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SLOPE FAILURE ASSESSMENT BY 3D RESPONSE ANALYSIS TECHNIQUES IN SEISMIC MICROZONATION

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Abstract

Seismic micro-zoning techniques have been used frequently to estimate earthquake damages and to develop earthquake disaster reduction plans. This paper focuses on earthquake-induced slope failures and reviews risk assessment methods by earthquake-induced slope failures metrics table. A new method of risk assessment for earthquake-induced slope failures is introduced. This method consists of 3D-FEM response analysis. Two methods are used to calculate seismic motion of the active fault associated with the 2000 Tottori-Ken-Seibu Earthquake. Seismic motion calculations are carried out with the usual seismic micro-zoning technique and compared to the proposed 3D-FEM response analysis by BESSRA (Bird's-Eye-viewed Slope analysis for Seismic Risk Assessment). Our proposed method integrates slope analysis by BESSRA with the instrumental seismic intensity delivered from seismic micro-zoning technique. It allows 1D micro-zoning seismic motion calculations to take into account 3D topographic effects. Modified instrumental seismic intensity including integrated 3D topographic effect delivered from the method is then adapted to the earthquake-induced slope failures metrics table, and risk assessment of earthquake-induced slope failures is improved with the proposed methodology.

Keywords: risk assessment, earthquake-induced slope failures, seismic micro-zoning technique, 3D-FEM analysis, 3D topographic effect of seismic motions

1. Introduction

Many local governments in Japan have been implementing local disaster management plans in preparation for future earthquake damages. Seismic micro-zoning techniques have been used frequently to estimate damages by earthquakes and to develop earthquake disaster reduction plans.

This paper focuses on earthquake-induced slope failures and reviews risk assessment methods in the seismic micro-zoning technique[1]. A new method of risk assessment for earthquake-induced slope failures is introduced. The method consists of a 3D-FEM response analysis of subsurface motion and an estimation of engineering bedrock input motion by statistical Green's function.

Two methods are used and compared each other to calculate subsurface seismic motion of the active fault associated with the 2000 Tottori-Ken-Seibu Earthquake. One is an usual seismic micro-zoning technique using 1D response analysis, and the other is a proposed 3D-FEM response analysis by BESSRA (Bird's-Eye-viewed Slope analysis for Seismic Risk Assessment)[2]. The stress and strain relationships by Ugai-Wakai model[3] are adopted to BESSRA.

2. General method of analyses

2.1 Risk assessment for earthquake-induced slope failures by seismic micro-zoning technique

Fig. 1 shows the flowchart of the risk assessment for the earthquake-induced slope failures by seismic micro-zoning technique. Methods of the analysis are as follows:

a) Divide the target area (typically the whole prefectural area) by 250x250m grid cells (Grid Square defined by the Static Bureau of Japan, which is frequently used for seismic micro-zoning in Japan).

b) Set fault parameters of the scenario earthquake. Calculate seismic motions at engineering bedrock in each grid cells by the statistical Green's function method.

c) Prepare ground analysis shear wave velocity layered model in each 250m grid cells.

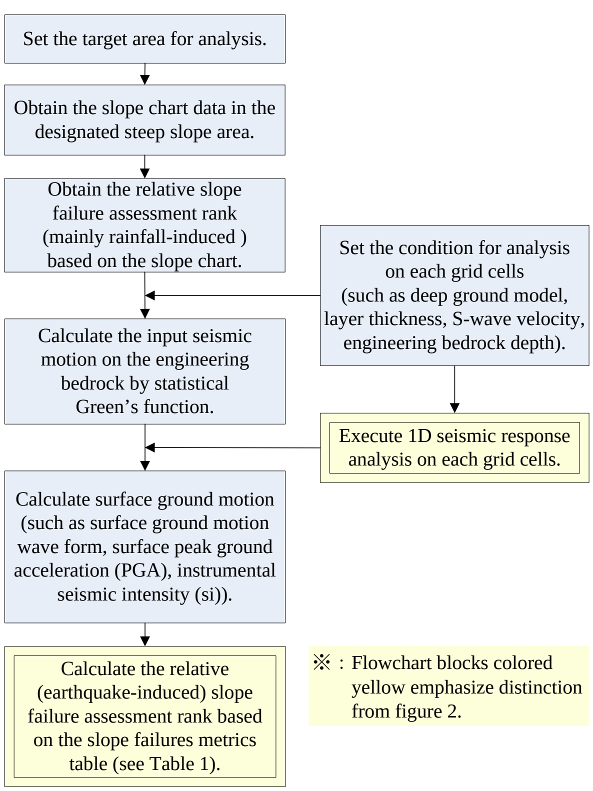


Fig. 1 - Flowchart of the slope failure prediction by seismic micro-zoning technique.

