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An Integrated Methodology for Assessment of Landslide Hazard around Residence Zones in Itoshima Area of Japan

by

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Abstract

In Itoshima area of Japan, many potential dangerous slopes are identified around residence buildings. The assessment map of landslide hazard has been developed based on the Japanese standard method. However, the method is based on the field investigation which is only effective for local and site specification and is usually difficult to apply for landslide hazard assessment in a wide area. This paper examines the major factor affecting landslide consequence in Itoshima area, discusses the Japanese standard method for measuring landslide hazard scenarios and proposes an integrated methodology by combining Japanese standard method and Geographical Information System (GIS) method to obtain the potential slope instability hazard in a wide study area. The identified potential slope hazards are evaluated with geology to find the most potential dangerous slope in the area. Moreover, a detail 3D slope stability analysis model is performed in the most potential slope instability area, and the variation of safety factor can be obtained.

Keywords: Landslide, Vulnerable slope, GIS, Hazard assessment, Slope unit, 3D slope stability analysis

1. Introduction

Landslides are important natural hazards that often result in significant damage to society every year in Japan. The nature of damage that can be caused by landslides is complex and diffuse because of the many interacting factors that are involved, and it may involve loss of life and injury or economic loss (Aleotti and Chowdhury, 1999). In Itoshima area, many potential landslides are identified around residence buildings and some of them may causes damage to the environment.

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Measuring dangerous slope area in Itoshima area is performed by using a Japanese standard method. A rational assessment of a dangerous slope, including the consideration of potential travel distance of debris and spatial distribution of the vulnerable building population is rarely carried out, and landslide consequences are commonly gauged only the basis of engineering judgment. Traditionally, the main emphasis of the Japanese standard method has often been placed on the evaluation of the likelihood of slope failure based on the slope angle. It is difficult to apply 3D model in a wide area due to difficulties in large spatially distributed data processing.

With the advent of Geographic Information Systems (GIS), their use for landslide hazard assessment has been increasing constantly in recent years (Carrara et al., 1991; Van Westen, 1997). For the analysis of the causative factors, the application of GIS is an essential tool in the data analysis and subsequent hazard assessment. Thus, has remarkably improved computations in the landslide researches and played an ever-increasing significant role in hazards evaluation since its coming in 1960's. In this research, the slope unit (mapping unit) is taken as the study object and the spatial data (5m DEM) will be use to carry out for the division of slope unit. The Japanese standard method adapted with GIS is utilized to identify potential slope instability in a wide study area. In order to know more hazard information regarding potential slope instability the geological characteristics will be carried out to analyze in hazard consequences area. Moreover, a detail 3D slope stability analysis will be used to conduct in the most dangerous slope instability area identified by GIS method. Finally, the aim of this research is to develop an integrated methodology by combination of Japanese standard method with GIS and incorporating geology, and 3D slope stability analysis model.

2. Landslide Hazard in Itoshima Area

2.1 Background and geographical condition

Itoshima area is located in the Itoshijma Peninsula, which is in the western part of Fukuoka Prefecture. Itoshima is bordered by Fukuoka city to the east, Karatsu city in Saga Prefecture to the west and Saga City in Saga Prefecture to the south. There were three towns in Itoshima area that were Maebaru city, Shima and Nijou were merging as the Itoshima city. Geographically, the study area is located in old Maebaru city, which is bounded between the latitude of 33°28'01"N 33°35'14"N question and the longitude of 130°17'31"E 130°09'31"E, as shown in **Fig. 1**.
Fundamental industry was agriculture before the 1960's, however, the decline of agriculture promoted to generate a new services business (Kiyoshi and Iwamoto, 2002). Successively, these areas were rapidly developed for the bed-town of Fukuoka city after the construction of a subway to the city center. As a result, a large number of land developments have been promoting around there, for example, housing area, suburb types of shopping, leisure center and golf field, etc.
The study area, mostly plain in the river basins and hilly-mountainous rock surrounds the southern part. Mountain slopes are composed of gravel terraces, low undulating hill and many valleys. The study area covers the total area of nearly 105 km^2; however, 42% (about 44 km^2) is almost flat area slope angle less than 8 degrees.

The remaining 58% of the total area composes sloping ground, and about 20% of the residence buildings in the study area are built on slopes. **Figure 2** shows the 3D view of surface topographic relief of the study area where the residence buildings are distributed even in the sloppy area. The topography illustrates the mountainous area mostly distributed in South part of the study area.

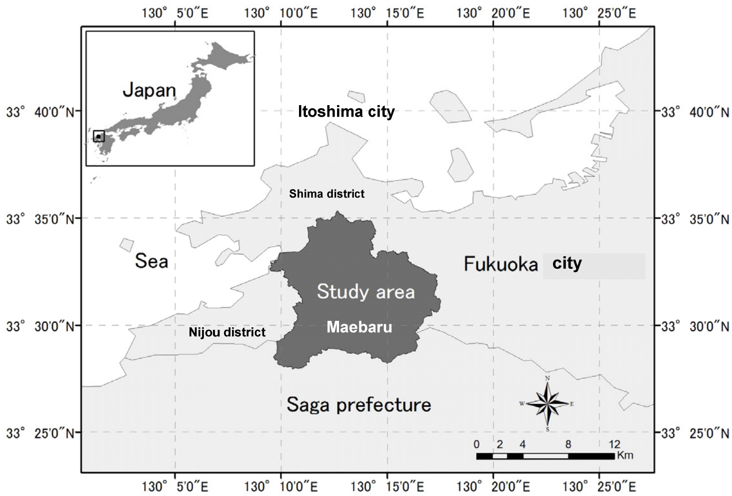


Fig. 1 Location of the study area.

