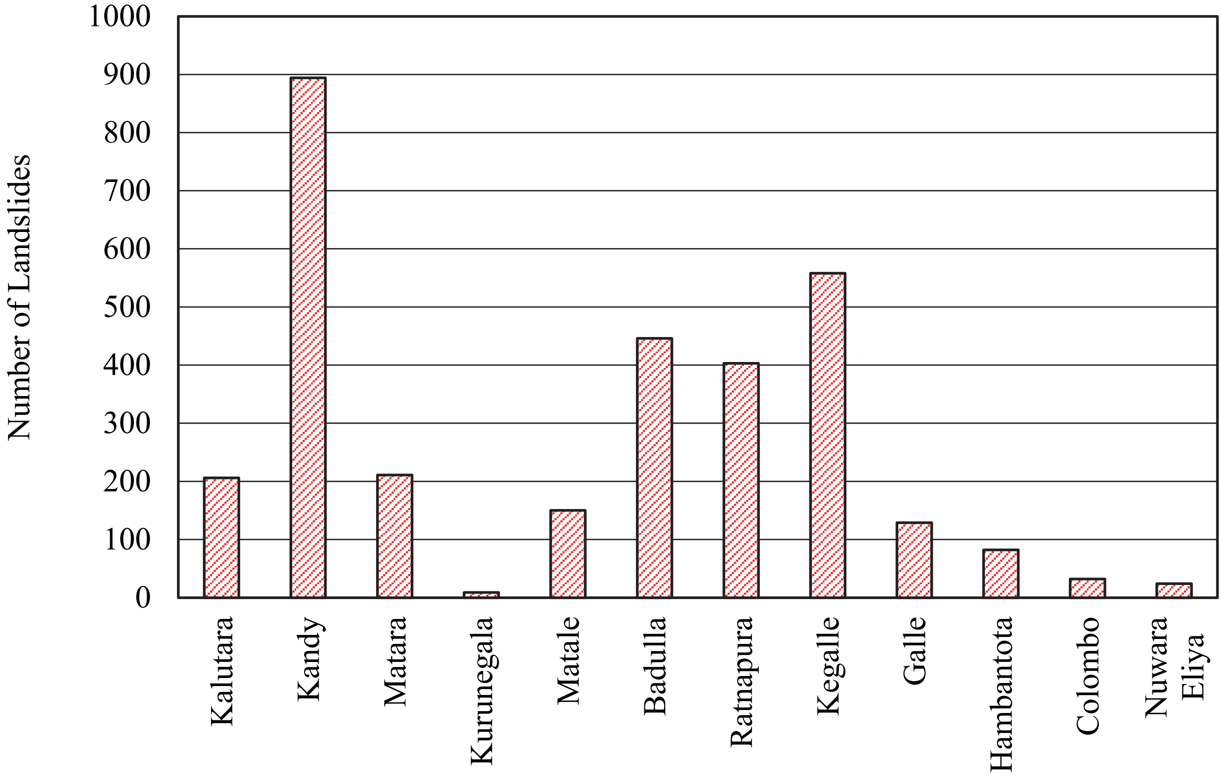


Figure 2.1 Distribution of Landslides by District

Landslides are one of the most dangerous and destructive natural hazards in Sri Lanka, and the number of landslides has been recently increasing nationwide (Figure2.2). Many landslides are associated with the slopes cut for house building and road construction. The recent increase in the number of landslides is largely due to inappropriate land use planning and unplanned development on sloping lands and previous landslide areas. Excavation at the base of slopes, particularly at the toes of potential and active landslides as well as colluvial slopes, is the most common human trigger of landslides. In addition, in Sri Lanka almost all landslides are associated with intense and/or prolonged periods of rainfall, indicating that rainfall is the main triggering factor of landslide disasters. Improper planning and inappropriate maintenance of surface drainage system also increase the potential for slope instabilities.

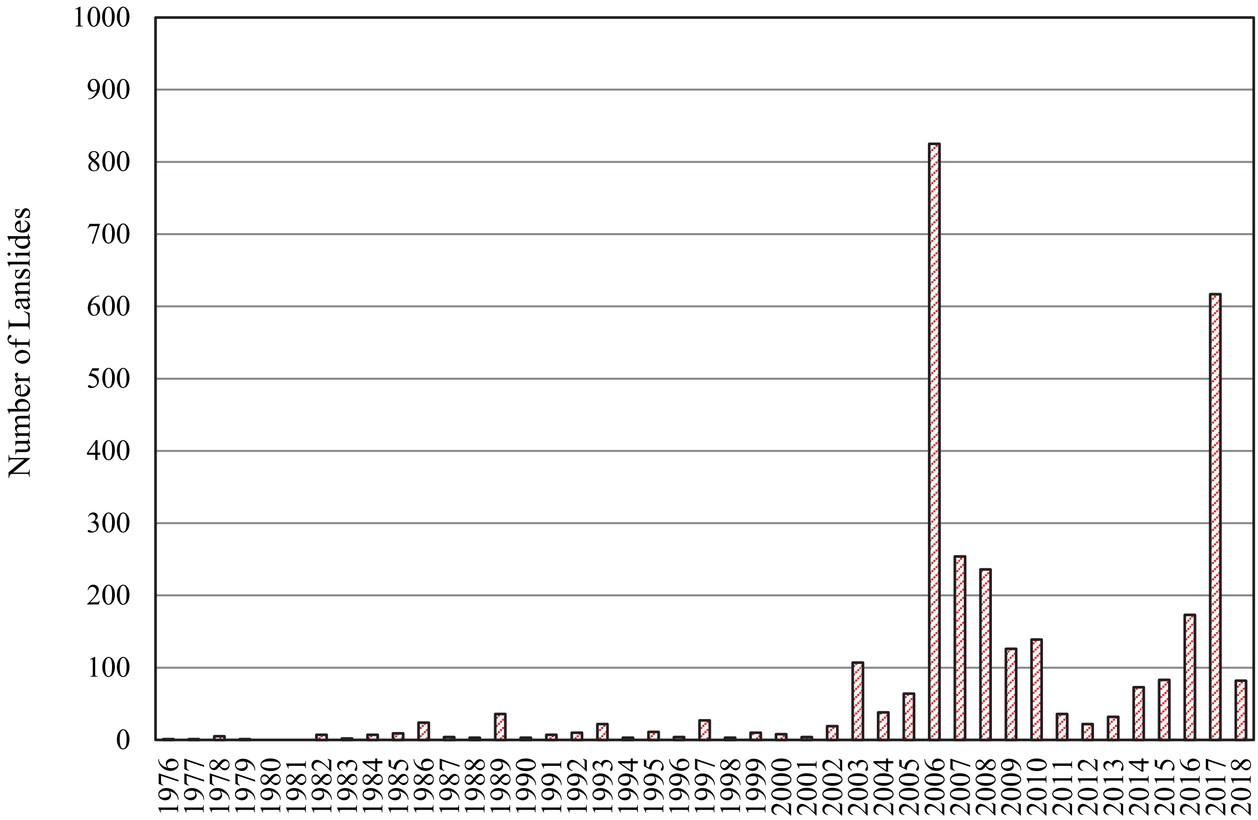


Figure 2.2 Occurrence of Landslides (1976 to 2018)

Landslides in Sri Lanka are due to the combination of fragile geology, steep topography, heavy and intense rainfalls, and earthquakes and human activities. The susceptibility of lands and slopes to slope instability is generally increased largely by human causes, such as inappropriate land use and development; thereby exposing people, their property and infrastructure to increased risk, and consequently causing significant damage to residential houses and infrastructures as well as loss of human life. Rainfalls, earthquakes, and human activities are the main triggers of landslides. While rainfalls and earthquakes cannot be controlled, human activities can be controlled and regulated to reduce the potential adverse impacts from developments, thereby improving the susceptibility of landslides.

2.2 Classification of Landslides in the Manual

Landslide classification is an important initial step to hazard identification and risk evaluation of landslides. There have been various classifications of landslides and other types of mass movement with different purposes, generally in consideration of the following factors or criteria:

a) Type and size of materials involved;
b) Type and velocity of movement;
c) State and distribution of activity;
d) History and the age of movement;

e) Dimension and size of landslide;
f) Causes of movement and triggering mechanism;
g) Underlying geology;
h) Morphology of landslide deposits;
i) Spatial composition and location; and
j) Others.

An important classification is Varnes's classification (Varnes, 1972). This classification is based on the type of movement and the kind of material involved. Movement is subdivided into falls, slides and flows. Later two more movement types, topples and lateral spreads, were added into the classification (Varnes, 1978). Cruden and Varnes (1996) further revised the classification, as outlined in Table 2.1 below, which includes five types of movements belonging to mass movement and complex movement involving one of the main types of movement followed by two or more of the other main types of movement. The classification has been widely used worldwide.

Table 2.1 Landslide Classification

Type of Movement		Type of Materials		
		Bedrock	Debris	Earth
Topple		Rock topple	Debris topple	Earth topple
Fall		Rock fall	Debris fall	Earth fall
Slide	Translational	Translational rock slide	Translational debris slide	Translational earth slide
	Rotational	Rotational rock slide	Rotational debris slide	Rotational earth slide
Flow		Rock flow	Debris flow	Earth flow
Spread		Rock spread	Debris spread	Earth spread
Complex		Combination of two or more principal type of movement		

Source: Cruden and Varnes, 1996.

However, four types of landslides have been recognized and classified from past landslide inventory survey in Sri Lanka, including 1) slides, 2) slope failures, 3) debris flows and 4) rockfalls. The classification scheme is simple and considers some of the factors of the above-mentioned classification criteria, such as 1) type of movement and 2) velocity of movement. The classification scheme has also been used for landslide hazard identification and subsequent risk assessment and management in Sri Lanka. This landslide classify cation scheme is thus recommended to be used in the manual.

The typical features of each type of landslides are summarized below.

(1) Slides

Slides are used, in a narrow sense, to describe the downward movement of slope materials along pre-existing or potential rupture surfaces or zones. They are the major types of landslides in Sri Lanka and are deep, rotational or translational sliding phenomena caused primarily by groundwater pressures within a gentle hillside or around previous slide areas. They normally occur on gently slopes of less than 20 degrees move slowly with a relatively large volume of displaced mass, thereby causing significant damages to properties such as houses, roads and other lifelines, but less loss of life.

(2) Slope failures

Like slides, slope failures are also the major type of landslides in Sri Lanka, but shallow, fast-moving types on steep slopes, natural and artificial, with a relatively small volume of displaced mass. Slope failures, because of their fast-moving nature and without indication prior to movement, frequently result in serious injuries and fatalities, even in the case of small volume of displaced mass.

According to the landslide inventory survey and other landslide studies in Sri Lanka, slope failures are characterized by fast movement of a mass of rock, debris, or earth downward a steep slope, mostly over 25 degrees. They occur suddenly, in a small size and at a shallow depth, but in group in most cases, and are mainly triggered by heavy or intense rainfall. Because of its sudden collapse and fast movement, many people fail to escape from slope failures, and therefore, slope failures commonly cause a higher rate of fatalities.

On the other hand, slides are marked by slow movement of a mass of rock, debris, or earth downward a gentle slope of less than 25 degrees along a pre-existing zone or surface of rupture. They are generally larger at size with a deeper surface of rupture and are triggered mainly due to rising groundwater level or increased pore-water pressure as a result of cumulative rainfall.

Because of the lack of inventory survey data relating to difference between slide and slope failure in Sri Lanka, a clear distinction between slide and slope failure has been recognized in Japan and is given in Table 2.2 for reference.

Table 2.2 Distinction between Slide and Slope Failure

Item	Slide	Slope Failure
1) Geology	Occurs at sites with specific geological and geological structures	Less relation to geological condition
2) Topography	Occurs on gentle slopes of 5 to 30°	Occurs on steep slopes of over 30°
3) Soil Type	Occurs mainly on clayey soils	Occurs frequently on sandy soils
4) Activity	Continuous, recurrent	Sudden, sporadic
5) Movement speed	Slow, from 0.001 to 10 mm/day	Fast, over 10 mm/day
6) Displaced mass	Little disturbed	Strongly disturbed/deformed
7) Main Cause	Ground water - pore water pressure	Heavy rainfall - infiltration and erosion
8) Scale	Large, 1 to 100ha	Small, frequently in group
9) Slip Surface	Gentle, 10 to 25°	Steep, 35 to 60°
10) Indication	Development of cracks, subsidence, bulging, groundwater fluctuation	Without indications

Source: Mechanism and Mitigation Measures of Slope Disasters, Sankaido, by M. Watari, 1986.

Slope failures are subdivided from slides in the manual mainly because the former, fast-moving, poses a greater threat to human life and has a higher potential to cause sudden and catastrophic damage to human and property, while the latter, slowly-moving, causes predictable damage only to properties and less to human life.

(3) Debris flows

Debris flows are also common types of very fast-moving landslides in Sri Lanka. They typically begin on upper steep hillsides, mostly as shallow slope failures or, on rare occasions, as slides during heavy rains, then rapidly flow down hills and/or into channels, before spreading widely on gently sloping grounds. Debris flows, normally together with driftwoods, generally claim many lives in addition to damage to roads, bridges, water supply lines, electricity and so on along their travelling paths because of their fast-moving velocity and long-travelling distance. Even small debris flows have the high potential to cause damage to properties and loss of life.

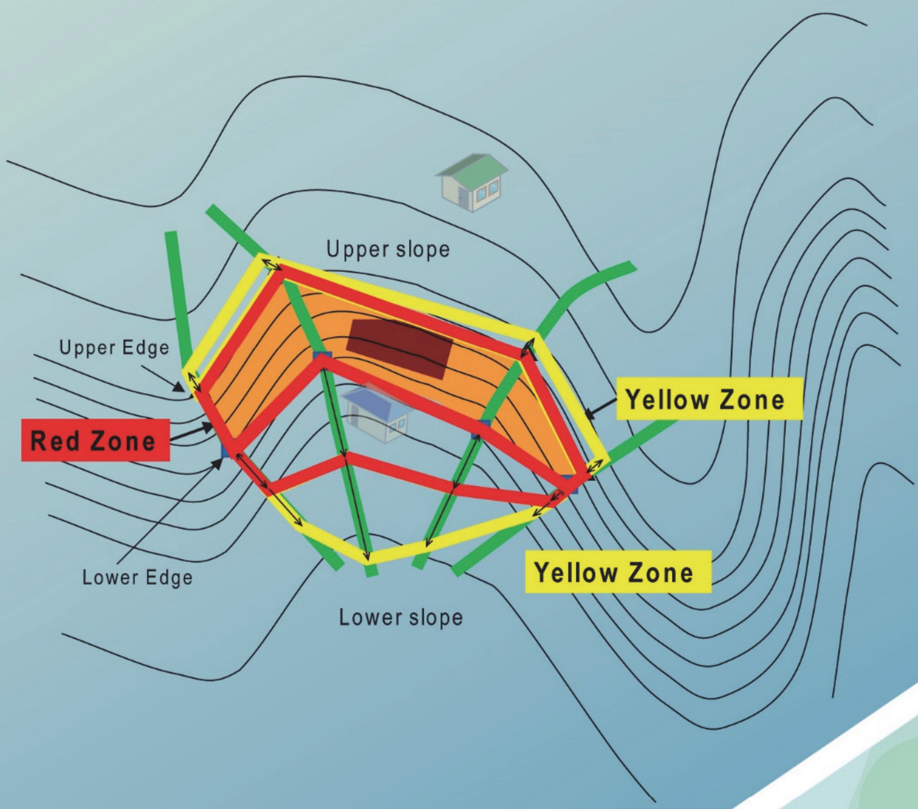
In Sri Lanka, two sub-types of debris flows have been recognized based on the landslide inventory survey, namely, channelized debris flow and hillslope debris flow. The channelized debris flows are generally formed by a source area, a stream transport channel and a depositional area showing a fan morphology. On the other hand, the open slope debris flows are formed similarly by a source area, by following their own path down valley slopes as tracks or sheets, before depositing materials on lower flatter areas. The clear difference is that the former flows along or in a preexisting channel, and the latter flows unconfined around an open valley slope or hillslope.

Hillslope debris flows are generally unpredictable or difficult to identify prior to occurrence because of the lack of evidence or indication, such as alluvial fans and mountain streams. Accordingly, the manual addresses channelized debris flow only.

(4) Rockfalls

Rockfalls are very rapid to extremely rapid falls of loosed and fractured rock blocks along steep rock slopes, natural, artificial or both. The fall-down movement takes place mainly through the air by free-fall, leaping, bounding, or rolling. An inventory survey shows that rockfalls are common along many cut slopes for road constructions and house buildings, and therefore threaten or damage transportations and residential areas.

In addition, because mapping and delineation of hazardous rockfall sites and its downslope affected areas are very complicated, rockfalls are excluded from the manual.



Chapter 3

Hazard Zoning for Slope Failure

This chapter presents the methodology and procedure of site-specific hazard zoning for slope failures

CHAPTER 3

HAZARD ZONING FOR SLOPE FAILURE

3.1 Procedure of Setting "Yellow Zone" and "Red Zone" for Slope Failure

Setting of "Yellow Zone" and "Red Zone" for slope failure is in accordance with the following steps (Figure 3.1).

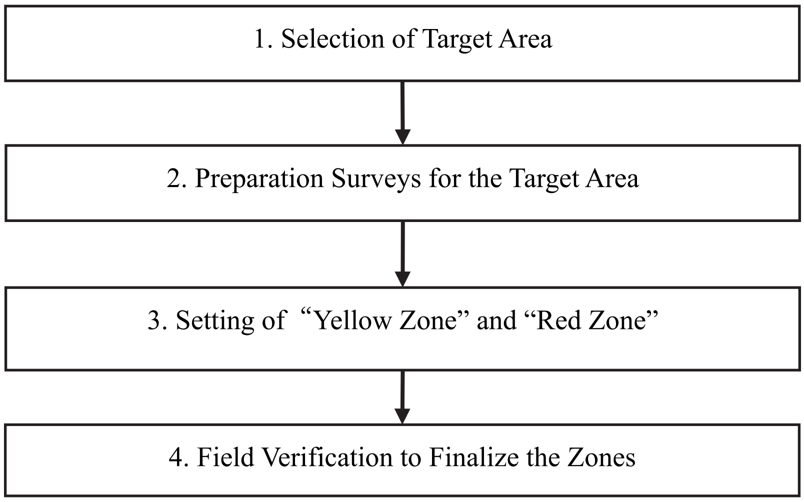


Figure 3.1 General Process of Setting "Yellow Zone" and "Red Zone" for Slope Failure

3.2 Methodology

This methodology is applicable to either natural slopes, man-made slopes, or their combinations.

3.2.1 Selection of the Target Area

In selecting the target area, the following three conditions are taken into consideration:

- Existing landslide hazard evaluation
- Present land use plan and social conditions
- Slope units

a) Existing Landslide Hazard Evaluation

The target area, as an "initial area or source area" related to potential slope failure, is selected by using the "Landslide Hazard Zonation Map (LHZM)" with a scale of 1:10,000 prepared by NBRO, which shows the areas that may have landslides in the future. The target area to be selected as the initial area of a slope failure shall be limited to the slopes or zones that are classified as "Landslides most likely to occur" which are indicated in brown color (hereinafter called "Brown zone") and/or "Landslides are to be expected" which are indicated in orange color (hereinafter called "Orange zone") in the LHZM, which both show higher likelihood of future landslides.

b) Present Land Use Plan and Social Conditions
   - The target area should include residential area in which at least one residential house or public building is located.
   - Areas that have no houses at present, but may be expected to be developed for housing or public building construction in future based on social conditions such as current land use and development plans should be also considered.
   - Areas where there is no possibility of residential house construction, such as high mountainous (inaccessible slopes) areas with no houses, etc. are excluded from target area selection.
   - Man-made slopes, either cutting or filling, along roads are excluded from target area selection.

c) Slope Unit
   - In the case of laterally continuous steep slopes that are classified as “Landslides most likely to occur” with brown zones and/or “Landslides are to be expected” with orange zones in the LHZM, the target area should be sectioned up to approximately 500 m in length based on topographical or administrative factor.
   - The setting of left and right edges of the area are described in Chapter 3.2.3 - (5) below.

3.2.2 Preparation Surveys for the Target Area

a) Survey of Past Disaster History

The past disaster history survey for the target area should be conducted to assess the size of the past slope failures and their damage conditions and set the range of hazard zone, by collecting the following:
   - Date, time, location and cause of a slope failure
   - Size or scale of a slope failure (height, width, length, depth, slope gradient, reaching distance and volume of collapsed sediment), as illustrated in Figure 3.2
   - Damage to humans (the number of fatalities/injuries), damage to houses (the number of damaged houses, completely or partially), and structural types of the damaged houses (reinforced concrete, brick, clay, wooden, etc.)
   - Rainfall information (cumulative rainfall, daily rainfall, hourly rainfall)
   - Others (thickness of inundated sediment, etc.)

b) Artificial structures

It should be checked in relation to their associated damage conditions if any artificial structures exist in the target area. The artificial structures may include:
   - Walls, Retaining walls
   - Pitching works
   - Embankments
   - Excavations
   - Drainage channels, ditches
   - Others

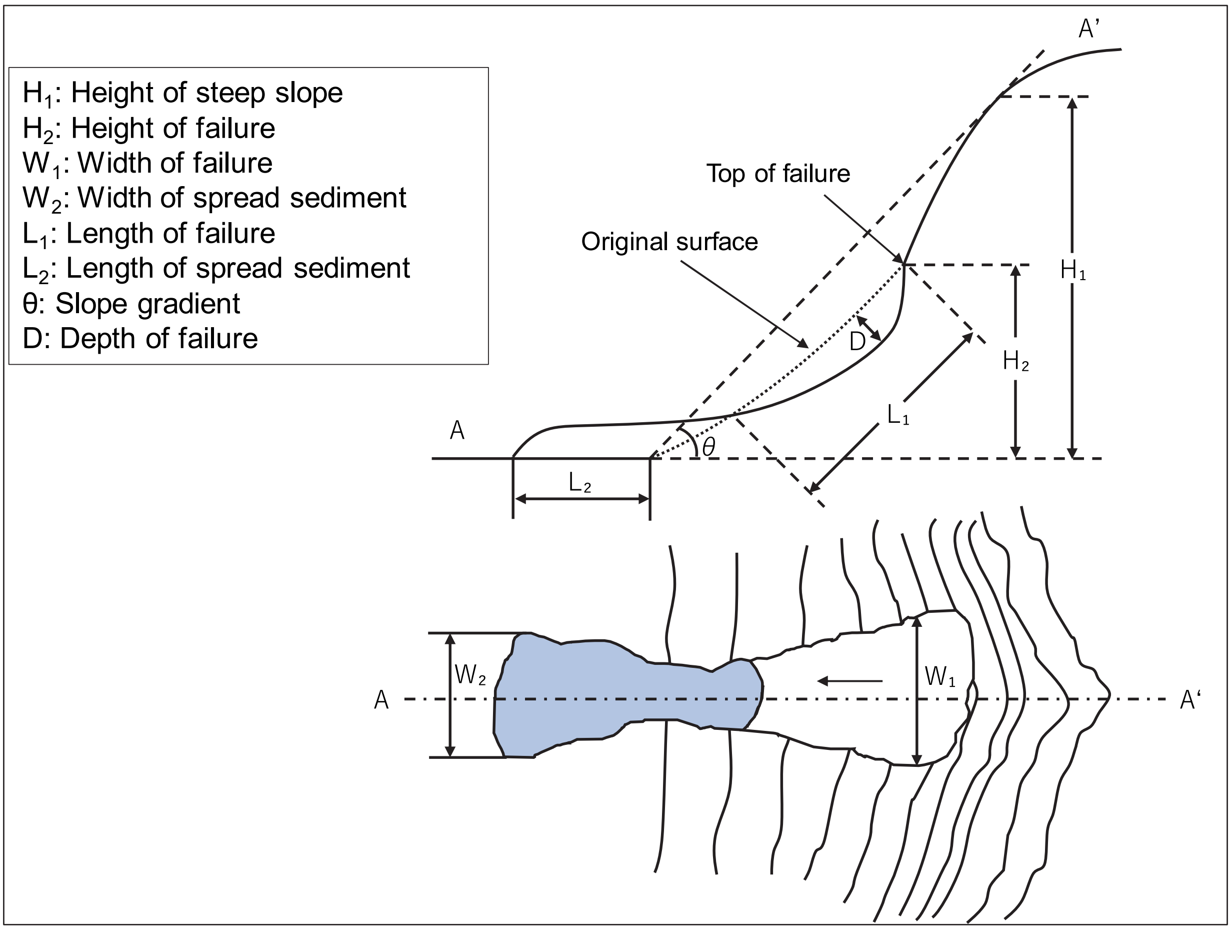


Figure 3.2 Diagrammatic Illustration of Slope Failure Dimension

3.2.3 Setting of "Yellow Zone" and "Red Zone"

Setting of "Yellow Zone" and "Red Zone" for slope failure is conducted according to the following steps (see Figure 3.3).

1. Extraction of "Landslides most likely to occur"/brown zones and/or "Landslides are to be expected"/orange zones from the LHZM

↓

2. Setting of Traverse Lines and Preparing of Cross Sections

↓

3. Setting of Upper Edge

↓

4. Setting of Lower Edge

↓

5. Measurement of Slope Height of Source Area of Possible Slope Failure

↓

6. Setting of Source Area of Possible Slope Failure

↓

7. Setting of Yellow Zone and Red Zone

↓

8. Excluding Areas where Slope Failure Sediment Cannot Reach

Figure 3.3 Flow chart of Desk Mapping of "Yellow Zone" and "Red Zone" for Slope Failure

(1) Extraction of "Landslides most likely to occur"/brown zones and/or "Landslides are to be expected"/orange zones from the LHZM

"Landslides most likely to occur"/brown zones and/or "Landslides are to be expected"/orange zones in the LHZM are extracted as source areas of possible or future slope failures, and delineated in a base map of 1:2,500 or 1:5,000 scale.

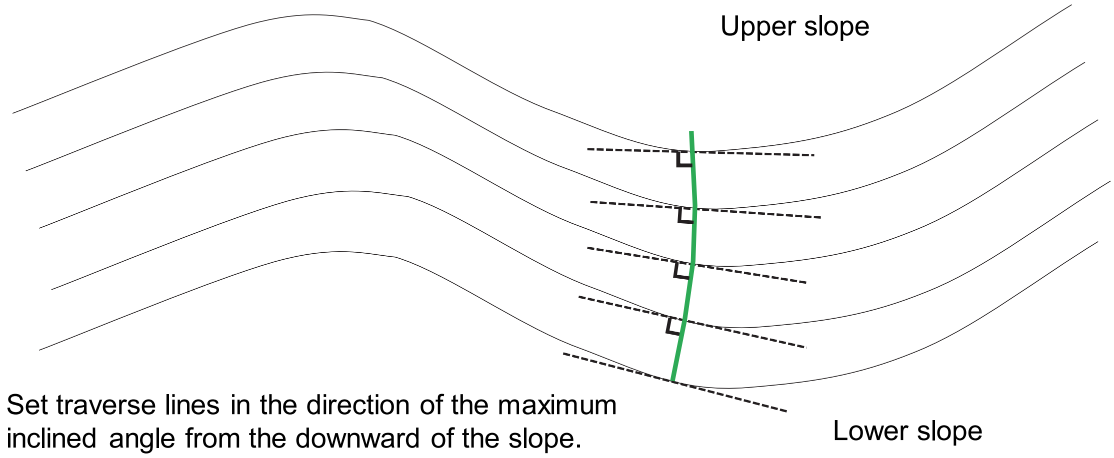
(2) Setting of Traverse Lines and Preparing of Cross Sections

Traverse lines are set in terms of their direction and location, as follows:

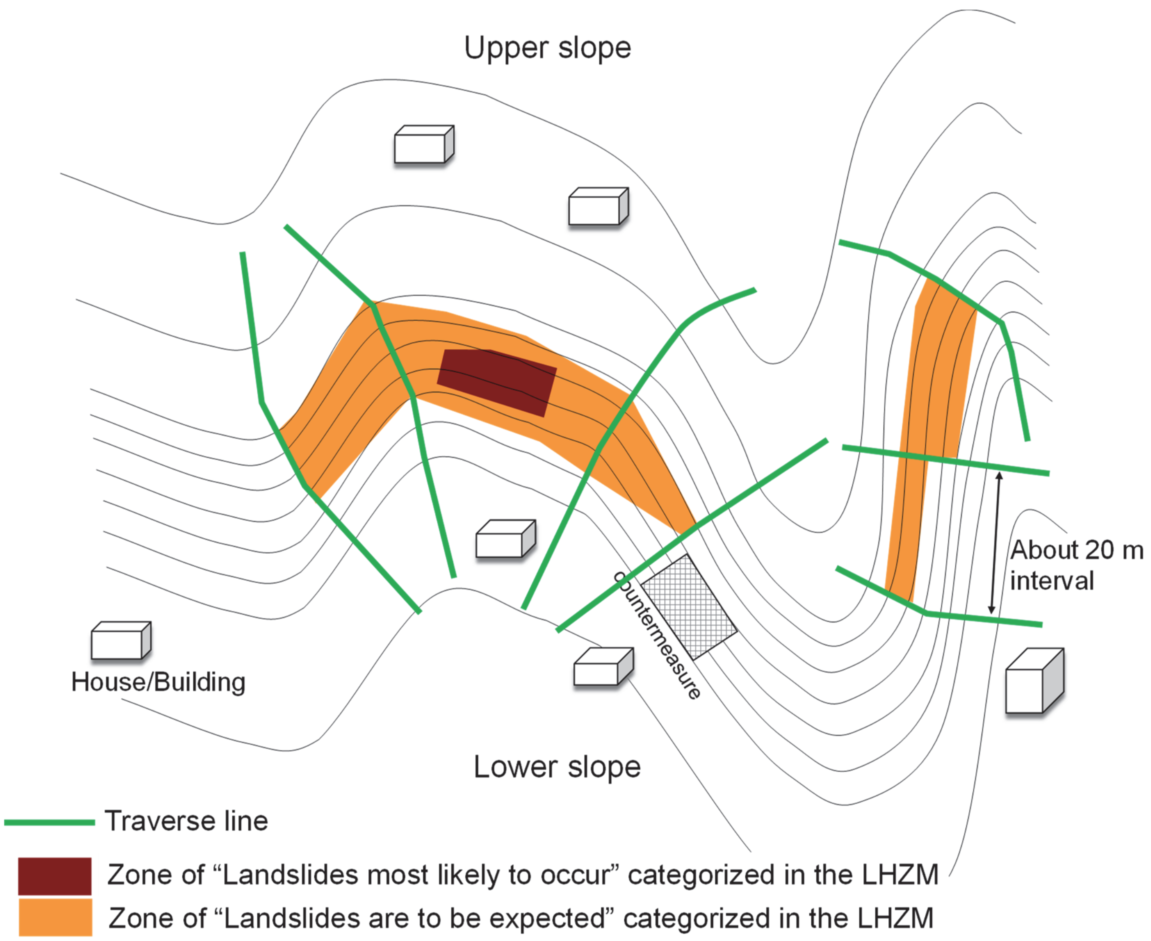
a) The traverse line should be oriented toward the maximum slope angle (Figure 3.4 - (a))
b) The location of traverse lines should be set at the lateral left and right edges of the Brown and/or Orange zone. Inside the Brown or Orange zones, traverse lines should be set at about 20 m interval along contours in consideration of topographical changing

points and artificial structures (Figure 3.4 - (b))

c) Then, a cross section must be prepared for each traverse line



(a) Direction of Traverse Line



(b) Location of Traverse Lines

Figure 3.4 Setting of Traverse Lines

(3) Setting of Upper Edge

The upper edge shall be set at the highest point of the hazard area on the cross section of each traverse line (Figure 3.5).

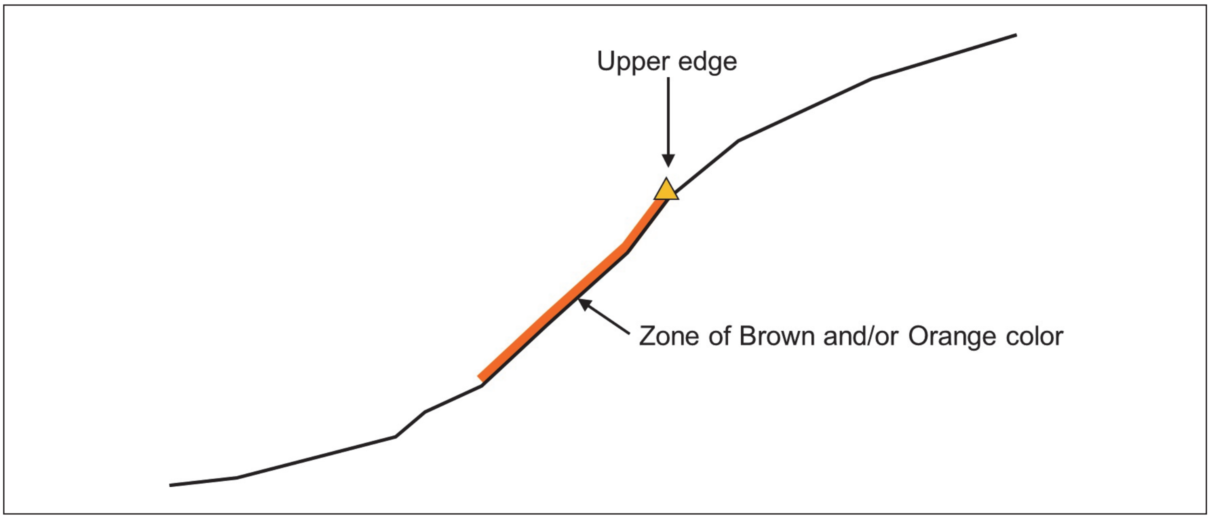
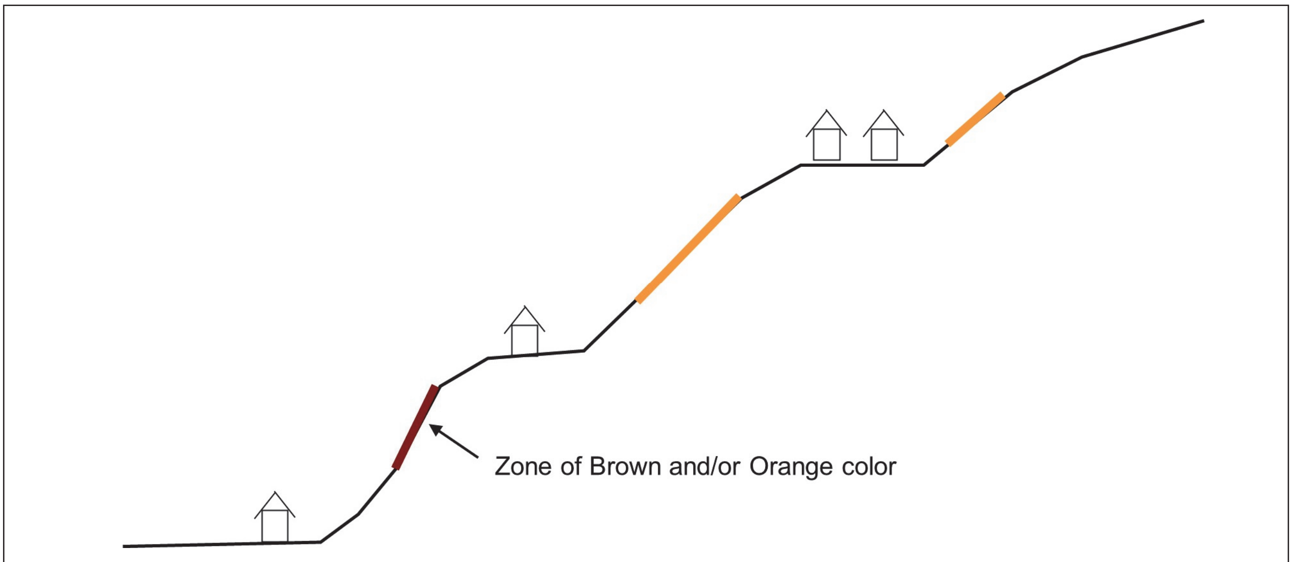


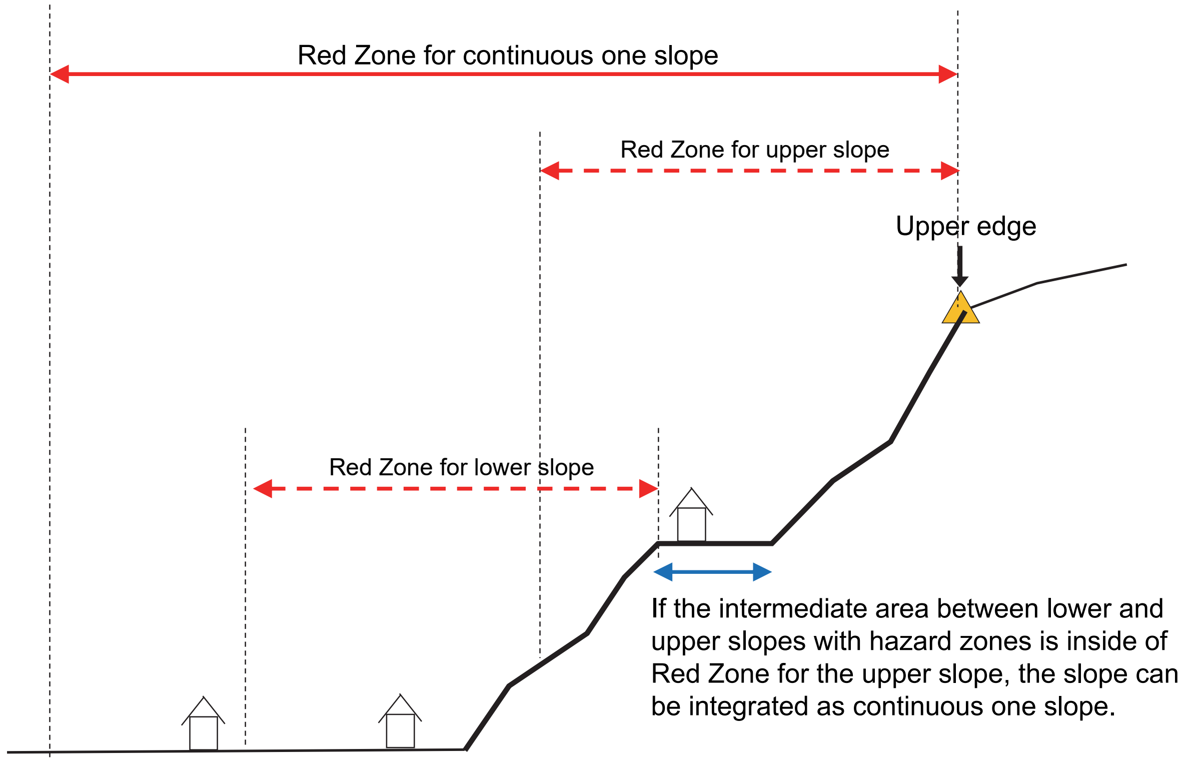
Figure 3.5 Diagram of Setting Upper Edge

Furthermore, in the area where there are multiple Brown and/or Orange zones in the slope direction (Figure 3.6 - (a)), the hazard zones should be set as follows:

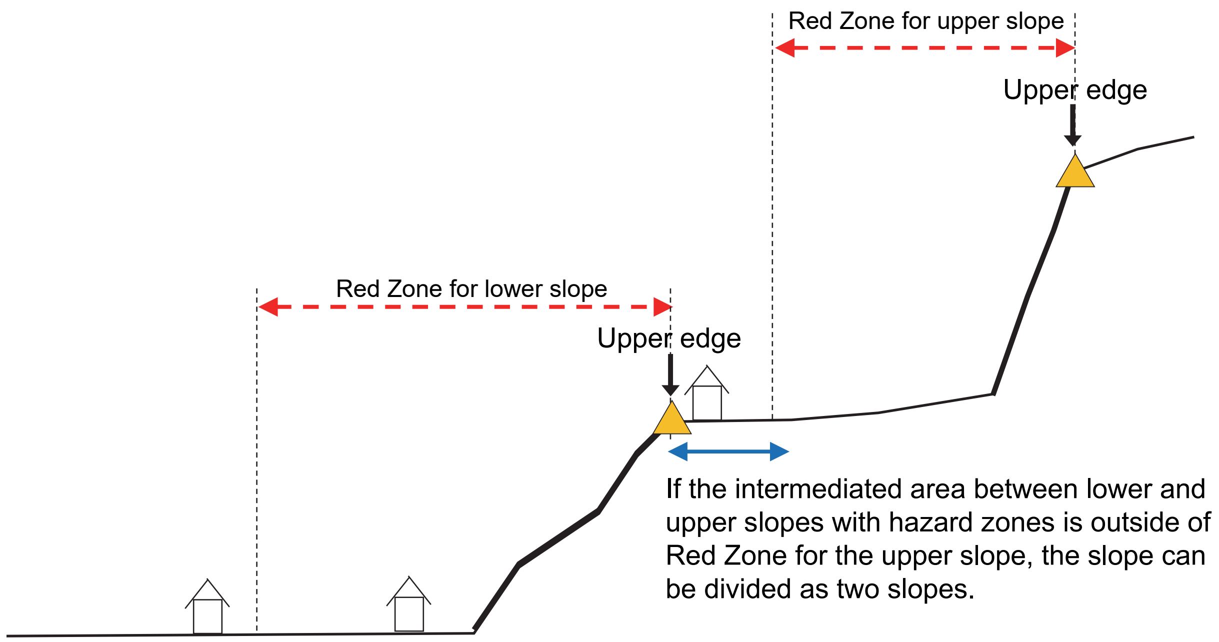
a) In principle, the hazard zones should be set for each of the Brown and/or Orange zones. However, if the Red Zones of the upper and lower slopes overlap (Figure 3.6-(b)), the upper and lower slopes are treated as one continuous slope
b) If there is no overlap between the Red Zones of the upper and lower slopes (Figure 3.6-(c)), the upper and lower slopes must be designated as separate Red Zones



(a) A Steep Slope with Multistep Gentle Slopes



(b) A Continuous Slope with Multiple Hazard Zones



(c) Division of Target Areas in Separate Hazard Zones

Figure 3.6 Diagrammatic Illustration of Setting Upper Edge for a Slope with Multiple Hazard Zones

(4) Setting of Lower Edge

The lower edge shall be determined at the lowest point of the hazard zone on the cross section of each traverse line (see Figure 3.7).

