Simple Method for Identifying Unstable Slopes Based on Topographical and Geological Conditions

Yuichiro NISHIKANE Takeshi KAWAGOE Takuya URAKOSHI
Geology Laboratory, Disaster Prevention Technology Division

Tomokazu ISHIHARA
Geology Laboratory, Disaster Prevention Technology Division

Previous studies have reported that topographical and geological conditions influence shallow landslides. However, identifying unstable slopes based on these conditions needs professional knowledge and detailed surveys. This report statistically examines topographical and geological data in order to extract topographical and geological conditions which are useful for identifying unstable slopes from those reported in previous studies. Based on the results, a simple procedure is proposed for identifying unstable slopes.

Keywords: shallow landslide, topographical and geological condition, field observations, map interpretation, Hayashi’s quantification method II

1. Introduction

Shallow landslides are affected by topographical and geological conditions. Therefore, these conditions are important clues for identifying unstable slopes susceptible to shallow landslides. Various conditions involved in landslides have been reported in literature about the analysis of past slope disasters [1]. Some of the conditions are explained qualitatively, and identification of unstable slopes based on these conditions needs professional knowledge and detailed surveys. Therefore, some simple method for identifying unstable slopes is desired to facilitate railway maintenance. This study presents a simple method developed for identifying unstable slopes. We examined statistically topographical and geological data in order to extract the topographical and geological conditions which are useful for identifying unstable slopes from those reported in previous studies. These data were obtained from field observations and map interpretations in the study areas where a number of shallow landslides have occurred recently.

2. Review of the previous studies

A study was made of topographical and geological conditions involved in shallow landslides and reported in previous studies. These conditions were categorized into two groups (a) and (b) (Table 1).

| Area               | Topographical and geological conditions | Reference | (a) The acquisition method | (b) The relationship with shallow landslides |
|--------------------|----------------------------------------|-----------|---------------------------|---------------------------------------------|
| Whole slope        | Angle of over 30 degrees               | [2]       | ○                         | ○                                           |
|                    | Concave slope                          | [3]       | ○                         | ○                                           |
|                    | Valley slope                           | [3]       | ○                         | ○                                           |
|                    | Outfacing                              | [4]       | ○                         |                                              |
|                    | Weathered soil                         | [4]       | ○                         |                                              |
|                    | Tree lean                              | [5]       | ○                         |                                              |
| Source area        | Convex break of slope                  | [3]       | ○                         | ○                                           |
|                    | Steep rock slope                       | [1]       | ○                         | ○                                           |
|                    | Spring                                 | [4], [6]  | ○                         | ○                                           |
|                    | Crack on slope                         | [6]       | ○                         | ○                                           |
|                    | Soil creep                             | [5]       | ○                         | ○                                           |
| Moving area /      | Fan-like gentle slope beneath an escarpment | [1]   | ○                         | ○                                           |
| Settled area       | Mound beneath an escarpment            | [1]       | ○                         | ○                                           |

Table 1 Topographical and geological conditions involved in shallow landslides

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(a) Acquisition method for topographical and geological data
- The conditions were classified into two categories based on the acquisition method for topographical and geological data; the first category contained data mainly obtained by map interpretation, and the other data collected through field observations. Some of the conditions were classified into both categories.
(b) The relationship between shallow landslides and topographical and geological conditions
- The conditions were classified into three groups, namely “factor”, “sign” and “result” based on their relationship with shallow landslides. The “factor” group contained conditions susceptible to cause a shallow landslide. The “sign” and “result” groups contained data relating to before and after a shallow landslide, respectively.

3. Study areas
The study areas were each 5 km × 5 km in size and located in Chuetsu, Niigata Pref. and in Hofu, Yamaguchi Pref., respectively in Japan. In Chuetsu, a series of earthquakes triggered a number of shallow landslides in 2004. This area had experienced heavy rainfalls three months before the earthquake, and the heavy rainfalls also triggered some shallow landslides [7]. In Hofu, a number of shallow landslides and mud flows occurred because of heavy rainfall in 2009 [8]. The Chuetsu study area is located in a hilly region with altitudes of 300-350 m, consisting mostly of alternation of strata of Miocene-Pliocene sandstone and mudstone. The study area in Hofu is located in a mountainous region with altitudes of 250-400 m, and consists mostly of late Cretaceous granitic rock.

4. Selection of landslide and non-landslide sites
Landslide sites in the study areas were selected by interpreting aerial photos taken before and after the disasters. 106 landslide sites were identified in the Chuetsu area and 193 in the Hofu area. Non-landslide sites were also selected in order to compare topographical and geological settings between landslide and non-landslide sites. Non-landslide sites in this report are defined as slopes that did not collapse. The non-landslide sites were selected by generating random numbers on the coordinates on maps of the study areas excluding landslide areas, ponds and artifacts. 400 non-landslide sites were randomly selected in each study area. The locations of the landslide sites and non-landslide sites for part of the study area are shown in Fig. 1.