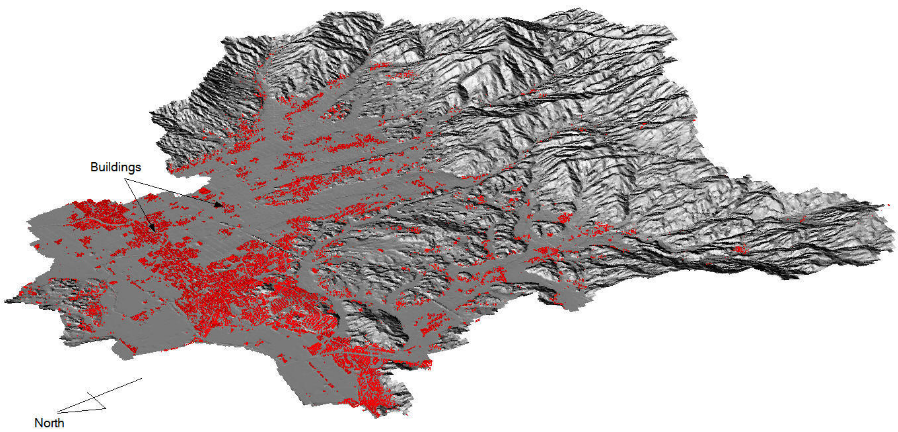


Fig. 2 3D view of the topographic relief of the study area overlaid with the building layers.

2.2 Geology

Granite is widely recognized to be very sensitive to weathering and vulnerable to landslides in Japan. Chigira (2001) reported that in Japan many disasters have occurred in granite soil areas following heavy rains, where the major disasters resulting from these rainstorms were owing to landslides that occurred on weathered granite slopes. In Itoshima area, the surface geology consists predominantly of weathered granite rock, intrusion of metamorphic rock, and quaternary sedimentary including gravel-sand and clay. The granite rock area is a significantly weathered surface ranging between 5~10 m, where many of the weathered granite is decomposed into soil (Ishibashi et al., 2007). **Figure 3** shows the surface geological map in 1:200,000 scales obtained from Japan Geological Society (JGS). The geological types are reclassified into three types of gravel-sand & clay, weathered granite and rock. In the plain area, surface geology is dominated by gravel-sand, silt and clay formatted by quaternary layer. In the mountain part, granite rock is mostly distributed in the southern part, and weathered granite is developed in the wide area of the hilly terrain. The phenomena that caused a slope abruptly collapse when the weathered granite or top soil that has already been the weekend by moisture in the ground losses its self retainability under the influence of a rain or earthquake Because the sudden slope collapse many people fail to escape from occurred place near residential area thus leading to a higher rate of fatalities (MILT, 2004). Mechanical factor should be considered as the factor contributing to the occurrence of landslide disaster (Cruden and Varnes, 1996).

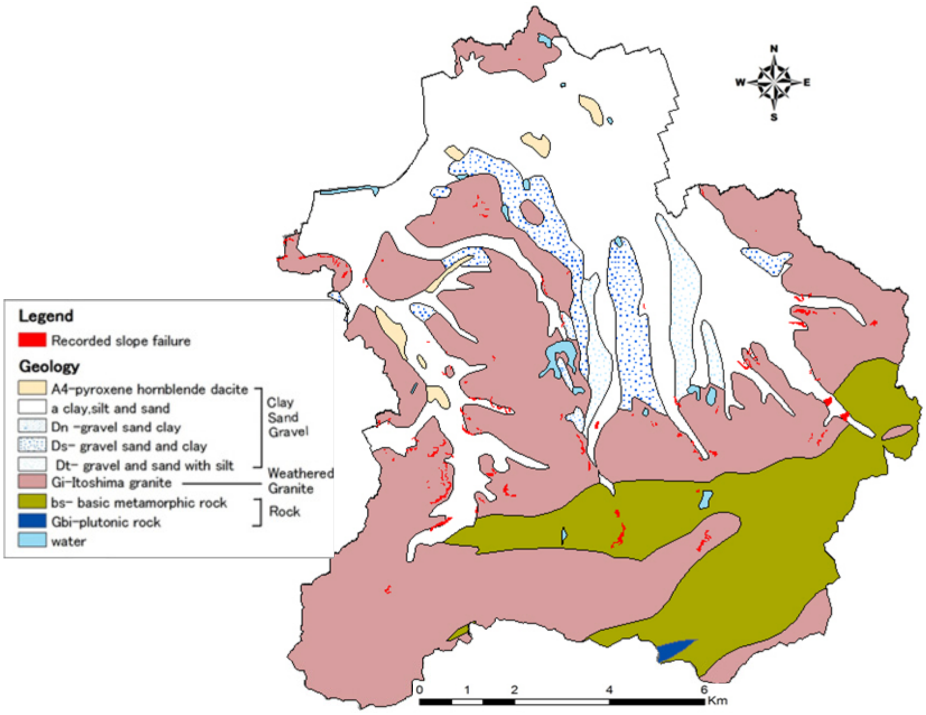
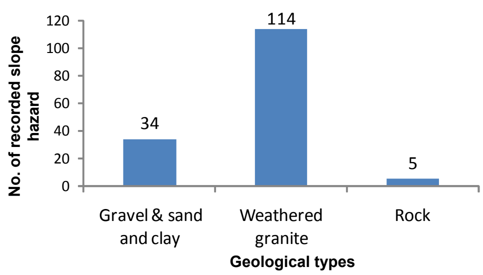


Fig. 3 1:200,000 scale of the surface geological map overlaid with identified dangerous slopes from a Japanese standard method.