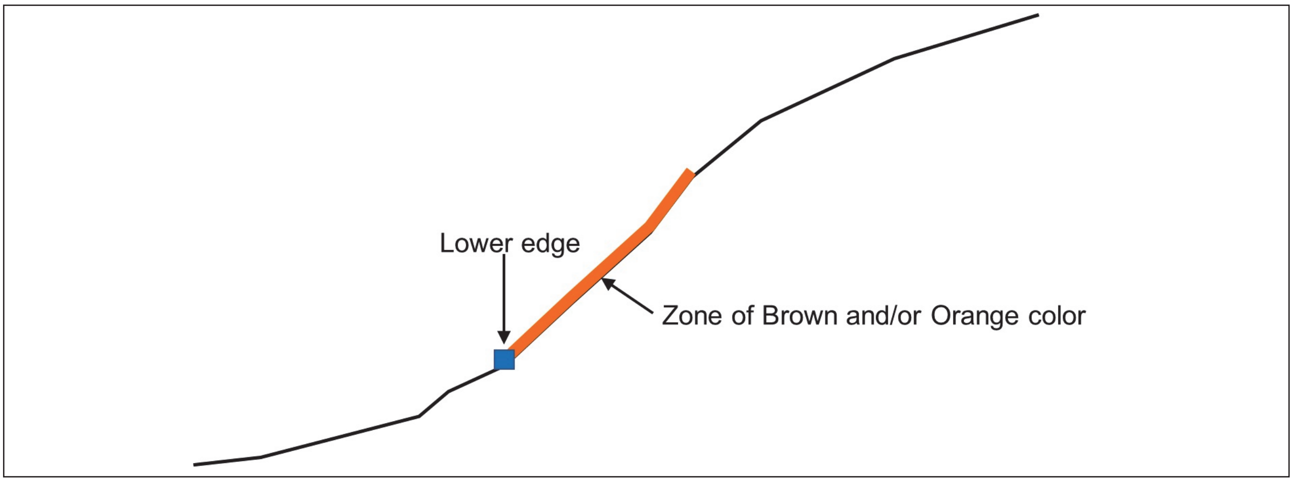


Figure 3.7 Setting of Lower Edge

(5) Measurement of Slope Height of Source Area of Possible Slope Failure

Slope height of the source area of possible slope failure is measured as the relative height between the lower and upper edges (Figure 3.8).

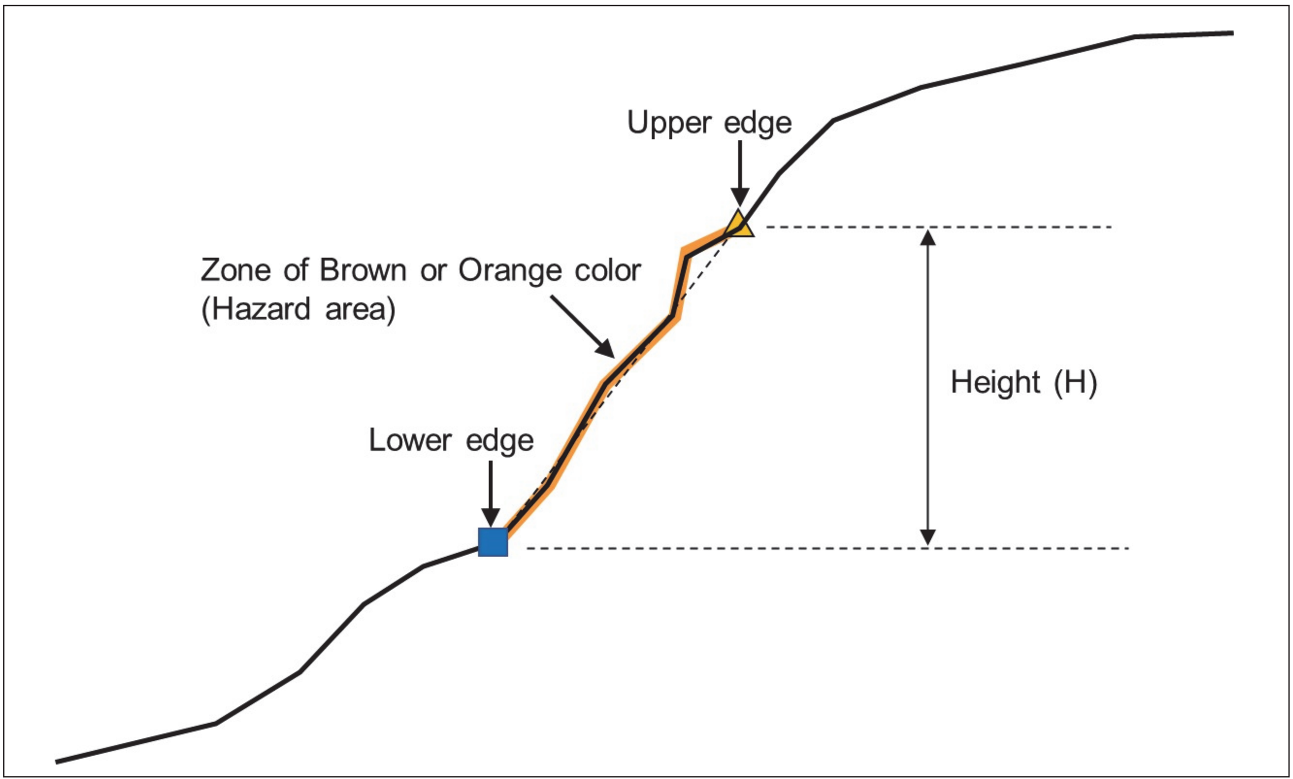


Figure 3.8 Measurement of Hazardous Slope Height

(6) Setting of Source Area of Possible Slope Failure

Source area of possible slope failure is set by straight lines connecting all upper and lower edges (Figure 3.9).

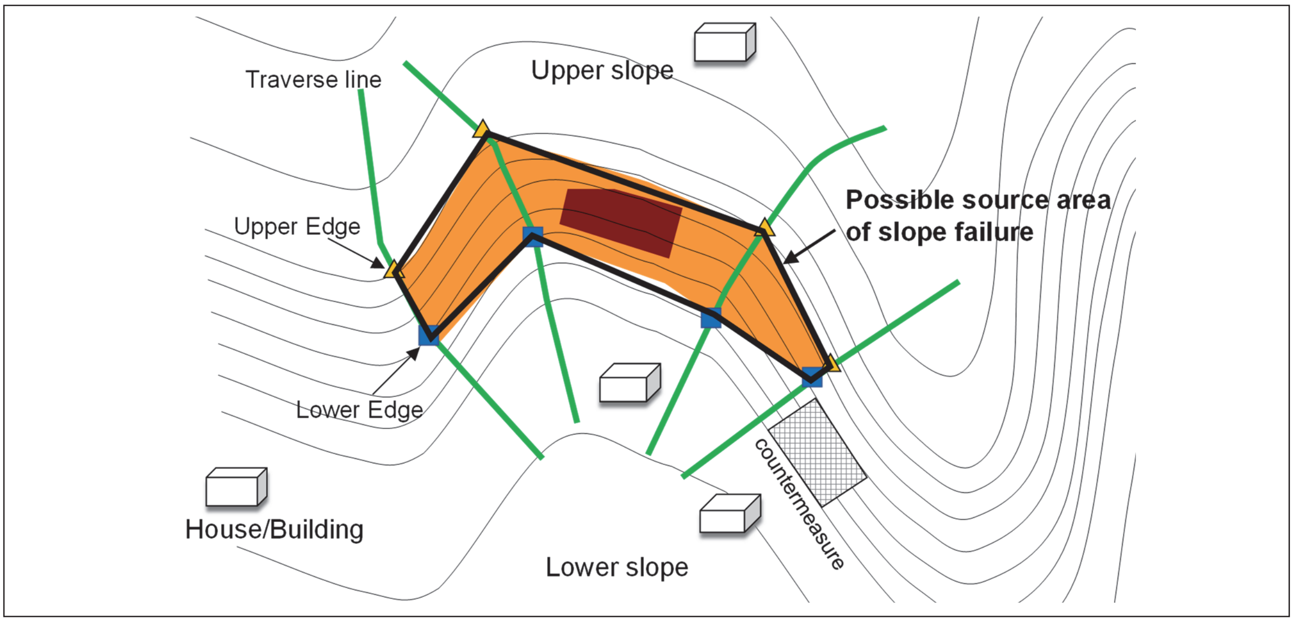


Figure 3.9 Diagrammatic Representation of Setting Source Area of Possible Slope Failure

(7) Setting of Yellow Zone and Red Zone

The Yellow and Red Zones are set as shown in Figure 3.10 below.

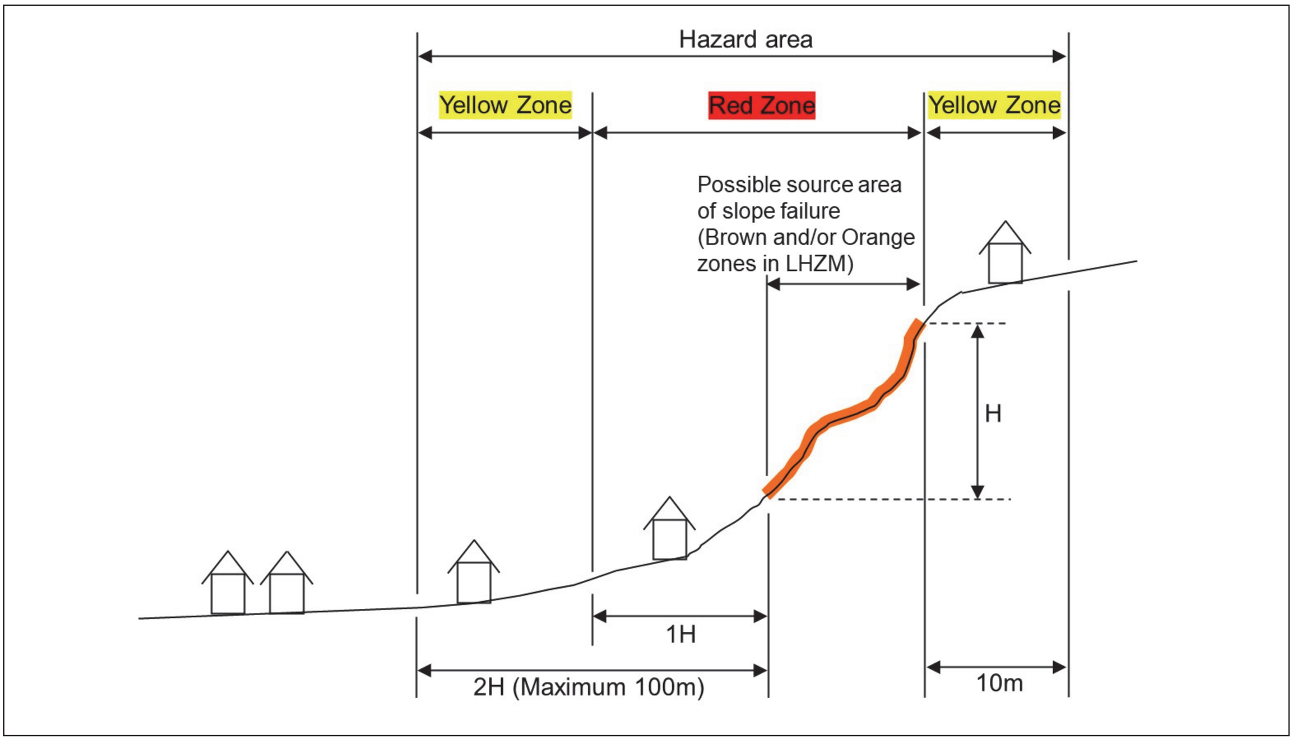


Figure 3.10 Representation of Yellow and Red Zones for Slope Failure

I) Red Zone

The Red Zone for slope failure shall be set to include (see Figure 3.11):

a) The source area (Brown and/or Orange zones)

b) The area located within the distance equivalent to the height of source area from the lower edge of each traverse line

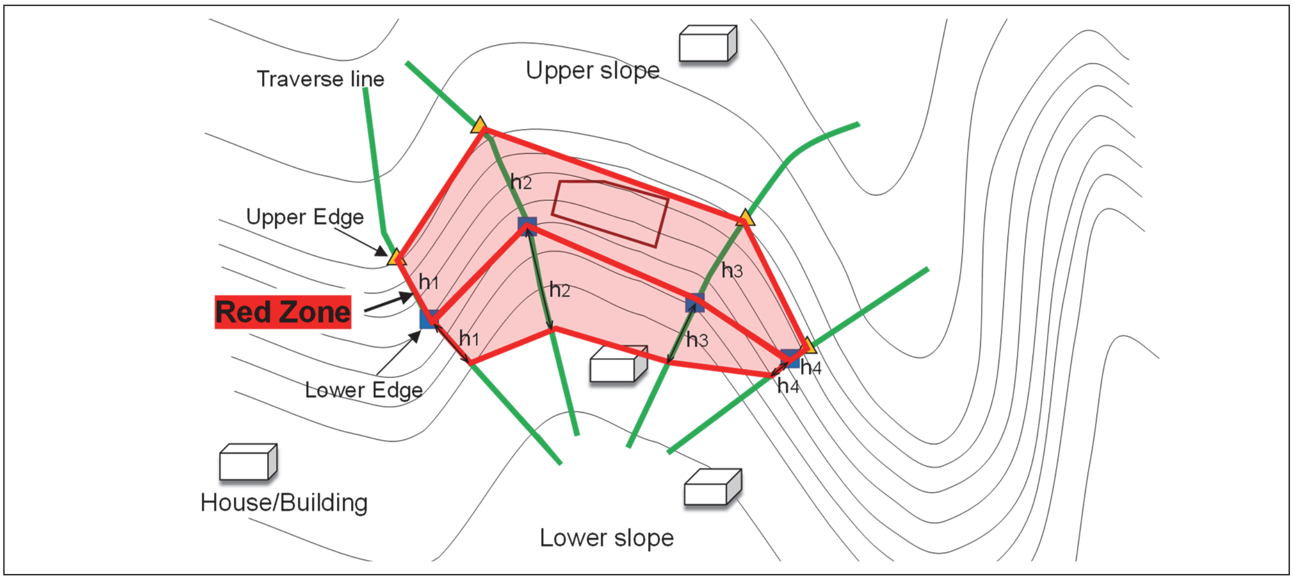


Figure 3.11 Representation of Red Zone for Slope Failure

II) Yellow Zone

The Yellow Zone for slope failure shall be set to include (see Figure 3.12):

a) The area located within a horizontal length of 10 m from the upper edge of each traverse line

b) The area located within the distance equivalent to twice the height of the source area (Maximum limit100 m) from the lower edge of each traverse line

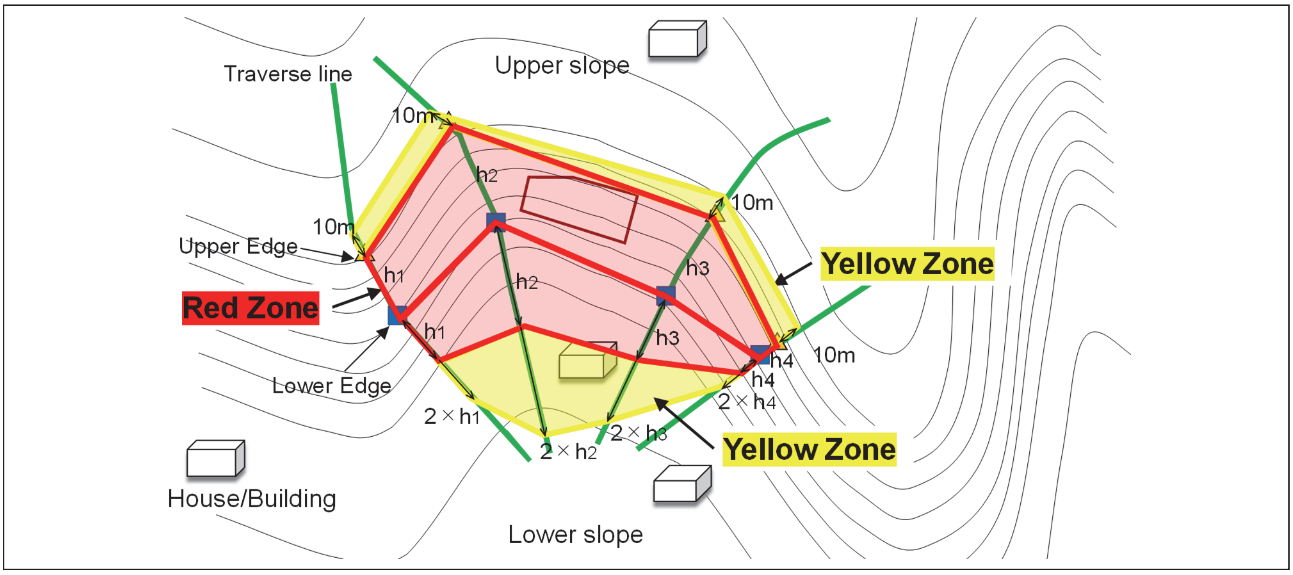


Figure 3.12 3D Representation of Yellow Zone for Slope Failure

(8) Excluding Areas where Slope Failure Sediment Cannot Reach

Areas which are clearly observed to be not within the reach or runout range of the collapsed sediment due to topographical features or structural obstacles should be excluded from the Yellow and/or Red zones (Figure 3.13).

Such topographical features and structural obstacles are as follows:

- Embankment
- Excavation
- Channel, river
- Wall, Retaining wall
- Other structures

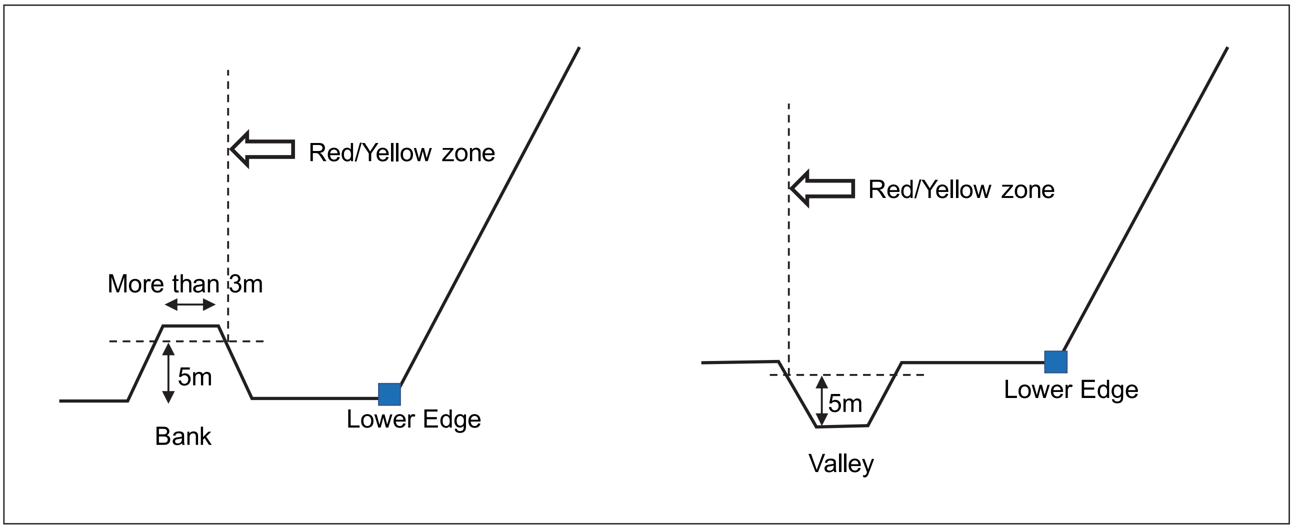


Figure 3.13 Diagrammatic Illustration of Excluded Part of the Yellow and Red Zones

3.2.4 Field Verification to Finalize the Zones

Field survey is conducted to finalize the Yellow and Red Zones set by the above-mentioned desk study. The field survey for the target area and its surroundings shall be conducted on the following items:

- Topographical conditions
- Location of Brown or Orange zones
- Lower and upper edges
- Slope angle and height
- Left and right edges
- Artificial structures, etc.

3.2.5 Verification of the Methodology for Yellow and Red Zones of Slope Failures

In developing this manual, several methodologies have been examined especially for setting of the source area of possible slope failure. In future, the criteria for setting the Yellow and Red Zones for slope failure should be reviewed and re-defined according to the results of further actual slope failure occurrences and damage situation surveys.

Alternative criteria for setting the Yellow and Red Zones for slope failure is shown below. In the alternative criteria, topographical features, especially slope inclination or angle related to slope failure is taken into consideration. As shown in the following figure, in case that the source areas of possible slope failures delineated from the Brown and/or Orange zones in the LHZM are located within two clear break points of a uniform slope, the source area of possible slope failure shall be extended into the upper convex break point and the lower concave break point. Geomorphologically, a slope between two break points is classified as an unformed landform or a unit slope that has the same susceptibility to sliding or slope instability. In addition, most of slope failures especially due to heavy rainfall have been reported to occur on a slope at or below the convex breaks. Convex breaks are geologically located at the forefront of the most significant erosion zone on a slope.

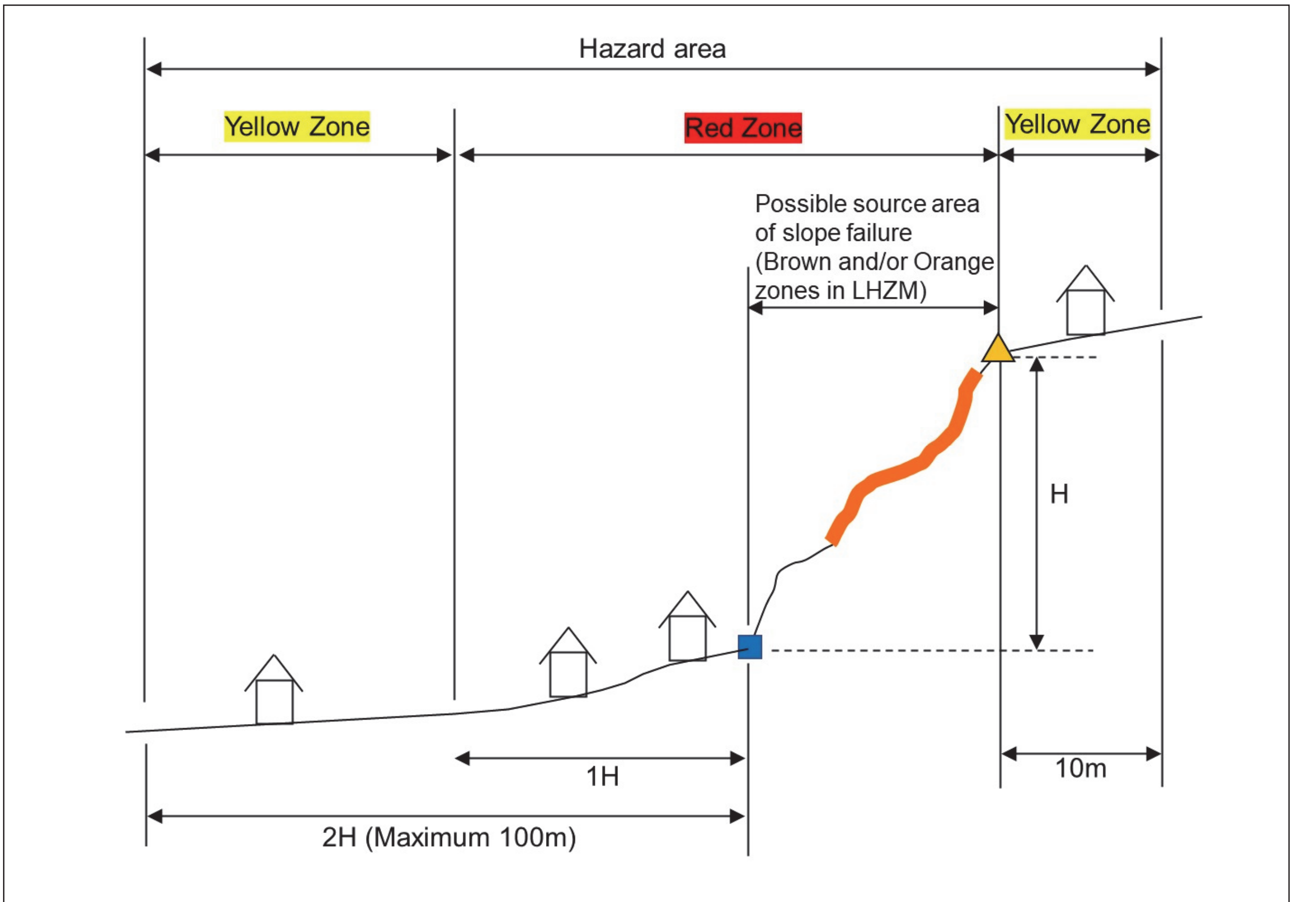


Figure 3.14 Representation of Yellow and Red Zones for Slope Failure considering Break Points (as a reference)

3.3 Reference Data

Background Data for Setting Hazard Zone for Slope Failures

About 60 past slope failure disasters were collected from:

a) Landslide Disaster May 2017 – Damages and Loss Assessment, Prepared by NBRO, including 35 disaster events occurring in 2017

b) Reduction of Landslide Vulnerability by Mitigation Measure Projects - Cost Benefit Analysis, Prepared by NBRO, in October 2018, including 50 disaster events.

The main results of the collected past slope failure disasters are shown in Figures 3.15 to 3.17 and summarized below:

a) Slope failures are related largely to slope steepness (Figure 3.15) and slope height (Figure 3.16). When slope angle is 25 degrees or more, the number of slope failures tends to increase rapidly. Most slope failures occurred intensively on slopes with a slope angle of 25 to 50 degrees and a slope height of 5 to 40 m, accounting for about 80% of the total number of the past slope failures.

b) The reaching distances of the collapsed sediment are related to the heights of slope failures (Figure 3.17). In most cases, the reaching distances are within twice the height of slope failures (Figure 3.17 - a)), but with a limit of about 100 m (Figure 3.17 - b)).

Geologically, the average friction angles are generally around 25 to 35 degrees for loose sandy soils, and 30 to 50 degrees for loose gravelly soils, respectively. A steep slope with a gradient of 25 degrees or more may be likely to occur especially as excessive pore water pressure increases during intense rainfall.

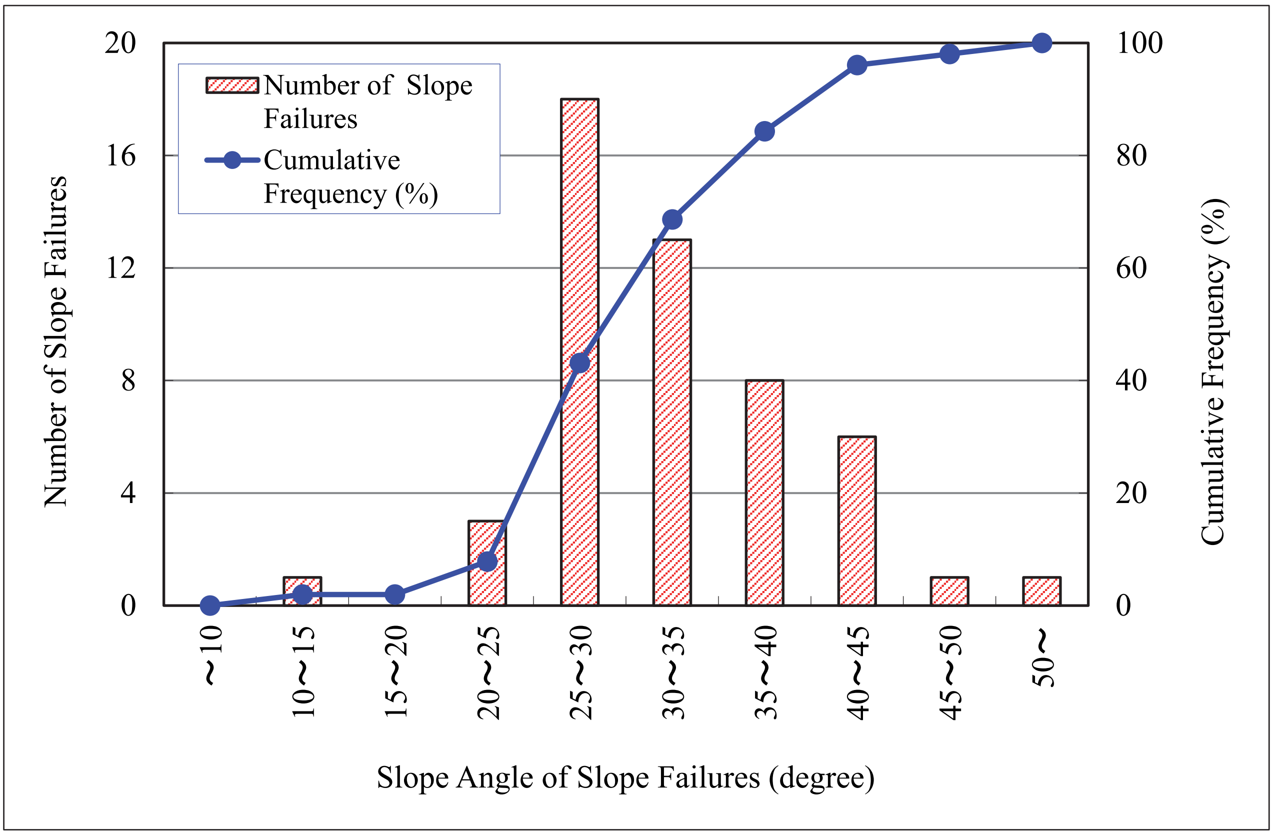


Figure 3.15 Frequency Distribution of Slope Angle in Slope Failures

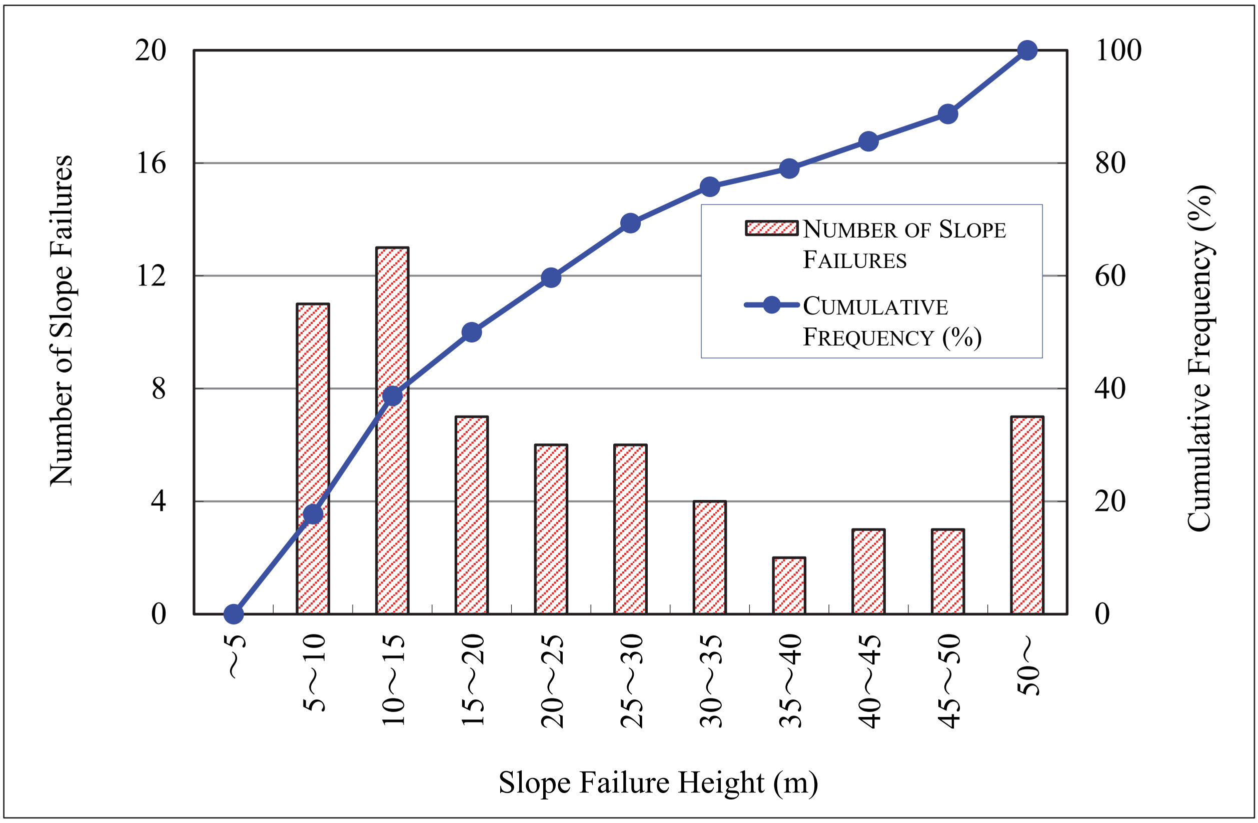
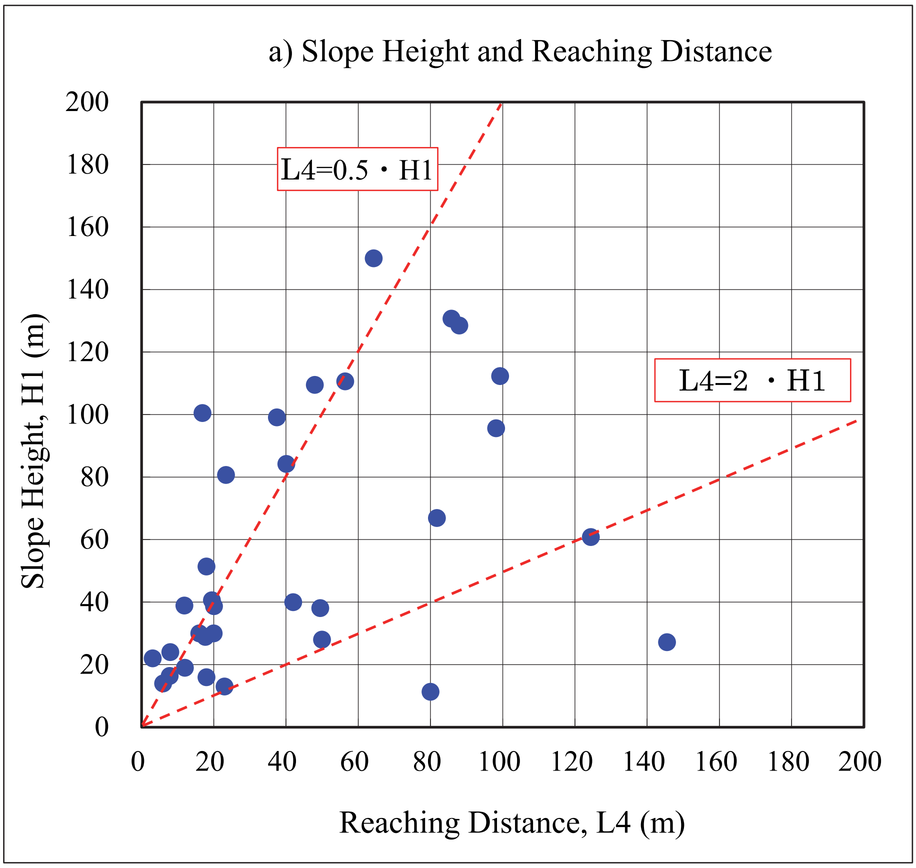


Figure 3.16 Frequency Distribution of Height of Slope Failures



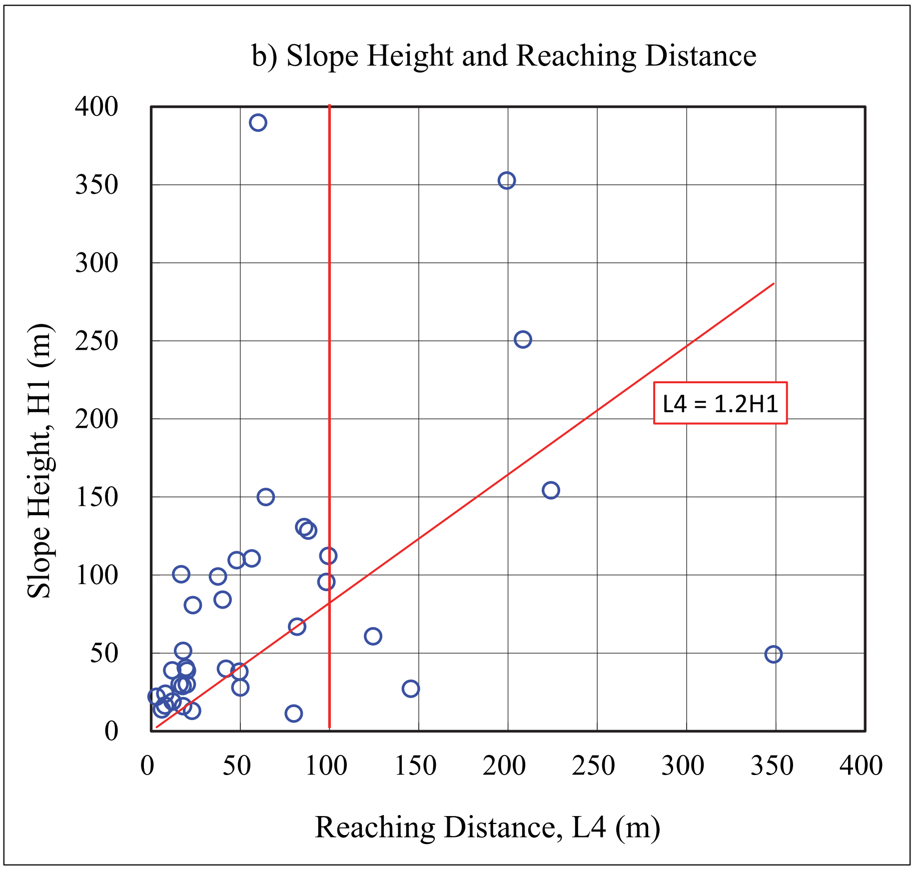


Figure 3.17 Relationship between Slope Height and Reaching Distance

Chapter 4

Hazard Zoning for Slide

This chapter presents the methodology and procedure of site-specific hazard zoning for slides

CHAPTER 4

HAZARD ZONING FOR SLIDE

4.1 Procedure of Setting "Yellow Zone" and "Red Zone" for Slide

Setting of "Yellow Zone" and "Red Zone" for slide is conducted according to the following steps (Figure 4.1).