Table 1 - Slope failures metrics table (Miyagi Pref. (1997) [6])

Risk ranks on the slope chart / JMA Instrumental seismic intensity(si)※2	Risk ranks on the slope chart※1		
	c	b	a
6.0≦si	A※3	A	A
5.5≦si < 6.0	B	A	A
5.0≦si < 5.5	C	B※3	A
4.5≦si < 5.0	C	C	B
si < 4.5	C	C	C※3

※1: Risk ranks on the slope chart are shown below:
ranka : high-risk
rankb : moderate-risk
rankc : low-risk

※2: Approximate Equivalent Rating on Mercalli Scale is as follows:
6.0≦si : IX - XII
5.5≦si<6.0 : VIII-X
5.0≦si<5.5 : VI-IX
4.5≦si<5.0 : V-VIII
si<4.5 : I-VII

※3: Risk ranks based on seismic motion are shown below:
rankA : high-risk
rankB : moderate-risk
rankC : low-risk
* Stabilized slopes are always ranked C.

d) Calculate surface ground motions by 1D seismic response analysis using b) and c) result. And calculate PGA (peak ground acceleration), PGV (peak ground velocity), JMA instrumental seismic intensity (si)[4], and seismic intensity scale[5] from surface ground motions in each 250m grid cells.

e) Investigate earthquake induced slope failures risk from the instrumental seismic intensity and the risk rank on the slope using slope failures metrics table (Miyagi Pref. (1997)[6]) shown in table 1.

2.2 Risk assessment for earthquake-induced slope failures by 3D FEM seismic response analysis

Fig. 3 shows the flowchart of the risk assessment for the earthquake-induced slope failures by 3D FEM seismic response analysis in BESSRA[2] that is developed for large area[7]. Methods of analysis are as follows:

a) Make 3D-FEM surface grid cells using elevation grid cells data such as 50m-DEM (Digital Elevation Model) of GSI (Geospatial Information Authority of Japan).

b) Make 3D-FEM grid cells ground model using the reference point ground model such as KiK-net[8] shear wave velocity layered model data. The 3D-FEM grid cells ground model is made on assumption that each layer thickness ratio of ground model to seismic bedrock is constant to the layer thickness ratio of the KiK-net reference point.

c) Execute 3D-FEM response analysis by BESSRA using the input motion calculated by the seismic micro-zoning technique (Fig. 1) at engineering bedrock to calculate the surface motion.

d) Investigate earthquake induced slope failures risk by the 3D-FEM response analysis in BESSRA result from PGA or maximum shear stress[1].