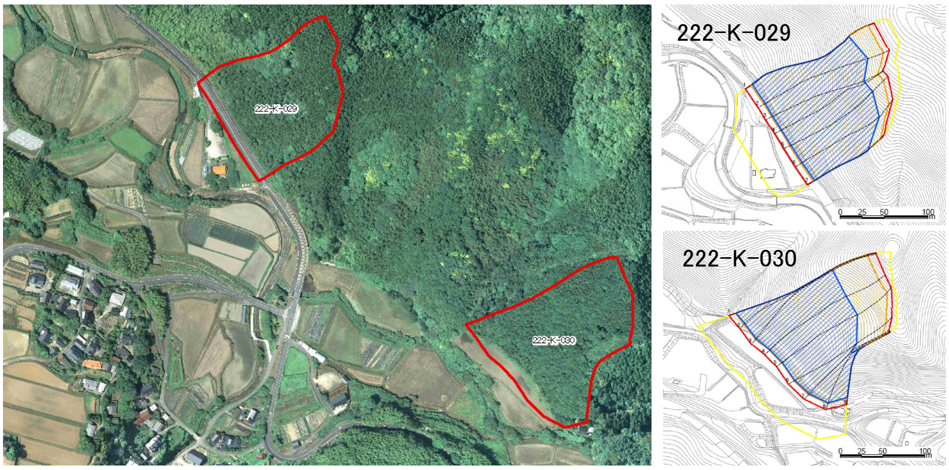
2.3 Landslide hazard inventory

In the study area, old Maebaru city 153 units of dangerous slopes are previously identified by field investigation using a Japanese standard method. **Figure 4a** shows the distribution of the dangerous slopes in three types of geology. 34 units are identified in the gravel-sand and clay zone, 5 units are located in rock, and 114 units are distributed in the weathered granite area.

The most representative dangerous slopes (code by 222-K-29 and 222-K-30) are measured in the Itoshima Oomaru site which is the largest slope area about 25,480 m^2 and 30,123 m^2, respectively (**Fig. 4b**). These slopes are measured 118.8m, 123.2 m, in maximum slope height and 136.8 m, 184.2 m in maximum length and 37.5^o, 32.8^o in average slope angle, respectively.



(a)



(b)

Fig.4 (a) Statistical distribution of the recorded landslide hazard on different geological types and **(b)** High accuracy satellite image and detected polygon of vulnerable slopes on the weathered granite zone.

The surface geology in those two slopes was also covered by weathered granite rock. Since weathered granite is composed by the material with low strength rock than the fresh rock, those slopes are potentially landslides. Based on a surface geological characteristics and past field investigation results, the distribution of vulnerable slopes is more probably occurred in weathered granite, which widely located in the hilly terrain than gravel-sand and clay, which distributed in the lowland.

Movement types of the slope failure are commonly classified into five main groups that are falls, topples, slides, spreads, and flows (Robert and Raymond, 1978). In the study area, predominant slope failures indicate a slide of weathered rock of natural slope failure resting over the bed rock. Surficial geology and rotational slides are the common slope failure types that measured in the Itoshima area. **Figure 5** depicts the illustration of the cross section of the slope which emphasizes the weathered granite rock to possibly become a weak layer that potential to slides.

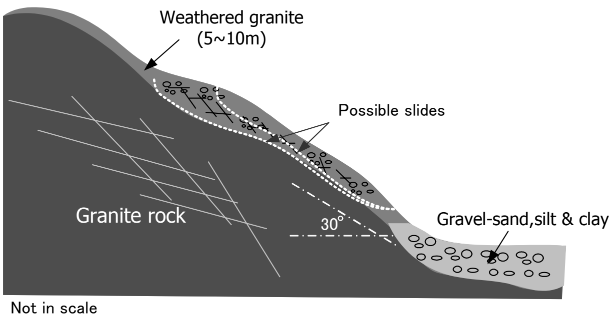


Fig. 5 Illustration of typical geological layers and slope failure modes in the study area.

2.3.1 A Japanese standard method for identifying dangerous slope by field investigation

A Japanese standard method involves detailed field investigation which needs a lot of manpower and normally incurs long time and high cost. Sometimes it is very difficult or nearly impossible to do the investigation or obtain sufficient data at the fields with steep slope in the high mountain areas. Landslide hazard is defined by Japanese standard method namely concerning prevention of disaster due to collapse of steep slopes, with gradient of 30^o or over defined as a steep slopes and they are assumed as hazardous slope at risk of collapse (Ministry of Land Infrastructure and Transportation (MILT), 1999). This method namely indented to cover a phenomenon in which soil and rock move downward at high speed. **Figure 6** shows the 30^o average angle and 5m of the minimum height of a slope is categorized as a dangerous slope.

The dangerous slopes zone can then be assessed by calculating the main direction of slope aspect and measuring the distance of twice of maximum slope height for lower part and the distance of maximum slope height for upper part of a slope and there are more than five buildings in the possible slope instability range.

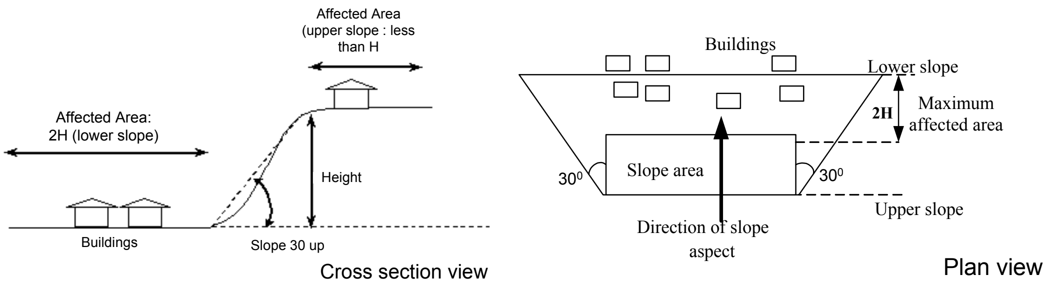


Fig. 6 Abstracting the Japanese method to measure the dangerous slopes in the vicinity of building.