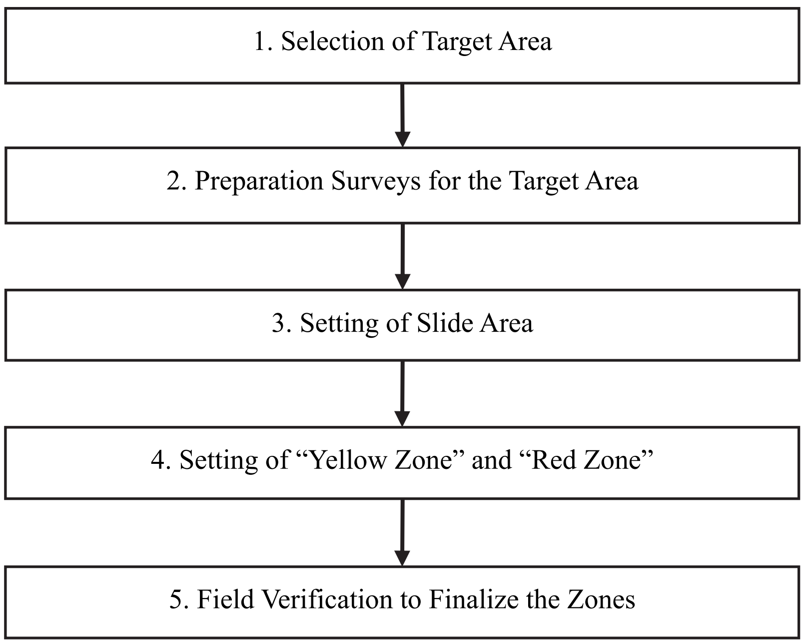


Figure 4.1 General Process of Setting "Yellow Zone" and "Red Zone" for Slide

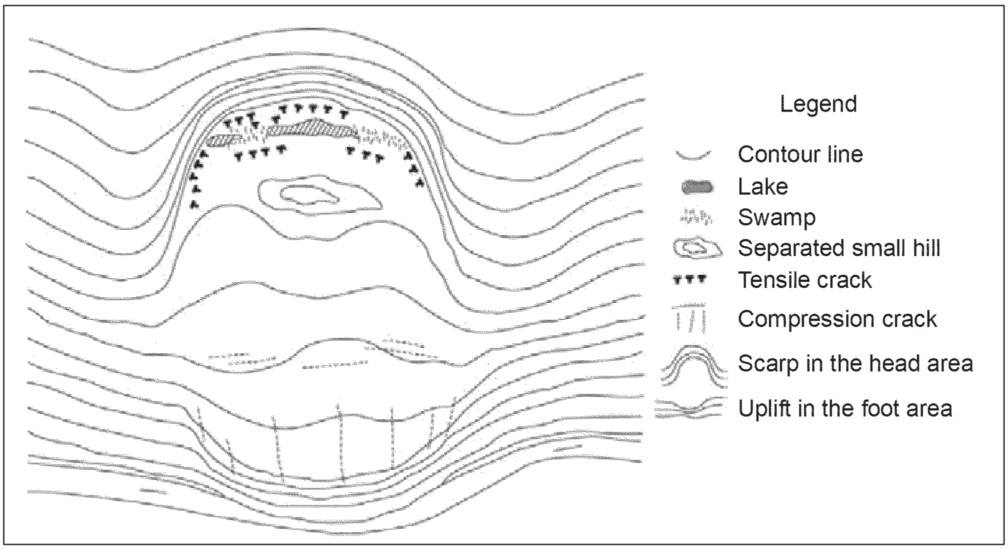
4.2 Methodology

4.2.1 Selection of Target Area

The target area for slide shall be selected using "Hazard Zonation Map" with a scale of 1:10,000 prepared by NBRO. In selecting the target area, the following topographical and social conditions are taken into consideration.

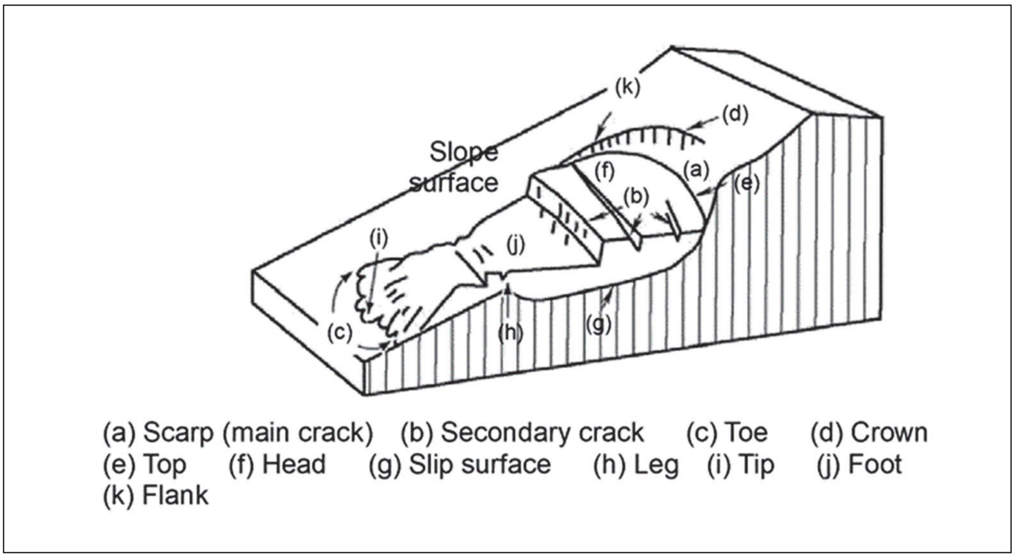
a) Topographical Conditions

The slide target area shall be limited to an area exhibiting distinctive topographies known as "slide topography," which are formed as a result of slide movement. Slide topographies, as shown in Figure 4.2.1 should be interpreted using Lidar, aerial photographs or topographical maps. Topographic interpretation of a slide is a very effective means for identifying slide distribution over a wide area, which is difficult to complete through field survey for a short period.



Source: PWRI Technical Note No.4077, Guidelines for Landslide Prevention Technologies (Draft), 2007, Public Works Research Institute, Japan

Figure 4.2. Schematic Representation of Typical Slide Topography



Source: PWRI Technical Note No.4077, Guidelines for Landslide Prevention Technologies (Draft), 2007, Public Works Research Institute, Japan

Figure 4.3 Terminology of a Typical Slide

Slide topographies are easily identified through the interpretation of Lidar, aerial photographs and topographical maps. However, the results of aerial photographs and topographical interpretations vary widely depending on a variety of factors, including the time of photographing, the scale of the photograph, vegetation cover, land use, and human activity. Therefore, following the interpretation of Lidar, aerial photographs or topographic maps and field survey shall be conducted to supplement the interpretation results.

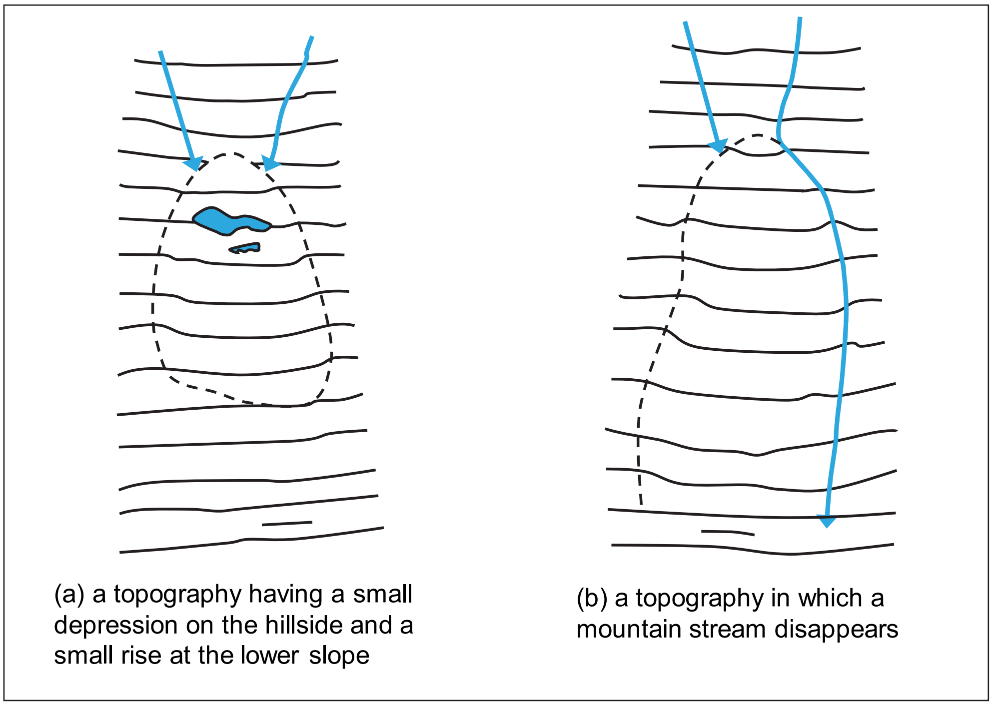
In interpreting slide topographies, the following geological and topographical features are also considered:

i) Geological Structure

- Areas adjacent to faults with fracture zones and areas along tectonic lines
- Areas on slopes consisting of strata that are parallel or nearly parallel to the slope (dip slopes)
- Areas near an axis of anticline or syncline of folds
- Areas around the boundary of igneous rock and intrusive rock

ii) Topography

- Areas categorized as water-collecting topographies, such as a topography having a small depression on a hillside and a small bulge at the foot of a slope, or a topography in which a mountain stream disappears (Figure 4.4)
- Areas where there is a scouring-prone slope consisting of rocks that is prone to slide, or areas on both sides of a scouring-prone slope consisting of hard rock
- Areas where a bend in a river has an unusual bulge that is being eroded
- Areas where a small- or large-scale terraced farm lands are present.



Source: Edited by JICA team based on Takeda and Imamura (1976)

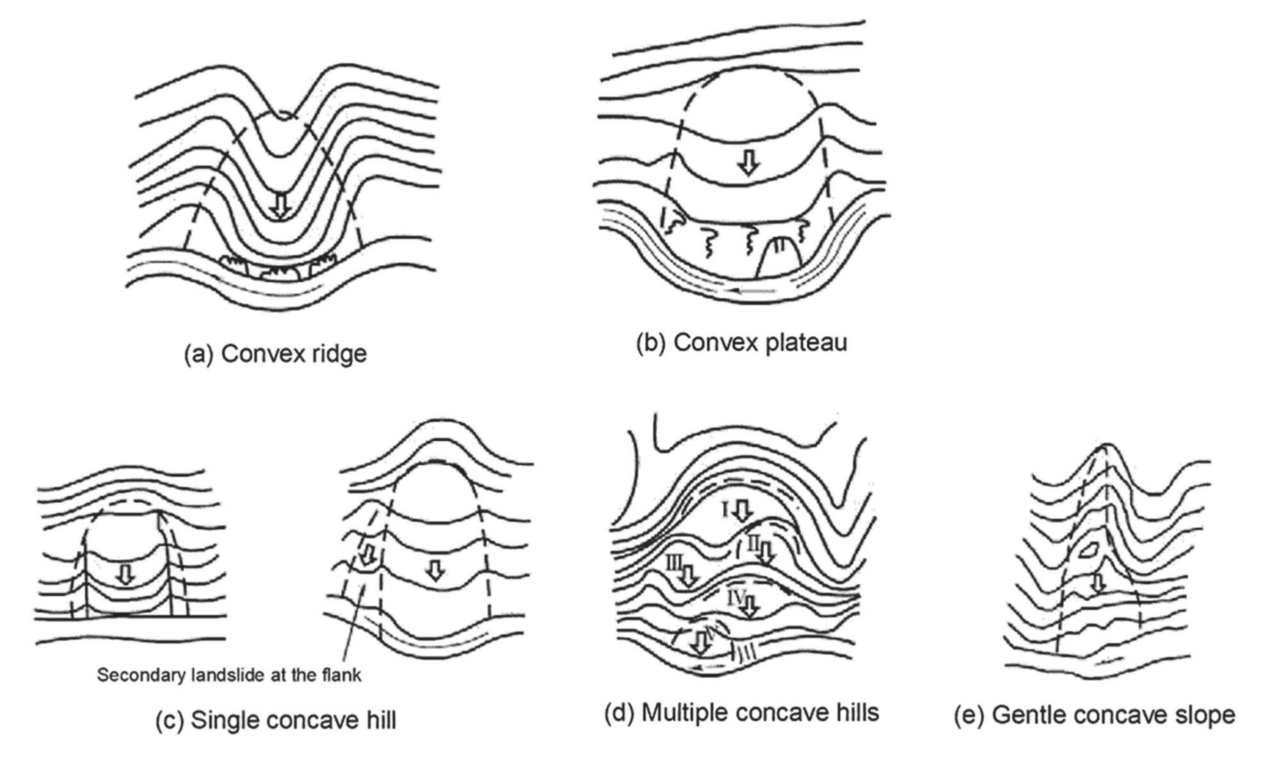
Figure 4.4 Slide Prone Areas Recognizable from the Condition of Water System

In addition, some characteristics of slide topographies should be considered, as listed below (Figure 4.5):

- Contour lines are disturbed. areas where the contour line interval is narrow in the upper part of a slope, spare in the middle, and narrow again at the bottom
- A circular or rectangular scarp is present at the head of a slope, a flat, gentle slope at the middle part of a slope, and again a steep slope at the foot of a slope. An isolated small hill may exist especially at the upper part
- There are depressions, subsidence, cracks, etc. A long, narrow depression may be present in a mountainous slope or at the top of a mountain
- There are regularly arranged ponds, marshes, and swamps

- There is a marshy zone or a crack on one or both sides of a slide area
- A depression is present in a ridge behind a slide
- Areas at the base of a steep slope have an upheaval or bulge
- A road or a railroad is unusually curved, or a structure is displaced
- A swamp or river is unusually curved; a river is narrower than in other sections

After a slide occurs, the slide topography may be gradually modified with time. For example, the scarp becomes gentle and the plateau scarred by erosion. The slide topography is also changed with its repeated movements, and a new slide may occur on the upper slope or the lower slope of the existing slide. As the movement of a slide becomes large with a great displacement, its slide topography generally turns into an extensively gentle slope, making it difficult to recognize the characteristics of the slide. Figure 4.5 shows some typical slide topographies.



Source: PWRI Technical Note No.4077, Guidelines for Landslide Prevention Technologies (Draft), 2007, Public Works Research Institute, Japan

Figure 4.5 Some Typical Slide Topographies

b) Social Conditions

The target area shall include:

- Residential area on which at least one residential house or public building is located; and
- Areas which have no residential houses or public buildings at the moment but which may be expected to be developed for housing or public building construction in the future based on social conditions such as current land use and development plans.

In addition, areas where there is no possibility of residential house construction, such as high and steep mountainous areas with no houses, etc. are excluded from the target area selection.

4.2.2 Preparation Survey for the Target Area

A preparation survey for the target area includes:

a) Data collection survey
b) Topographical survey
c) Field survey

a) Data Collection Survey

Slides often occur in areas with specific topography and geology. Also, the same type of slides tends to occur in areas having similar topographic and geologic conditions. Accordingly, information on the topography, geology, weather conditions, and past slide history shall be collected, providing valuable clues for identifying the characteristics of slide occurrence and activity in a given area.

Data collection survey includes the following items:

i) Past disaster records

- Date, time, location; and cause of slide
- Scale of a slide (length, width, depth, area, volume of displaced mass, reaching distance of displaced mass, etc.)
- Damage to human (the number of fatalities/injuries)
- Damage to residential houses, including structural types of damaged houses (reinforced concrete, brick, clay, wooden), degrees of damage (completely or partially), and the number of damaged houses
- Rainfall information (cumulative rainfall, daily rainfall, hourly rainfall)
- Others (photo, etc.)

ii) Evaluation of effectiveness of existing countermeasures

- Data on the existing countermeasures if available should be collected to determine if the target area is in a hazard zone through evaluation of effectiveness of the existing countermeasures, if available
- Assessment of the various elements of countermeasure facilities (width, length, height, etc.), such as drainage channel, horizontal drainage boreholes, retaining wall, embankment, etc.

iii) Investigation reports (geological investigation/monitoring)

iv) Number of households and public buildings

b) Topographic Survey

Topographic survey is conducted to identify the shape of slide block and its movement direction. Lidar, aerial photographs and topographic maps are used for topographic interpretation in a general way. In contrast to phenomena of slope failure and debris flow, there is a technical challenge to identifying a slide block by the above interpretations since the method is highly subjective and hence depends on the skill, experience and knowledge of the interpreters. To avoid personal variation and oversights, a topographic survey should be conducted by at least two people.

A slide block is delineated on base map, as follows:

i) Shape of a slide block (top, sides or flanks and toe of slide)

- If the shape of a slide block is definite, the block outline should be indicated by solid line on base map; or

- If the shape of a slide block is indefinite, the block outline should be described by dash line.

ii) Movement direction of a slide block

- The movement direction of a slide block should be indicated on base map by arrowed line in consideration of its shape and the direction of maximum slope inclination.

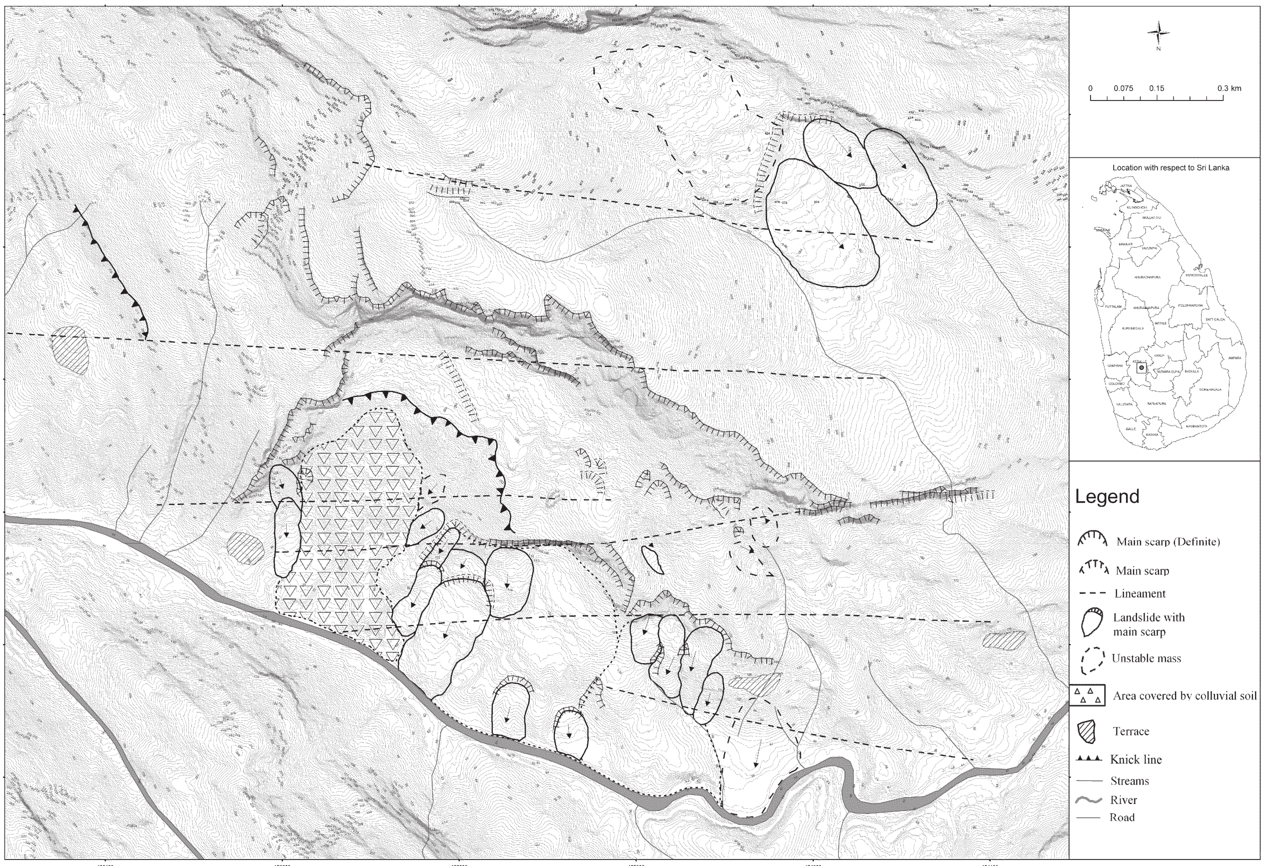


Figure 4.6 An Example of Slide Blocks Identified by Aerial Photograph Interpretation (Udapotha in Kegalle District)

c) Field Survey

A field survey is conducted to verify the shape of slide block (or area) and its movement direction, and to determine its activity and any signs of slide movement.

Main survey items are as follows:

i) Uniting of the Extracted Slide Blocks

Some slide blocks extracted from topographic survey should be united as one block when they affect one another.

ii) Verification of Shape and Clarity of Slide Topography

The shape and clarity of a slide topography should be checked at field, such as:

- Crown, main scarp, open crack, and depression at the upper slope
- Flank, gully erosion, convex and concaves

- Upheaval, bulge, abnormally crooked valleys and rivers
- Abnormality in a road, waterway, retaining wall, drainage channel, etc.

iii) Estimation of Movement Direction and Activity

The movement direction and activity of a slide block is estimated from the following field information:

- Location and direction of tension cracks, side cracks and cracks above the scarp
- Location and direction of upheaval, bulge and compressive cracks
- Deformation of artificial facilities

iv) Confirmation of the Lower Area Conditions of a Slide Block

Areas where slide mass cannot be reached should be confirmed mainly on the following items at the lower area from the slide block:

- Location, height and width of an inversed slope or mount
- Location, height and width of a river or stream
- Location, height and width of artificial structures such as channel, cut slope or filling slope

4.2.3 Setting of Slide Area

Setting of slide area is conducted according to the following steps (Figure 4.7).

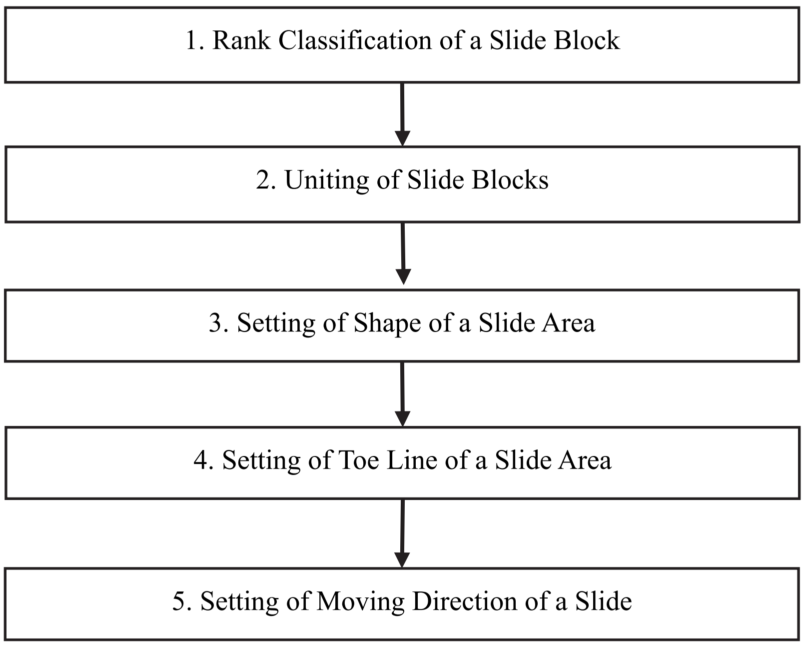


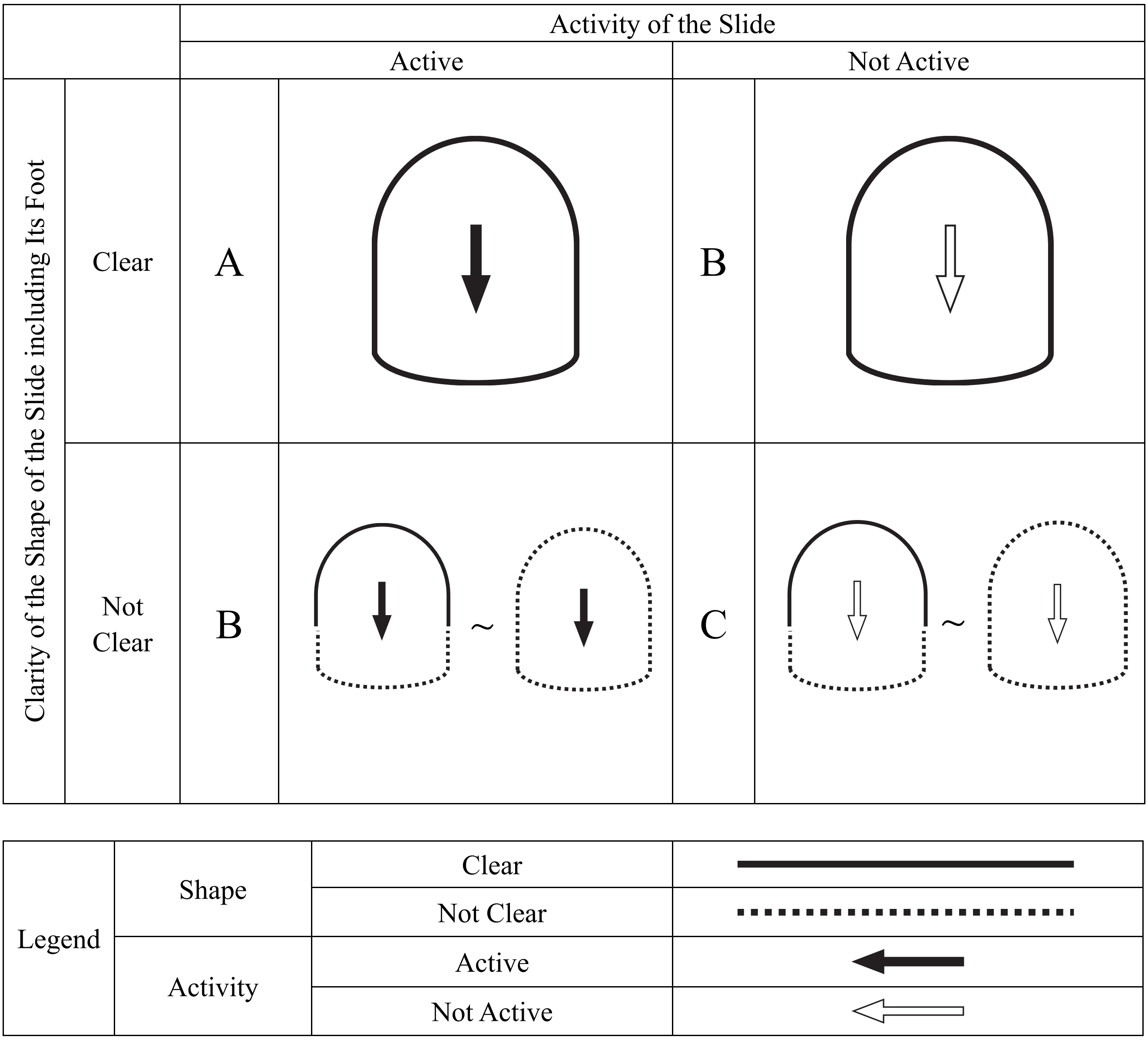
Figure 4.7 Process of Setting of Slide Area

(1) Rank Classification of a Slide Block

The extracted slide block is classified into three ranks, A, B and C, in terms of the clarity of slide topography and its activity based on the above-mentioned survey results. These ranks are defined and shown in Table 4.1

Table 4.1 Classification of Ranks of a Slide Block

Classification of Ranks	Definition
Rank A	- The slide is confirmed to be completely active at the field survey; and - Its shape including its foot is clearly identifiable.
Rank B	- The shape of the slide including its foot is clearly identifiable, but the slide is not confirmed to be active at the field survey; or - The slide is confirmed to be locally active, and its shape is not clearly identifiable.
Rank C	- The slide is not confirmed to be active at the field survey, and also its shape including its foot is not clearly identifiable.



Source: Edited by JICA team based on "Draft manual on Basic Investigation related to Sediment Disaster Prevention (2008)", Gunma Prefecture

From the above rank assessment:

✓ When a slide is assessed as Rank A, Yellow Zone and Red Zone are set for the slide; and

✓ When a slide is assessed as Rank B or C, only the Yellow Zone is set for the slide.

The present activity of a slide block shall be assessed according to the following criteria:

a) Clear signs of slide movement are observed at the field survey; or

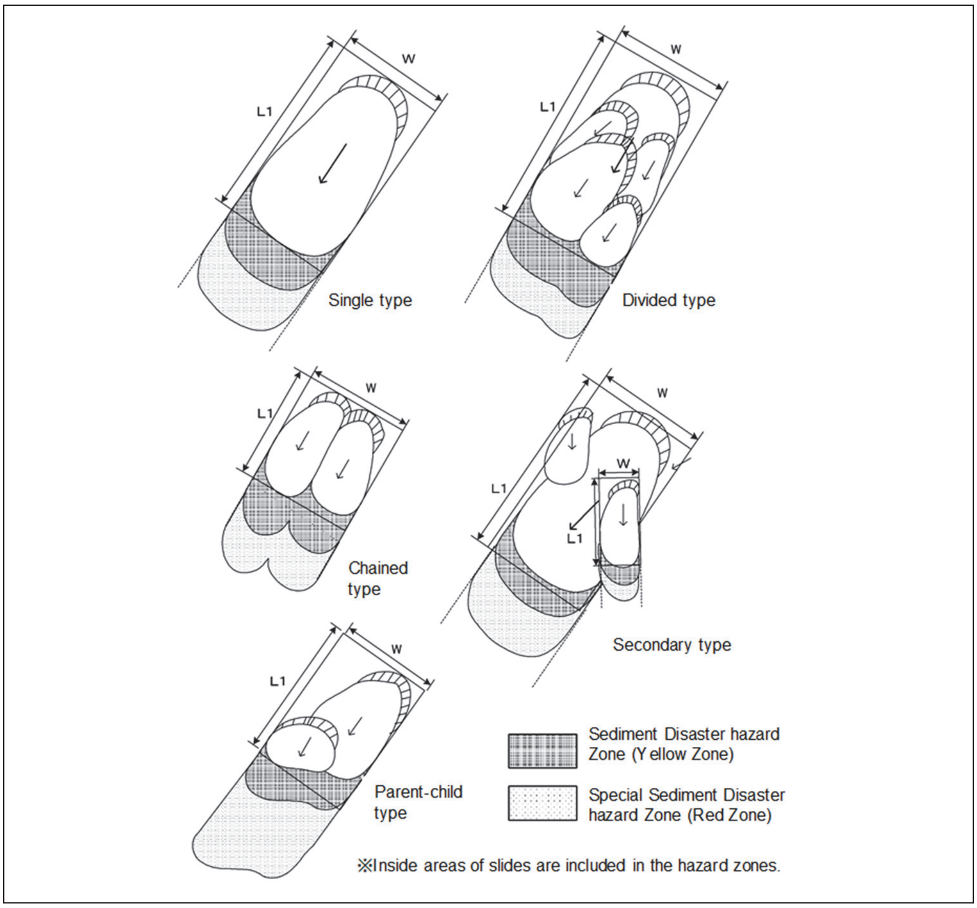
b) Monitoring data by instruments show a cumulative movement or displacement, as listed below:

- Cumulative displacement of 1mm/day or more over 5 consecutive days by extensometer; or
- Cumulative movement of 1,000μ strain/month or more by pipe strain gauge.

If countermeasures against a slide block have been installed, and then their effectiveness should be evaluated based on the field survey and monitoring results.

(2) Uniting of Slide Blocks

Slides may occur as single block or in a group. If slides occur in a group and affect one another, for example, as secondary slide block or multiple slide blocks, these slides should be united as one slide area based on their rank assessment, such as a combination of slide blocks with Rank B and C (Figure 4.8).

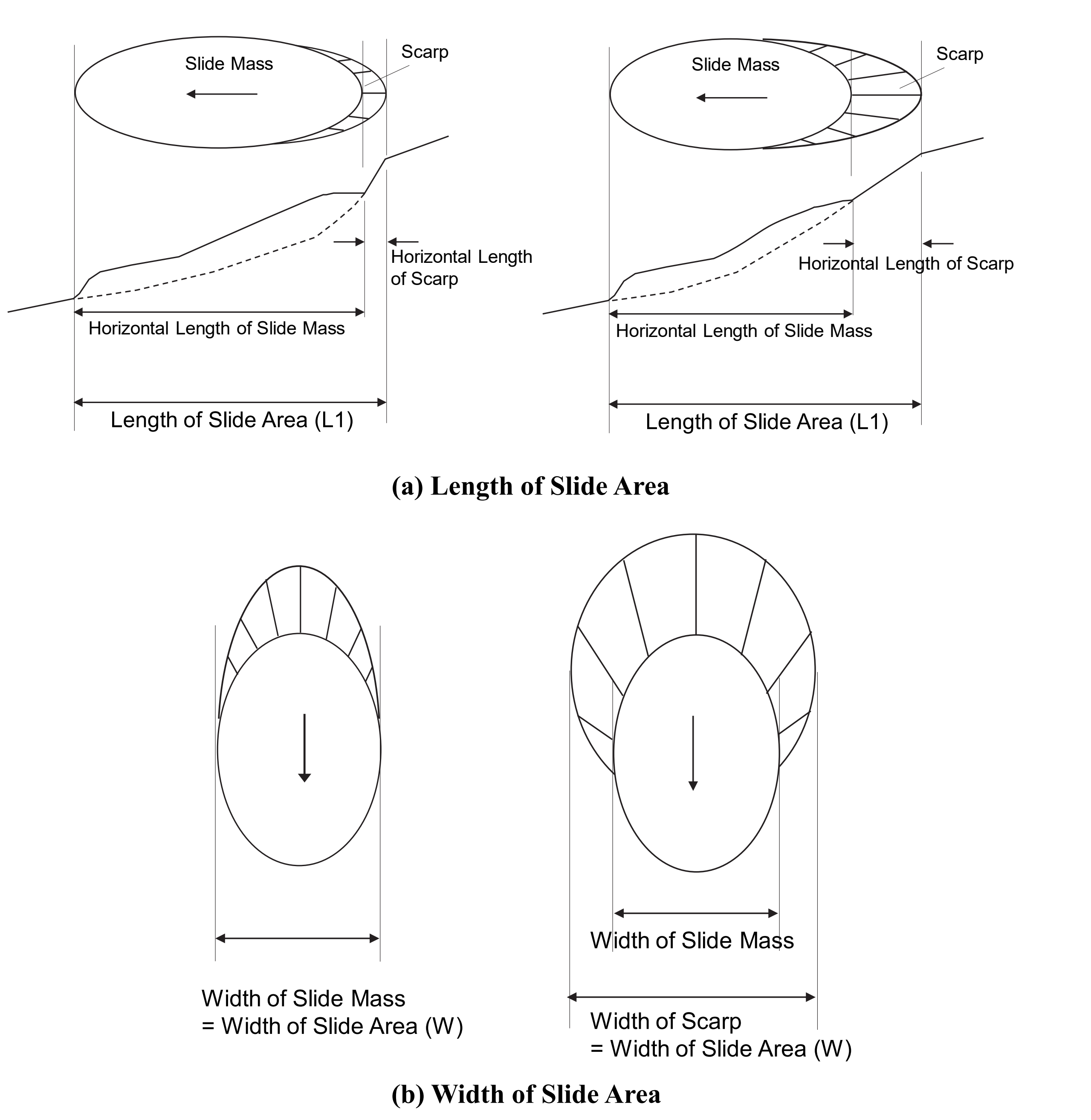


Source: Edited by JICA team based on "Draft manual on Basic Investigation related to Sediment Disaster Prevention (2008)", Gunma Prefecture

Figure 4.8 Examples of United Slide Blocks

(3) Setting of Shape of a Slide Area

The length and width of a slide area should be set based on the following procedures (Figure 4.9).



Source: Edited by JICA team based on "Draft manual on Basic Investigation related to Sediment Disaster Prevention (2008)", Gunma Prefecture

Figure 4.9 Diagrammatic Determination of Length and Width of a Slide Area

(4) Setting of the Toe Line of a Slide Area

In general, it is more difficult to identify the toe line of a slide than its top. In determining the hazard area of a slide area, firstly, it is necessary to identify its toe line. The toe line of a slide area shall be determined based on the following survey results (Figure 4.10):

a) Existing geological investigation and monitoring data

If geological investigation or monitoring data is available, the toe line of the slide area should be determined based on these investigations or monitoring results.

b) Clear ground deformations at the toe area

If clear ground deformations, such as upheaval, bulge or tension crack are observable at the site, the toe line of the slide area should be determined based on the distribution and locations of such ground deformations (Figure 4.10).

c) Topographical features

In the absence of ground deformations or geological investigation and monitoring results, the toe line of a slide area should be estimated based on the topographic features, such as an abnormally bent river or knick line (Figure 4.10).

