Slope Management Planning for the Mitigation of Landslide Disaster in Urban Areas

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Abstract

Japan is susceptible to slope failures and landslides. This paper will demonstrate how municipal governments can manage landslides with the use of inspection records and spatial data. Specifically, the study applies a multivariate analysis method, quantification theory type 2, to statistically evaluate the risk of slope failures caused by geomorphological factors. The scores from these analytical results reflect the risk of the slopes sampled in the analysis. We also analyze rainfall factors in order to determine the critical rainfall line and evaluate the critical line of the linear type conventionally used in disaster forecasting. By applying these methods, we identify the areas prone to landslides using GIS. Further, we developed a database system capable of combining spatial data with existing data on potential landslides. Two features of the system enable its application to all municipalities and prefectures throughout Japan: all local governments can make use of the inspection results, and all have access to various spatial data established under the 'e-government' policy. This paper explains how to use rainfall data, existing inventory data on steep slopes, and records of past landslides for the management of landslides. The results of these analyses will specify and predict areas prone to collapse for warning and evacuation procedures.

Keywords: slope failure; landslide disaster; theory of quantification; rainfall; disaster management

1. Introduction

Three-fourths of Japan is occupied by mountains. For this reason, as many as 125 million people in the country reside in relatively confined areas nearby dangerous slopes. More than half of all casualties of natural disasters are victims of landslides, debris flow, and slope failures. Urban areas have been expanding so rapidly, local governments have been unable to establish adequate protection against these types of disasters for the growing numbers of people living in dangerous areas. This calls not only for the implementation of more rigorous structural measures, but also nonstructural measures such as the establishment of (1) warning and evacuation systems, (2) regulations on structures, and (3) financial aid for those who move from high-risk areas. The first major step in this direction was the institution of the Sediment-Related Disaster Prevention Act in 2000.3) One of the most important tasks is to adequately manage damage-prone areas in densely populated cities.

This paper demonstrates how local governments in Yokohama City of Kanagawa prefecture of Japan can manage damage-prone areas and landslides using inspection records and spatial data. The Landslide Disaster Mitigation System has been developed as a prototype system for this purpose.

Yokohama is a hilly and densely populated city accommodating about 3 million residents over an area of approximately 400 km². According to slope inspections, the city has more than 1,400 "areas at risk of slope failure" (Table 1., Fig.1.)4) Under the criteria used for the nationwide prefectural inspections in 2002, "areas at risk of slope failure" are areas with slopes of at least 5 m in height with inclinations of at least 30 degrees. In the inspections conducted within Yokohama City of Kanagawa prefecture, 3,400 slopes were classified as steep slopes of at least 3 m in height.5)

The Kanagawa Prefectural Government reported that there have been more than 240 landslide disasters in the Yokohama area in the past decade, including about 60 in 2004 alone (Table 2.)6) According to the city government of Yokohama, more than 350 landslide disasters took place in the same area in 2004. This study uses landslide disaster reports from 1998 to 2004.

Table 3. lists the various improvements in public works for the management of damage-prone areas and the mitigation of landslide disasters. The information was collected during interviews with officers from the following branches of municipal government: the SABO Division of the Kanagawa Prefectural Government, the Residential Land Coordination Division, the Emergency Management and Operation Office, the Fire Bureau, and the Ward Administration...
Office of Yokohama City Government. It became quite clear, in the course of the interviews, that these organizations face considerable confusion in assigning priority to prevention works, cooperating with other organizations, and searching and managing paper documents. The principal methods for exchanging information during emergencies are telephone and FAX.

This study proposes a method of slope management planning to mitigate landslide disasters, solve related problems, and improve disaster-prevention works by analyzing existing inspection records and data (Table 3.). The next section of this paper presents factors that contribute to landslide disasters, as determined from the analysis of inspection and rainfall data (Fig.2.). The final part of this paper introduces the Landslide Disaster Mitigation System developed by our group as a prototype system. This system employs a prediction method based on the results of analyses of factors affecting slope failures in urban areas.

Rapid advancements in Information Technology and the "e-government"*1 policy in Japan have led to rapid increases in the number of information systems and types of spatial data available.  

As many as one-third of prefectural governments in Japan now provide downloadable image files (maps) indicating local areas at risk of landslide disasters. In addition, as many as one-third of prefectural governments provide spatial information on areas at risk of landslide disasters using a web-based Geographic Information System (WebGIS) with interactive maps and data tables. Similarly, as many as half of prefectural governments provide precipitation data for landslide and flood alerts via the internet. Some even send out disaster alerts to citizens based on local precipitation data. In spite of these efforts, the use of different systems and standards by local governments or offices has made it difficult to identify the areas most prone to landslide and rainfall disasters simply by perusing these maps. This problem can only be surmounted by integrating the information for slope management and collapse prediction.