3. A GIS Based Spatial Model for Landslide Hazard Zonation

3.1 Methodology

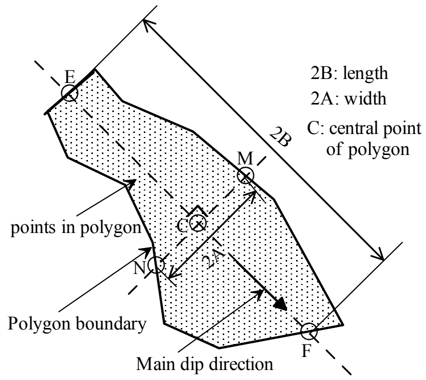
3.1.1 Slope unit characteristic and division model

For the large scale analysis of landslide hazard assessment with complicated geometry and geological conditions, a key problem is how to extract the appropriate study objects. The slope unit, namely, the portion of land surface that contains maximum internal homogeneity differing from the adjacent units, has relatively similar topographic and geological characteristics respectively, (Xie et al., 2003). Slope unit can be considered as the left or right part of a catchment.

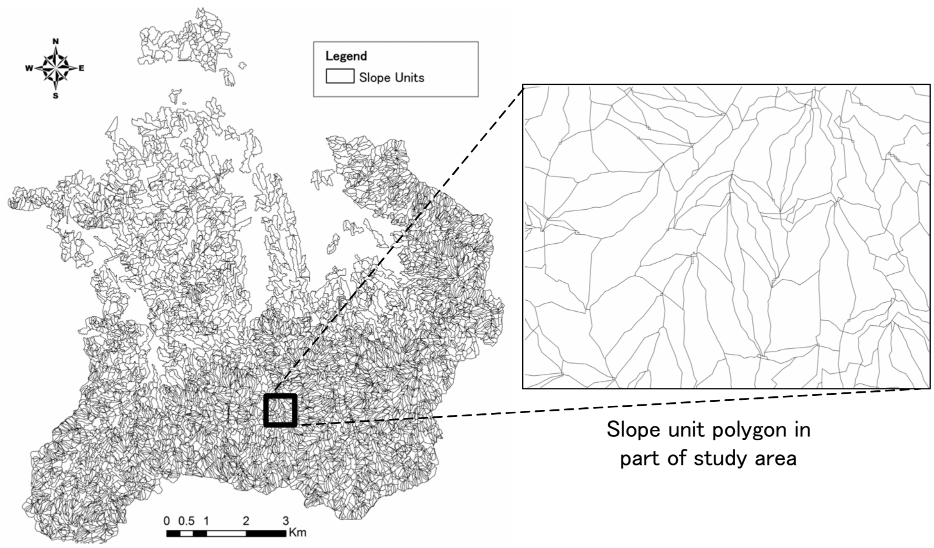
Therefore, it can be identified by a ridge line and a valley line. Breaks of slope are often identified as significant topographic features, such as namely dividing lines, indicating the boundaries between adjacent geomorphologic units on a map and size of slope unit can be determined. Although Carrara (1988) has indicated that the appropriate size of the slope unit should be dependent on the average size of the landslide bodies present in the study area. The parameters for describing the characteristics of slope unit is the plane extant of slope unit, here, two parameters *A* and *B* are used for describing the width and length of slope unit. As shown in **Fig. 7a**, for one polygon feature of slope unit, its central point can be identified to be point *C*, along the main dip direction drawing the line *EF* and its perpendicular line *NM*, then the length of line *NM* is *2A* and the length of line *EF* is *2B* .

Since it is virtually impossible to consistently draw and dividing lines on topographic maps covering large regions, an automatic computer procedure is required. In this study, using the python language, the geoprocessing model builder has been used for simplicity and faster process for slope unit division. Model builder is an application in which the model can be created, edited, and managed efficiently by logical workflow process sequence. In model builder, the catchment polygon and the stream line of a study area can be obtained easily from digital elevation model

(DEM). Topologically, the outline of the catchment polygon can be considered as the ridge line. Assume that if the terrain is reversed, valley line will become the ridge line. The catchment of this reversed terrain is generated; the edge of the catchment is the valley of the original terrain. Dividing the catchments by the valley line, the distribution of slope units can be generated effectively using model builder. The distribution of slope units of the study area is shown in **Fig. 7b**.



(a)



(b)

Fig.7 (a) Width, length, main direction and angle of a slope unit polygon boundary (After Xie, 2003) and **(b)** the distribution of generated slope units in the study area.

3.1.2 GIS based model for identifying dangerous slope by adapting Japanese standard method

GIS provides strong functions in spatially distributed data processing and analysis. Correct results depend on the reliability of the data and the appropriateness of the model, though the input data will be greatly influential on the landslide hazard, hence a reliable GIS model is more important for obtaining the reliable results. **Figure 8** shows the flow chart of GIS based model to obtain landslide hazard assessment in the study area. The calculation process can be performed within or outside the GIS. If the calculations are performed outside the GIS, the system is only used as a spatial database for storing, displaying and updating the input data. In this flow chart, the digital elevation model (DEM) 5m-grid point was used to produce the division of the slope units by geoprocessing model builder. Using the GIS function of spatial analysis, DEM, slope and aspect is converted to the point data for inputting parameters in the join analysis. By inputting slope unit polygon, converted point data and building polygon, a spatial join analysis can be performed to obtain the average height, average slope angle and average slope aspect of a slope. Moreover, the distance from each feature from the centre of the slope units within an affected area is calculated using the distance analysis tools, slope angle greater than 30^{o} is obtained by select analysis from the average slope angle of the slope unit, and the slope unit direction to the building is resulted by parallel analysis from the slope unit average aspect.