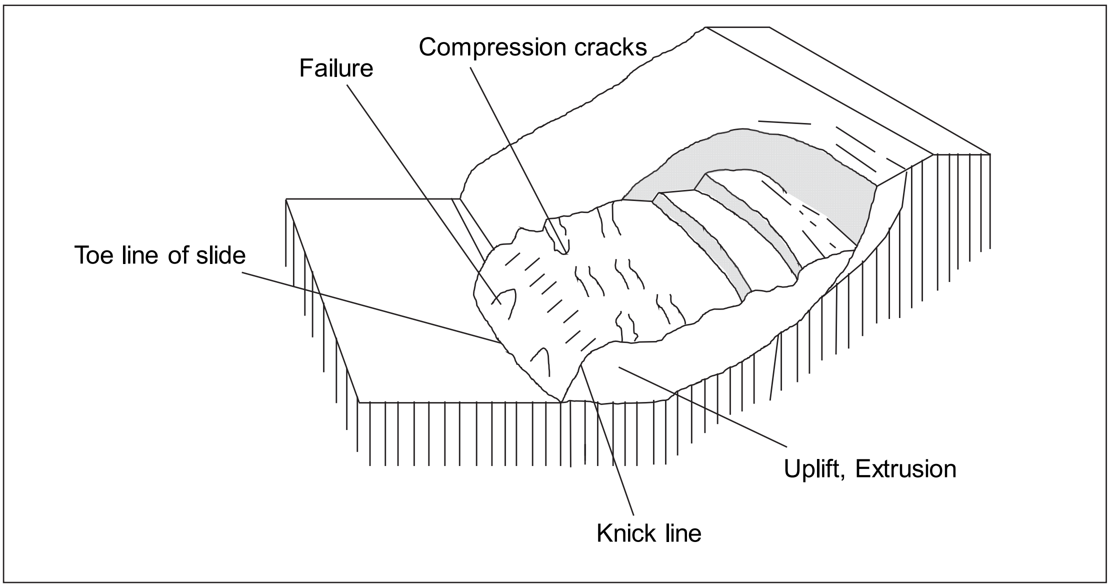


Figure 4.10 Typical Features of the Toe Line of a Slide Area

(5) Setting of Movement Direction of a Slide

The movement direction of a slide block should be determined based on the following investigation and/or monitoring results:

- Present monitoring data (for example, by inclinometer, etc.)
- Distribution and direction of tension and compression cracks, upheaval, bulge, etc
- Interpretations of Lidar, aerial photographs and topographic maps

4.2.4 Setting of "Yellow Zone" and "Red Zone"

(1) Setting of the Zones

Concept of setting a hazard area for slide is shown in Table 4.2., and Figures 4.11 and 4.12

Table 4.2 Hazard Zoning for Slide Area

Area		Zoning	
		Rank A Slide	Rank B or C Slide
Slide block plus the area of main scarp and cracked or uneven slope behind the main scarp		Red Zone	Yellow Zone
Lower slope below slide block	Area which has half (1/2) of the length of the slide area	Red Zone (Maximum 100 m)	-
	Area which has same length and width of the slide area	Yellow Zone (Maximum 250 m)	Yellow Zone (Maximum 250 m)

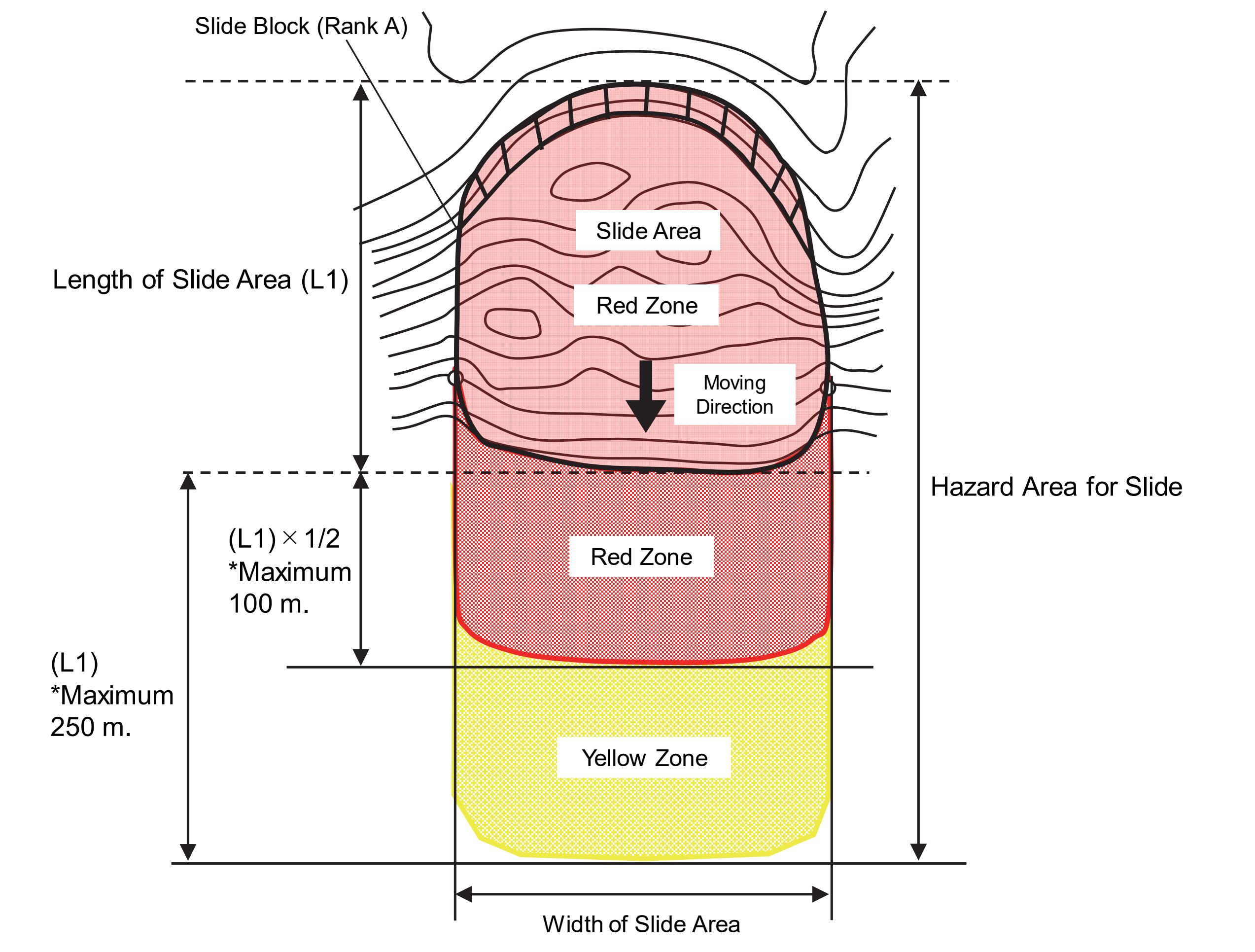


Figure 4.11 Concept of Hazard Area for Rank a Slide

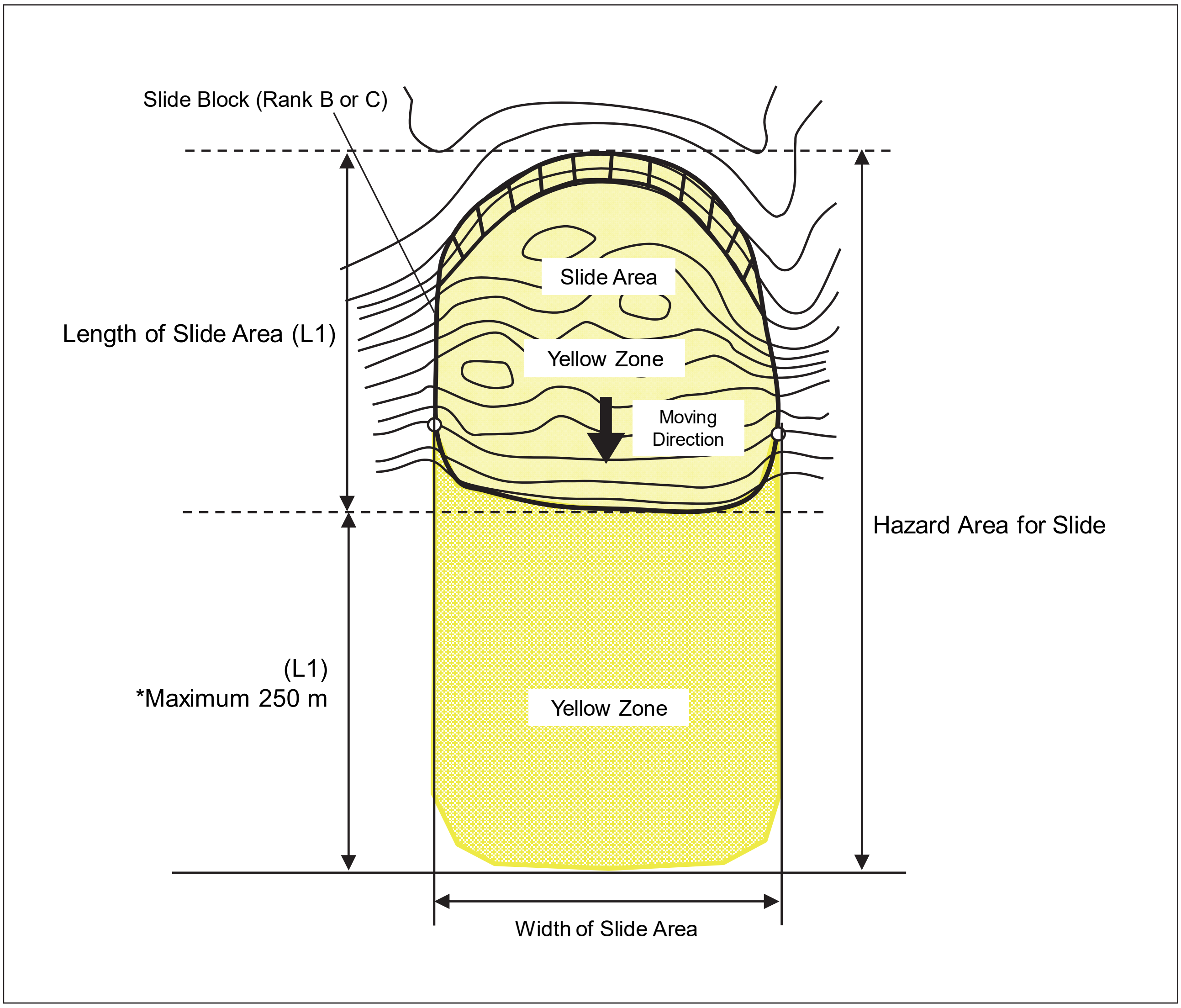


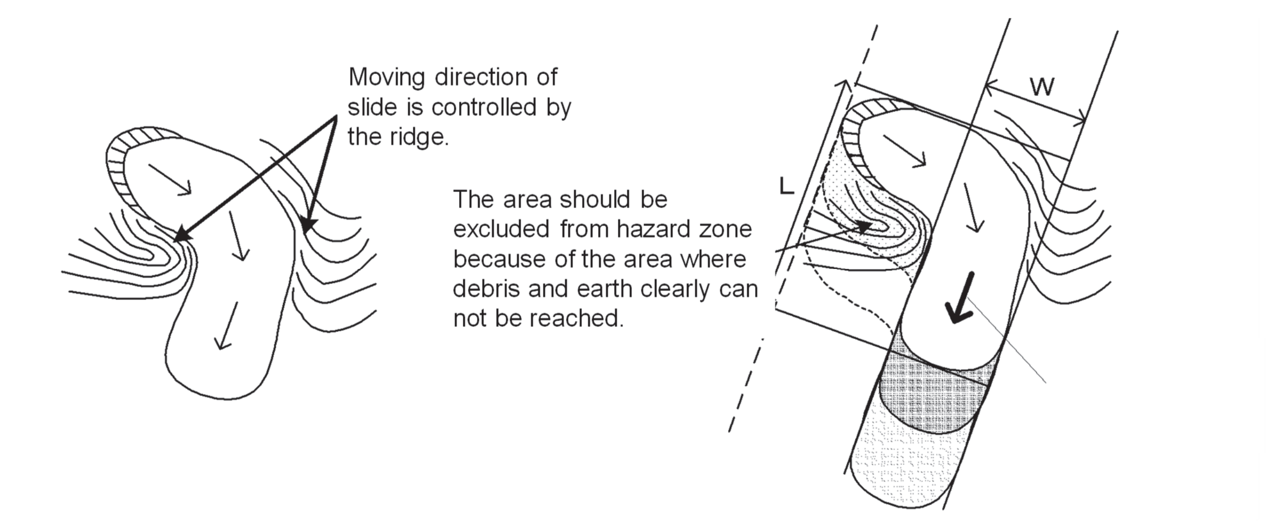
Figure 4.12 Concept of Hazard Area for Rank B or C Slide

In addition, the maximum lengths are set to be 100 m for the Red Zone (Figure 4.11) and 250 m for the Yellow Zone (Figure 4.12), respectively, which are based on past slide disaster survey in Japan and should be revised by following further past slide disaster survey in Sri Lanka.

(2) Excluded Areas where Slide Mass Cannot Reach

If the following landforms or obstacles are present within the Yellow or Red Zone, the zone should be modified properly to exclude areas where the slide mass cannot be reached, for example:

- Ridge or valley which controls the moving direction of slide mass (Figure 4.13); and
- River or valley which is at the toe part of a slide area (Figure 4.14).



Source: Edited by JICA team based on "Draft manual on Basic Investigation related to Sediment Disaster Prevention (2008)", Gunma Prefecture

Figure 4.13 Ridge or Valley Controlling the Moving Direction of a Slide

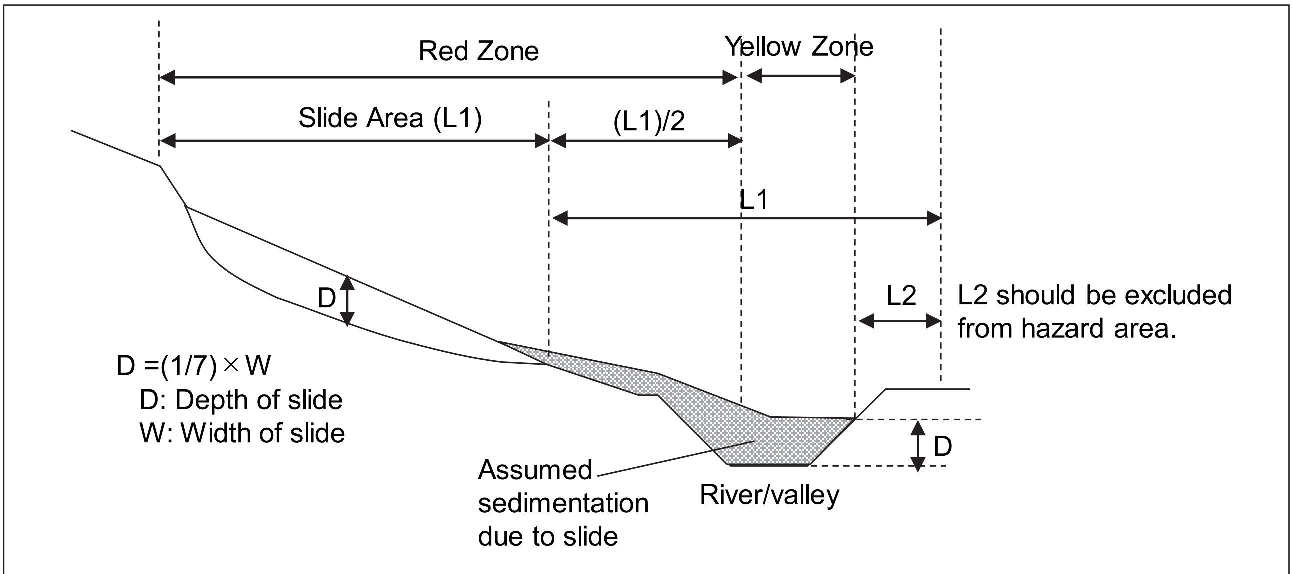


Figure 4.14 Yellow and Red Zones in the Case that River or Valley Existing at the Toe Part of a Slide

(3) Combination with Zoning of Debris Flow

A slide of Rank A may turn into a debris flow under the following conditions:

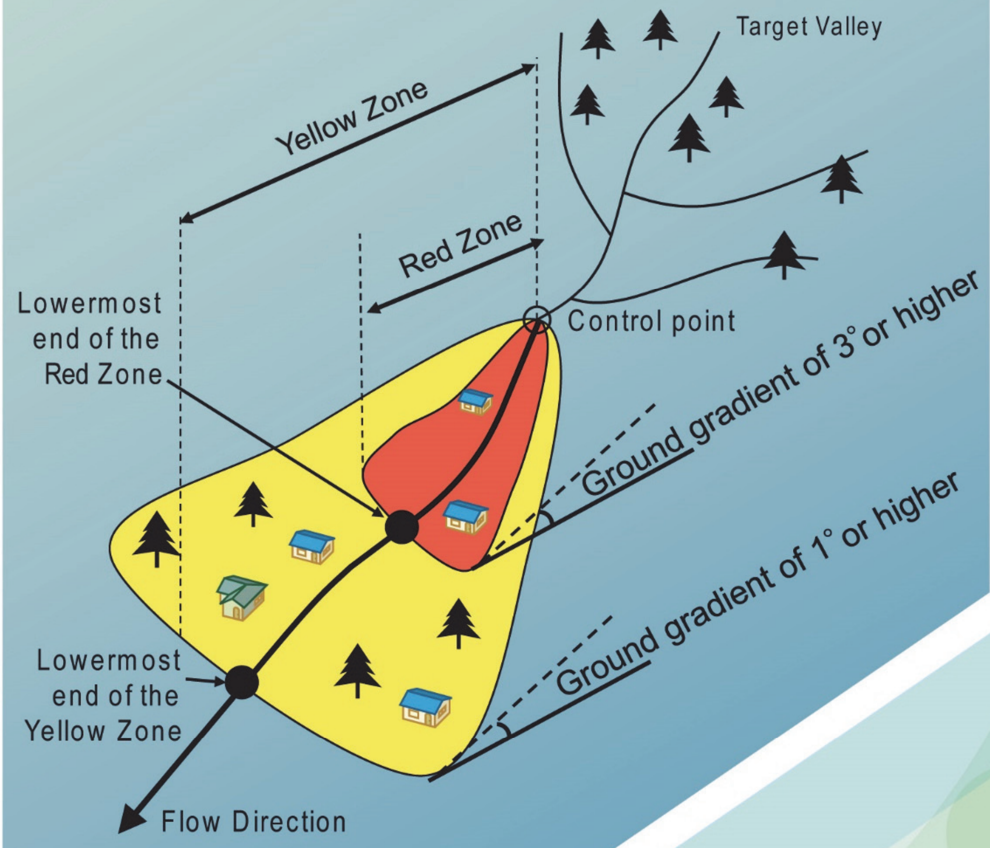
- On average, the slope gradient or streambed gradient beneath the toe of the slide is steeper than 10 degrees (Figure 5.3 of REFERENCE DATA, CHAPTER 5 HAZARD ZONING OF DEBRIS FLOW); or
- An existing debris fan is observable below Rank A slide.

In the above-mentioned cases, the hazard zoning for slide should be combined with that of a debris flow.

4.2.5 Field Verification to Finalize the Zones

The field survey is conducted to finalize the Yellow and Red Zones which were set by desk study. The following items should be checked in the field survey:

- Slide area;
- Activity of the slide;
- Movement direction;
- Areas which are unlikely to be reached by the sliding mass; and
- Artificial structures, etc.



Chapter 5

Hazard Zoning for Debris Flow

This chapter presents the methodology and procedure of site-specific hazard zoning for debris flows

CHAPTER 5

HAZARD ZONING FOR DEBRIS FLOW

5.1 Procedure of Setting of "Yellow Zone" and "Red Zone" for Debris Flow

Setting of "Yellow Zone" and "Red Zone" for debris flow is conducted according to the following steps (Figure 5.1).

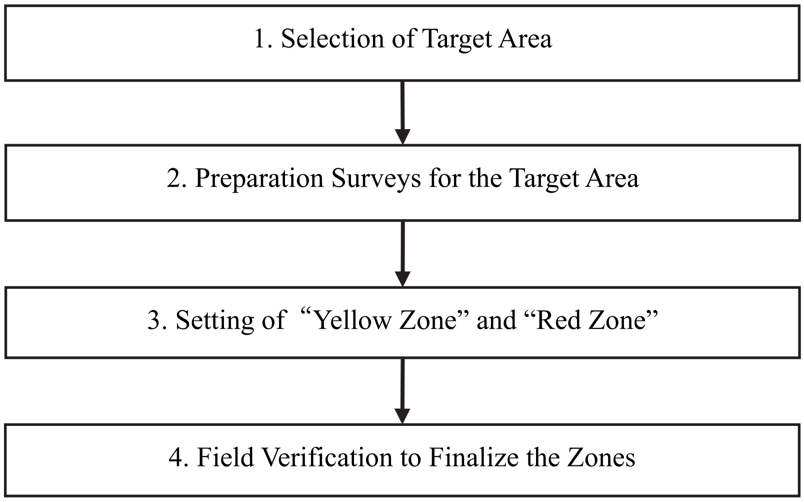


Figure 5.1 General Process of Setting "Yellow Zone" and "Red Zone" for Debris Flow

5.2 Methodology

5.2.1 Selection of Target Area

The target area for debris flow is selected by using the "Hazard Zonation Map" with a scale of 1:10,000 prepared by NBRO. In selecting the target area, the following topographical and social conditions are taken into consideration.

a) Topographical Conditions

A mountain stream at risk of debris flow is defined basically as valley topography on a 1:10,000 scale topographic map (Figure 5.2). In Figure 5.2, "a" is the valley width on a same contour line and "b" is the longest distance from front to back on the same contour line.

Valley topography is determined as follows (Figure 5.2):

i) Point with a ≦ b is to be a valley topography; or

ii) Even if a point is with a > b, the point is to be considered as valley topography if one of the followings applies:

- A mountain stream which has a history of debris flow (including alluvial fan topographies); or
- A mountain stream which may be considered prone to debris flow in view of its topographical and geological features such as collapsed sediments, slope failure/landslide scars, bare lands, etc.

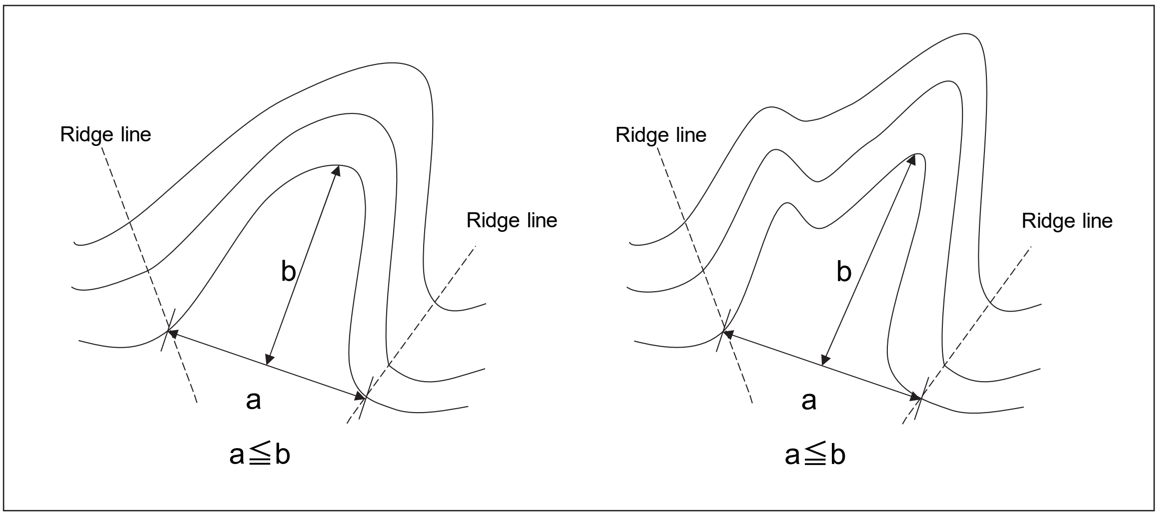


Figure 5.2 Determination of Valley Topography

In addition, a mountain stream is also expected to be a target area of debris flow if the following topographical conditions are confirmed:

- A mountain stream has a clear alluvial fan topography at its downstream – possible evidence of past debris flows; or
- A mountain stream is covered with unstable sediment at its upper stream - as source of debris flows.

b) Social Conditions

- The target area should comprise a residential area in which at least one residential house or public building is located along and below the mountain stream at risk of debris flow.
- Areas that have no residential houses or public buildings at present, but may be expected to be developed for housing and/or public building construction later based on the social conditions such as the current land use and development plans should be considered for the target area selection.
- Areas where there is no possibility of residential house construction, such as high mountainous areas with no houses, etc. are excluded from the target area selection.

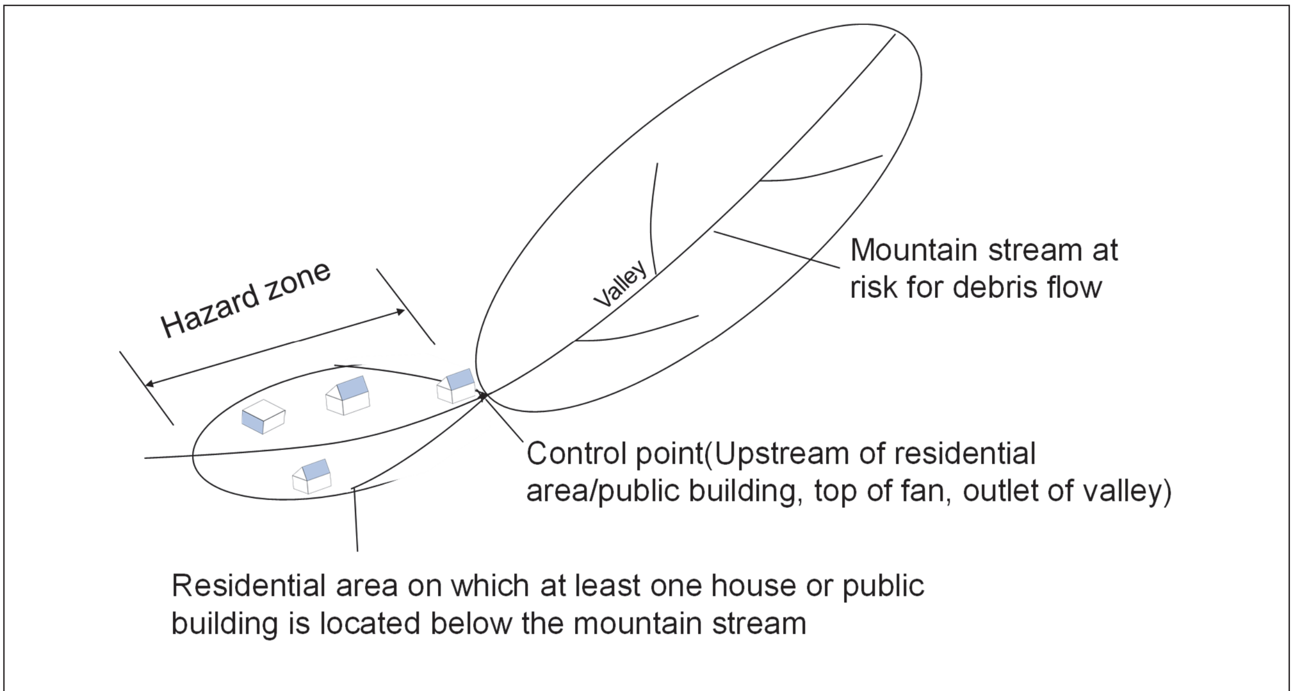


Figure 5.3 Conceptual Representation of Target Area for Survey

5.2.2 Preparation Surveys for the Target Area

a) Survey of Past Disaster History for the Target Area

Survey of past disaster records for the target area is conducted to assess the past debris flow extent and its damage conditions and then to obtain data for setting the area of hazard zones, mainly on the following items:

- Date, time, and location, and cause of a debris flow disaster;
- the size of the debris flow (the amount of sediment discharged and the area inundated);Damage to human (the number of fatalities/injuries);
- The number of damaged houses; the structural type of damaged houses (reinforced concrete, brick, clay, and wooden); the degree of damage (completely or partially);
- Rainfall information (cumulative rainfall, daily rainfall, hourly rainfall, etc.); and
- Others (thickness of sedimentation due to flooding or debris flow, etc.).

b) The number of dwellings and public structures

5.2.3 Setting of "Yellow Zone" and "Red Zone"

Setting of "Yellow Zone" and "Red Zone" for debris flow is conducted according to the following steps (Figure 5.4).

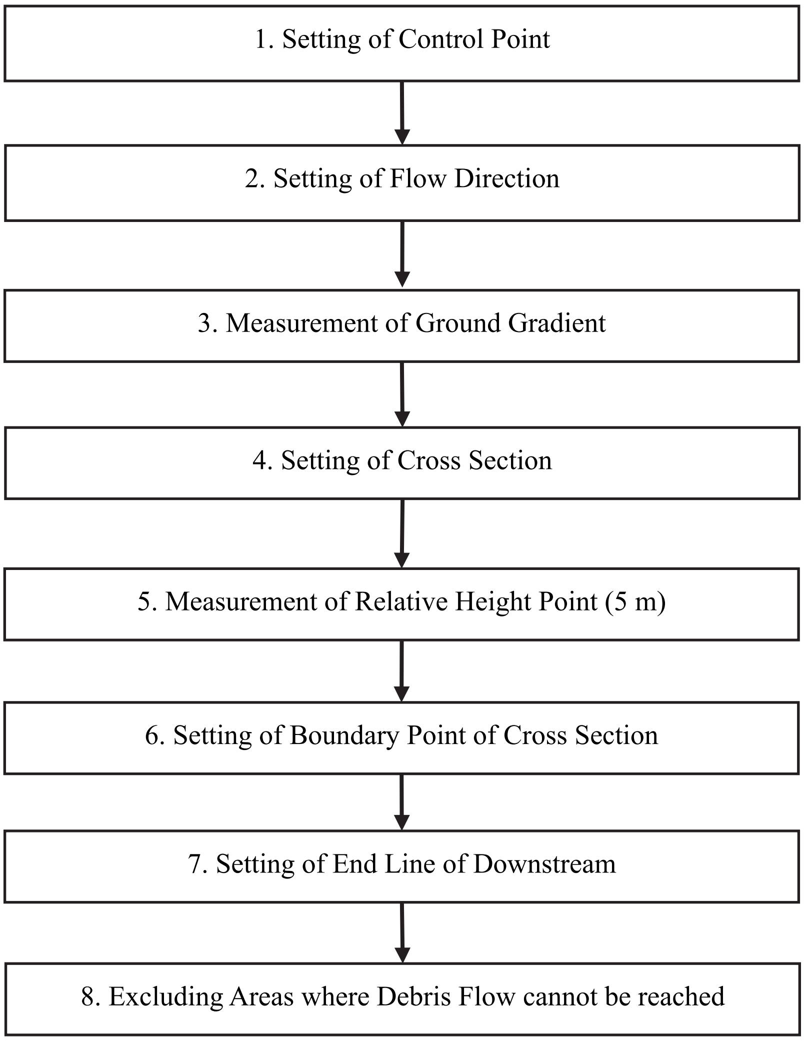


Figure 5.4 Flow chart of Desk Mapping of "Yellow Zone" and "Red Zone" for Debris Flow

(1) Setting of Control Point

A Control point is the uppermost stream point of the set Red Zone in the target area. Basically, the control point is determined from topographic feature and field survey results, focusing on the following items (Figure 5.5):

a) Outlet of a valley: A point at which the valley becomes open and wide
b) Top of fan: A point at which the valley becomes wide and the streambed gradient becomes gentle
c) Point of gradient change: A point where the streambed gradient abruptly changes from steep to gentle (concave point)
d) River bend: A point at which the river course is bent sharply (flooding may be occur on the exterior side because a debris flow flows straight)

e) Outlet of a narrow valley section: A point At which the valley width abruptly changes from narrow to wide, morphologically similar to the outlet of a valley
f) Debris flow flooding point: A point where a debris flow began to flood in the past debris flow disasters

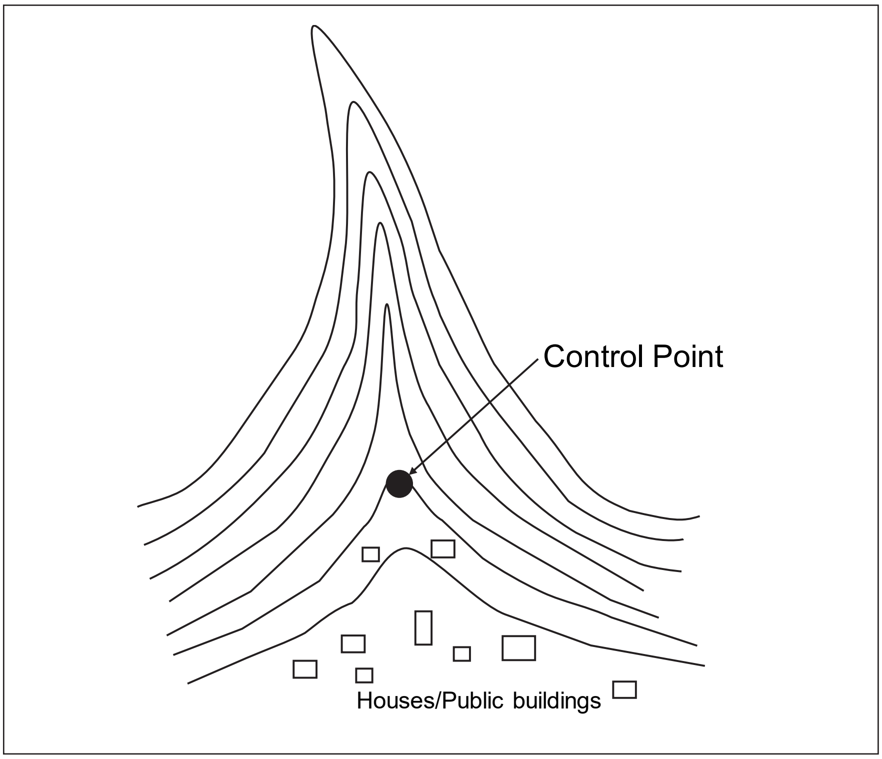


Figure 5.5 Determination of Control Point

However, in Sri Lanka, some residential houses or public buildings are often located along the mountain stream above the top of alluvial fans; therefore the control point should be shifted to the upper stream of the residential houses or area to be protected (Figure 5.6).

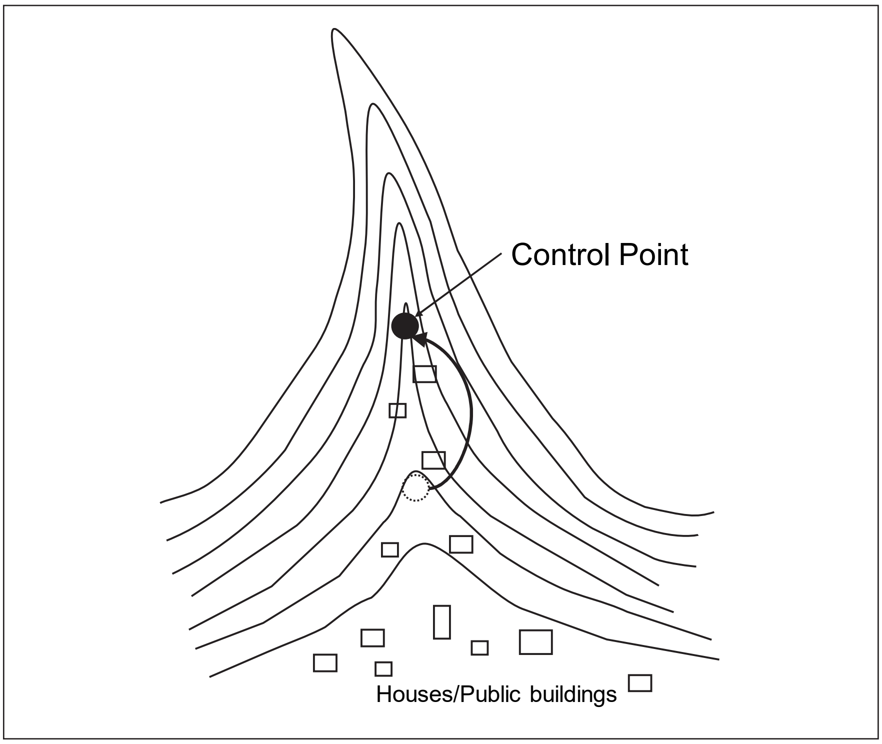


Figure 5.6 Shifting of Control Point

(2) Setting of Flow Direction

The direction of a debris flow shall be determined from topographical features and confirmed by field survey result (Figure 5.7).

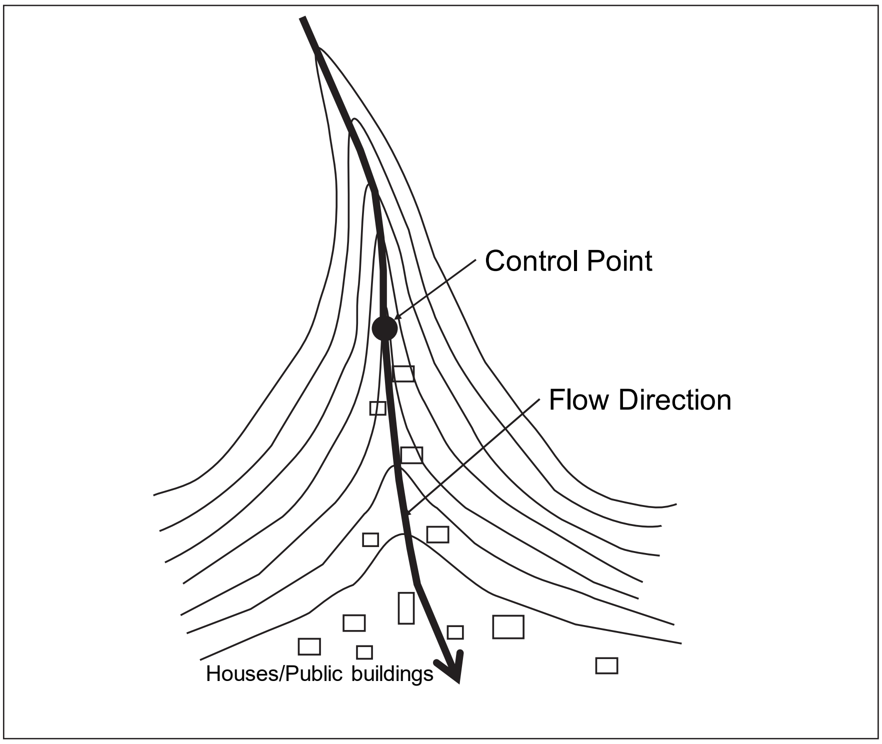


Figure 5.7 Determination of Flow Direction

If there is a bend in the course of the mountain stream, the straight-flowing nature of the debris flow is used to determine the flow direction (Figure 5.8).

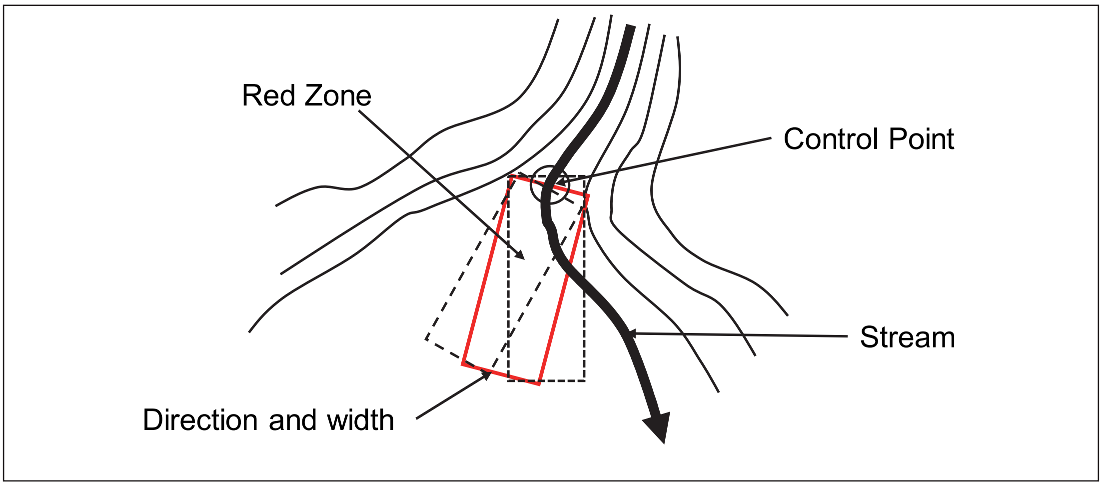


Figure 5.8 Diagrammatic Representation of Setting Flow Direction at River Bend

If the original shape of a valley is obscured due to residential land developments or if there are ditches, the flow direction of a debris flow is set in view of its straight-flowing nature (Figure 5.9).

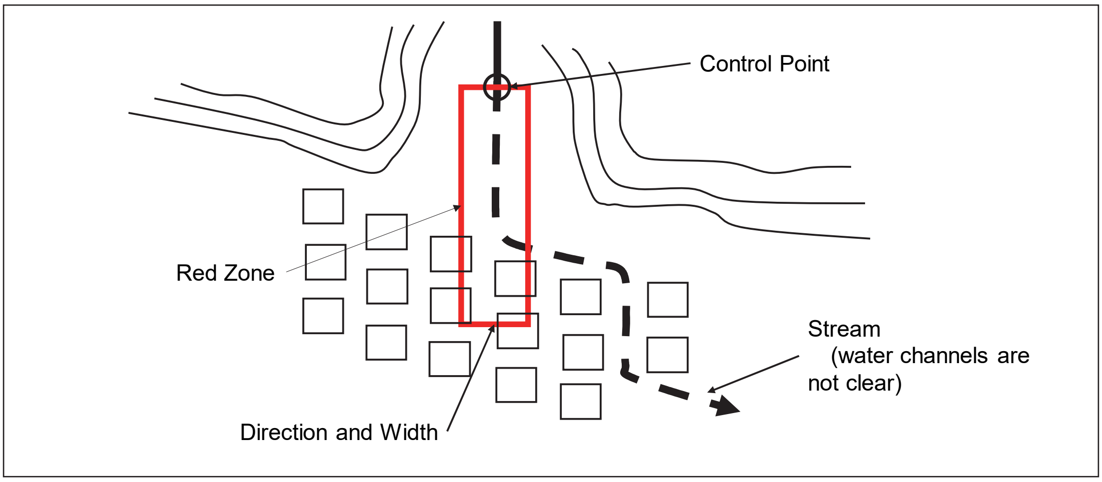


Figure 5.9 Conceptual Diagram of Setting Flow Direction when Valley Topography or Water Channels is not clear

(3) Measurement of Ground Gradient

The lower ends of the Yellow Zone and Red Zone shall be determined based on the ground gradient or inclination from the profile of the target area. The ground gradient of the lowermost end is set as below (Figure 5.10):

a) 1 degree for Yellow Zone
b) 3 degrees for Red Zone

In addition, the ground gradient should be based on the average value of the section that has the same ground inclination along the valley profile.