5. Map interpretation and Hayashi’s quantification method II
5.1 Acquisition of topographical and geological information
Topographical and geological data of slopes where landslide and non-landslide sites were located was acquired using 1:25,000 topographic maps and geological maps. Topographical data of landslide sites was interpreted using topographic maps drawn before the landslides occurred. The items of topographical data used are described below based on their topographical classification [9, 10].
(a) Vertical cross-section shape of slope (Fig. 2(a))
(b) Horizontal cross-section shape of slope (Fig. 2(b))
(c) Slope angle
(d) Location on vertical cross-section of slope (Fig. 2(c))
Additionally, the following items of geological informa-
Fig. 3 Relationship between the direction of the dip in the slope and that of the geological structure

Fig. 4 Result of Hayashi’s quantification method II

Table 2 is the ratio of sites where each condition was satisfied, defined by (1). It was calculated both in the landslide site and that of the non-landslide site. The results of this verification are shown in Table 2. Cross-checks were conducted at 44 landslide sites and 36 non-landslide sites in Chuetsu, and 5 landslide sites and 2 non-landslide sites in Hofu. The “satisfaction ratio” in the Table 2 is the ratio of sites where each condition was satisfied, defined by (1). It was calculated both in the landslide site and in the non-landslide site.

6. Field observation

Field observations were made and checked to ascertain whether or not the respective landslide and non-landslide sites in both the study areas satisfied the topographical and geological conditions reviewed in Chapter 2.

The results of this verification are shown in Table 2. Cross-checks were conducted at 44 landslide sites and 36 non-landslide sites in Chuetsu, and 5 landslide sites and 2 non-landslide sites in Hofu. The “satisfaction ratio” in the Table 2 is the ratio of sites where each condition was satisfied, defined by (1). It was calculated both in the landslide site and in the non-landslide site.

\[ R = \frac{N_{\text{satisfied}}}{N_{\text{checked}}} \]  

where \( R \) is the “satisfaction ratio” (%); \( N_{\text{satisfied}} \) the number of sites where a condition was satisfied; and \( N_{\text{checked}} \), the number of sites where fulfillment of the condition could be checked.

A Fisher’s exact test [12] was carried out to examine the significant difference between the satisfaction ratio of the landslide site and that of the non-landslide site. The Fisher’s exact test is a statistical significance test used in the analysis of contingency tables, and is valid for all sample sizes. As a result of the test, the significant difference at 5% significant level was confirmed in the satisfac-
Table 2 Result of field observations in Chuetsu and Hofu

| Area              | Topographical and geological conditions | Checked Chuetsu | Recognized Chuetsu | Non-landslide site | P-value* |
|-------------------|----------------------------------------|----------------|--------------------|--------------------|----------|
| Whole slope       | Angle of over 30 degrees               | 44             | 5                  | 43                 | 3        | 93.9    | 36       | 2        | 22      | 2        | 63.2    | < 0.001 |
|                   | Concave slope                          | 25             | 4                  | 3                  | 0        | 10.3    | 34       | 2        | 6       | 0        | 16.7    | 0.72     |
|                   | Valley slope                           | 40             | 5                  | 20                 | 5        | 35.6    | 34       | 2        | 7       | 1        | 22.2    | < 0.001 |
|                   | Tree lean                              | 8              | 4                  | 5                  | 0        | 41.7    | 17       | 2        | 9       | 0        | 47.4    | 0.4      |
|                   | Convex break of slope                  | 42             | 4                  | 37                 | 3        | 87.0    | 35       | 2        | 8       | 1        | 24.3    | < 0.001 |
| Source area       | Steep rock slope                       | 11             | 0                  | 4                  | 0        | 36.4    | 35       | 2        | 4       | 0        | 10.8    | 0.068    |
|                   | Spring                                 | 22             | 4                  | 10                 | 1        | 42.3    | 15       | 1        | 1       | 0        | 6.3     | 0.015    |
|                   | Crack on slope                         | 5              | 4                  | 0                  | 0        | 0.0     | 9        | 0        | 0       | 0        | 0.0     | 1        |
|                   | Soil creep                             | 2              | 3                  | 1                  | 0        | 20.0    | 9        | 0        | 1       | 0        | 11.1    | 1        |
| Moving area/      | Fan-like gentle slope beneath a steep  | 23             | 5                  | 10                 | 3        | 46.4    | 25       | 2        | 1       | 0        | 3.7     | < 0.001 |
| Settled area      | Mound beneath a steep escarpment        | 21             | 5                  | 1                  | 0        | 3.8     | 26       | 2        | 0       | 0        | 0.0     | 1        |

* P-value was calculated by the Fisher’s exact test (two-sided test).

It was confirmed that the “Slope angle” contributed to discriminating between landslide and non-landslide sites only in Chuetsu. In Hofu, a lot of shallow landslides occurred in lower slopes (valley walls) whose angles are around 40 degrees and on gentle slopes near crests. Weathered granitic bedrock was distributed in the lower slopes, and decomposed granite soil was distributed near the crests. It is considered that the reason why “slope angle” was excluded from the explanatory variables applied to the analysis is because a large number of shallow landslides occurred not only on steep slopes but also on shelving slopes in Hofu.