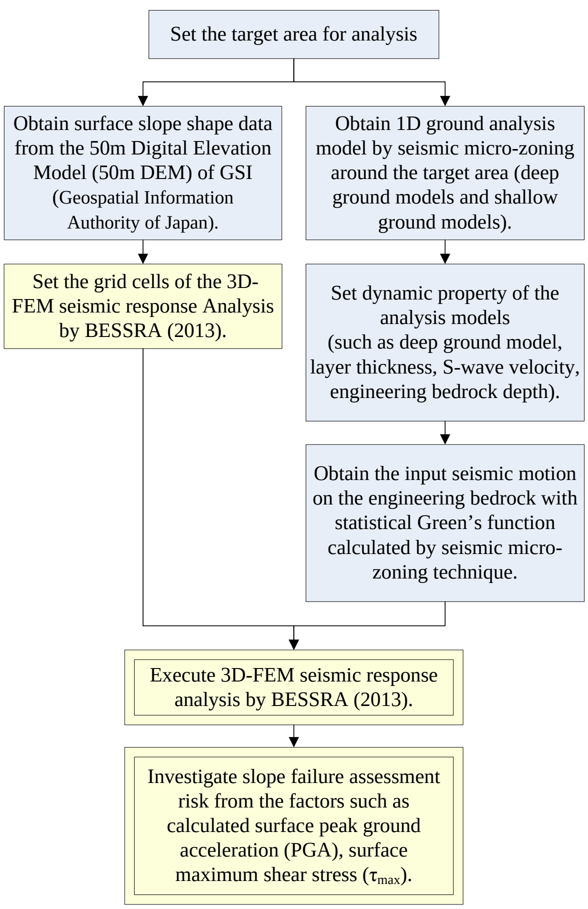
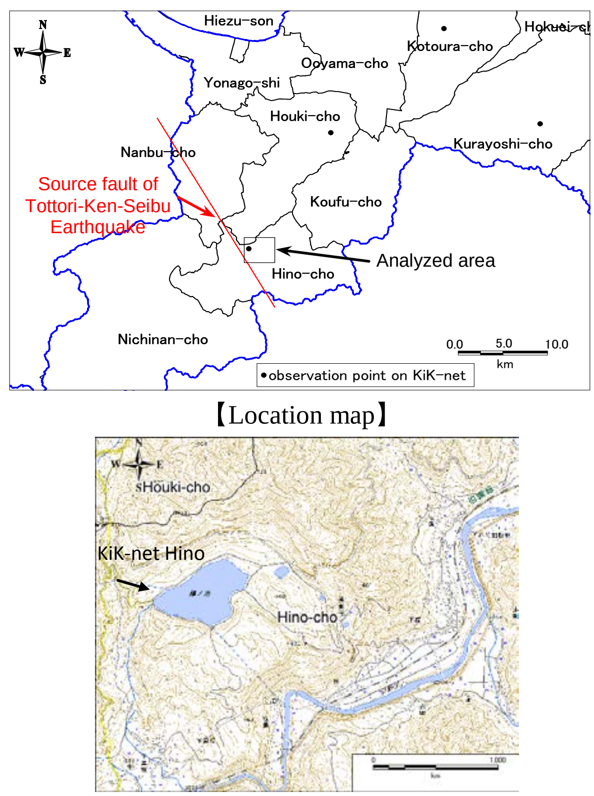


Fig. 2 - Flowchart of the slope failure prediction by 3D seismic response analysis (BESSRA(2013)[2]).



【Analyzed area】

※The electric topographic map 25000 issued by GSI is used as background.

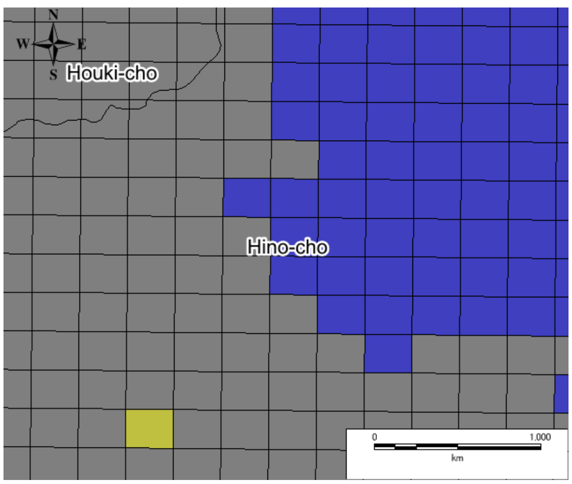
Fig. 3 - The location map and the analyzed area.

3. The new combined method of analysis

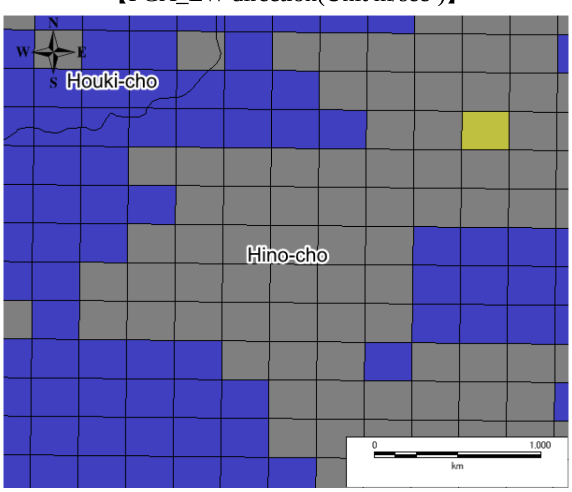
3.1 Risk assessment examples by seismic micro-zoning technique