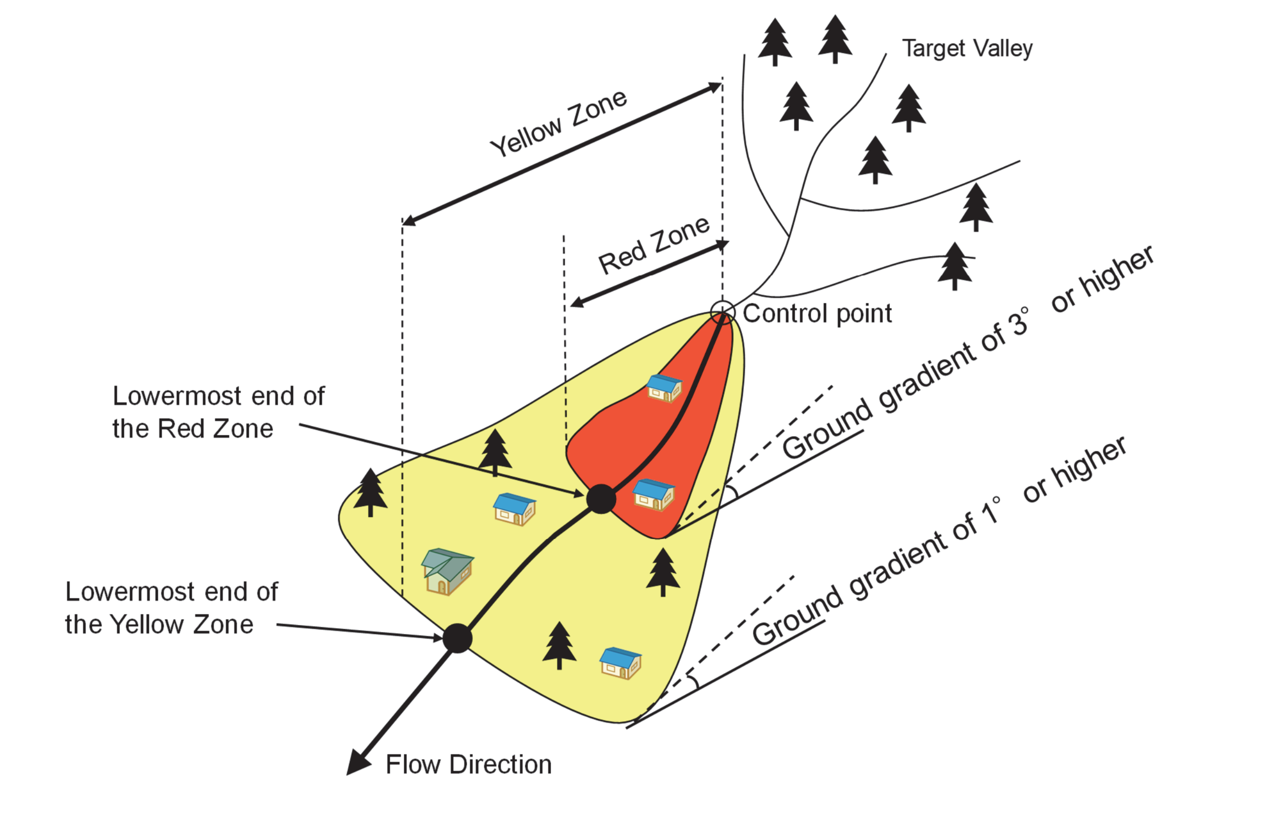


Figure 5.10 Determination of the Lowermost End of the Zones

(4) Setting of Cross Section

The cross sections shall be roughly set perpendicular to the flow direction every 20 m (Figure 5.11). The length of cross section should be drawn from the present streambed to about 10 m of the relative height.

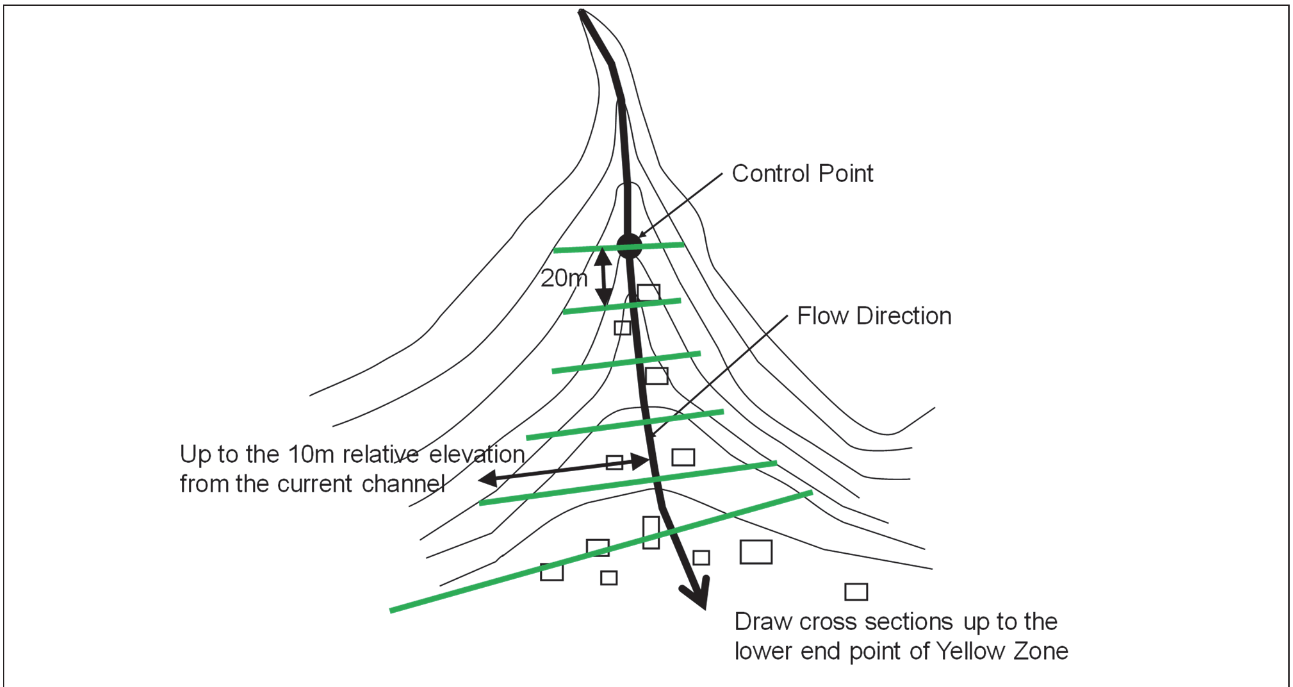


Figure 5.11 Setting of Cross Section

(5) Measurement of Relative Height Point (5 m)

As the depth of debris flow is generally within 5 m, a point of relative height of 5 m shall be demarcated from the elevation of the current streambed or the center of flow direction toward both sides of the stream (Figure 5.12).

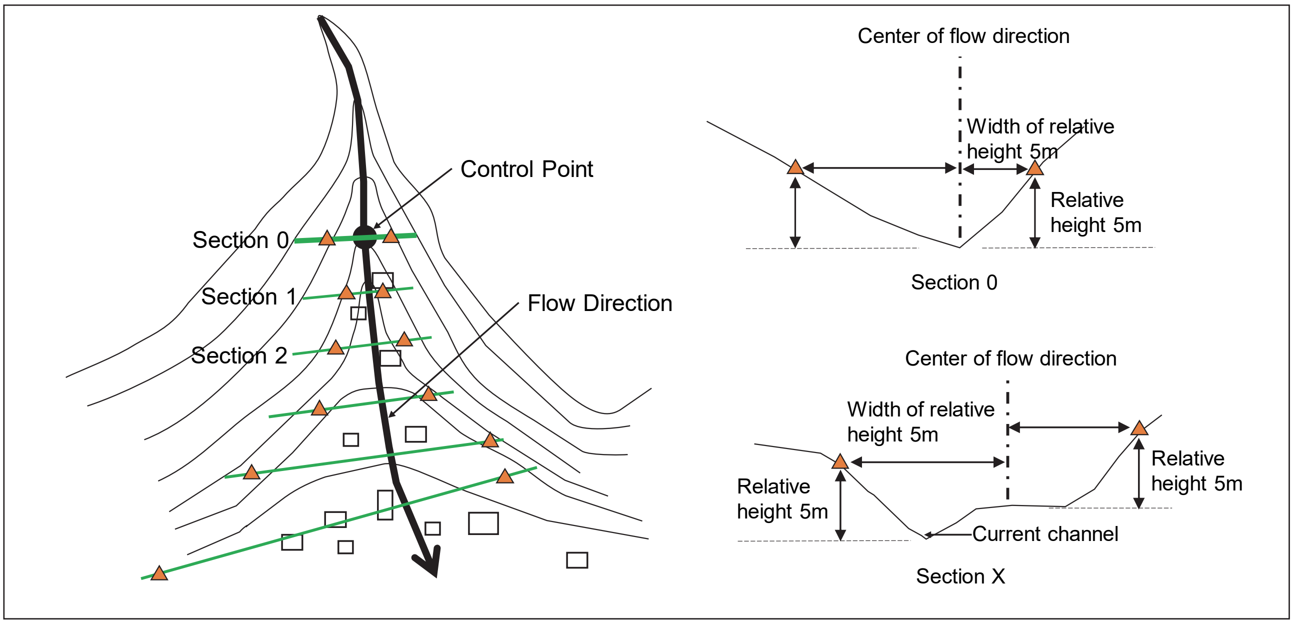


Figure 5.12 Measurement of Relative Height 5 m Point

(6) Setting of Boundary Point of Cross Section

The boundary points of each cross section shall be set by the following steps.

i. Set relative height points of 5 m on Section 0

ii. Set spreading points on Section 1 from the 5 m relative height points on Section 0 with the spreading angle outside as follows for each zone (Figures 5.13 and 5.14).
   - 30 degrees for the Yellow Zone; and
   - 15 degrees for the Red Zone.

   These angles were empirically derived by the results of the past debris flow survey in Sri Lanka.

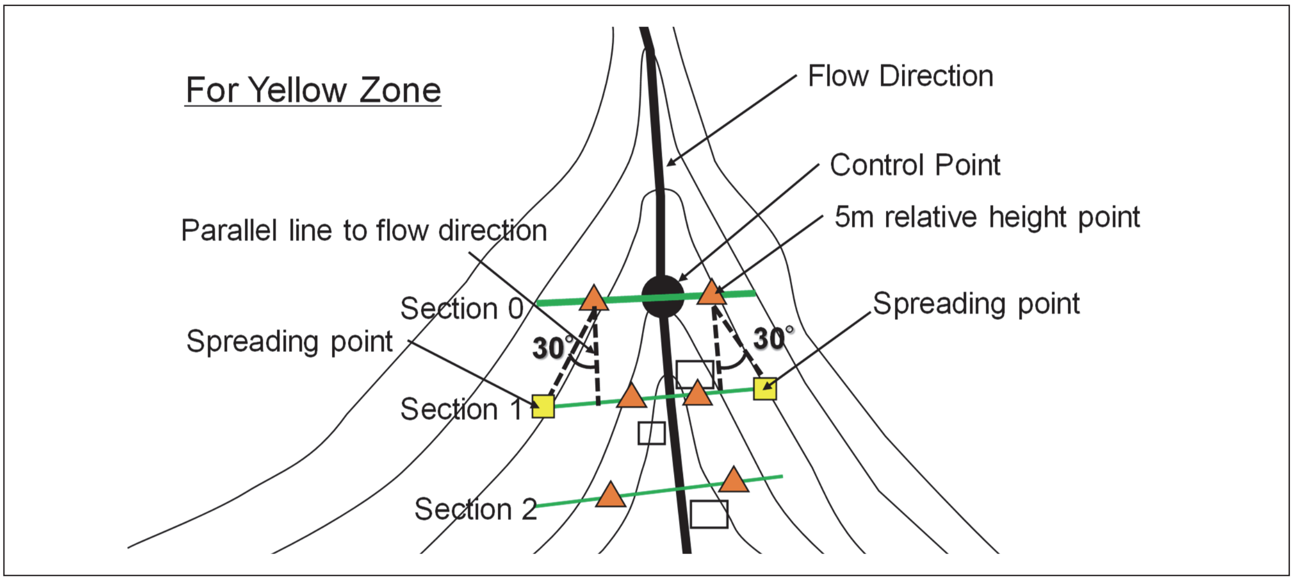


Figure 5.13 Setting of Spreading Points for Yellow Zone

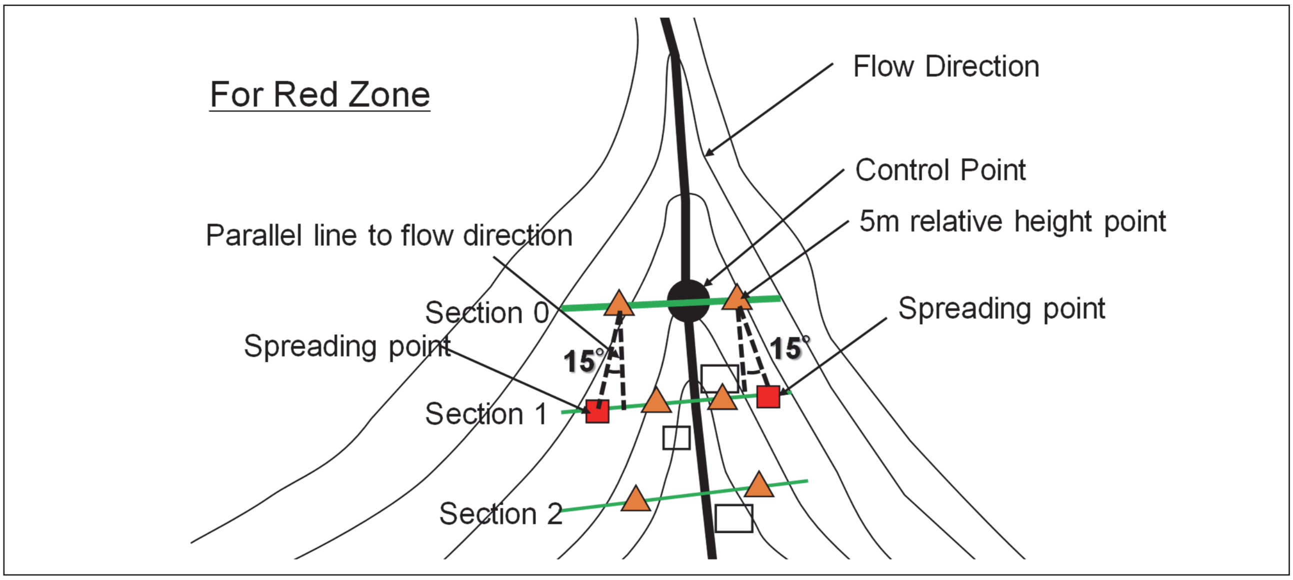


Figure 5.14 Setting of Spreading Points for Red Zone

iii. Set spreading points on Section 2 at the points which have given dispersion angles outside of the closest point to the stream, which is either a 5 m relative height point or spreading point on Section 1 (Figures 5.15 and 5.16). The closest point to the stream is selected as the boundary point.

iv. Set spreading points from the boundary points of the previous section again in the same way up to the lowermost end.

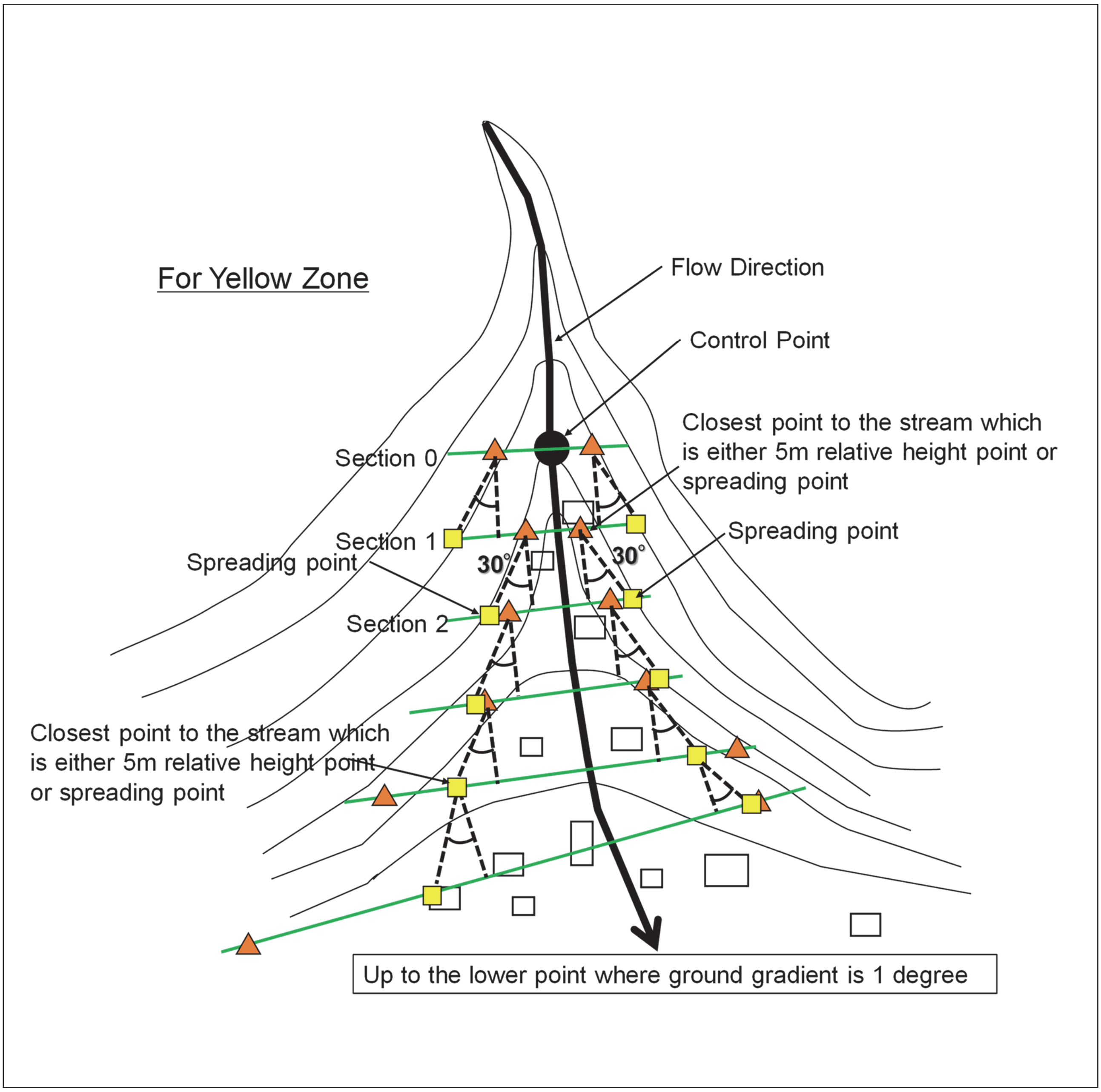


Figure 5.15 Setting of Boundary Points for Yellow Zone

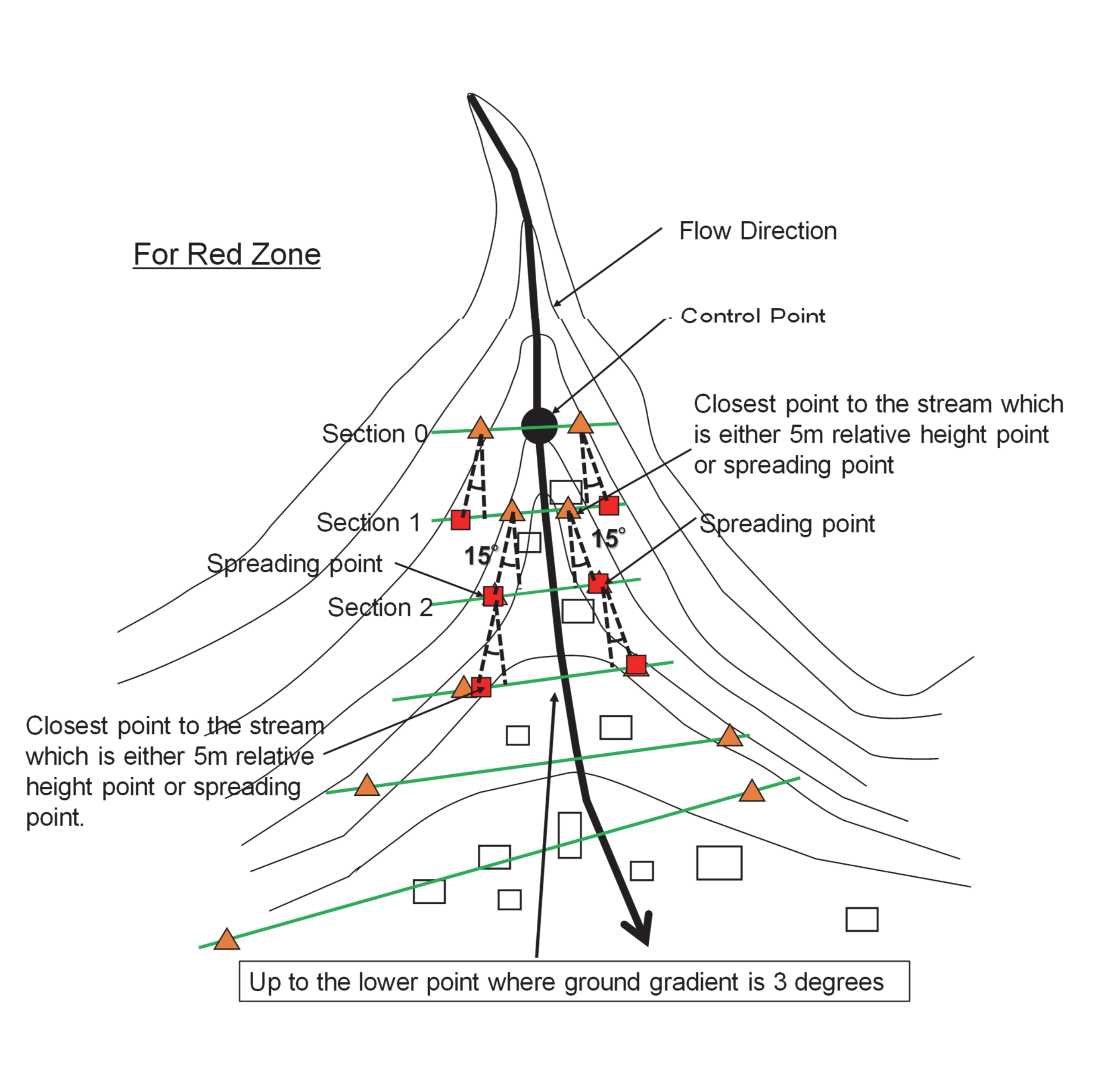


Figure 5.16 Setting of Boundary Points for Red Zone

v. Connect the boundary points on each cross section (Figures 5.17 and 5.18).

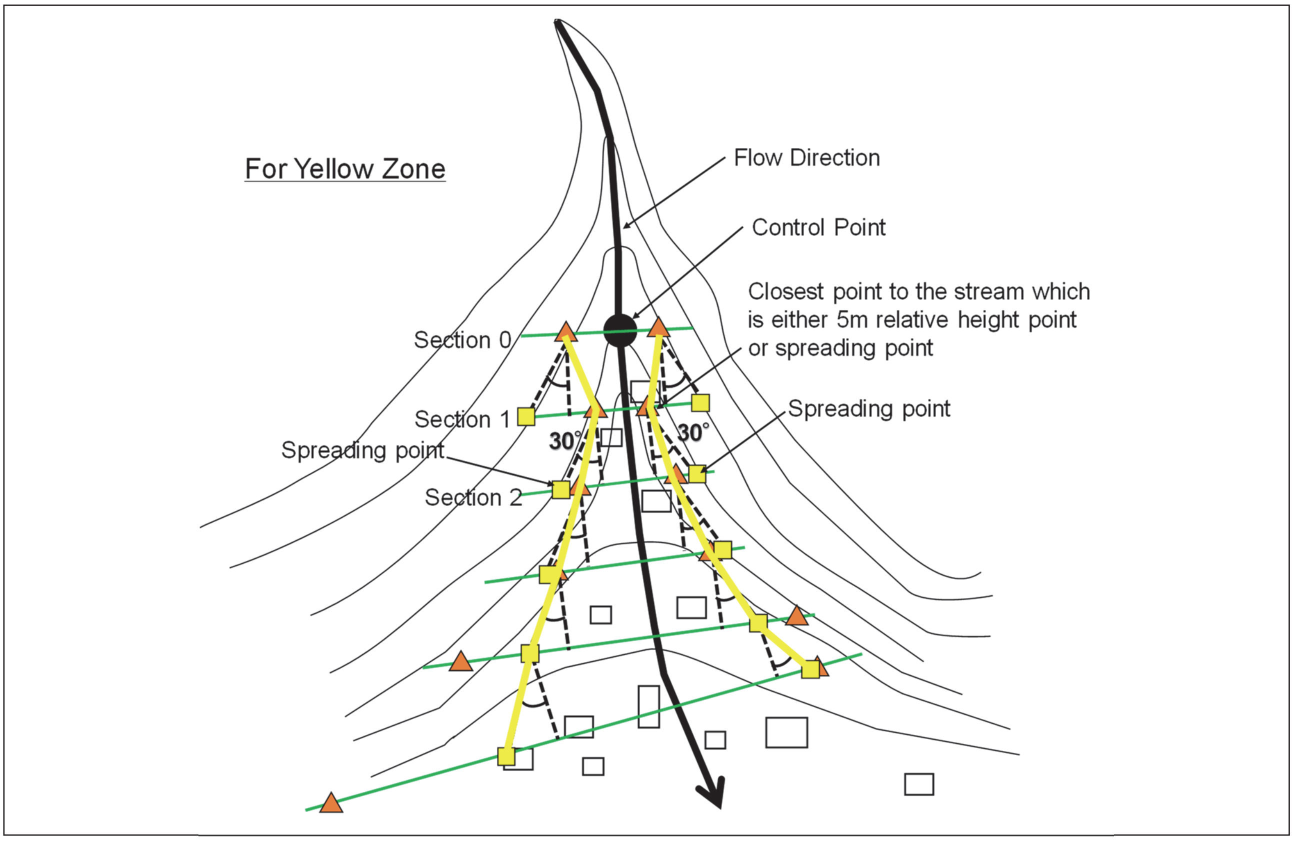


Figure 5.17 Connection of the Boundary Points for Yellow Zone

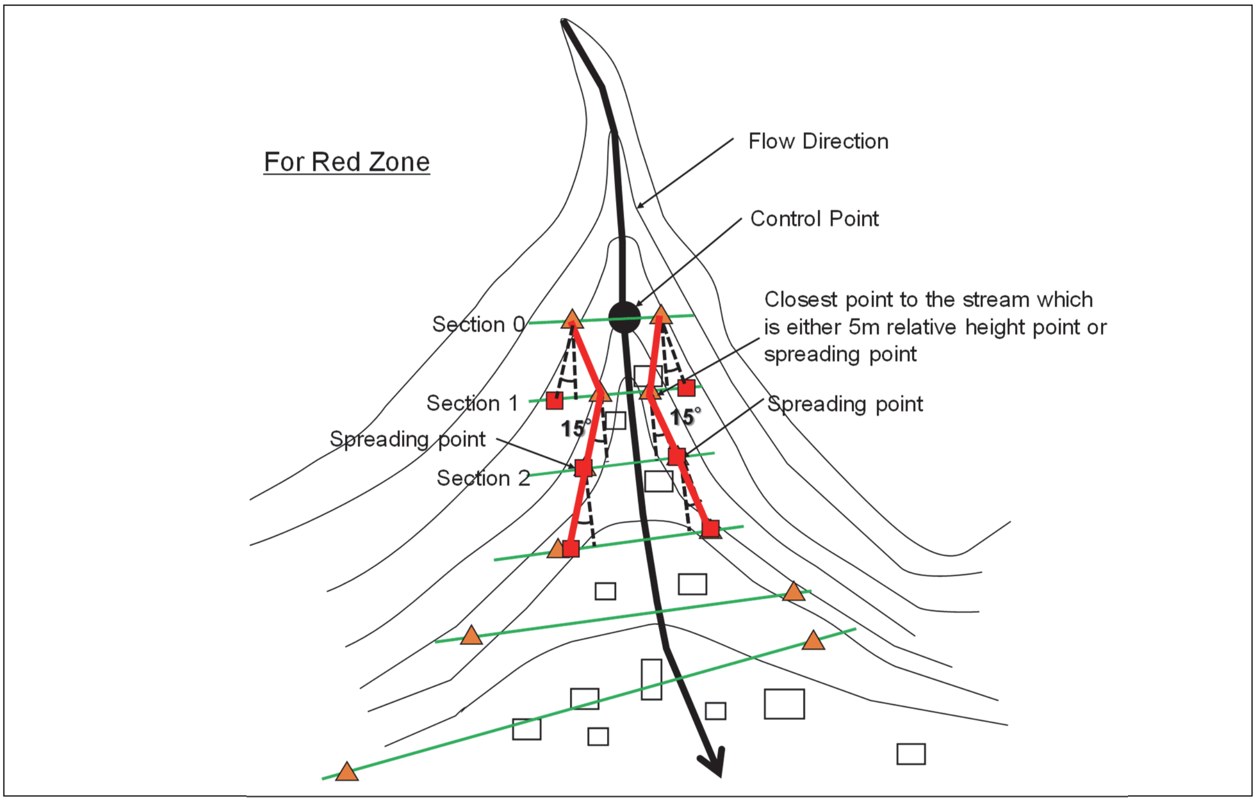


Figure 5.18 Connection of the Boundary Points for Red Zone

(7) Setting of the End Line of Downstream

The end line of downstream shall be set by the following steps. (Figure 5.19)

i. Set an auxiliary line from the lowermost point for Yellow or Red Zone connecting the lowermost point and the control point.

ii. Turn the line around the lowermost point to the same direction as downstream.

iii. Set a reference point on the rotated line.

iv. Draw an arc line from the reference point with a radius of the distance between the reference and the lowermost point.

v. Connect the arc line and the boundary line. (Figure 5.20)

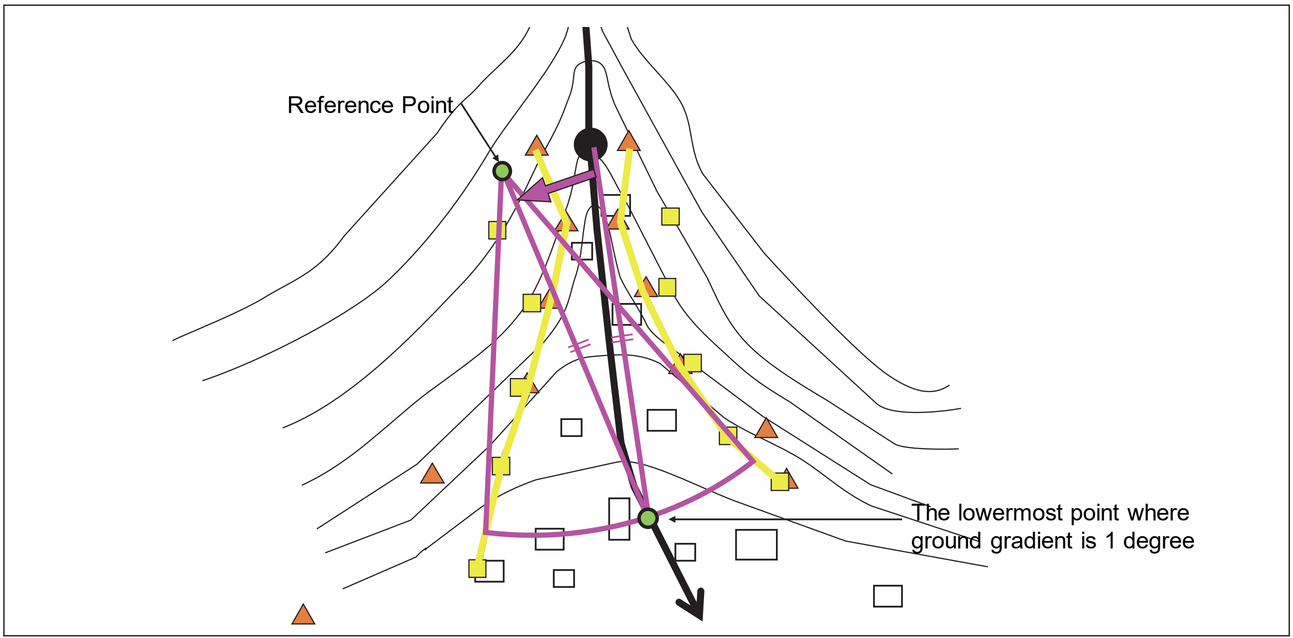


Figure 5.19 Setting of End Line of Downstream for Yellow Zone (1)

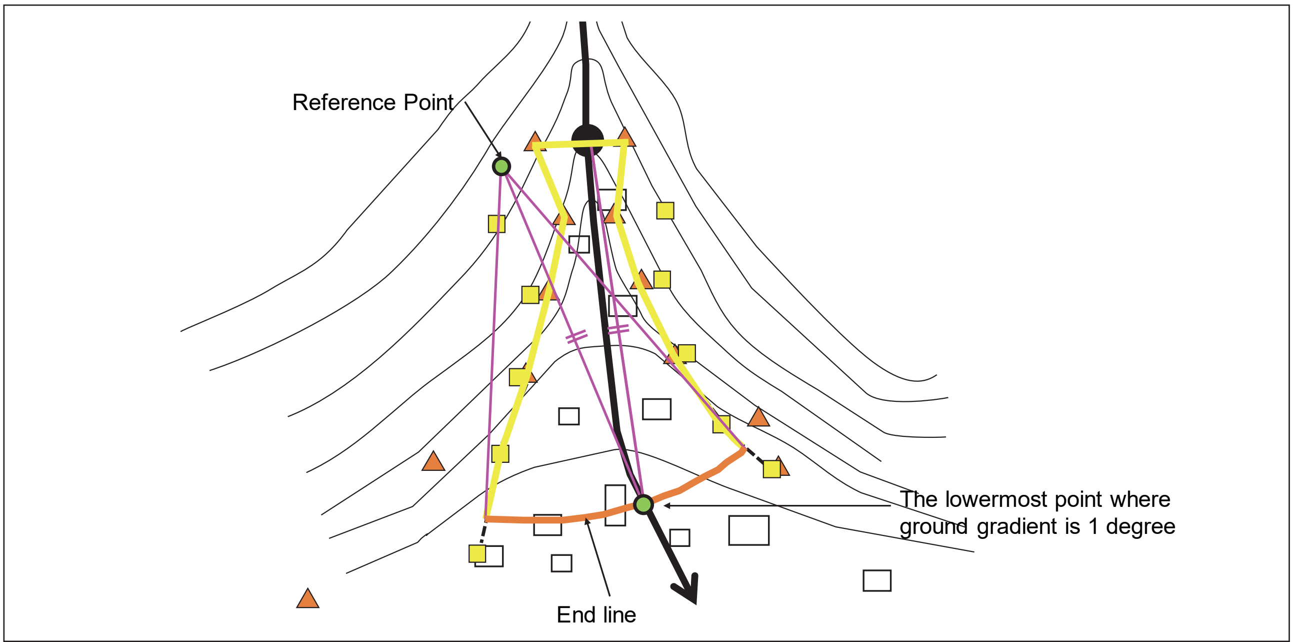


Figure 5.20 Setting of End Line of Downstream for Yellow Zone (2)

(8) Excluding Areas where Debris Flow cannot be reached

If the following landforms or obstacles are present in the drawn Yellow or Red Zone, the zone should be modified properly to exclude areas where debris flow cannot be reached. (Figure 5.21)

- Main stream/channel with a width or depth of 5 m or more; or
- Bank slope with a height of 5 m or more, etc.

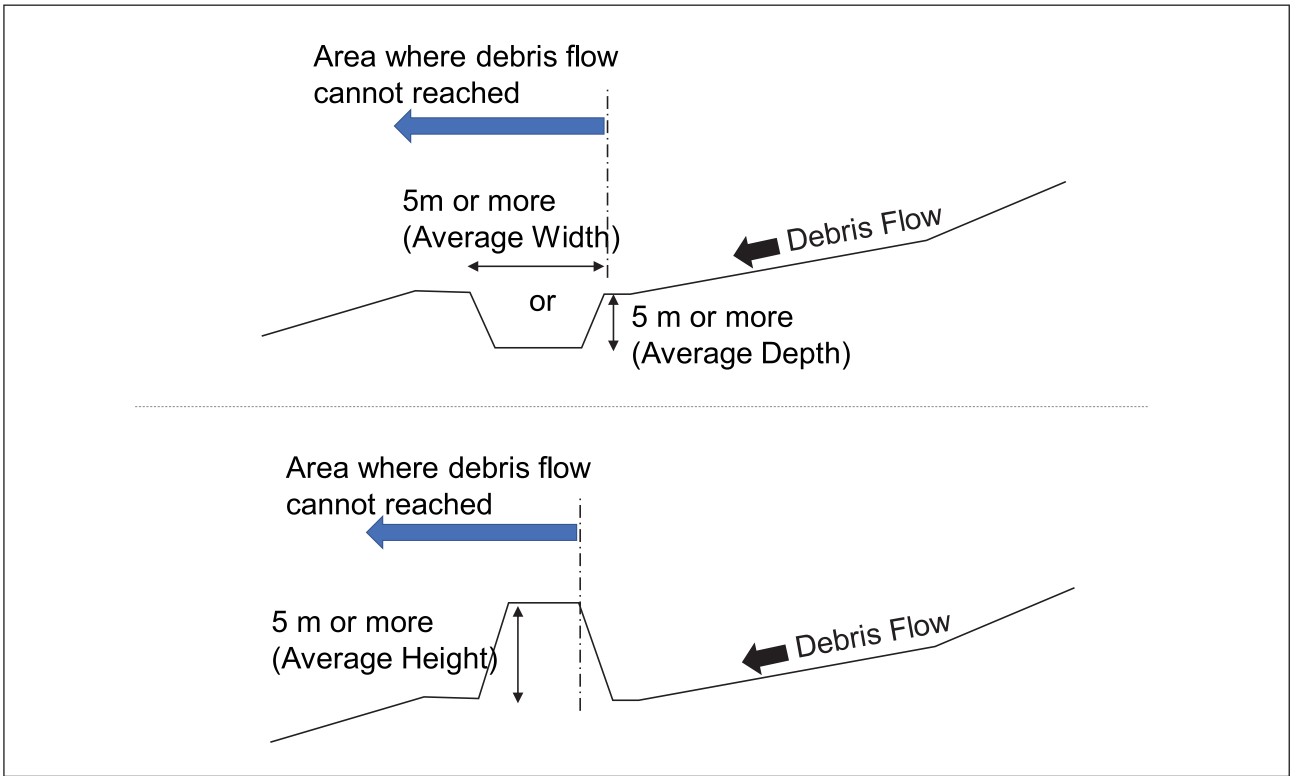


Figure 5.21 Conceptual Lateral Profile of an Area where Debris Flow Cannot Be Reached

(9) Setting of Yellow and Red Zones in Case of the Bending Flow Direction

Debris flows generally move in a straight direction, especially with a large-scale volume of debris. In the case of bending flow direction, the Yellow and Red Zones shall be set by the following procedure:

i. If the profile has a mountain ridge with a relative height of less than 5 m, set a subsidiary line of flow direction from main the flow (Figure 5.22). If the profile has a mountain ridge with a relative height of over 5 m, there is no need to set a subsidiary line.

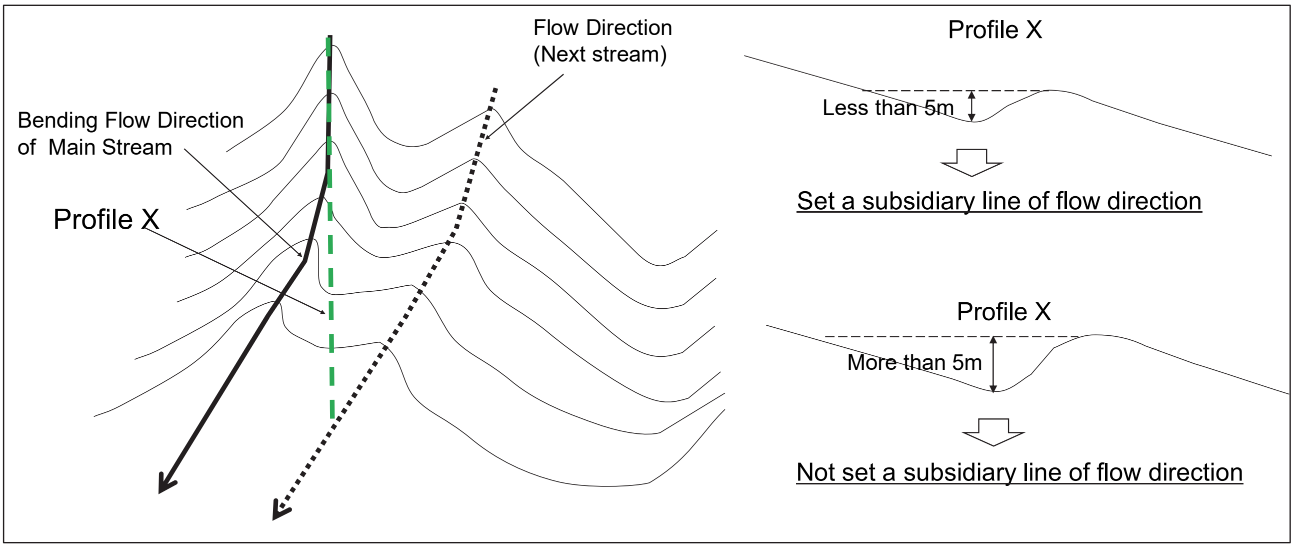


Figure 5.22 Setting of a Subsidiary Line of Flow Direction

ii. In cases where the mountain ridge is present between two mountain streams with a relative height of less than 5 m, set the boundary points for the Yellow Zone either at point of the relative height of 5 m or spreading point for the flow direction of main stream and the subsidiary line of flow direction as well (Figure 5.23, case 1).

iii. In cases where the mountain ridge of relative height of 5m or more is present between two valleys, set the boundary points for the Yellow Zone either at point of the relative height of 5 m or spreading point for the flow direction of main stream and from where the relative height of the ridge drops below 5 m or from the spreading point of the flow direction of next valley (Figure 5.23, case 2).