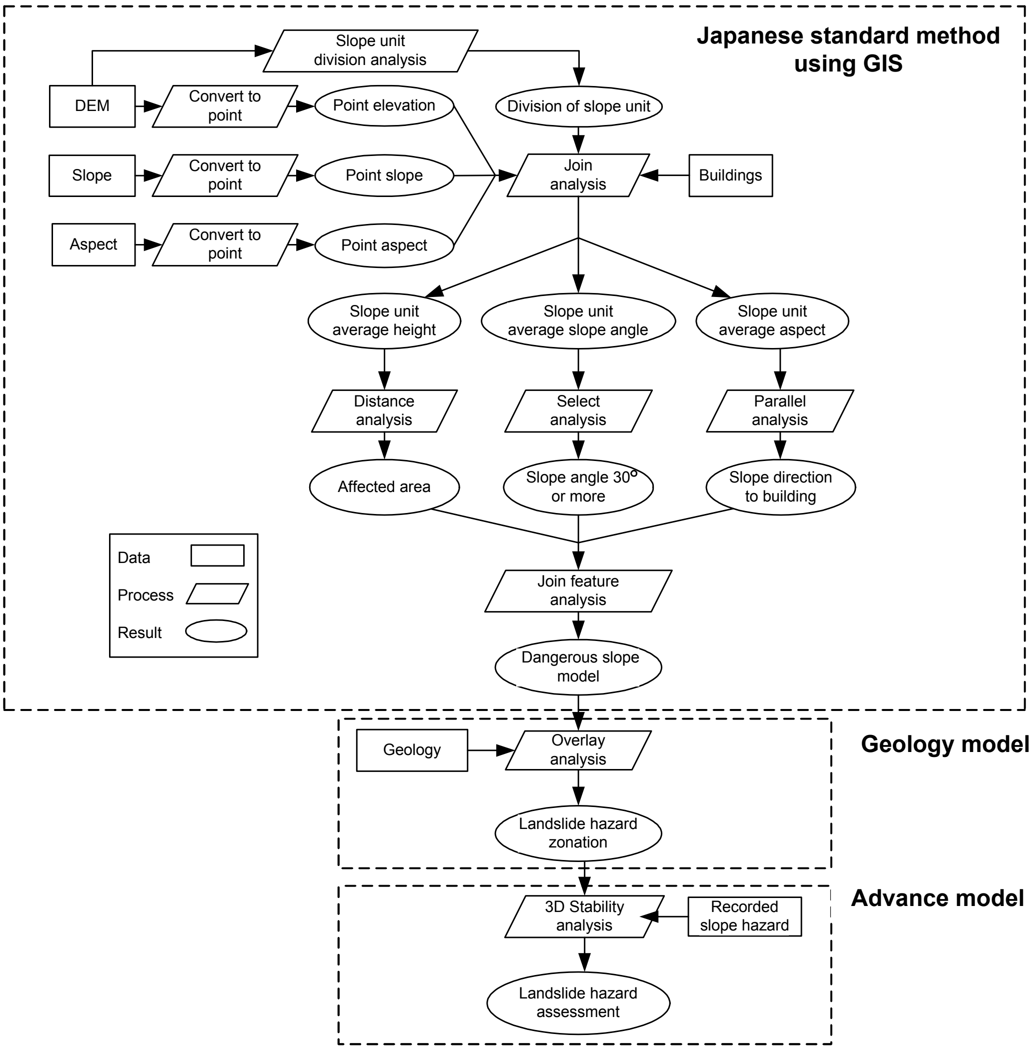


Fig. 8 Proposed methodology of the GIS based model for obtaining a landslide hazard assessment in study area.

In order to obtain the vulnerable slope model, spatial join analysis is then conducted by applying the data parameters from the value of the affected area, slope more than 30^{o} and slope direction to building. In addition, geological characteristics are analyzed to obtain the more hazard information. Finally, 3D slope stability analysis is carried in GIS to assess the minimum safety factor on each dangerous slope zonation, where the geomechanical parameters are obtained from previous field measurement results. Furthermore, all the process of analysis was conducted in GIS system to reduce effort of data conversion and calculation.

3.2 Assessing the hazard zonation from landslides in a wide area of the Itoshima area

3.2.1 Dangerous slope zonation analysis

In this research, a GIS based model has been developed for estimating the hazard from landslide in Itoshima area by adopting a Japanese standard method. The advantage of the use of GIS based model is the dangerous slopes identification which can be rapidly done by using spatial data. Without a GIS, the assessment of landslide hazard would be a difficult and time-consuming task for whole area of Itoshima. **Figure 9** shows the distribution of dangerous slopes which analyzed in GIS and by the Japanese standard method.

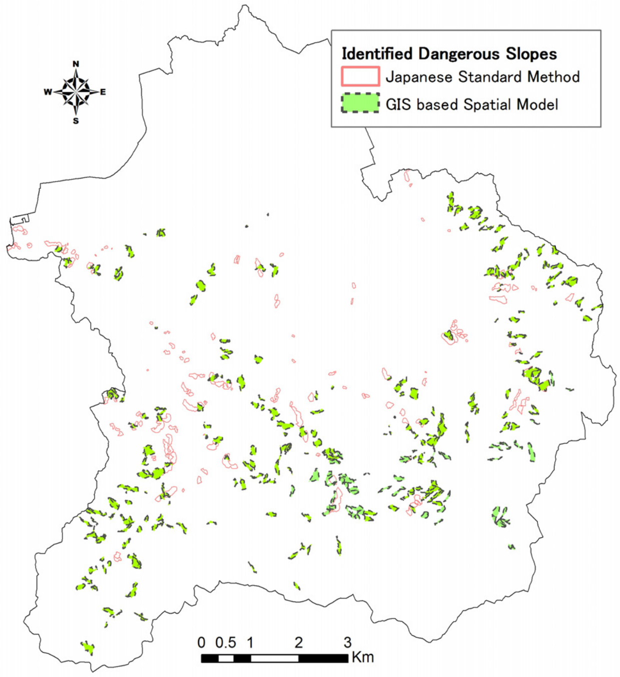


Fig. 9 Identified dangerous slopes by GIS based model and Japanese standard method.