7. Discussions

7.1 Comparison of the results between Hayashi’s quantification method II and field observation

As a result of Hayashi’s quantification method II, the conditions of “convex” in the vertical cross-section shape of slope and “valley” in the horizontal cross-section shape of slope were confirmed to contribute largely to shallow landslides both in Chuetsu and in Hofu. In Chuetsu, the condition of “over 40 degrees” in the slope angle was also confirmed to contribute largely to shallow landslides. The condition of “convex” in the vertical cross-section shape of slope corresponded to the convex break of slope in the field observations. The positional relation between landslide sites and the topographical conditions which contribute largely to shallow landslides in Chuetsu is shown in Fig. 5. This figure shows that most landslide sites are located on slopes with these topographical conditions.

7.2 Conditions worthy of particular attention for identifying unstable slopes

The topographical and geological conditions reviewed in Chapter 2 should be useful for identifying unstable slopes susceptible to shallow landslides. Among these conditions, “valley slope” and “convex break of slope” were verified by Hayashi’s quantification method II in Chuetsu and in Hofu. Both these conditions also showed a significant difference in the satisfaction ratio. Therefore, both conditions are largely involved in shallow landslide, and should be given particular attention for identifying unstable slopes.

The condition “Angles of over 30 degrees” had been detected as a condition involved in shallow landslides according to the review of results from previous studies. Furthermore, slope angles of over 40 degrees were found to contribute to shallow landslides in Chuetsu, through Hayashi’s quantification method II. These results confirm that angles of over 30 degrees, especially over 40 degrees, are a condition which can cause shallow landslides.

The conditions of “spring” and “fan-like gentle slope beneath an escarpment” were also confirmed to be involved in shallow landslides. The former is a “sign” of shallow landslide occurrence, while the latter is a “result” (Table 1). Conditions which are a “sign” of shallow landslide occurrence are important for identifying unstable slopes. Therefore, the spring should be checked in field observations to identify unstable slopes. From these discussions, “convex break of slope”, “valley slope”, “angle of over 40 degrees” and “spring” were categorized as conditions worthy of particular attention. A simplified schematic showing these conditions is shown in Fig. 6.

Conditions to be focused on for identifying unstable
slopes were arranged into two lists (“List A” and “List B”) (Table 3). List A and List B show conditions which are mainly recognized through map interpretation and field observations, respectively.

### 7.3 Use of the lists for identifying unstable slopes

A procedure for identifying unstable slopes adjacent to railway lines using the lists was proposed (Fig. 7). The procedure is as follows:

1. **Map interpretation (using List A)**
   - Check whether or not slopes adjacent to the railway line satisfy the conditions in List A through topographic and geological map interpretation.

2. **Selection of slopes with conditions indicating instability**
   - Select slopes which match either one or more conditions in List A indicating instability. The selected slopes are then flagged as being potentially unstable.

3. **Field observations**
   - Conduct field observations of the selected slopes to confirm the results of the map interpretation conducted in procedure (1) and to check whether or not the slopes satisfy the conditions in List B relating to field observations.

4. **Selection of slopes which should be investigated in detail**
   - Select slopes which also satisfy many of the conditions in List B. The selected slopes should be investigated in detail to assess susceptibility to shallow landslides.

### Table 3 The lists of the conditions worthy of focus for identifying unstable slopes susceptible to shallow landslides

| List A                                                                 | List B                                                                 |
|-----------------------------------------------------------------------|-----------------------------------------------------------------------|
| **Conditions which are mainly recognized by the map interpretation**  | **Conditions which are recognized by the field observation**          |
| Convex break of slope                                                 | Angle of over 40 degrees                                              |
| Valley slope                                                          | Spring                                                                |
| Angle of over 30 degrees                                              | Tree lean                                                             |
| Fan-like gentle slope beneath a steep escarpment                      | Weathered soil                                                       |
| Outfacing                                                            | Soil creep                                                           |
| * The conditions in bold are the conditions worthy of particular attention. | Crack on slope                                                       |
8. Conclusions

This study confirms topographical and geological conditions involved in shallow landslides reported in previous studies using statistical surveys. As a result of the statistical surveys, the following conditions were confirmed as being a significant contribution factor to shallow landslides in the study areas: 1) convex break of slope, 2) valley slope, 3) angle of over 40 degrees and 4) spring. Additionally, the key conditions identified as contributing to landslides were organized into two lists and a procedure was proposed for identifying unstable slopes using these lists.

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Authors

Yuichiro NISHIHKANE
Researcher, Geology Laboratory, Disaster Prevention Technology Division
Research Areas: Engineering geology

Takeshi KAWAGOE
Senior Chief Researcher, Laboratory Head, Geology Laboratory, Disaster Prevention Technology Division
Research Areas: Engineering geology, Civil Engineering

Takuya URAKOSHI
Assistant Senior Researcher, Geology Laboratory, Disaster Prevention Technology Division
Research Areas: Ground water, Engineering geology

Tomokazu ISHIHARA
Researcher, Geology Laboratory, Disaster Prevention Technology Division
Research Areas: Engineering geology