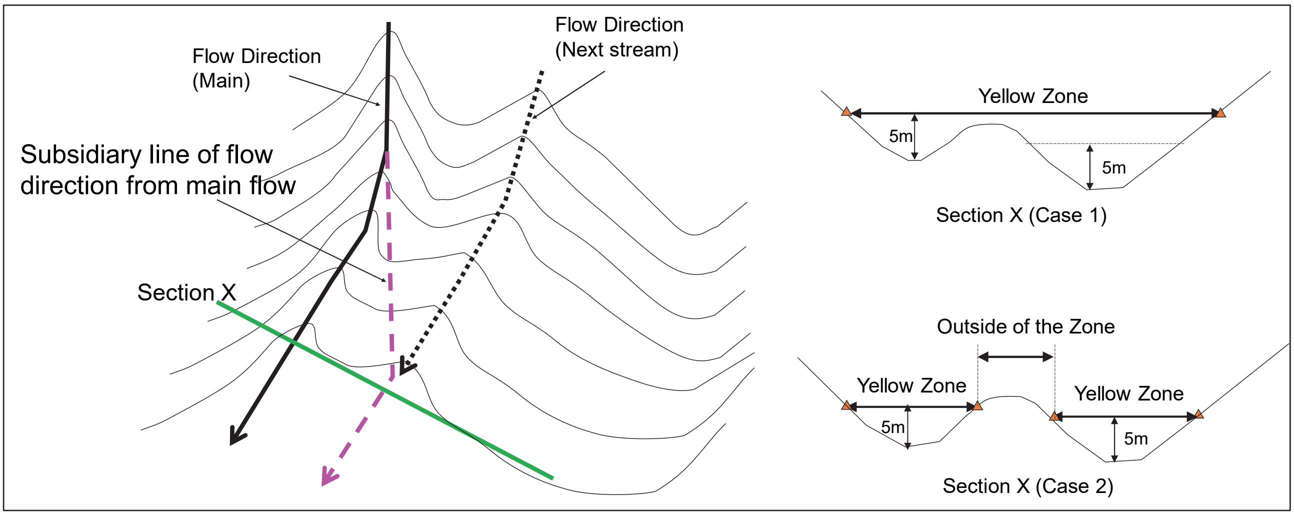


Figure 5.23 Setting of Boundary Points of Main and Subsidiary Flow Directions for Yellow Zone

iv. In setting of the Red Zone, only the main flow direction is used because the energy of debris flow is decreased by a mountain ridge or valley outlet.

5.2.4 Field Verification to Finalize the Zones

The field verification is conducted to finalize the Yellow and Red Zones set by desk study, focusing mainly on the following items:

a) Ground Gradient

Field surveys are conducted to supplement the ground gradient data obtained from topographic maps and to obtain ground gradient data that cannot be obtained from maps. Measurement points are locations where there are drops caused by structures, etc., as well as gradient shift points and relative heights at upstream and downstream of structures in the river channel.

b) Cross-section profile

For the cross-section profile, field surveys are implemented to obtain base data used to predict the starting point/range of inundation of a debris flow on the following items:

- Cross-section profile: Sketch of outline shape, simple cross section measurements
- Embankment slope: Measure the slope of the stream's embankment (boundary between water flow area and slope surface is approximately equal to the cut bank)
- Channel width: Measure the distance between the banks of the stream, giving the width of water flow and stream topography
- Relative heights of protection targets and riverbed: Measure elevation differences between the ground height of the protection target and the stream bed

c) Plan Shape

Field surveys are implemented to assess the plan shape through its ground inclination, aerial photo interpretation, and the cross-section profile. This is done to obtain base data for predicting the size and extent of debris flow inundation. Through map surveys, unique landforms such as river bends, narrow passes, valley plains, flatlands (residential and arable land), and roads are assessed. These will then be confirmed through field surveys.

d) Artificial Structures

For artificial structures, field surveys are implemented to understand the detailed topographical conditions that restrict flow and inundation range of debris flow.

Survey targets include artificial structures that impact the flow of debris flow such as embankments (roads, railways, etc.), bridges, culverts (box culverts, etc.), and retaining walls, etc. Basically, the position and size of artificial structures is assessed through field surveys, assessing whether they are transverse or longitudinal to the flow direction of debris flow.

The following items set for desk study should be checked if they are appropriate:

- Location of control point
- Direction of debris flow
- Location of downstream end point of Yellow Zone and Red Zone
- Area where debris flows cannot be reached

5.3 Reference Data

Background Data for Setting Hazard Zone for Debris Flow

Nineteen (19) past debris flow disasters were collected from:

a) Landslide Disaster May 2017 – Damages and Loss Assessment, Prepared by NBRO, including 35 disaster events occurring in 2017.

b) Reduction of Landslide Vulnerability by Mitigation Measure Projects - Cost Benefit Analysis, Prepared by NBRO, in October 2018, including 50 disaster events.

The main results of the collected past debris flow disasters are shown in Figures 5.1 to 5.5 and summarized below:

a) The slope angle at the source area of failures is in the range of 20 to 40 degrees, and mostly between 30 and 40 degrees (Figure 5.1).

b) The streambed gradient around the control is mostly between 5 and 20 degrees (Figure 5.2).

c) The streambed gradient within the flow paths is between 10 and 40 degrees on average (Figure 5.3).

d) The spreading angle of the depositional area is mostly between 30 and 60 degrees, accounting for about 80% of the total number of past debris flow disasters (Figure 5.4). On the other hand, the spreading angle of the depositional area covering the completely damaged houses is between 5 and 30 degrees (Figure 5.5).

e) The streambed gradient at the ending point of the depositional area is mostly in the range of 1 to 5 degrees (Figure 5.6). The streambed gradient at the end point of the depositional areas covering the completely damaged houses was found to be between 3 to 8 degrees based on the limited past debris flow disasters.

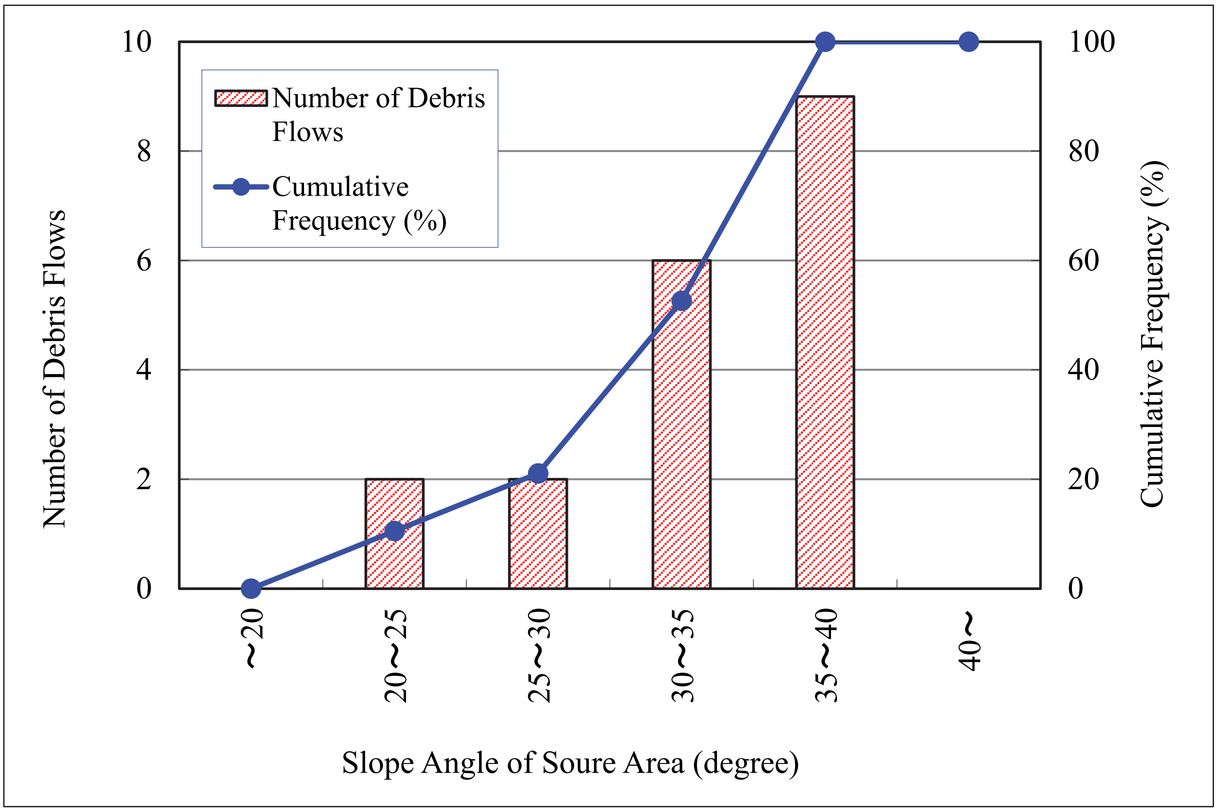


Figure 5.24 Frequency Distribution of Slope Angle of Source Area

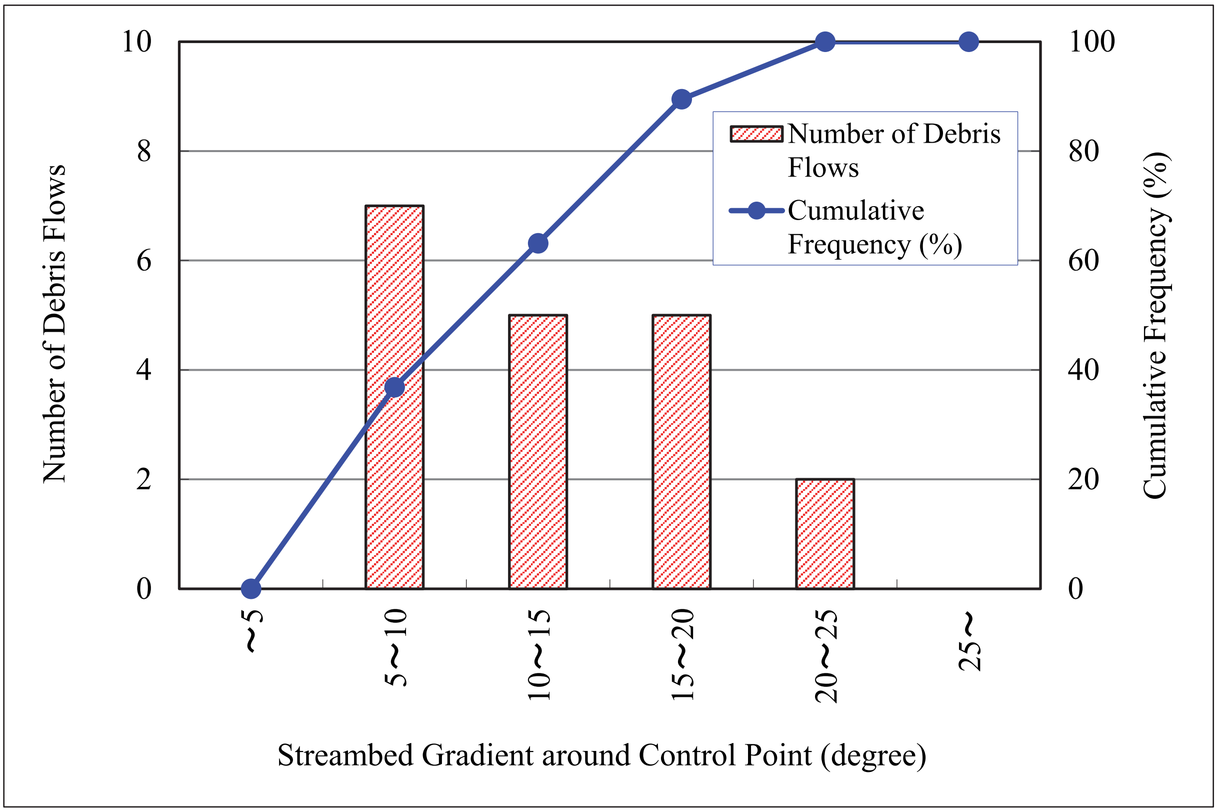


Figure 5.25 Frequency Distribution of Streambed Gradient around Control Point

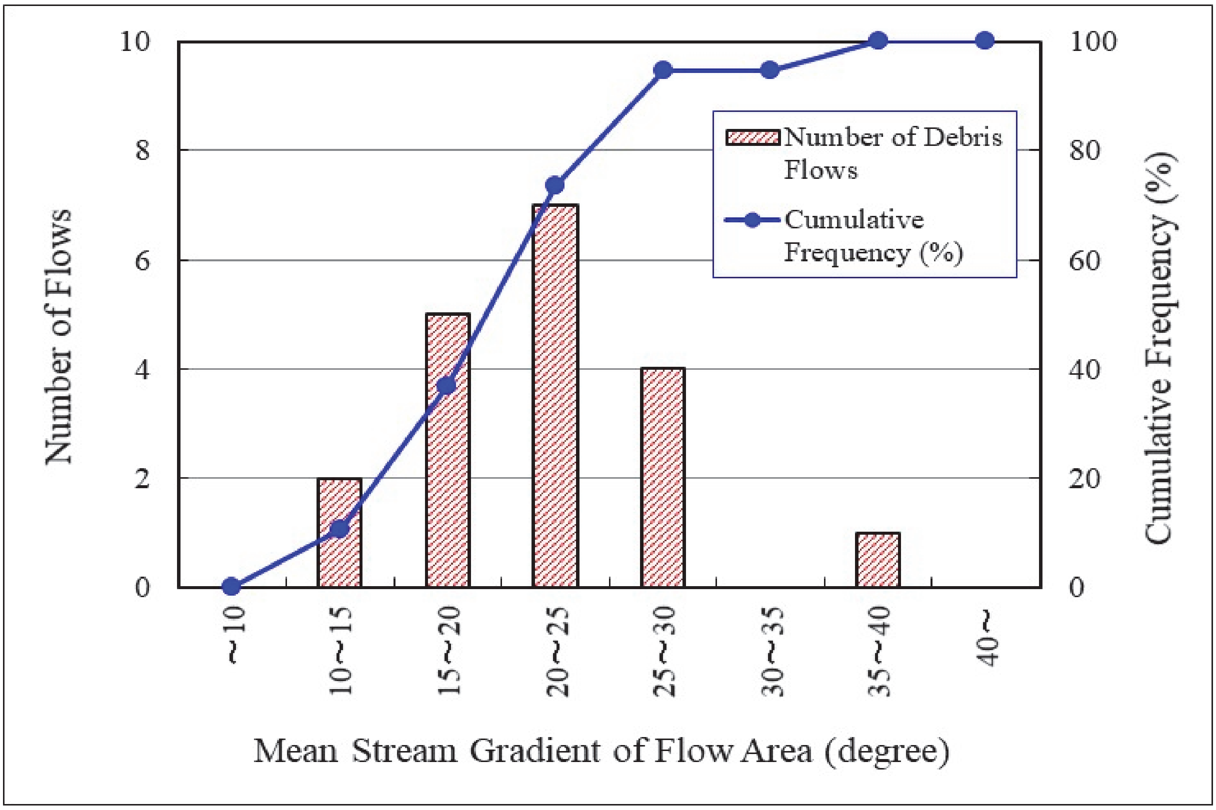


Figure 5.26 Frequency Distribution of Mean Streambed Gradient of Flow Paths

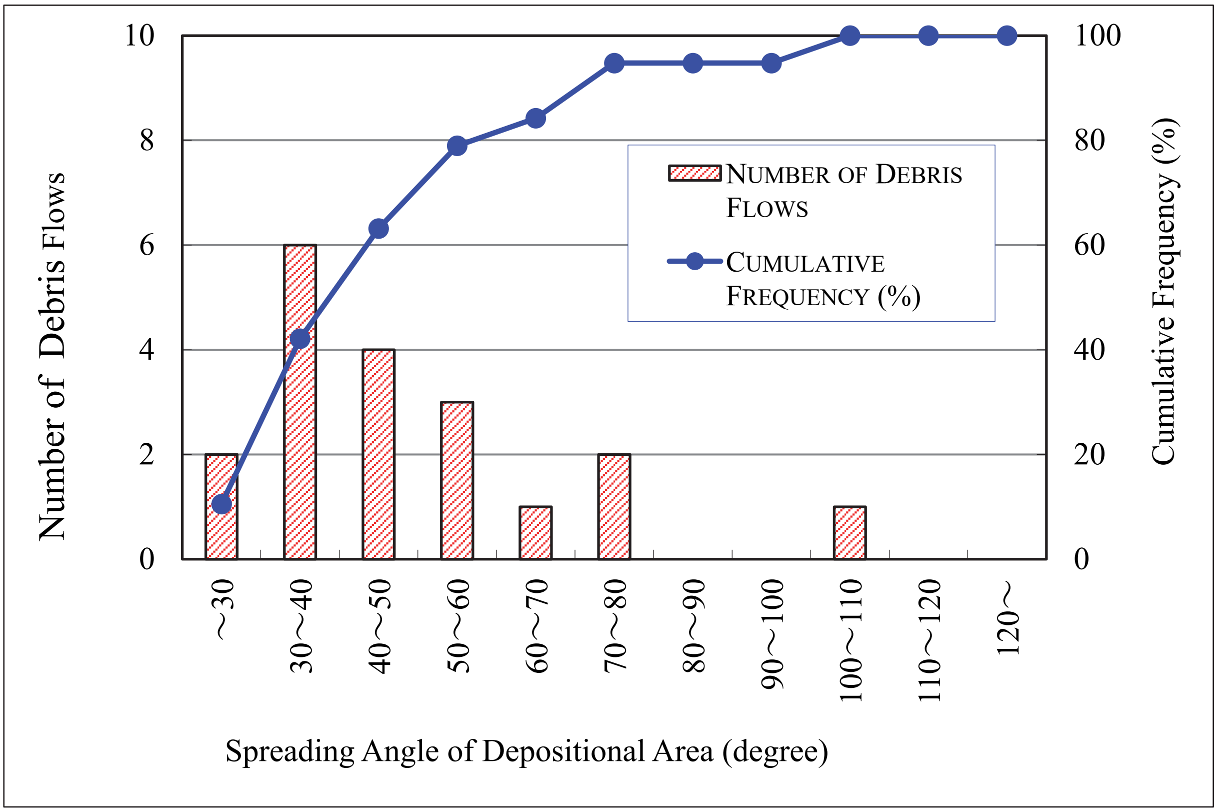


Figure 5.27 Frequency Distribution of Spreading Angle of Depositional Area

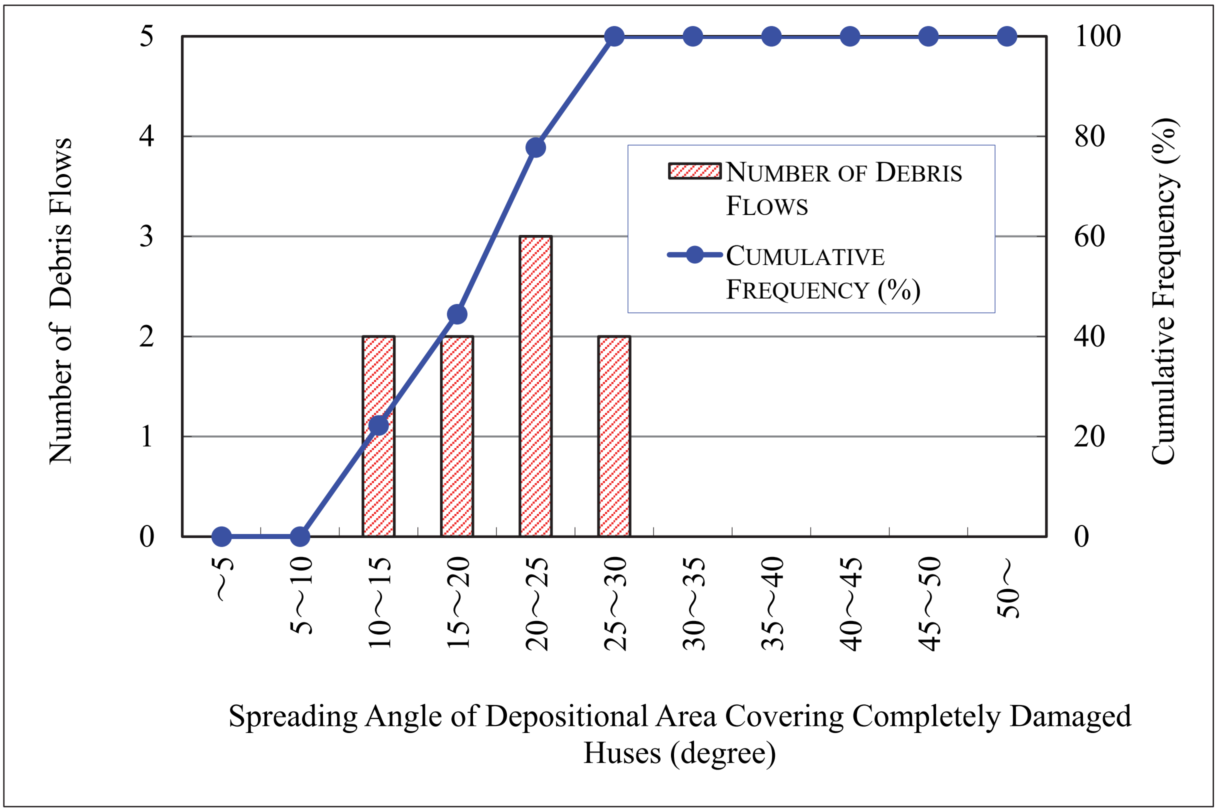


Figure 5.28 Frequency Distribution of Spreading Angle of Depositional Area Covering Completely Damaged Houses

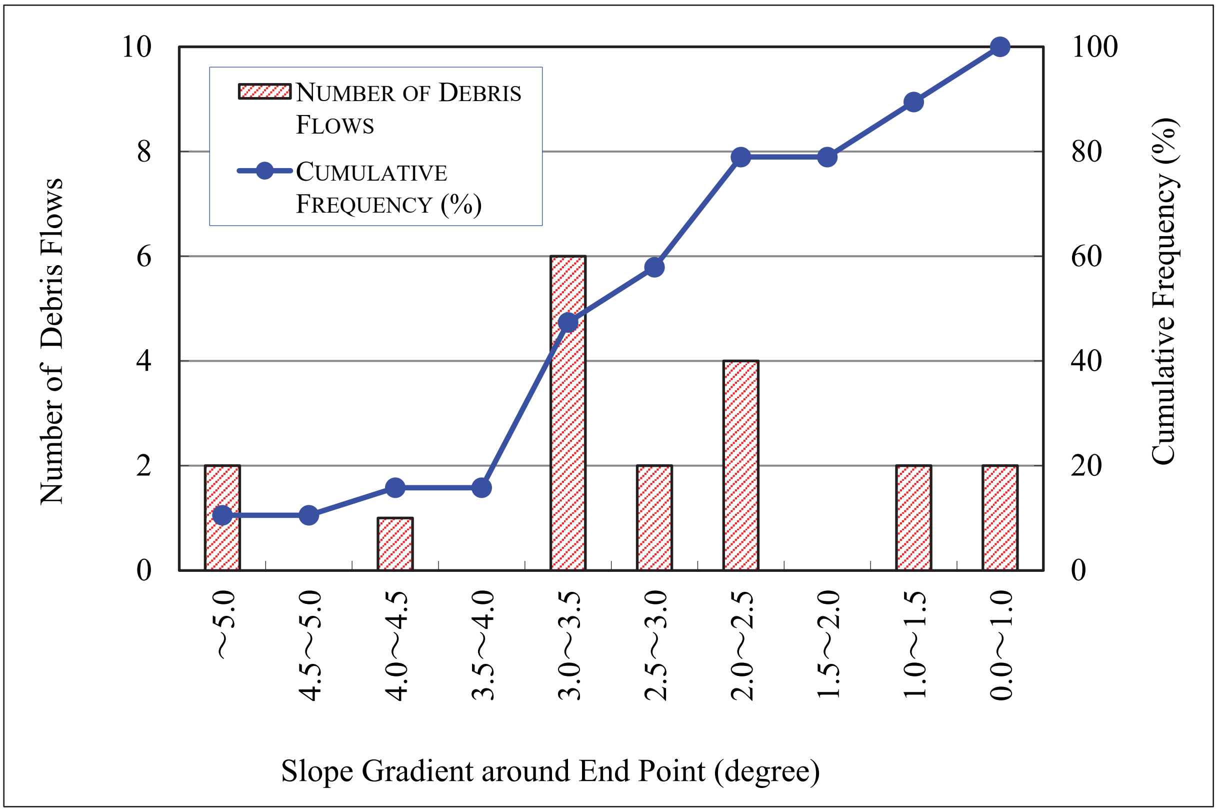
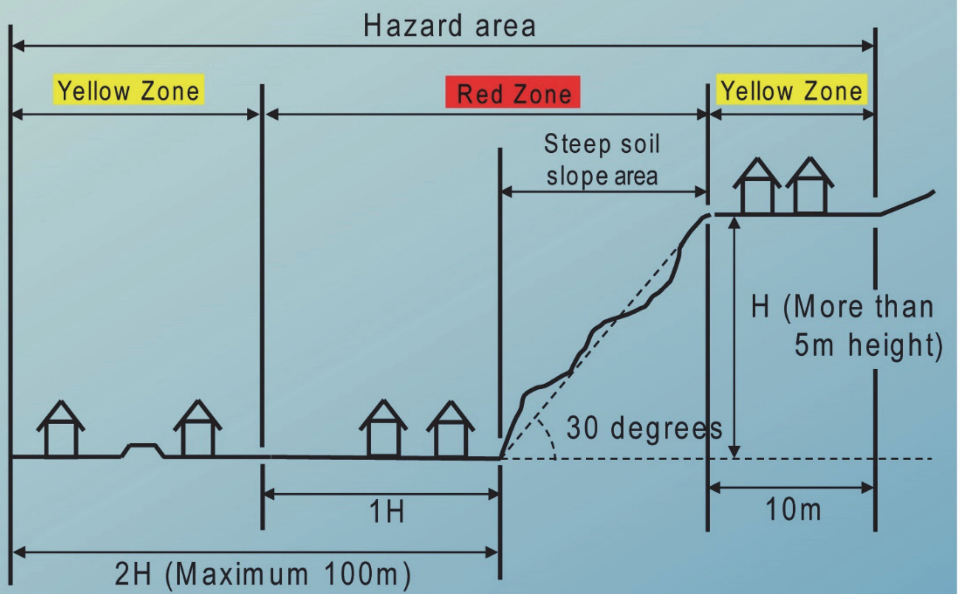


Figure 5.29 Frequency Distribution of Streambed Gradient around End Point of Depositional Area



Technical Note 1

Hazard Zoning Methodology for Slope Failure by Reference to Japanese Criteria

This technical note provides the methodology of slope failure hazard zoning by reference to Japanese concept

TECHNICAL NOTE 1

HAZARD ZONING FOR SLOPE FAILURE

BY REFERENCE TO JAPANESE CRITERIA

1 Procedure of Setting "Yellow Zone" and "Red Zone" for Slope Failure

Setting of "Yellow Zone" and "Red Zone" for slope failure are in accordance with the following steps (Figure 1).

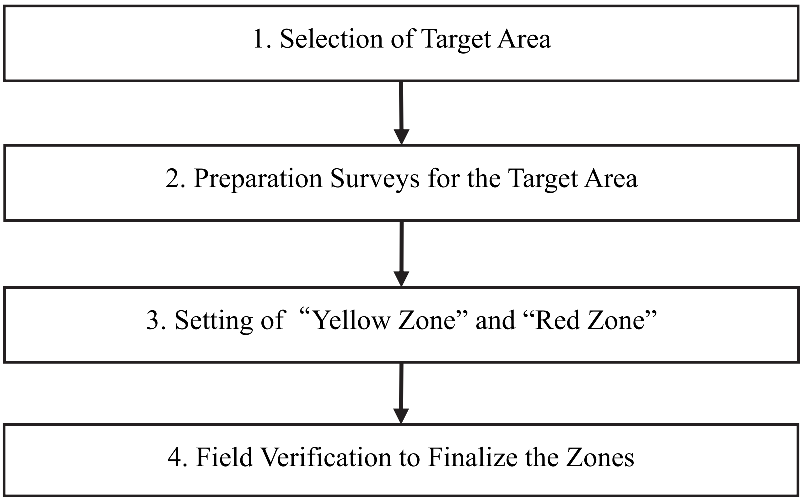


Figure 1. General Process of Setting "Yellow Zone" and "Red Zone" for Slope Failure

2 Methodology

2.1 Selection of Target Area

The target area including "Initial area" is selected using "Hazard Zonation Map" with a scale of 1:10,000 prepared by NBRO. The present land use plans and social conditions are also considered for the target area selection.
In selecting target area, the following three conditions are taken into consideration:

- Topographical conditions
- Social conditions
- Slope unit

This methodology is applicable not only to natural slope but also man-made cut slope.

a) Topographical Conditions

The target area to be selected for slope failure shall be a steep soil slope having a gradient between 25 and 50 degrees and a height of 5 m (Figure 2).

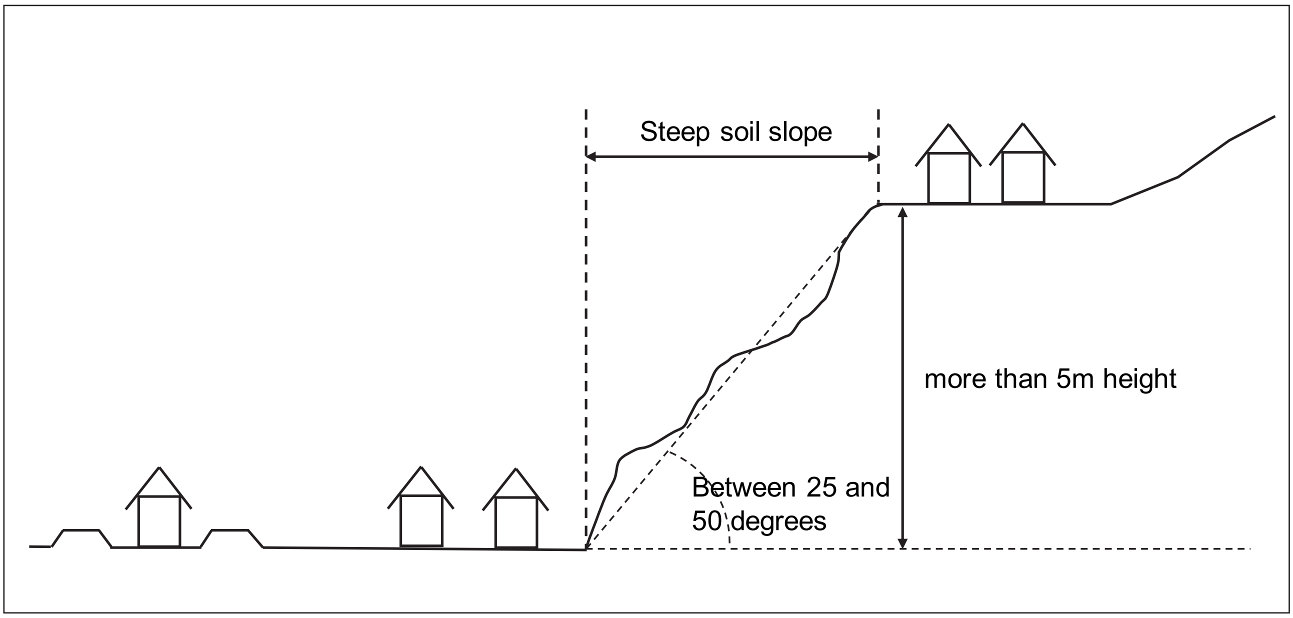


Figure 2. Conceptual Representation of Target Area for Slope Failure

b) Social Conditions
- The target area should include residential area on which at least one residential house or public building is located
- Areas with no houses at present, but may be expected to be developed for housing or public building construction later based on the social conditions such as current land use and development plans should be also considered
- Areas where there is no possibility of residential house construction, such as high mountainous areas with no houses, etc. are excluded from target area selection
- Cutting slopes along road are excluded from target area selection because such slopes have been managed by other administration authority

c) Slope Unit
- In the case of laterally continuous steep slope, the area should be sectioned up to approximately 500 m in length based on topographical or administrative factor.
- Setting of left and right edges of the area is described in Chapter 2.3 - (5) below.

2.2 Preparation Surveys for the Target Area

a) Survey of Past Disaster History for the Target Area

Survey of past disaster history for the target area is conducted to assess the past slope failure size and its damage conditions and then obtain data for setting the range of hazard zone mainly on the following items:
- Date, time, location and cause of a slope failure
- Size or scale of a slope failure (height, width, length, depth, slope gradient, reaching distance and volume of collapsed sediment), as illustrated in Figure 3
- Damage to human (the number of fatalities/injuries), damage to houses (the number of damaged houses, completely or partially), and structural types of the damaged houses (reinforced concrete, brick, clay, wooden, etc.)
- Rainfall information (cumulative rainfall, daily rainfall, hourly rainfall)
- Others (thickness of inundated sediment, etc.)

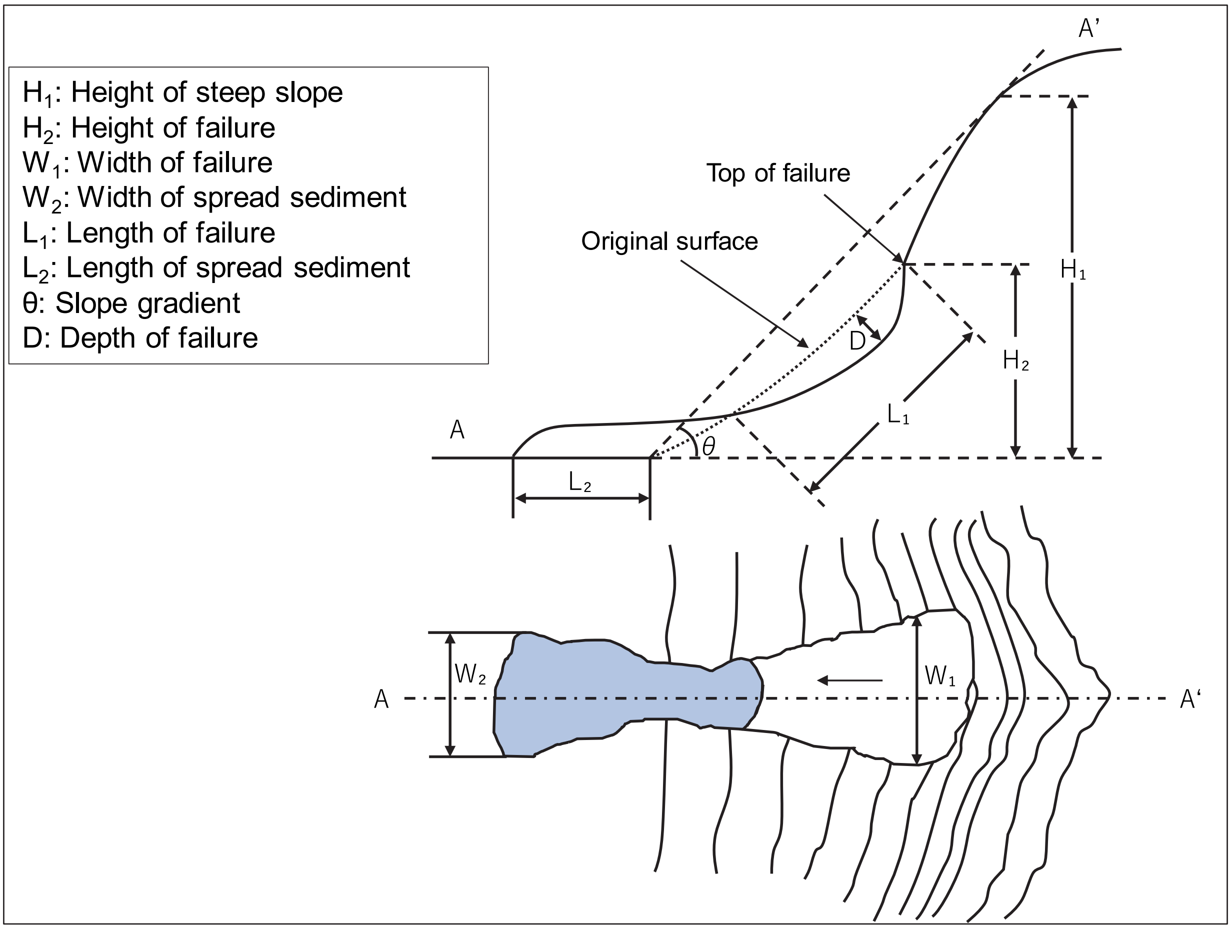


Figure 3. Diagrammatic Illustration of Scale of Slope Failure

b) Artificial structures

Artificial structures should be checked if they exist in the target area, such as:

- Wall, Retaining wall
- Pitching works
- Embankment
- Excavation
- Drainage channel, ditch
- Others

2.3 Setting of "Yellow Zone" and "Red Zone"

Setting of "Yellow Zone" and "Red Zone" for slope failure are conducted according to the following steps (Figure 4).