By a Japanese standard method, 153 units of dangerous slopes are identified and distributed mostly in the low elevation of the slope area around building; however, using a GIS based model, 303 units of the dangerous slopes has been identified. Moreover, the identified dangerous slopes are overlaid with surface geological layer and 178 units of slopes are founded in the rock. From the view of point, the phenomena of dangerous slope in rocks are probably fewer than weathered rock, in the study area. About more than 100 units of the dangerous slopes were distributed even in the high elevation of mountainous rock with the complex topography region. GIS based model can identify the dangerous slope even in the complex topographic region and remote area with small villages.

3.2.2 Comparative results

In the identification of dangerous slopes, the accuracy of these methods has been compared based on the mean value of the slopes. The identified dangerous slopes are overlaid with surface geological layer and 178 units of the dangerous slopes are widely distributed in the weathered granite zone and 125 units of slopes are founded in the rock. From the view point, the phenomena of dangerous slopes in rocks are probably fewer than weathered rock, in the study area. In the Japanese standard method, field investigation identifies 153 units of the dangerous slopes and GIS method indentifies 178 units after geological investigation of the dangerous slopes, as shown in **Table 1**. The comparison is explained as follows:

- *Average slope length*: the slope distance in meter was compared to the output results of Japanese method which length is about 153 m, whereas, in GIS method is about 165 m. Both results seems close accuracy because of high resolution (5m DEM)
- *Maximum slope angle*: Slope angle analysis was carried out for comparison of maximum slope among the methods. The GIS method results found that the maximum slope is 55^o. Similarly, 47^o of slope angle is recorded by Japanese method.
- *Average height*: The Japanese method detects 17.36 m of the average slope height while GIS method detects 66.9m. However, both results did not match very close since, in the slope unit division the variation size of potential instability and average slope height is calculated by maximum slope height minus minimum slope height by an automatic calculation process.
- *Average slope*: it can be seen that Japanese method recorded average slope is 38.16^o; while GIS method is 32.25^o. The output result of both methods gives similar result. Both results appear close since, the accuracy is high.
- *Slope area*: Japanese method identifies that the affected area is 9,508 m^2 and GIS method calculate that the dangerous slopes area is 9927 m^2.

Comparison between GIS based model and Japanese standard method for slope geometries on the weathered granite zone shows the similarity and different. Since, the Japanese standard method identify based on site specific field investigation. Whereas GIS based method identified the potential slope instability using 5m digital elevation model (DEM) by an automatic process in the wide study area.

Table 1. Comparison between GIS based model and Japanese standard method for slope geometries on the weather granite

	Mean value of the slopes					Number of Slopes
	Average slope length (m)	Maximum slope angle (^{o})	Average slope height (m)	Average slope angle (^{o})	Slope area (m^2)	
GIS based model	165.34	55.24	66.69	32.25	9927	178
Japanese method	153.12	47.15	17.36	38.16	9508	153

Therefore, in order to obtain comprehensive landslide hazard assessment results in the study area, a 3D slope stability analysis is conducted to calculate the minimum safety factor for each slope in the dangerous slopes zonation.

4. Integrated Dangerous Slope Assessment by 3D Stability Model Analysis

4.1 Model for slope stability analysis

Landslides have fixed relations to the geological and geomorphologic aspects of the study area. So in this research, the slope unit is taken as the object of study. Using the functions of GIS spatial analysis, the following parameters are available:

a. Topographical parameters (such as surface elevation, inclination, and aspect);
b. Spatial distribution and size parameters of dangerous slopes;
c. Geomechanical parameters for each geological section;

By inputting these parameters into the model of slope stability, the value of the safety factor or the probability of failure can be obtained. Based on Hovland's (1977) model, the 3D safety factor can be expressed as following equation:

$$F_{3D} = \frac{\sum_{J}\sum_{I}(cA + W\cos\theta\tan\phi)}{\sum_{J}\sum_{I} W\sin\theta}$$

where, F_{3D} = the 3D slope safety factor; W = the weight of one column; A = the area of the slip surface; c = the cohesion; ϕ= the friction angle; θ= the normal angle of slip surface; and J,I = the numbers of row and column of the pixel in the range of slope failure.

4.1.1 Monte Carlo simulation for critical slip surface

To avoid the difficulty of evaluating the multi dimensional integral, many attempts have been made to estimate the failure probability using Monte Carlo Simulation. The computation of probabilities by Monte Carlo simulation is a procedure commonly adopted to solve problems that are not readily solved by analytical means (Garry and Robin, 1997). The procedure is:

- Choose a 3D stability analysis procedure;
- Decide which input parameters are to be modeled;
- Select input values for each parameter; and
- Use the distribution of the result to determine the probability failure

Thus the Monte Carlo procedure consists of solving a deterministic problem many times to build up a statistical distribution. **Figure 10** shows the computation process using GIS for assessing dangerous slopes by means of minimum 3D safety factor of the slopes in the study area.

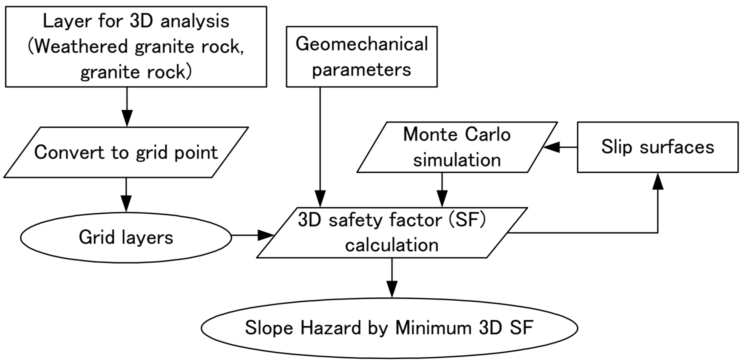


Fig. 10 Flow chart of the GIS based model for 3D slope stability assessment by means of the minimum safety factor calculation for each of the slope unit.