Encouragingly, an abundance of landslide disaster reports, maps, and other paper documents are now available. This information will be useful not only for municipal governments, but also citizens who seek to manage damage-prone areas more efficiently themselves.

This paper will also explain effective ways to use existing inventory data on steep slopes, past landslides, and rainfall to manage landslides and high-risk areas.

2. Evaluating Primary Causes Using Steep Slope Inventories and Statistical Analysis

This evaluation uses of "areas at risk of slope failure," a statistic available from uniform inspection records covering all of Japan. Each local government has inspected more than 30 detailed factors, including

| Year | Kanagawa Prefecture | Yokohama City |
|------|---------------------|---------------|
| 1998 | 117                 | 29            |
| 1999 | 117                 | 34            |
| 2000 | 87                  | 30            |
| 2001 | 39                  | 17            |
| 2002 | 67                  | 43            |
| 2003 | 103                 | 29            |
| 2004 | 207                 | 61            |
| TOTAL| 737                 | 243           |

Source: Disaster Report of Kanagawa Prefectural Government

Table 3. Improvements in Disaster Mitigation Work

| Usual Time | Emergency | Info. |
|------------|-----------|-------|
| 1) Share information with other organizations | 1) Introduce an efficient communication system | 1) Search and access information rapidly |
| 2) Cooperate with other organizations | 2) Give priority to emergency responses | 2) Establish uniform formats for records |
| 3) Refer to existing information | 3) Establish an alert system for evacuations | 3) Keep correct records |
| 4) Update data on frequent basis | 4) Provide information to local residents | 4) Link records with locations |
geology, height, vegetation, surface thickness, and water leakage (Fig.3.). In this study we quantified 10 important factors in order to perform a multivariate analysis on Yokohama City. Our use of existing inspection records in Kanagawa Prefecture will make this method useful for all local governments in all of Japan. The criterion variable and CONSTRUCTION WORK, one of predictors, are based on records of past landslides (1998-2003) in our analysis. Steep slopes are divided into four groups (Fig.4.) based on geology and collapse patterns in Yokohama City.7 Slopes at risk of Pattern-3 are eliminated, as the risk of fall-type landslides is unrelated to rainfall. A total of 521 samples are included in the analysis.

This study identifies factors which influence slope collapses, then quantifies the strength of their influences by applying a multivariate analysis method known as quantification theory type II. Tables 4. and 5 show the results of an analysis for slopes in the Yokohama area. The values given are contribution ratios; the higher values contributing strongly to collapse, the lower values contributing weakly.

CONSTRUCTION WORK (finished vs. unfinished), CROSS SECTION, AGE OF TREE, and SLOPE are all strong factors for collapse.

Moreover, the sum of the weighted-coefficient "sample score" can be used to evaluate the risk of collapse.
future slope failure based on past collapse records. As indicated in Fig.5., most steep slopes with values higher than about 0.433 have actually collapsed in the past. As a result, the potential of collapse can be estimated to be accurate in 73.32% of all cases. Fig.5. also presents the frequency distribution of sample scores of slopes damaged by typhoons in 2004 (in order to inspect certainty). The "sample score" clearly shows the risk of collapse.

3. Evaluating the Primary Cause Using Landslide Reports and Rainfall data

Adequate prevention of landslide disasters during heavy rainfalls requires a clear understanding of the relationship between rainfall and collapses. The Soil Water Index shows the level of soil moisture in each 5 km grid (Fig.6.). The index is calculated based on the Tank Model\textsuperscript{2} using rainfall observed by radars covering all parts of the country. The order of the index in the grid has recently been used as a criterion for issuing warnings against landslide disasters.\textsuperscript{8,9) Some local governments, on the other hand, fix Critical Lines (CL), Evacuation Lines (EL), and Warning Lines (WL) using rain gauges.

This study uses half-lives of effective rainfall over periods of 1.5 hours and 72 hours for the short-term and long-term rainfall indexes, respectively. A rainfall series is defined as a period of rainfall falling between consecutive 24 hour periods of no rain. Effective rainfall as an antecedent precipitation index,

\[ R_t = \sum_{n} \alpha_n \cdot r_{t-n} \]  
\[ \alpha_n = 0.5^{n/T} \]  
(1)

Precipitation data is to be collected at 99 fire stations in Yokohama. Past data was collected at 34 stations run by the national government and various local governments (Fig.6., Table 6.).

The critical lines for the risk levels used in the collapse prediction in this study are determined based on the levels of precipitation at sites of past slope failures. Rainless collapses are excluded from the analysis. Fig.7. shows the levels of precipitation at sites of slope failures from 1998 to 2003 (circle symbols) and 2004 (triangle symbols), centers of gravity (1998-2003), and critical lines. The critical lines are boundaries between areas prone to different levels of risk, as follows.