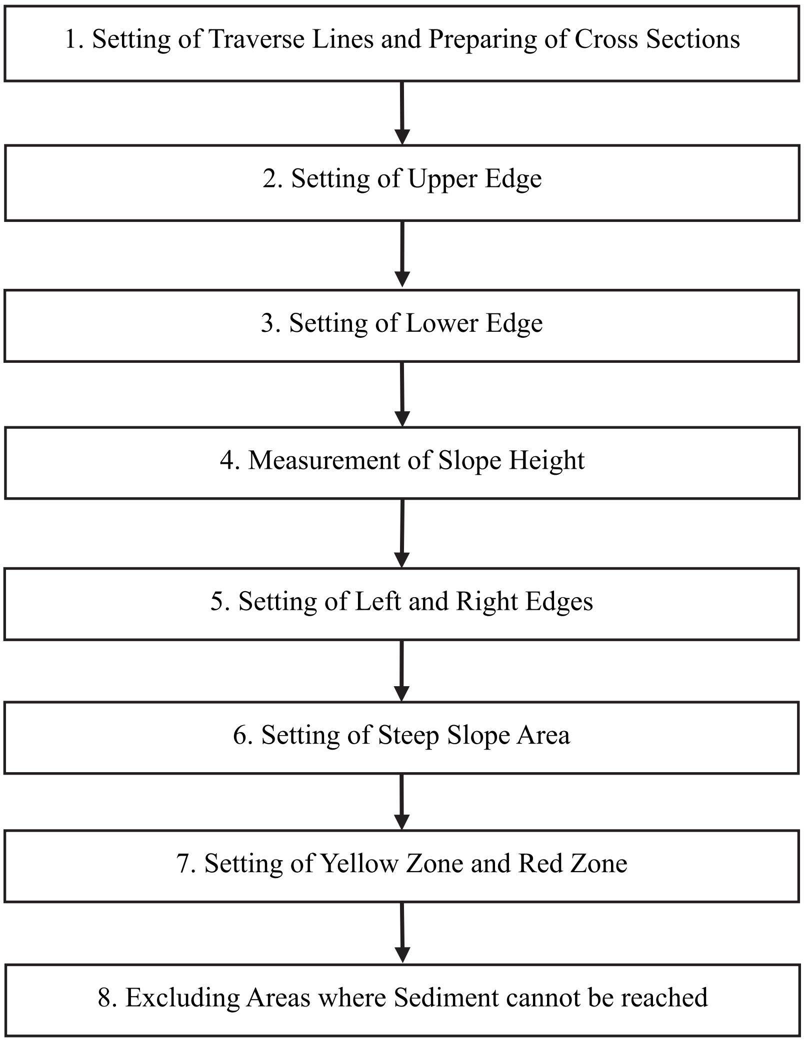
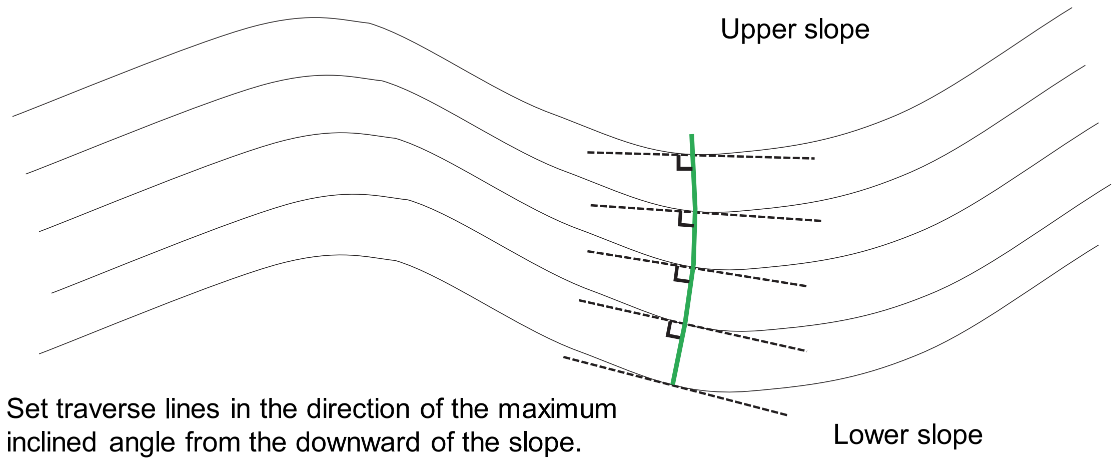


Figure 4. Flowchart of Desk Mapping of "Yellow Zone" and "Red Zone" for Slope Failure

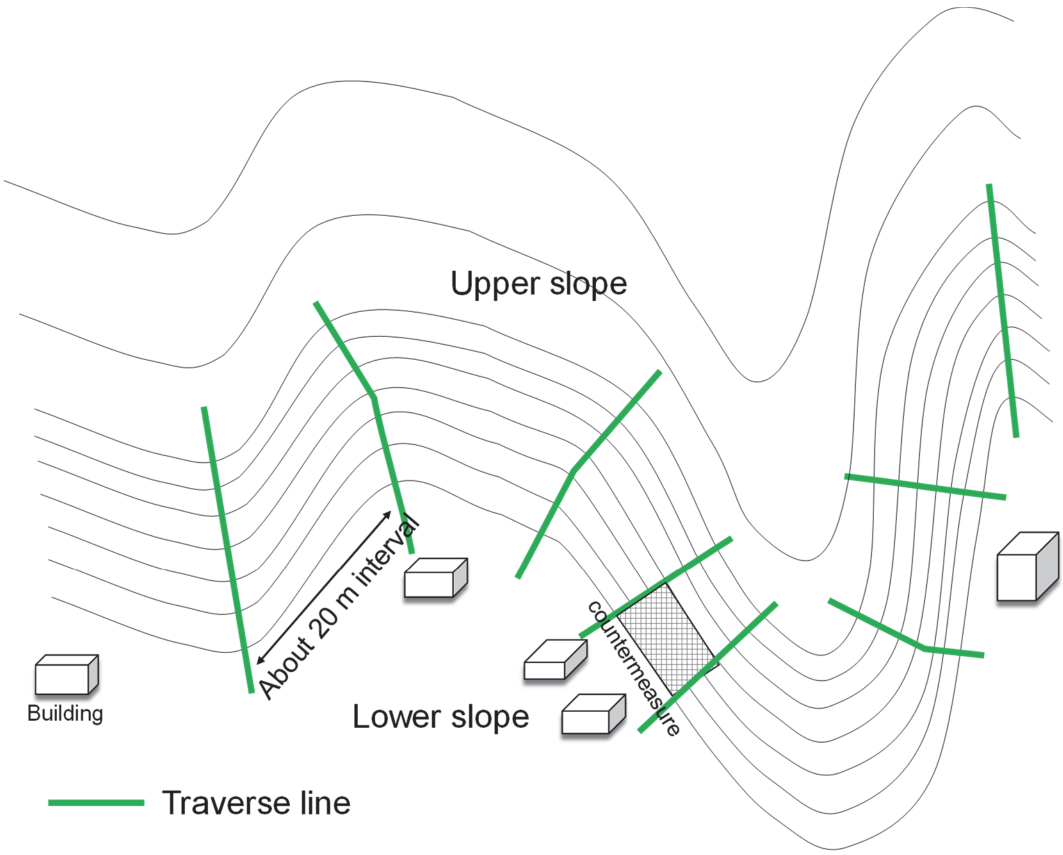
(1) Setting of Traverse Lines and Preparing of Cross Sections

Traverse lines are set in terms of their direction and location, as follows:

a) The direction of traverse line should be set toward maximum slope angle (Figure 5 - (a)).
b) The location of traverse line should be set at about 20 m interval along contours in consideration of topographical changing points and artificial structures (Figure 5 - (b)).
c) Cross section of each traverse line shall be then prepared.



(a) Direction of Traverse Line



(b) Location of Traverse Lines

Figure 5. Setting of Traverse Lines

(2) Setting of Upper Edge

The upper edge shall be determined basically at the topographical changing (or knick) point where a continuous upper slope has a gradient of less than 25 degrees or more than 50 degrees when observing upslope on cross section of each traverse line (Figure 6).

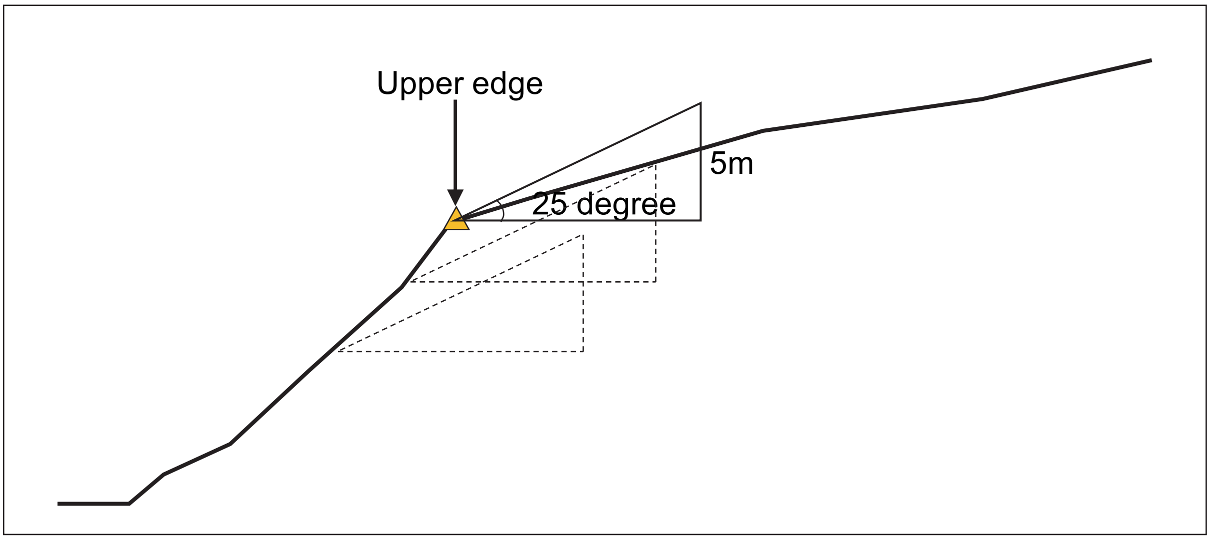
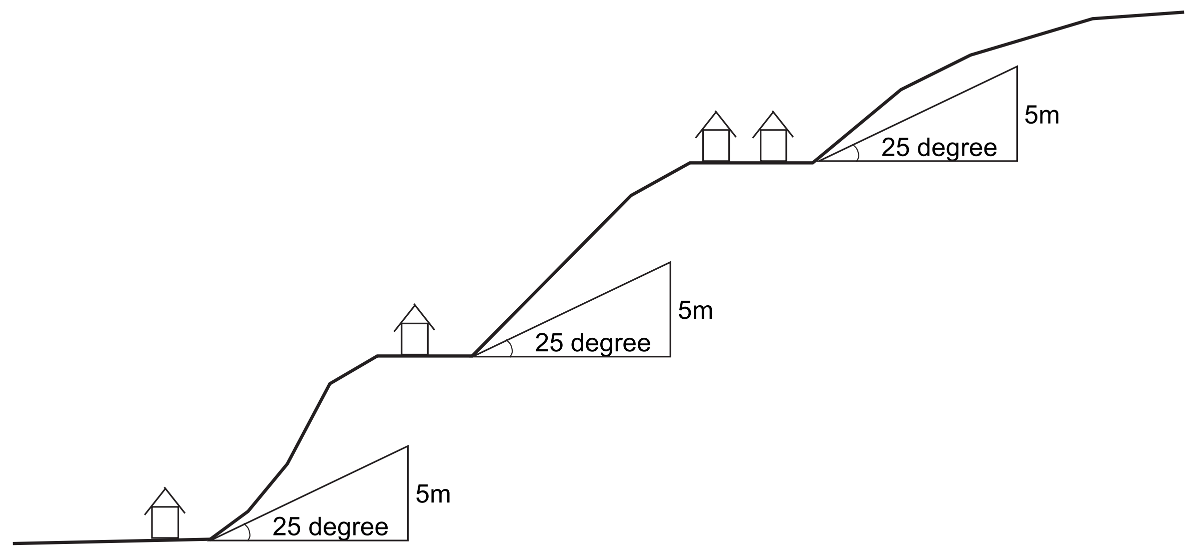


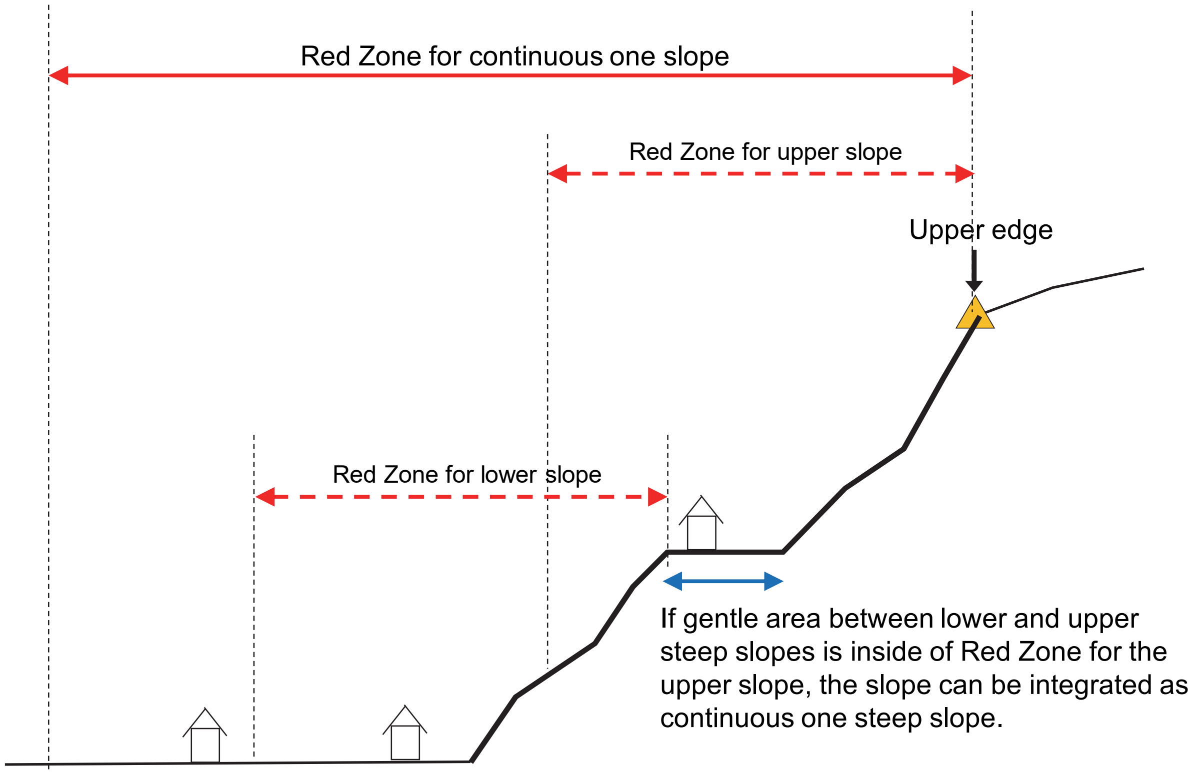
Figure 6. Diagram of Setting Upper Edge

In addition, in the case where a steep slope includes multistep gentle slopes (Figure 7- (a)), the target area should be set as follows:

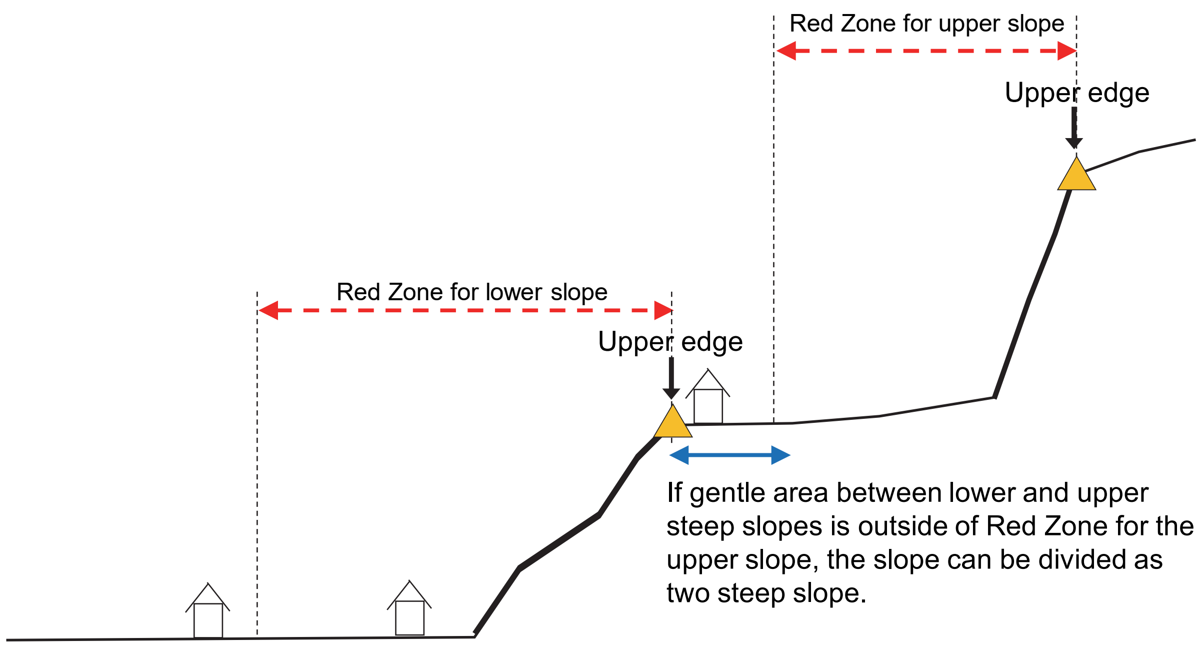
a) In principle, the target area shall be set for each steep slope. However, if there is an overlay between the Red zones of the upper and lower steep slopes (Figure 7 - (b)), the upper and lower steep slopes shall be considered as a continuous steep slope; and
b) If there is no overlay between the Red zones of the upper and lower steep slopes (Figure 7 - (c)), the upper and lower steep slopes shall be set as different target areas, respectively.



(a) A Steep Slope with Multistep Gentle Slopes



(b) A Continuous Steep Slope with Multistep Gentle Slope Slopes



(c) Division of Target Areas in Separate Steep Slopes

Figure 7. Diagrammatic Illustration of Setting Upper Edge for a Steep Slope with Multistep Gentle Slopes

(3) Setting of Lower Edge

The lower edge shall be determined at the topographical changing point where a continuous lower slope has a gradient of less than 25 degrees or more than 50 degrees when looking downslope on cross section of each traverse line (Figure 8).

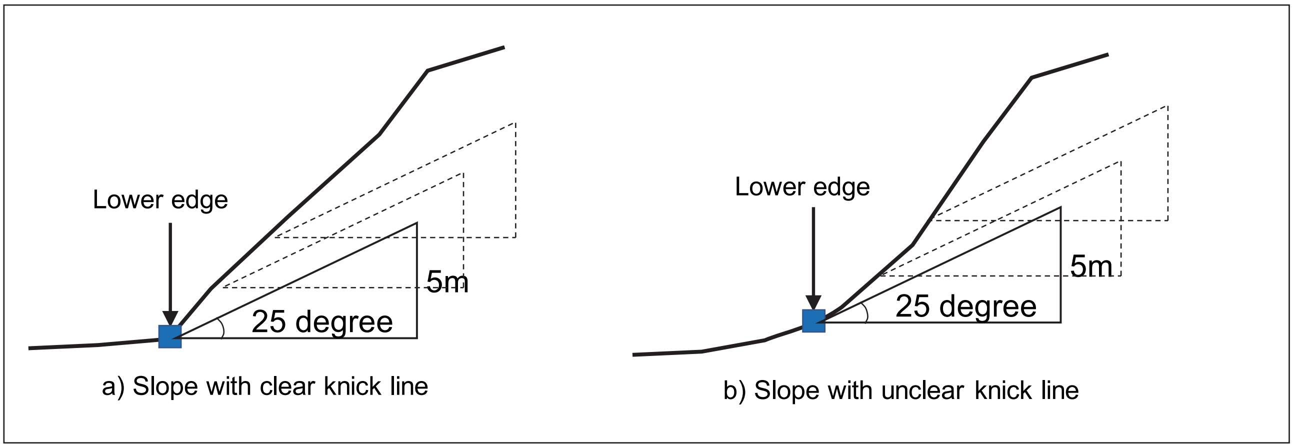


Figure 8. Setting of Lower Edge

(4) Measurement of Slope Height

Slope height is measured as relative height between the lower and upper edges (Figure 9).

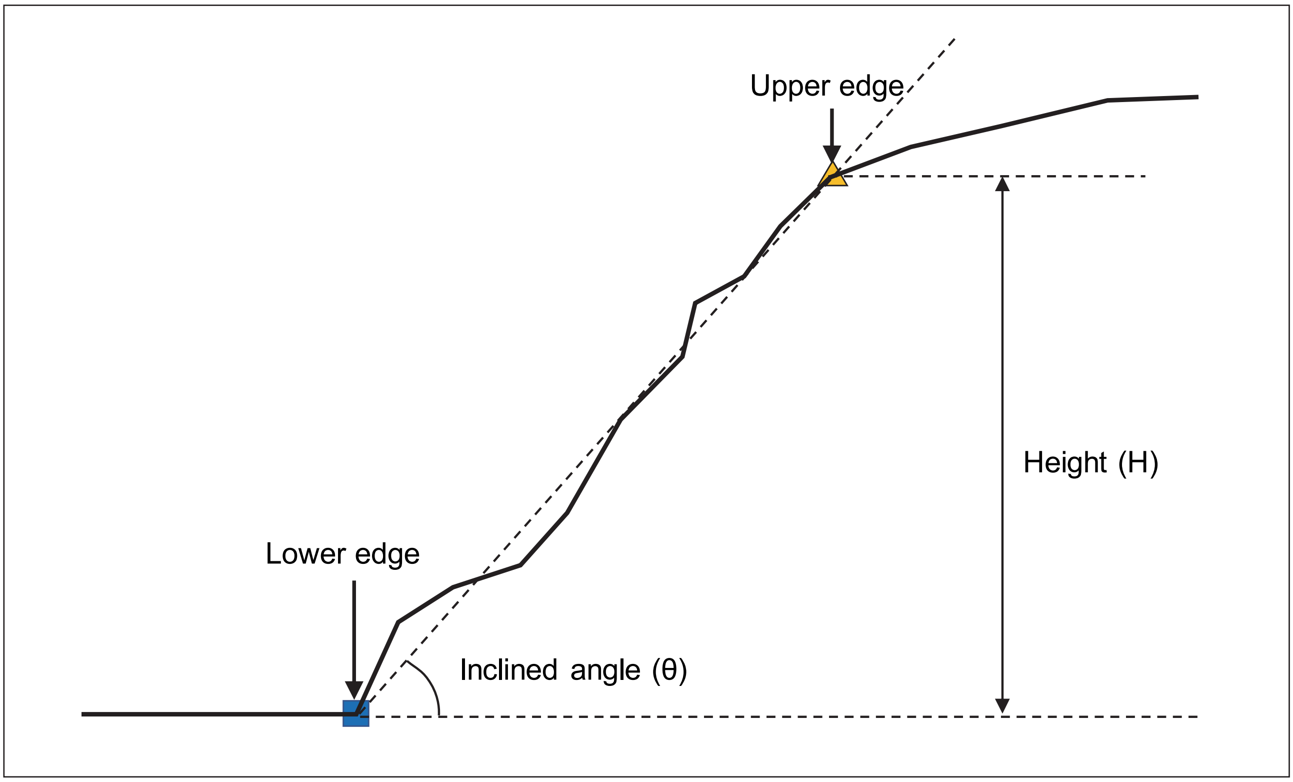


Figure 9. The Measurement of Slope Height

(5) Setting of Left and Right Edges

The left and right edges are set based on the following conditions:

- Boundary of the slope where the slope height is less than 5 m
- Boundary of the slope where the slope angle is less than 25 degrees and more than 50 degrees
- Boundary of mountain stream
- Boundary of a clear mountain ridge
-

(6) Setting of Steep Slope Area

The steep soil slope area is set by straight lines connecting of all upper and lower edges (Figure 10).

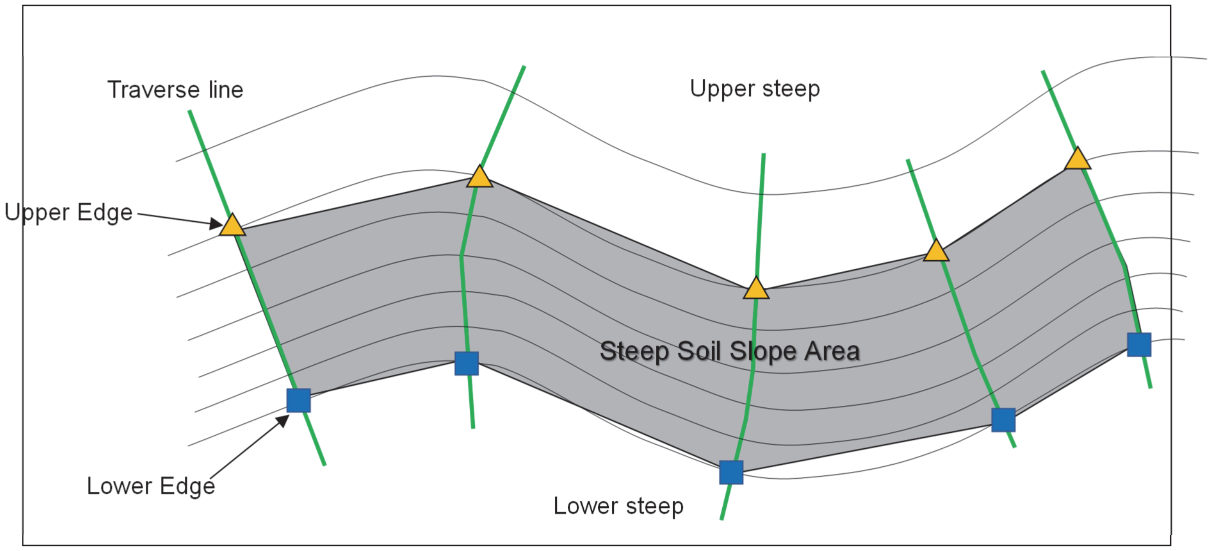


Figure 10. Diagrammatic Representation of Setting Steep Soil Slope Area

(7) Setting of Yellow Zone and Red Zone

The slope failure hazard zone is set as shown in Figure 11 below.

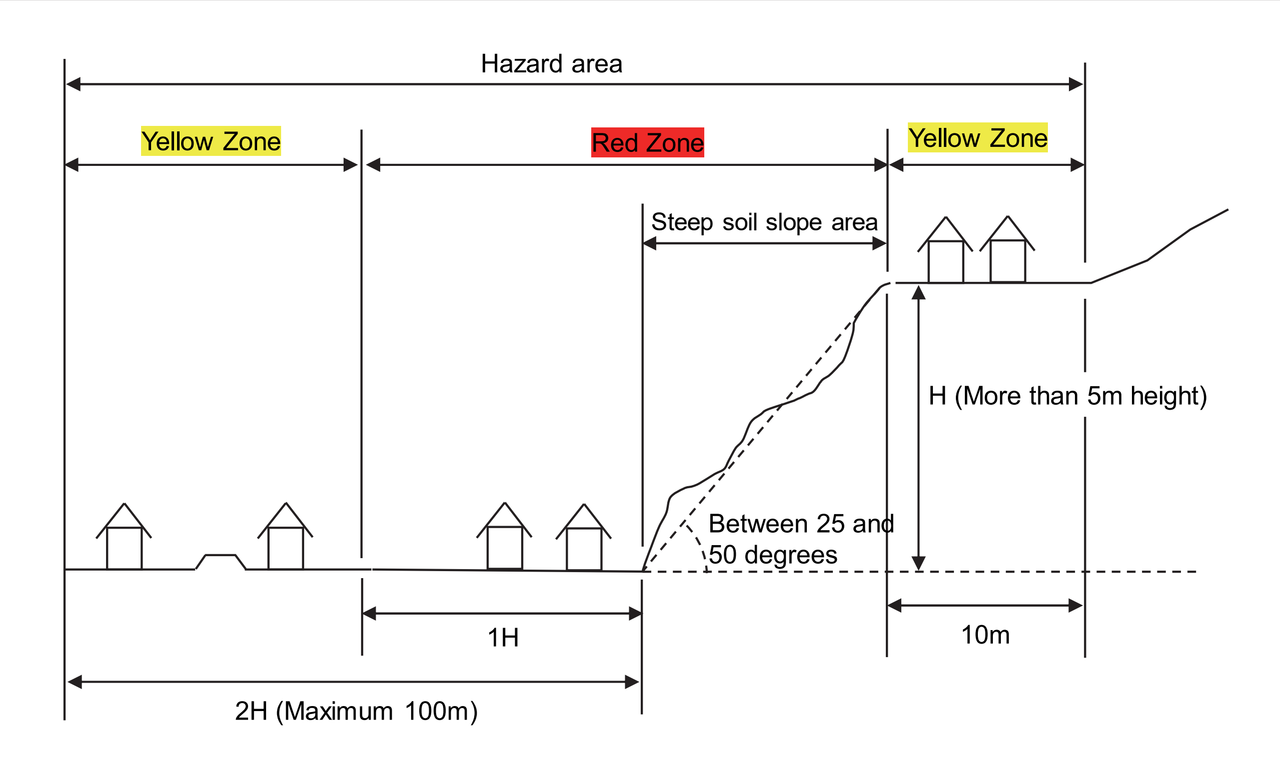


Figure 11. Representation of Yellow and Red Zones for Slope Failure

I) Red Zone

The Red Zone for slope failure shall be set to include (Figure 12):

c) Steep soil slope area (an area having a gradient between 25 and 50 degrees and a height of more than 5 m); and

d) An area located within the height of the steep slope from the bottom of a steep soil slope area.

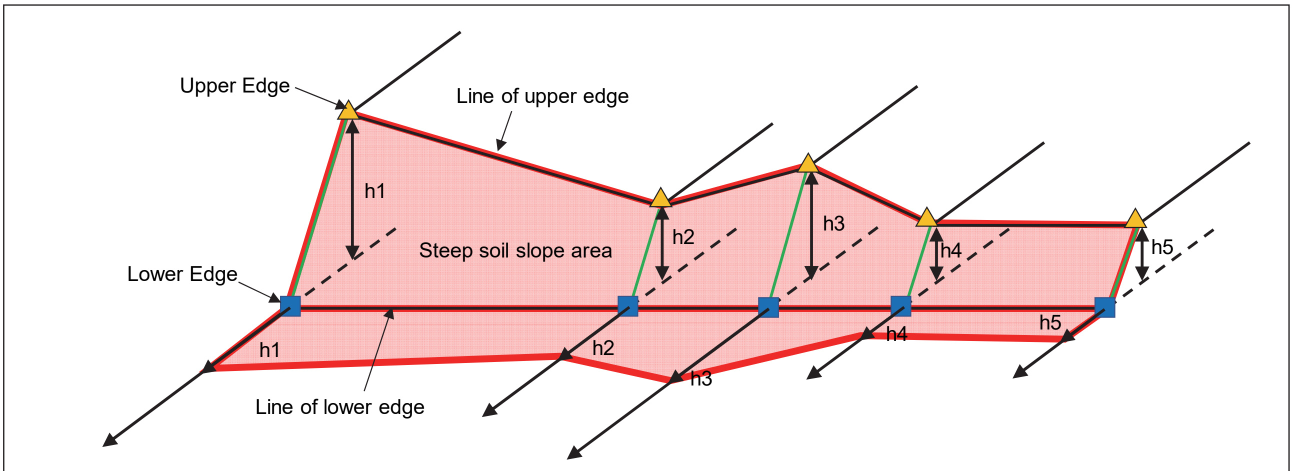


Figure 12. 3D Representation of Red Zone for Slope Failure

II) Yellow Zone

The Yellow Zone for slope failure shall be set to include (Figure 13):

a) Steep soil slope area (an area having a gradient between 25 and 50 degrees and a height of more than 5 m);
b) An area located within a horizontal length of 10 m from the upper edge of a steep soil slope area; and
c) An area located within twice the height of the steep soil slope area (if this exceeds 100 m, the limit is 100 m) from the bottom (or lower edge) of a steep slope area.

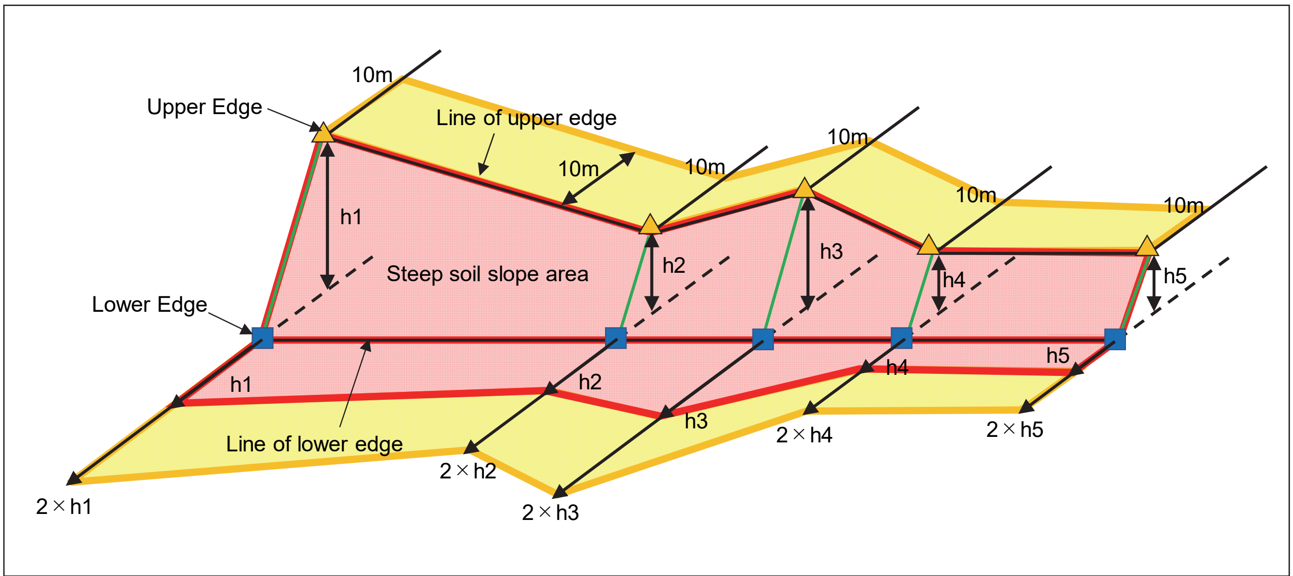


Figure 13. 3D Representation of Yellow Zone for Slope Failure

(8) Excluded Part of the Area where No Collapsed Sediment Is Reached

A part of the area which is clearly not observed within the reach of the collapsed sediment from its topographical features or structural obstacles should be properly modified and then excluded from the Yellow and/or Red zones (Figure 14). These topographical features and structural obstacles are as follows:

- Embankment, Excavation
- Channel, river
- Wall, Retaining wall
- Other structures

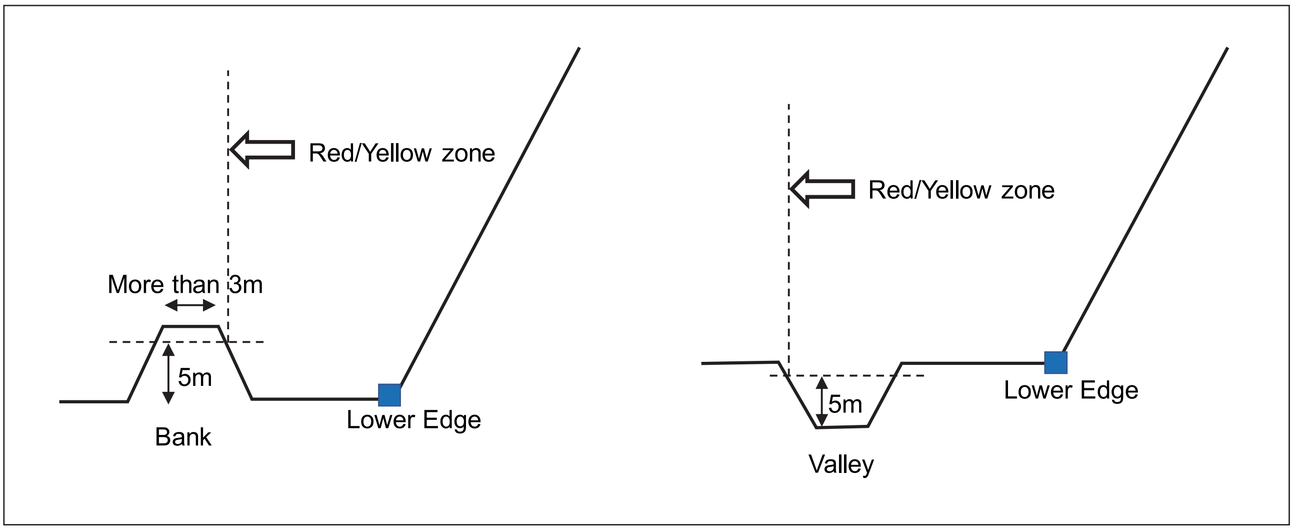


Figure 14. Diagrammatic Illustration of Excluded Part of the Yellow and Red Zones

2.4 Field Survey to Finalize the Zones

Field survey is conducted to finalize the Yellow and Red Zones set by the above-mentioned desk study. The field survey for the target area and its surroundings shall be conducted on the following items:

- Topographical conditions
- Lower and upper edges
- Slope angle and height
- Left and right edges
- Artificial structures, etc.

In addition, if the target area is observed from the field survey to have a slope height of over 100 m and consist of fresh hard rocks with less fractures, it should be excluded from the hazard zones.

REFERENCE DATA

Background Data for Setting Hazard Zone for Slope Failures

About 60 past soil slope failure disasters were collected from:

a) Landslide Disaster May 2017 – Damages and Loss Assessment, Prepared by NBRO, including 35 disaster events occurring in 2017

b) Reduction of Landslide Vulnerability by Mitigation Measure Projects - Cost Benefit Analysis, Prepared by NBRO, in October 2018, including 50 disasters events

The main results of the collected past slope failure disasters are shown in Figures A.1 to A.3 and summarized below:

a) Slope failures are related largely to slope steepness (Figure A.1) and slope height (Figure A.2). When slope angle is 25 degrees or more, the number of slope failures tends to increase rapidly. Most slope failures occurred intensively on slopes with a slope angle of 25 to 50 degrees and a slope height of 5 to 40 m, accounting for about 80% of the total number of the past slope failures.

b) The reaching distances of the collapsed sediment are related to the heights of slope failures (Figure A.3). In most cases, the reaching distances are within twice the height of the slope failures (Figure A.3 - a)), but with a limit of about 100 m (Figure A.3 - b)).

Geologically, the average friction angles are generally around 25 to 35 degrees for loose sandy soils, and 30 to 50 degrees for loose gravelly soils, respectively. A steep slope with a gradient of 25 degrees or more may be likely to occur especially as excessive pore water pressure increase during intense rainfall.

In addition, the elevated steep slopes are more susceptible to become unstable, especially relating to soil slopes. Accordingly a slope height of 5 m or higher can be used to limit the target steep slope selection in consideration of its susceptibility or vulnerability.