The weathered granite rock and granite rock layer are designed for 3D analysis. For geomechanical parameters, the previous field investigation results were used from the old Maebaru city office. The slip surface is obtained by detailed geotechnical investigation, but generally speaking, the detail of a slip surface is uncertain. To detect the 3D critical slip, the search is performed by means of a minimization of the 3D safety factor using the Monte Carlo simulation. The initial slip surface is assumed as the lower part of an ellipsoid slip and the slip surface will change according to differing layer strengths and conditions of discontinuous surface. Finally, the critical slip surface will be obtained, and consequently, a relative minimization of the 3D safety factor can be achieved.

4.2 3D slope stability analyses

Parts of study area (weathered granite zone) for the landslide hazard assessment have been selected for priority assessment of safety factors of the slope where the most dangerous slopes have also been identified by field investigation in the past using a Japanese standard method. For surface geological layer, the weathered granite parameters of cohesion (5 kN/m^2), friction angle (30^o) and unit of weight (18 kN/m^3) is used and for sub-geological layer, the granite rock parameter of cohesion (30 kN/m^2), friction angle (40^o) and unit of weight (26 kN/m^3) is used. Both of geotechnical parameters are estimated by referencing from the previous field investigation. General geometrical parameters of the slopes have been investigated for assessing their probability geometrical calculation range value using Monte Carlo simulation. **Table 2** shows the mean value of the slope geometrical parameters. From geostatistical analysis, the realistic geometrical parameters of width (*b*) and length (*c*) axes of the ellipsoid for 3D slope stability calculation can be predicted. In this study, the geometrical calculation parameters ranges from 1st Quartile to 3rd Quartile have been used and parameters ranges of depth (*c*) is 2.5~15 m, to simulate the critical sliding surface by Monte Carlo simulation. **Figure 11** shows the distribution of 3D safety factor calculated by GIS-based 3D slope stability analysis for specific dangerous slopes units in weathered granite area which has been identified by GIS-based model.

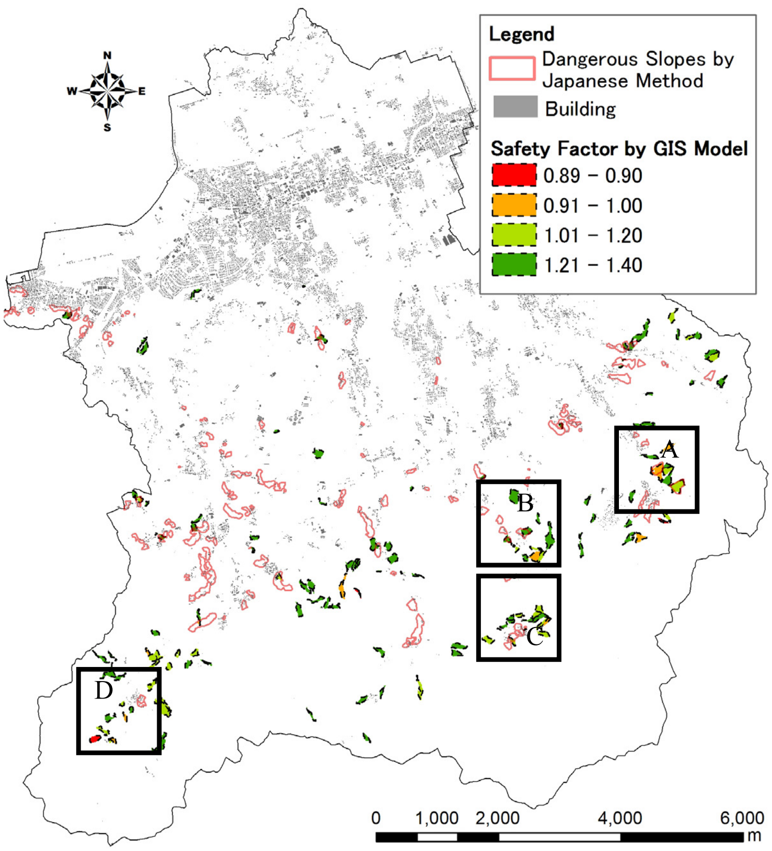


Fig. 11 Identified dangerous slopes by GIS-based model in weathered granite zone and their distribution of 3D minimum safety factor model.

Table 2. Geostatistical analysis of the slope geometries for 3D stability input parameters

	Min	Max	Mean	Std dev.	1st Quartile	3rd Quartile
Length (m)	23.74	591.47	167.37	79.53	116.31	209.35
Width (m)	11.12	175.86	30.36	67.16	20.19	45.10

Figure 12 gives the detail comparative results in which dangerous slopes is detected by field investigation and probability slope hazard is calculated in GIS-based method using a 3D slope stability model. As a result, dangerous slope area identified by Japanese standard method can then be accurately recognized as the high probability of slope hazard by result of GIS based model.