LINE 1 connects intersections of the horizontal and vertical axes and runs perpendicularly from the center.

Table 4. Results of Quantification Theory Type II - 1

| ITEM       | CATEGORY         | WEIGHTED COEFFICIENT | RANGE |
|------------|------------------|----------------------|-------|
| SLOPE      | 1 UNDER 40 DEGREE | 0.94                 | 0.71  |
|            | 2 40 DEGREE-55 DEGREE | 0.13             |       |
|            | 3 55 DEGREE AND OVER | 0.03              |       |
|            | OVER HANGING      | -0.76               | 0.94  |
| CROSS SECTION | 1 UN Even        | 0.18                 |       |
|            | 2 FLAT            | -0.13                |       |
| KINNECKLINE | 1 CLEAR          | 0.06                 | 0.23  |
|            | 2 NOT CLEAR       | -0.17                |       |
| THICKNESS OF SURFACE | 1 UNDER 60CM | 0.05                  | 0.07  |
|            | 2 60CM AND OVER   | -0.02                |       |
| OPEN CRACKS | 1 EXIST          | 0.52                 | 0.71  |
|            | 2 NONE            | -0.19                |       |
| VEGETATION | 1 FIELD           | -0.17                | 0.46  |
|            | 2 BAMBOO          | 0.20                 |       |
|            | 3 CONIFER, BROADLEAF WOOD | 0.03 |       |
| AGE OF TREE | 1 UNDER 40 YEARS | 0.17                 | 0.92  |
|            | 2 40 YEARS AND OVER | -0.75              |       |
| LEAKING WATER | 1 EXIST          | 0.18                 |       |
|            | 2 EXIST AT RAIN   | -0.01                | 0.22  |
|            | 3 NONE            | -0.04                |       |
| LANDUSE OF HILLTOP | 1 ROAD, HOUSES | 0.08                 | 0.16  |
|            | 2 OTHERS          | -0.06                |       |
| CONSTRUCTION | 1 UNFINISHED    | 1.02                 | 1.75  |
|            | 2 FINISHED        | -0.72                |       |

Table 5. Results of Quantification Theory Type II - 2

| ACTUAL COLLAPSE | COLLAPSE | NO COLLAPSE | TOTAL |
|-----------------|----------|-------------|-------|
| 73.32% DISTINCTION RESULTS | 39       | 15          | 54    |
| NO COLLAPSE     | 124      | 343         | 467   |
| TOTAL           | 163      | 358         | 521   |

Fig.5. Frequency Distribution of Discrimination Result

Fig.6. Soil Water Index Grids and 99 Fire Stations in Yokohama City
of gravity to each axis. LINE 2 runs parallel with LINE 1 on the center of gravity. LINE 2 typifies precipitation levels at sites of past collapses. LINE 1 is the half level of LINE 2. According to records, 93.75% of rainfall levels at sites of slope failures in 2004 are over LINE 2. This verifies the applicability of these lines (Fig.7.)

Typhoon No.0422 and typhoon No.0423 led to about 400 slope failures in the Yokohama area in October of 2004. Given that slopes that have previously collapsed are less likely to collapse again, we need to move the critical lines to the upper precipitation level in order to make this precipitation index effective. Fig.8. shows critical lines based on precipitation data from 1998 to 2004. In addition to being applicable, this method is easier to update and understand than the non-linear critical line model. The predictions by this model will also become more accurate in the future as precipitation points are eliminated around sites where rain gauges work improperly or the landslides are attributed to factors other than rainfall. The results of these analyses will specify and predict areas prone to collapse for warning and evacuation procedures.

LEVEL 1, LEVEL 2, and LEVEL 3 are set based on these critical lines in the Landslide Mitigation System to predict collapses based on real-time precipitation data. LINE 1 is the boundary between LEVEL 1 and LEVEL 2. Likewise, LINE 2 is the boundary between LEVEL 2 and LEVEL 3. (Fig.7., Fig.8.)

4. Landslide Disaster Mitigation System

The Landslide Disaster Mitigation System was developed as a prototype system for municipal governments in Yokohama based on the results of these analyses. The system has three components, (1) Management of slopes by officers, (2) Analysis of landslides based on information on slopes and landslides, and (3) Prediction of areas prone to landslide based on the results of this time analysis and real-time precipitation data collected at 99 fire stations. Information on slopes, landslide reports, and rainfall data are all integrated within the system. The Prefectural and City governments manage the slopes in same area and contribute this data to the database. In coming years, it may become possible to integrate rainfall data recorded by the Japan Meteorological Agency, the River Bureau, Fire Stations, the Environmental Planning Bureau, and other entities. Officers responsible for emergency responses and slope management on a day-to-day basis will find this system useful. (Fig.9.)