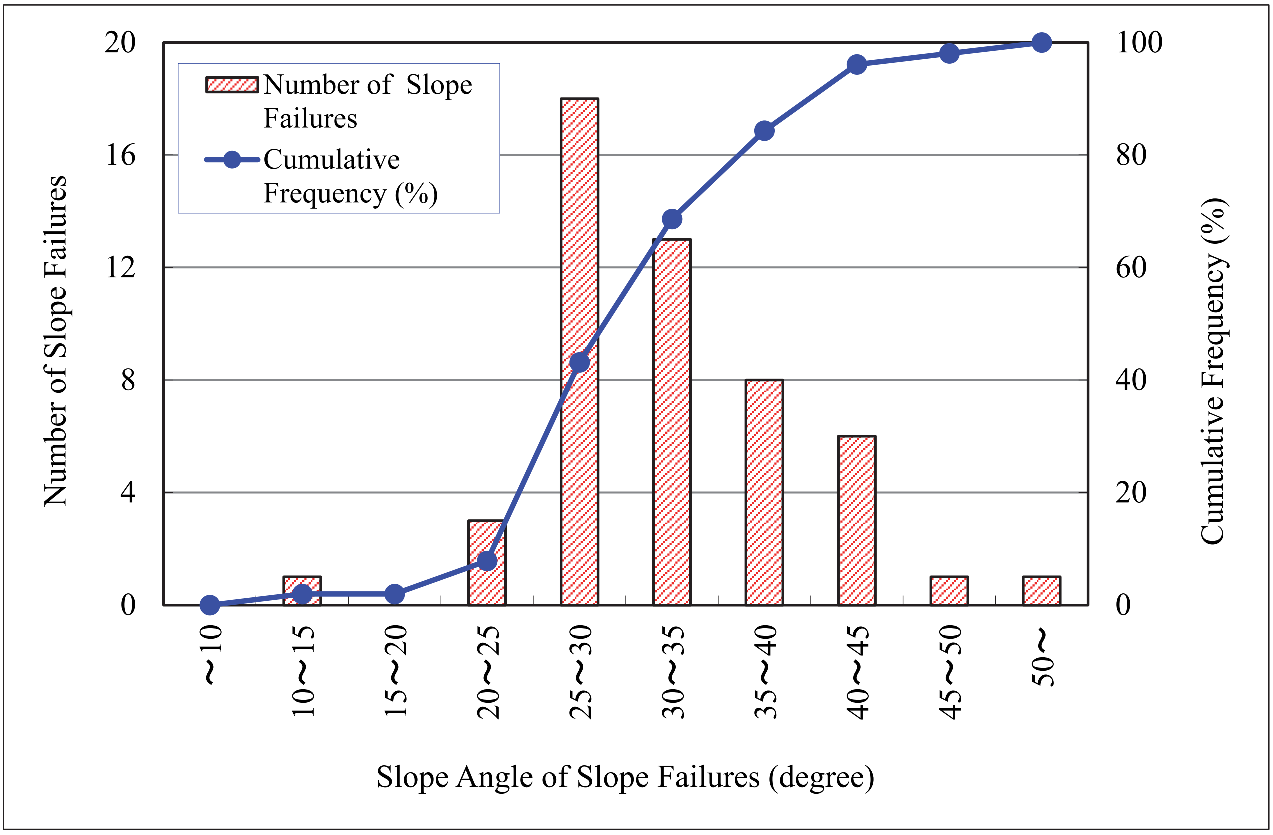


Figure A.1 Frequency Distribution of Slope Angle in Soil Slope Failures

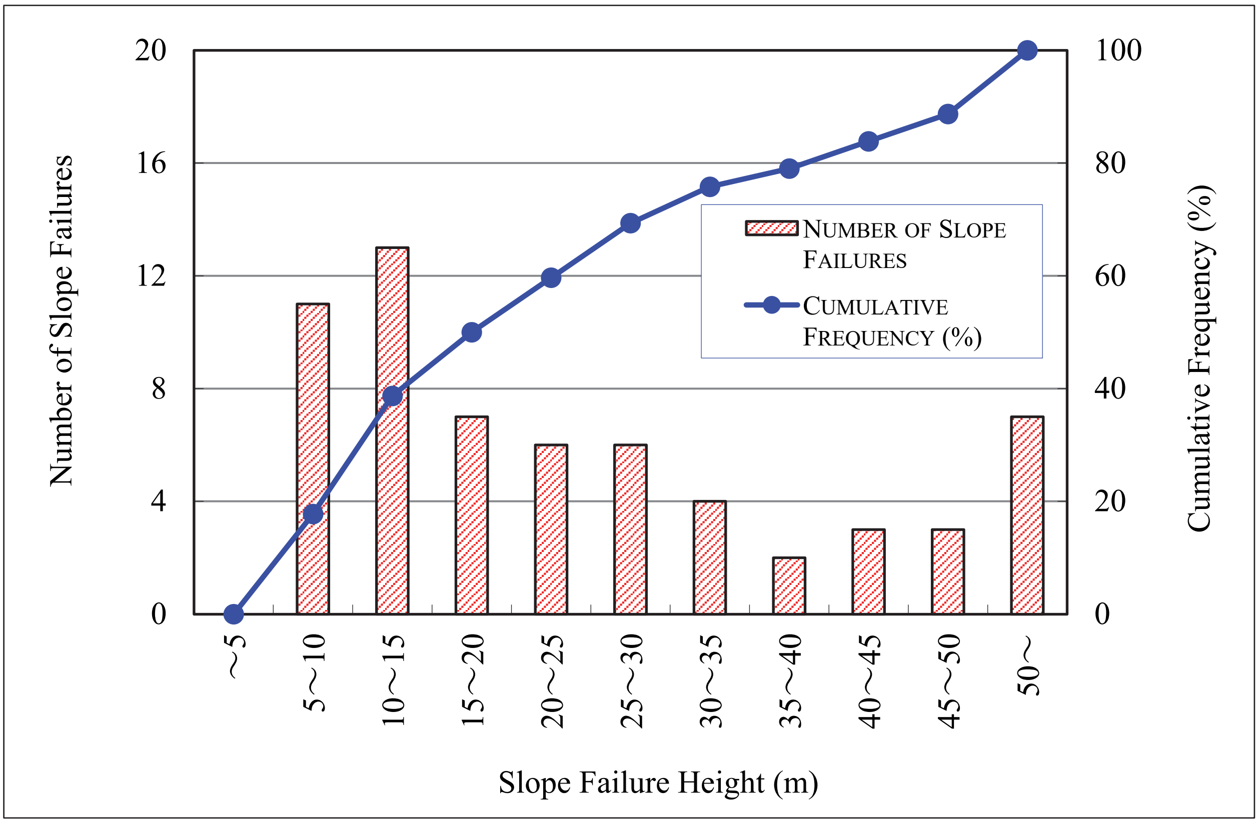
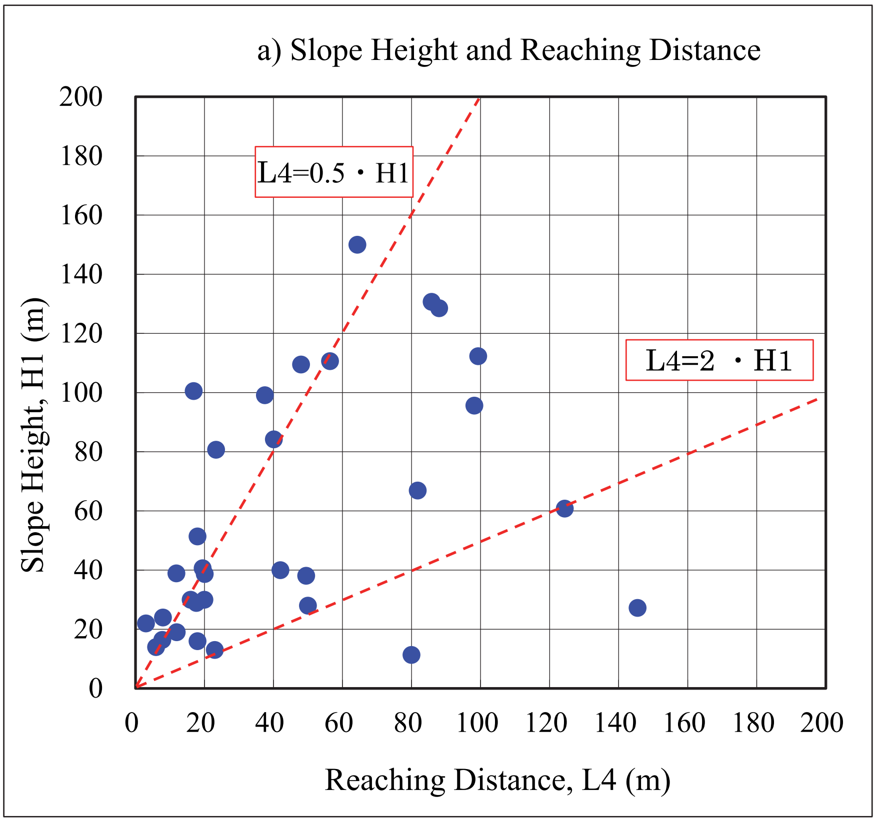


Figure A.2 Frequency Distribution of Height of Soil Slope Failures



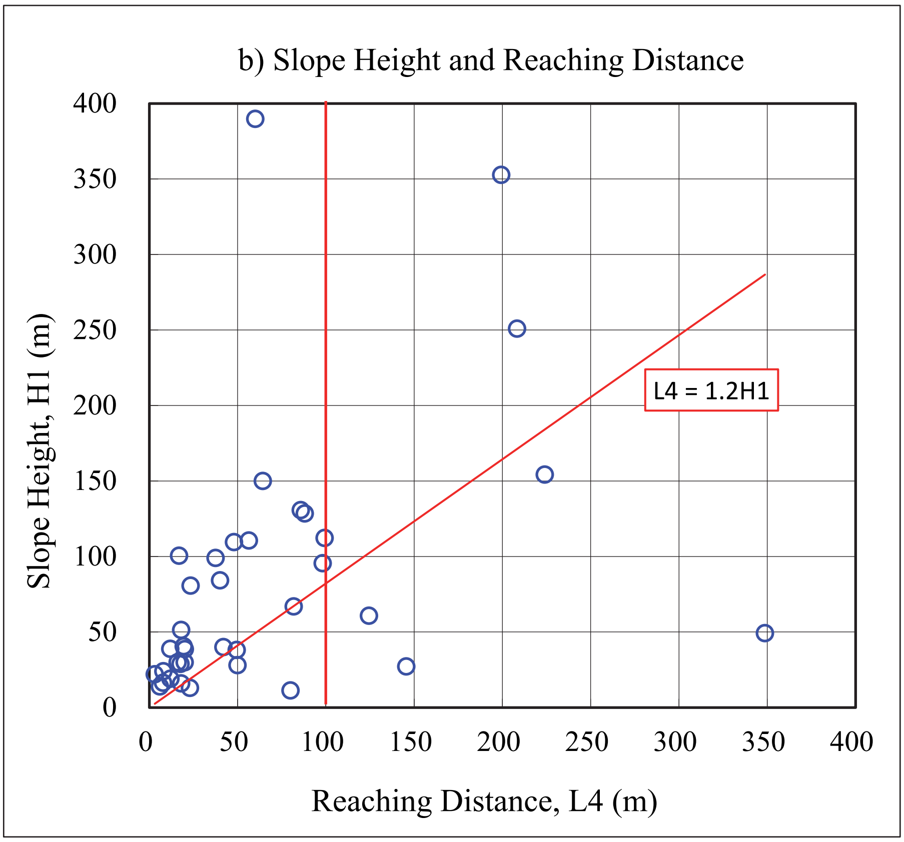
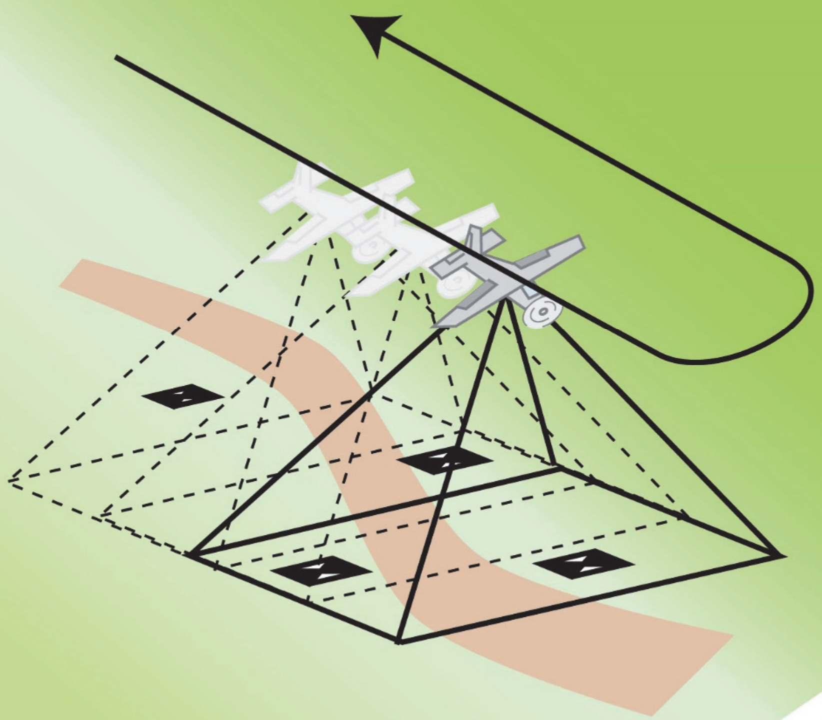


Figure A.3 Relationship between Slope Height and Reaching Distance



Technical Note 2

Aerial Photograph Interpretation of Landslides

Under this technical note, aerial photograph interpretation of landslides is provided as reference for Chapter 5

TECHNICAL NOTE 2

No. : WG01-01
Date : 2019/02/28

Aerial Photograph Interpretation of Landslides

1. Introduction

Previous studies on landslides have indicated that landslides are mostly likely to occur in areas where they have already occurred in the past. In many cases, the topographical features surrounding a landslide area provide evidence of past and ongoing landslide activity. Geologically, landslide activity or movement is one of the geomorphic processes through which hillslopes evolve. The history of landslide activity in any region through time can often be deciphered on scales ranging from some years to decades even longer period. Accordingly, landsliding areas, either past or ongoing, are particularly important to identify, as they may pose a substantial potential for future instability and help identify areas that are susceptible to future landslides.

Aerial photograph interpretation (API) of landslides is done through the visual analysis of stereoscopic aerial photographs, to identify landslide morphological forms - landforms or topographies that are formed associated with landslide activity, thereby identifying landslide areas. The API is the first and important step of landslide investigations. The API technique, as well as other image interpretations such as high-resolution satellite image and light detection and ranging (LIDAR), has become a useful tool for landslide inventory mapping, greatly contributing to assessing landslide hazard, susceptibility and risk, and to developing susceptibility models to predict landslides based on past conditions.

The term “landslide” has been widely used in general sense to describe all types of gravitational slope movements of a mass of rock, debris or earth down a slope, including fall, topple, flow, slide and spread (Varnes, 1978, and Cruden and Varnes, 1996). However, this technical note focuses mainly on landslides that narrowly refers to the slow movement of a mass of rock, debris or earth along a pre-existing shearing surface or zone (surface of rupture). Such landslides generally occur repeatedly over a long period of time.

This technical note is based on the synthesis of literature reviews of relevant references and our experiences. The purpose of this technical note is to provide basic knowledge and guidance on aerial photograph and topographical interpretations for identification and recognition of landslides.

2. Basic Knowledge and Information

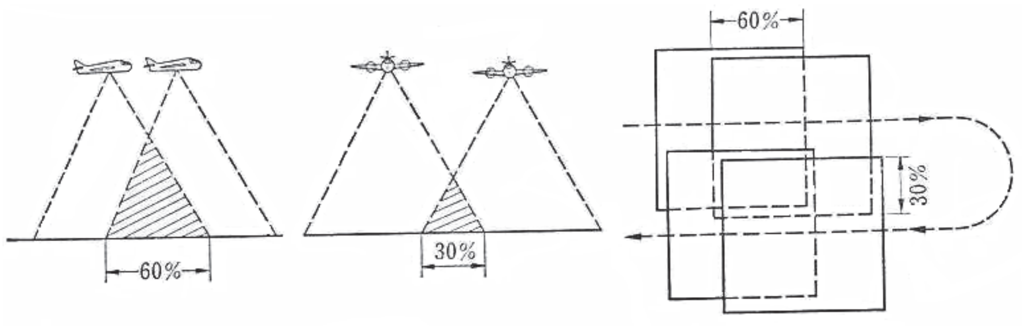
2.1 Photograph Overlap

Aerial photographs are taken from high up in the sky looking down vertically at the ground. The aerial photographs record everything on the ground through the lens of the camera. They consist of a series of images taken from an airplane flying on pre-determined flight paths or lines. These lines are equidistant from, and parallel to one another. Thus, the resulting photographs line up at equal intervals within the flight path, generally with 60% overlap and 30% sidelap (Figure 1).

2.2 Principle Point

The exact center of an aerial photograph is called Principal Point. The principle point is the point on the ground located immediately below the camera lens looking down vertically. The principal point is defined as the intersection point of two diagonal lines between principal point indicating marks on the outer frame of an aerial photograph.

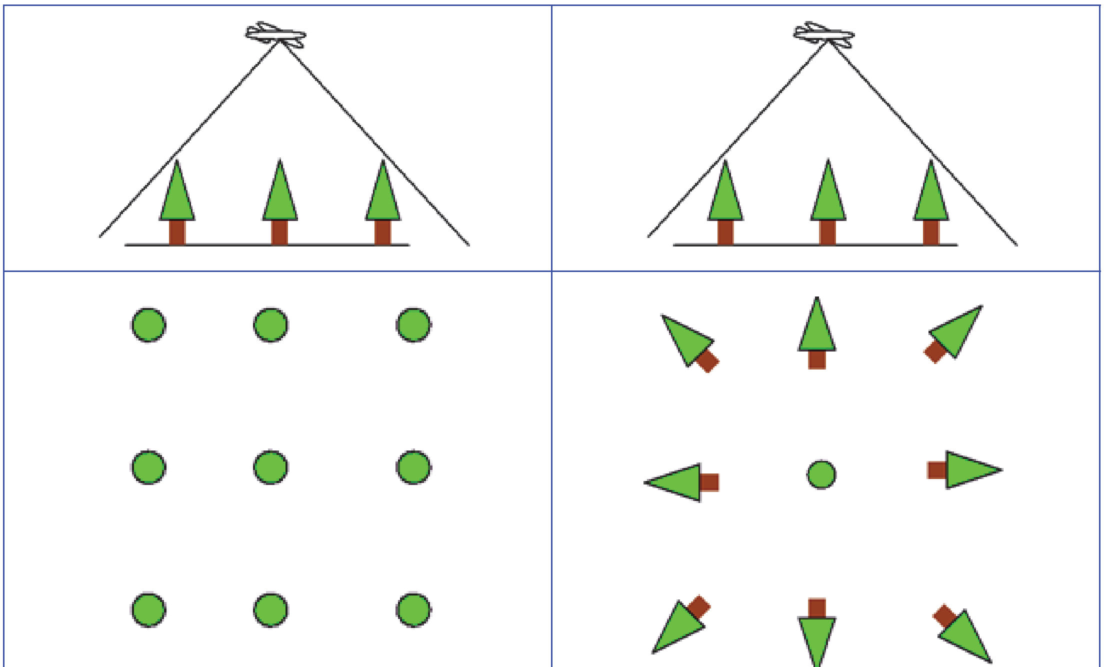
If the airplane is carrying the camera by maintaining a straight-and-level flight path, the appearance of objects at the principal point is identical to how they appear on the ground (Figure 2a). However, when the airplane deviates from a straight-and-level flight path due to air turbulence, the camera lens will tilt slightly, and the photograph will show a slightly slanting view of the objects (Figure 2b).



b) Overlap c) Sidelap a) Photograph overlap

Figure 1 Overlap and Sidelap of Aerial Photographs

In the middle of a photograph (i.e. the principal point), objects are correctly presented in their standing (vertical) position. As airplane moves away from the principal point toward the edge of the photograph, objects appear in a slanting position.



a) Orthographic projection

b) Center point projection

Figure 2 Difference between Center Point and Orthographic Projections

2.3 Principal Line

Because aerial photographs are taken with a 60% overlap., and therefore, the same scene is shown on the right half of the left photograph and the left half on the right photograph. This pair of two photographs is called Paired Photographs. Paired Photos show the same scene but from different slants (or angles). This is the basis for obtaining a stereo view. The principal points of each aerial photograph are also shown on the other aerial photographs of the same scene. The line connecting the principal point on the paired photographs is called the Principal Line. The line shows the flight path followed by the airplane used to take the aerial photographs.

2.4 Photograph Scale and Screen Size

Aerial photographs are generally taken at a scale of 1:10,000 to 1:50,000. The photograph scale, S, is the ratio of a distance between two points on a photograph (picture) to the corresponding actual distance, as in the case of topographic map.

$$S = f/h$$

Where, f: focal distance of lens (mm) and h: flight altitude (m).

For example, if the focal distance and the flight altitude of photographed ground surface are 150 mm and 1,500m respectively, then the aerial photograph scale is

$$S = 150\text{mm}/1{,}500\text{x}1{,}000\text{mm} = 1/10{,}000$$

If the average flight altitude of photographed ground surface is 750m, then the aerial photograph scale is

$$S = 150\text{mm}/(1500\text{-}750)\text{x}1{,}000\text{mm} = 150/750{,}000=1/5{,}000$$

In addition, the effective screen size of aerial photograph is generally 230 mm×230 mm (or 9 inch×9 inch).

2.5 Interpretation Equipment

Aerial photograph interpretation is conducted with a zoom-stereoscope or pocket stereoscope. In addition, ruler, color pencil, and topographical map need to be prepared. The ruler is used for locating principal points and setting the principal lines. Topographic map is used to delineate landslide areas interpreted from aerial photographs for future field check and confirmation.

An experienced geologist can often obtain a stereo-view only through his naked eyes. The following is simple method to help beginners practice stereo-viewing with the naked eye.

a) Place a card standing upright between photograph on the right side and photograph on the left side. This will block the right eye from seeing the left side photograph and the left eye from seeing the right-side photograph.
b) Bring your face close to the photographs and focus each on the photograph (i.e. right eye on right photograph and left eye on left photograph).
c) Focus intensively. You will image that the photographs move close to one another and finally overlap, producing a three-dimensional image.

d) Repeat the above process, to become familiar with the phenomena of two pictures blending into one image.
e) Try the same practice without a card between the right and left side pictures.

3. Aerial Photograph Interpretation (API)

The API generally involves the identification of significant differences appearing on the photographs (ground surface), and then determining what these differences mean. The main factors in interpreting the photographs include shape, size, photographic color, tone, mottling, texture, pattern of objects, site topography, and setting. Shape refers to the form of the topographic surface. Because of the vertical exaggeration of stereoscopic vision, shape is the most useful characteristic for the identification of a landslide from aerial photographs.

Once a landslide occur, the area leaves discernible signs, most of which can be recognized and mapped through the interpretation of (stereoscopic) aerial photographs or field investigation. Most of the signs left by a landslide are morphological i.e., they refer to changes in the form, shape, position, or appearance of the ground (or topographic) surface. Size describes the area extent of an object. The physical dimensions of an object are used to identify properties such as extent and depth. Color, tone, mottling and texture depend on the light reflected by the surface, and can be used to infer rock, soil and vegetation types. Mottling and texture are measures of terrain roughness and can be used to identify surface types and the size of debris. Pattern is the spatial arrangement of objects in a repeated or characteristic order or form.

The interpretation of aerial photographs to recognize landslides generally involves the following three steps (Harold and Liang, 1978):

a) To examine the photographs to get a 3D perception

b) To identify and interpret ground conditions and ground surface features by looking for certain elements (for example, landforms, landscape unit, patterns, etc.) appearing in the photographs

c) To analyze specific problems (landslide topography or similar landforms by geological processes) by the association of ground conditions using photograph interpretation techniques

Figure 3 schematically illustrates landslide features, while Table 1 summarizes typical points for the identification of landslide area. Typically, a landslide area shows below (Figure 3):

a) A horseshoe-shaped or concave scarp – abrupt change in slope profile is interpreted and distinguished by a near vertical or concave slope at the head of the landslide.

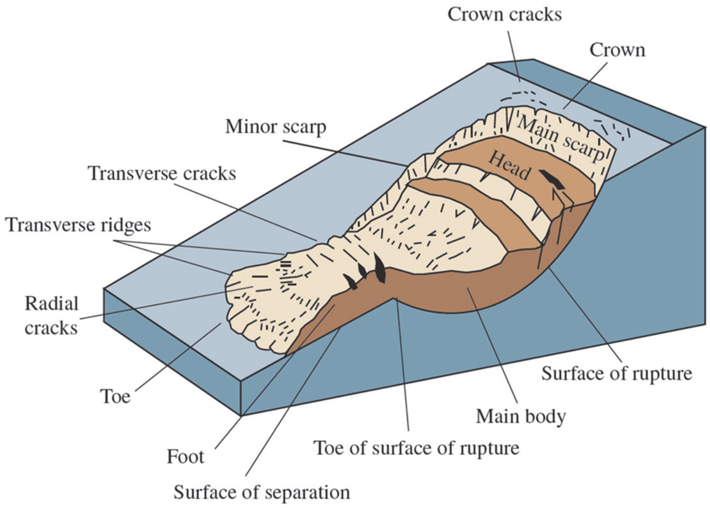
b) There are concavities, depressions, parallel cracks, etc. or there is a long and narrow depression at the upper part of the landslide.

c) Gently, hummocky topography – local topography is uneven particularly in comparison to adjacent areas at the middle part of the landslide.

d) Bulge toe - convex, hummocky zone of accumulation is characterized by the presence of a convex profile and arcuate plan.

e) Deep gullies eroded into the weak, disturbed soils and rock, disrupted or poorly developed drainage patterns and high drainage density; closed depressions and ponds within the landslide area.

a) Photo



b) Graphic illustration

Figure 3 Typical Landslide Topography

In addition, the morphological signature of a landslide depends on landslide type, movement rate and activity. In general, the same type of landslide will result in a similar landslide signature. The morphological signature left by a landslide can be interpreted to determine the extent and arrange of the landslide, to infer the type of landslide, and to divide the landslide area into different movement blocks and their relationship (for example, main blocks, joining blocks, ending blocks, branch blocks, etc.). From the visual appearance of a landslide, qualitative information on the degree of activity, age, and depth and geometry of the rupture surface can be inferred.

Based on the landslide characteristics of the identified items, landslide areas are identified and plotted for further topographic interpretation and field investigation.

Table 1 Summary of Main Features to Be Identified and Interpreted

Item		Description
1	Surface deformation	Head or main scarps, cracks, toe collapses, a marshy zone or a crack on one or both sides of landslide area
2	Micro-relief	Depressions, bulge, small steps, and irregular undulation of slopes.
3	Abnormal landforms	Arch-shaped escarpments, convex ridge, concave mound, steep scarp above a gentle slope, hummocky topography, hillside benches, constrictions and widening of valleys and asymmetrical cross sections, hanging valleys, unusual changes in slope angle, colluvial slopes and alluvial filled river courses, active down cutting.

4	Water fluctuation	hillside ponds, swamps, marshes, linear arrangement of springs and ponds, small gullies, seepage areas, local infiltration sources, disrupted drainages
5	Vegetation	landslide area is generally covered by thin vegetation than its surrounding areas
6	Landslide area	bordered by head scarps (or cracks), toe bulges (or small collapses) and side cracks
7	Movement direction	perpendicular to head scarps or head cracks, and almost parallel to side cracks
8	Geologic information	lineament, rock type, joint condition, double ridges, weathering
9	Deformed facilities	Cracks on house walls, on or across a road, subsidence of house foundation, etc.

4. Topographical Expression and Topographic Interpretation

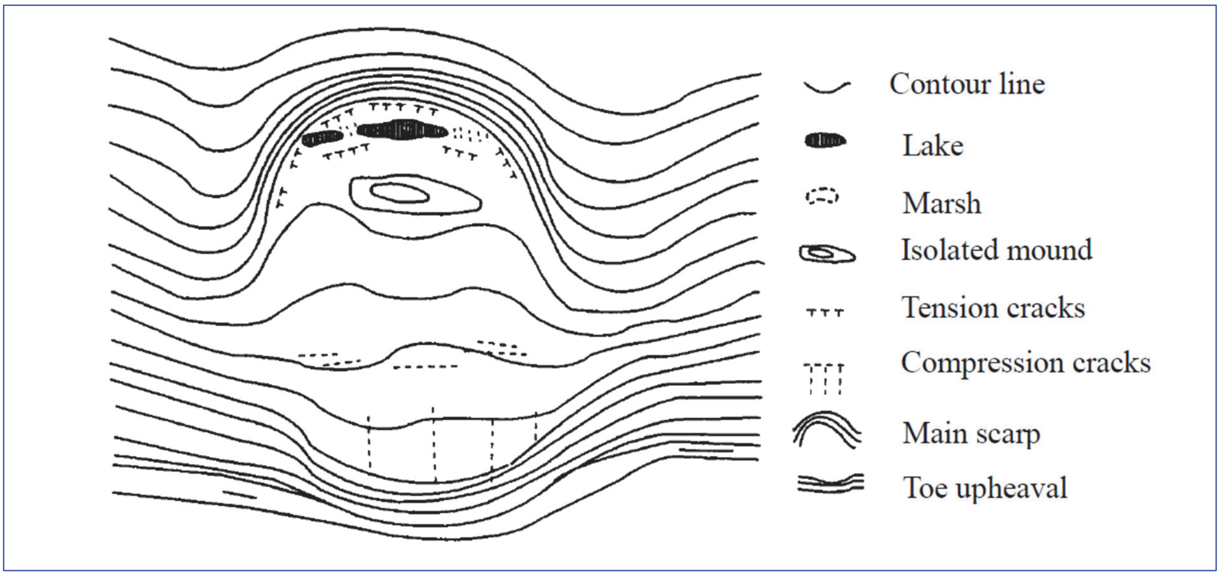
Like aerial photograph interpretation, topographical maps have been used to delineate landslide areas. In general, topographic maps at a scale of 1:1,000 to 1:10 000 is most effective and useful for interpreting landslide areas.

Figure 4 shows the topographical expression of a typical landslide areas. On topographic map, a landslide area shows irregular contour lines compared to its surrounding areas, - contour lines are dense in the upper section of a landslide area, sparse in the middle section, and dense again in the lower section (Figure 4).

In general, different types of landslides have different diagnostic topographic features. As described above, a landslide may move again and again over a long time. In Japan, landslides are subdivided, in terms of movement process and material type, into the following four types (Watari, 1987), as shown in Figure 5, of which type has different topographical features, as summarized in Table 2.

a) Bedrock landslide
b) Weathered rock landslide
c) Colluvial soil landslide
d) Cohesive soil landslide

The classification scheme considers mainly a) type of landslide material, b) geology and topography, c) velocity of movement, and d) degree of activity, and has been used for the identification of landslides, and the management and reduction of landslide risks in Japan.



Source: Modified from Watari, 1987

Figure 4 Topographical Expression of a Landslide Area

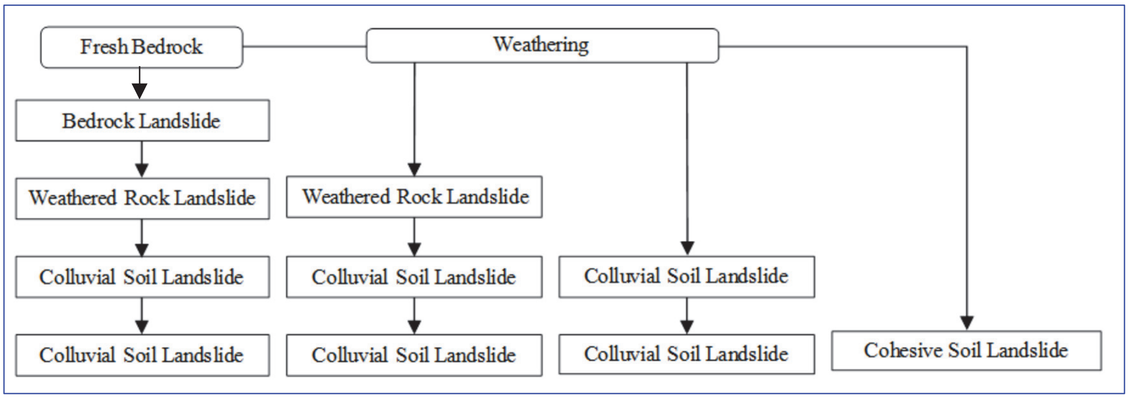
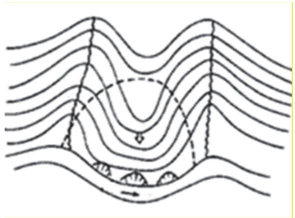
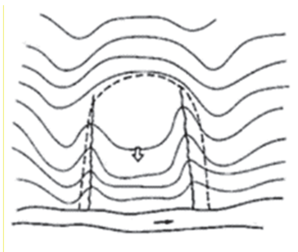
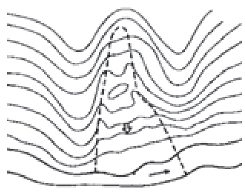


Table 2 Summary of Topographic Features Related to Different Landslide Type

Landslide Type	Main Topographic Feature	Plan sketch
Bedrock	- Mostly occurs with a convex-ridge type landform, but generally without clear topographic features because of first-time slide - Involves fresh rock with joint controlled crown and rupture surface. - Main carps are near vertical, with chair-shaped or planar rupture surface. - Cracks occur in proportion to the movement distance, first developing at the flanks, toes and heads of the landslides. - Small collapses may be caused by compression at the toes.	
Weathered rock	- Has a clear landslide topography – convex-plateau landform due to its large-distance movement and recurrence. - The rupture surfaces tend to be planar near the toe and become circular towards the heads with further movement. - Accompanying colluvial and cohesive soil collapses may occur around the toes. - Shows clear vegetation contrast with surroundings, and absence of land use indicative for activity.	
Colluvial soil	- Has a clear landslide topography – concave landform, mostly subdivides into some blocks. - Shows stepped and hummocky slope within the landslide areas. - Accompanies the distribution of ponds, swamps and hollows. Sometime shows parallel drainage on both sides of landslide areas	
Cohesive soil	- Shows clear landslide topography – generally long, gently, narrow, concave slopes, and mostly subdivides into multiple small slide blocks. - Landslide mass displays clear flow structure (ground appearance) with arcuate convex toe part. - Drainage is generally defected or blocked by frontal bulges	

5. Field Check and Confirmation

The identification of landslide areas and blocks based on the interpretation of aerial photographs and topographic maps is an essential part of landslide investigation. However, the results and precision of photograph and topographic interpretations generally vary with such factors as the time when the photographs are taken, photograph scale, difference in flight altitude within the landslide areas to be investigated, vegetation cover, colors, land use, etc.

In addition, landslides are mostly undergoing dissection due to erosion and human activity, and therefore are difficult to be recolonized from aerial photograph and topographic interpretations. Moreover, because morphological convergence is possible, resulting in the same or similar morphological forms from different geological processes, not from landslide activity.

Therefore, following the interpretation of aerial photographs and topographic maps, field investigation shall be further conducted to supplement the interpreted results.

In addition to the above-mentioned landslide topographies, field investigation should be carried out to verify landslide occurrences and to identify any landslide signs not observed on aerial photographs and topographical maps, particularly focusing on the followings:

a) Shape of scarps and distribution of cracks: The location and direction of movement of landslide head part can be generally estimated from the shape of concave scarps. The boundaries of a landslide area and its blocks can be delineated from the distribution of cracks.
b) Local small settlements and bulges: Geometric shape of topography and configuration of cracks indicate approximate locations and ranges of tension and compression zones. This information is very useful for delineating landslide area and subdividing movement blocks within a landslide area.
c) Steps, land use (boundaries of land, location of roads and houses, etc.): These may show signs of previous ground movements. Such information is useful in identifying landslide area and its movement blocks.
d) Coniferous trees with curved or bent roots and bamboo forest (which are usually wet/damp): These are places to check and determine if there is any potential or previous landslide areas.
e) New cracks and signs of previous cracks: The arrange of landslide areas, and previous and present movements can be estimated from such cracks and signs of previous cracks. The information is useful in evaluating landslide activity and delineating landslide areas.
f) Distribution and location of cracks, present and previous: The information provides clues to estimating or identifying landslide activity, movement direction, geometry of rupture surface, and tension and compression zones.

6. Summary and Recommendations

a) Aerial photograph and topographic interpretations together with field investigation have been the most useful and widely used methods to locate and identify landslides particularly on a wide scale. They have been used to develop landslide inventory maps to a large region, providing the basis for assessing landslide hazard, susceptibility and risk.

b) No standards of aerial photograph and topographic interpretations exist. Such interpretations, empirical and uncertain techniques, are based on interpreter's experience and on the analysis of a set of landslide morphological forms (or signatures by landslide) identified and interpreted from aerial photographs. An effort should be made to improve interpretation capacity through the repetition of interpretation and field confirmation.

c) The interpretation of aerial photographs has been described in detail, including geological and topographic interpretations in many textbooks, to which reference is made for further information and guidance.

7. References

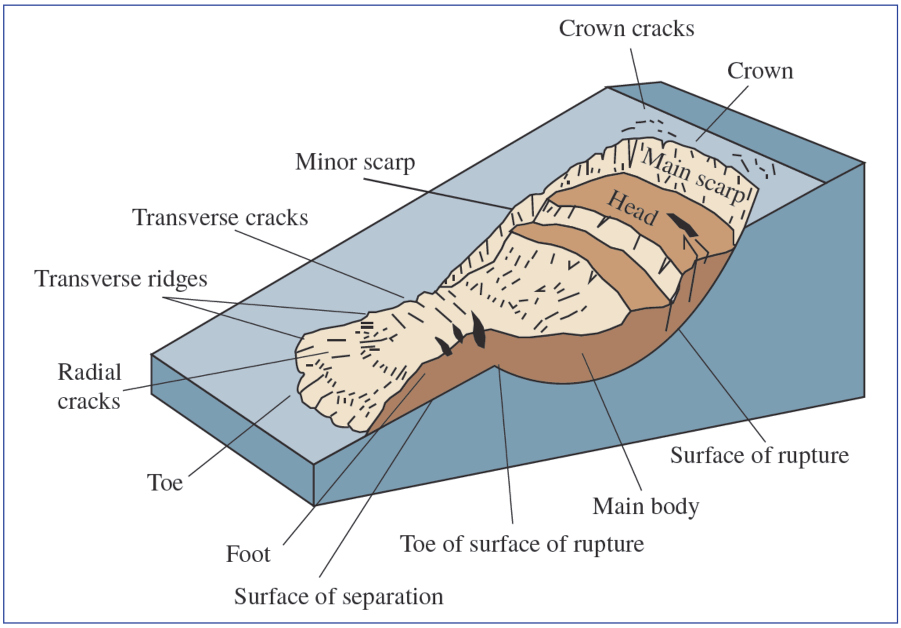
Cruden, D. M., & Varnes, D. J. (1996). Landslide Types and Processes. In A. K. Turner & R. L. Schuster (Eds.), Landslides Investigation and mitigation. Washington, D. C.: Transportation Research Board, Transportation Research Board. Special Report 247, p. 36–75.

Harold T. R. and T. Liang, 1978, Recognition and Identification, in Schuster, R.L., and Krizek, R.J., eds., Landslides Analysis and Control, Special Report 176: Washington, D.C., Transportation Research Board and National Academy of Sciences, p.34–79.

Varnes, D.J., 1978, Slope movement types and processes, in Schuster, R.L., and Krizek, R.J., eds., Landslides Analysis and Control, Special Report 176: Washington, D.C., Transportation Research Board and National Academy of Sciences, p.11–33.

Appendix A Definitions of Key Landslide Features

The key landslide features are generally defined as follows (see Table A01 and Figures A01 and A02):



Source: Varnes (1978)

Figure A01. Typical Landslide with Commonly Accepted Terminology

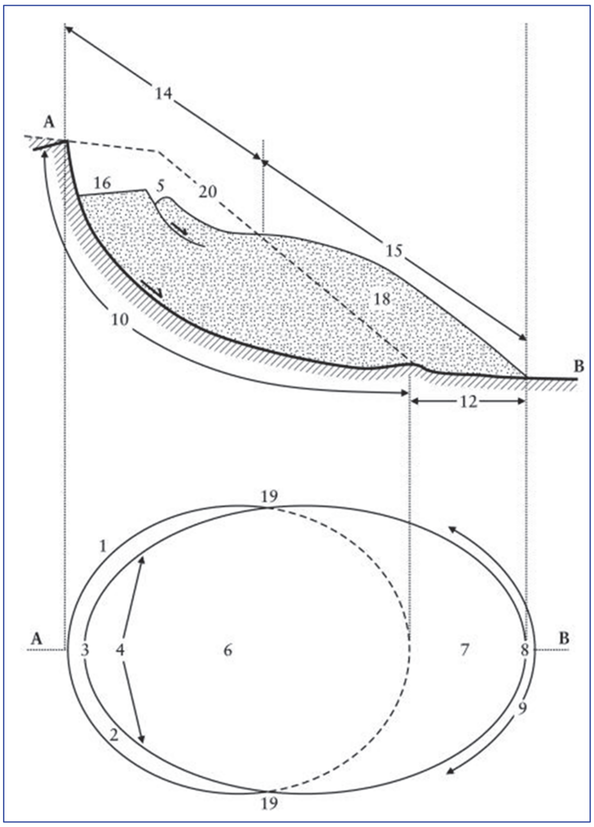


Figure A02. Illustration of section and plan views of a landslide

Table A01. Definition of Key Landslide Features

No.	Name	Definition
1	Crown	The practically un-displaced material still in place and adjacent to the highest parts of the main scarp.
2	Main Scarp	A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part if the surface of rupture.
3	Top	The highest point of contact between the displaced material and the main scarp.
4	Head	The upper parts of the landslide along the contact between the displaced material and the main scarp.
5	Minor Scarp	A steep surface on the displaced material of the landslide produced by differential movements within the displaced material.
6	Main Body	The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture.
7	Foot	The portion of the landslide that has moved beyond the toe of the surface of rupture and overlies the original ground surface.
8	Tip	The point of the toe farthest from the top of the landslide.
9	Toe	The lower, usually curved margin of the displaced material of a landslide, it is the most distant from the main scarp.
10	Surface of Rupture	The surface which forms (or which has formed) the lower boundary of the displaced material below the original ground surface.
11	Toe of the Surface of Rupture	The intersection (usually buried) between the lower part of the surface of rupture of a landslide and the original ground surface.
12	Surface of Separation	The part of the original ground surface overlain by the foot of the landslide.
13	Displaced Mass	Material displaced from its original position on the slope by movement in the landslide. It forms both the depleted mass and the accumulation.
14	Zone of Depletion	The area of the landslide within which the displaced material lies below the original ground surface.
15	Zone of Accumulation	The area of the landslide within which the displaced material lies below the original ground surface
16	Depletion	The volume bounded by the main scarp, the depleted mass and the original ground surface.
17	Depleted Mass	The volume of the displaced material, which overlies the rupture surface but underlies the original ground surface.
18	Accumulation	The volume of the displaced material, which lies above the original ground surface.
19	Flank	The un-displaced material adjacent to the sides of the rupture surface. Compass directions are preferable in describing the flanks but if left and

		right are used, they refer to the flanks as viewed from the crown.
20	Original Ground Surface	The surface of the slope that existed before the landslide took place.

Source: Modified from Multilingual Landslide Glossary (WP/WLI, (1993).

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