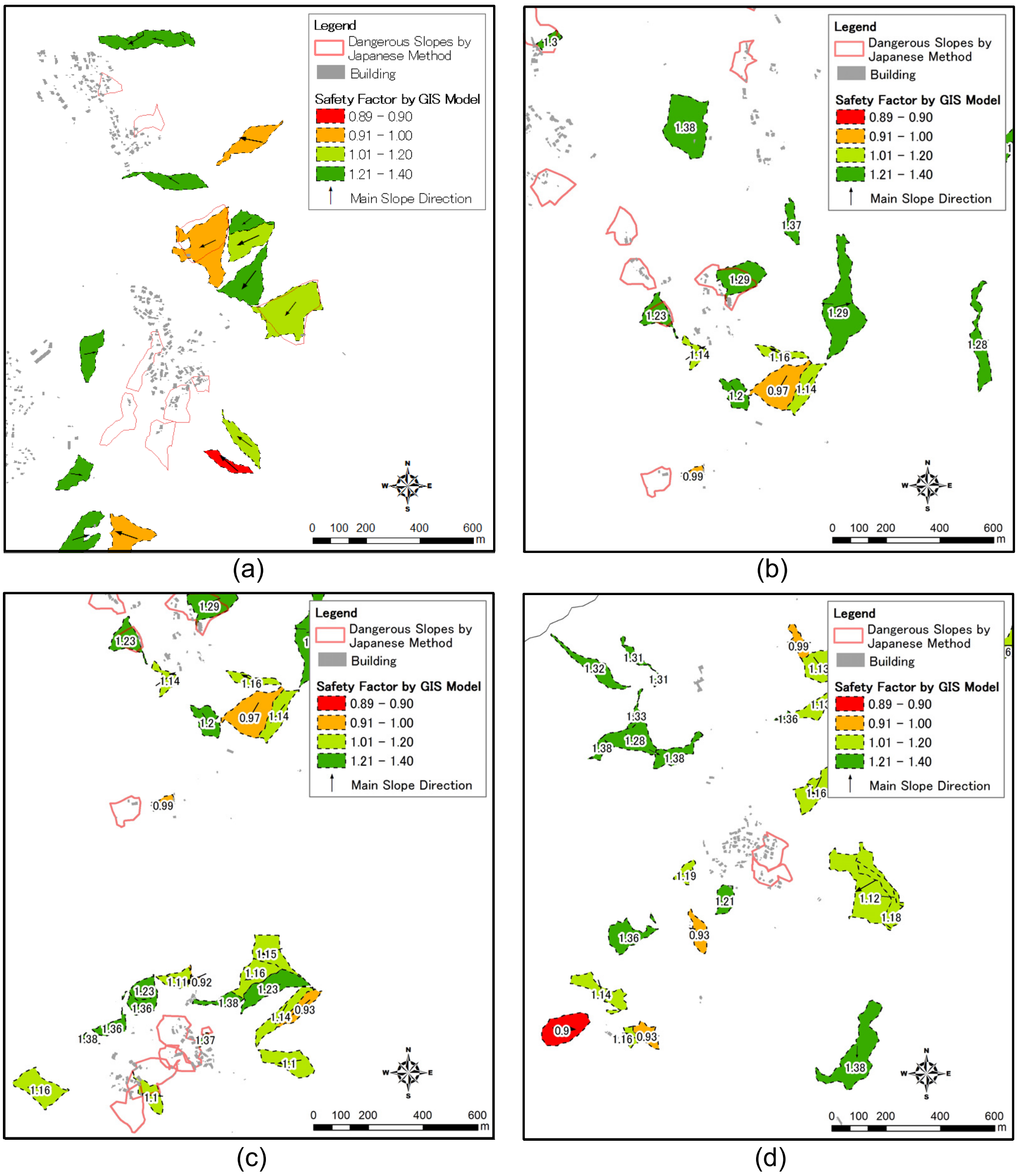


Fig. 12 Detail comparison results between the measured dangerous slopes by the Japanese standard method and the assessed slope hazards by GIS-based integrated slope stability model

As an example in **Fig.13**, the measured of dangerous slopes by Japanese standard method in part of study area is identified where the high potential slope hazard has the safety factor less than 1.

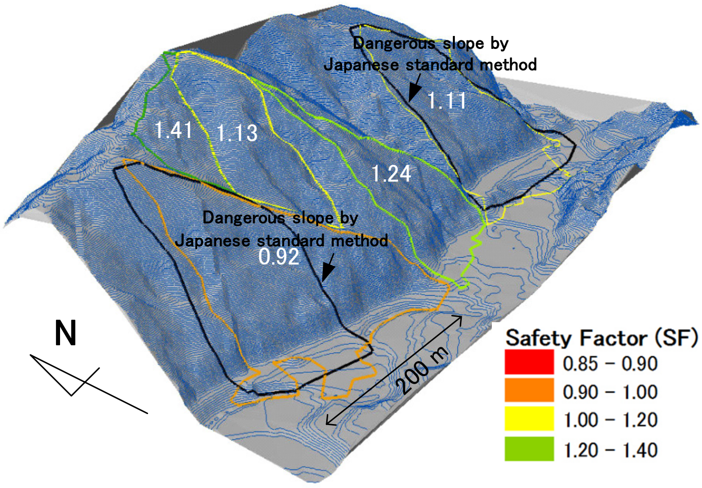


Fig. 13 Comparative results in part of weathered granite zone between past recorded dangerous slopes by field measurement and GIS based model for 3D safety factor analysis.

5. Conclusions and Discussion

An integrated methodology for landslide hazard assessment in Itoshima area has been developed in this paper. A simple GIS based model has been developed for estimating the potential slope instability by adopting Japanese standard method. The geological characteristics of the identified potential slope hazards are analyzed by overlaid with surface geological layer and founded the most dangerous slopes in the weathered granite. In addition, detail 3D slope stability analysis is performed by using the Monte Carlo simulation to calculate the minimum safety factor for each danger slope area that has been identified by GIS based model in weathered granite to identify their detail instability levels. The result of GIS analysis was found that 143 units of the possible slope instability are distributed in the weathered granite zone.

Moreover, an automatic process using geoprocessing model builder has been developed for identifying the slope unit for study area. Slope unit deriving is based on the hydrology analysis model and accuracy of surface elevation model. Because the slope unit size is generated based on the 5-m grid digital elevation model, thus the optimum method used for setting the slope unit can be adapted to the accuracy geometrical slope identification by field measurement. The GIS based model shows similarity result of the slope geometry identification with the past recorded dangerous slopes area by a Japanese standard method.

Thus, the integrated methodology is considered as an effective approach for rapid assessment of landslide hazard in a wide area even in the complex topography. The instability criterion of Japanese standard method by field investigation techniques may be the difficult and time consuming task, and sometime it is very hard or nearly impossible to do the investigation in complex topography. Considering the Japanese standard method, the slope hazard is commonly gauged only by the qualitative evaluation to judge whether the slope are dangerous or not. However, using GIS based method, dangerous area can be quantified more accurately by making the quantitative evaluation based on the 3D model, thus the location of most slope hazards in the dangerous areas can be identified rigorously.

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