Fig.10. shows the functions and interface for the management of slopes. All functions are based on a web system and all spatial data are managed and displayed on a Geographic Information System (GIS). Fig.11. illustrates the flow for predicting areas prone to landslides using slope information, landslide reports, and precipitation data based on the analysis of this study for the Landslide Disaster Mitigation System.

Table 6. Precipitation Data within Yokohama City

| RAINFALL | METEOROLOGICAL OBSERVATORY | 2 | WEB | 1HR | JAPAN |
|----------|----------------------------|---|-----|-----|-------|
|          | RIVER BUREAU               | 4 | WEB | 1HR | JAPAN |
|          | LAND DEVELOPMENT DEPARTMENT| 6 | WEB | 1HR | PREF. |
|          | FIRE STATION               | 99| △   | 15MIN | CITY |
|          | ENVIRONMENTAL PLANNING BUREAU| 22| ×   | 1HR | CITY |

| RADAR | PRECIPITATION ANALYSIS | 2.5km-mesh | ONLINE | 30MIN | JAPAN |
|       | PRECIPITATION ANALYSIS AND FORECAST | 1km-mesh | ONLINE | 10MIN | JAPAN |
|       | ENVIRONMENTAL PLANNING BUREAU | WEB | 5MIN | CITY | — |

Fig.7. Risk Level Based on Precipitation Levels at Collapse Sites (1998-2003)

Fig.8. Risk Level Based on Precipitation Levels at Collapse Sites (1998-2004)
The colors shading the damage-prone areas correspond with three levels of risk encountered whenever the system indicates a rainfall in excess of the critical line: LEVEL 1, LEVEL 2, and LEVEL 3 (Fig.12.). Damage-prone buildings and the names of the building owners are shown for each slope (Fig.13.). Users can thus ascertain the areas and buildings facing high risk simply by checking the display colors used and the scores from the statistical analysis. This system will prove useful to officers as they patrol high-risk areas and formulate evacuation plans for residents during heavy rains. Better still, residents themselves can take advantage of the system in their own efforts to manage slopes and mitigate landslide risk.

Many local governments in the U.S. are using WebGIS to integrate various types of regional information for area management. In Ventura County, California, for example, local government is using WebGIS to formulate a comprehensive coastal area plan incorporating "hazardous landslide areas" as one layer. The municipality of La Conchita in Ventura County is particularly prone to landslides. The latest landslide in the area took place on January 10, 2005. The City of Laguna Beach, California has used WebGIS data to formulate a capital improvement program, a series of environmental constraints, an FEMA 100-year floodplain map, and both general and coastal plans. "Seismic Hazard Landslide Areas" constitute an important layer of the Constraints Map used for these plans. (The latest landslide took place on June 1, 2005 at Laguna Beach.)

Yokohama in Japan has used WebGIS to show its "Wai Wai Bosai Map" for the Earthquake Disaster Prevention Information system. The map displays steeply sloped areas together with other disaster-related information. Similarly, the website of the Kanagawa Prefectural Government provides maps indicating areas at risk of slope failure, locations of past landslides, and precipitation data. Areas prone to landslides are most effectively managed when various types of regional information for area management are applied.
5. Conclusion

This paper has demonstrated how local governments can manage landslides with the use of existing records and spatial data. On a more specific level, it has described an effective method for predicting areas prone to damage using data on slope inspections, landslide records, and precipitation data provided in real time.

Quantification theory type 2, a method of multivariate analysis, was used to statistically evaluate the risk of slope failure caused by geomorphological factors, based on existing records on inspections of steep slopes. The scores from these analytical results reflect the risk of the slopes sampled in the analysis. In addition, rainfall factors were analyzed to determine the critical rainfall line for landslide prediction.

Through the aforesaid steps, we developed a Landslide Disaster Mitigation System as a prototype system. This system was used to identify areas prone to landslides using GIS. In addition, spatial data has been effectively combined with existing data on potential landslides within the system database.

This system can be applied to all municipalities and prefectures throughout Japan, as all of these entities can make use of the inspection results. This paper also explained how to use existing data to manage landslides.

This system will prove useful not only for officers engaged in landslide-prevention work, but also citizens involved in slope management planning for landslide mitigation in urban areas.

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Notes

*1 e-government (electronic government): Residents and companies can take advantage of national government and local government services much more conveniently through the use of Information Technology. In the near future, everyone who needs to obtain government information or perform an official procedure will be able to do so by accessing online government services from their homes and offices via the internet on an around-the-clock basis.  

*2 Tank Model: The tank model comprises many simple tanks with outlets arranged vertically one above the other. The structure was suggested by Sugawara (1974) for the runoff analysis of basins for flood forecasting. The Soil Water Index is calculated using this model with three tanks in a vertical series and the values of parameters identified for River Kizu.
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