The analysis examples introduced in this chapter are ordered by Tottori prefectural government (2015) [9]. The scenario earthquake chosen here is the 2000 Tottori-Ken-Seibu Earthquake. The seismic micro-zoning analyses are carried out on each 250m grid cells. The surface waves are calculated with the incident motion at engineering bed rock by the statistical Green's function method. The 1D seismic response analyses are executed with the 1D shear wave velocity layered ground model. The surface seismic motions are calculated all over Tottori prefecture. The bottom graph of Fig. 3 shows the analyzed area in this paper. The fault location (the top of Fig.3) and the fault parameters of the earthquake are referred from the documents of 2000 Tottori-Ken-Seibu Earthquake by Headquarters for Earthquake Research Promotion of Ministry of Education [10].

Fig. 4 and Fig. 5 show the PGA and instrumental seismic intensity of surface layer. The earthquake induced slope failures risk is investigated with this instrumental seismic intensity and the risk rank on the slope using slope failures metrics table shown in table 1.



【PGA_EW direction(Unit m/sec^2)】



【PGA_NS direction(Unit m/sec^2)】

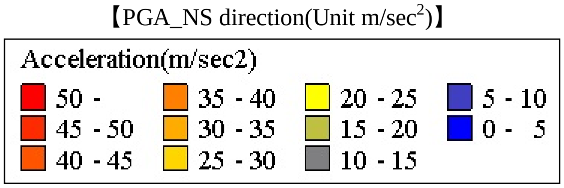


Fig. 4 - Distribution map of surface peak ground accelerations (PGA) in 250m grid cells by seismic micro-zoning survey.

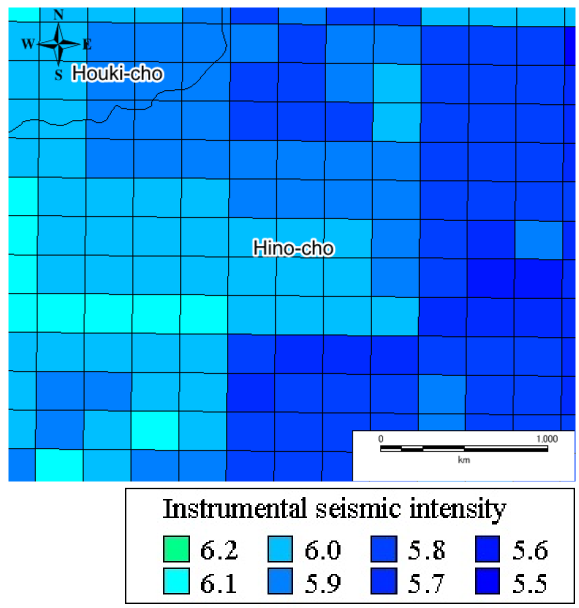
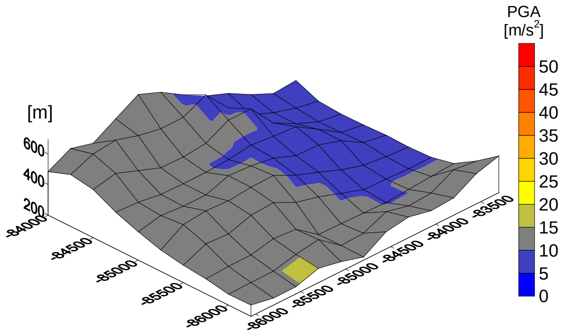
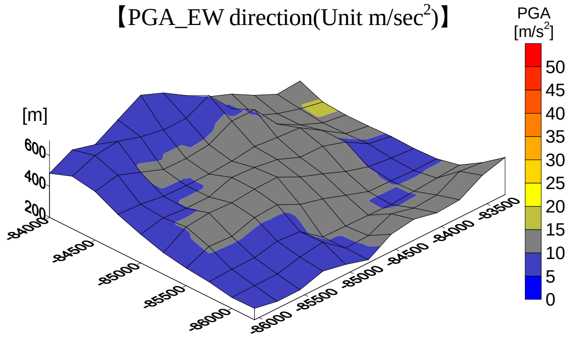


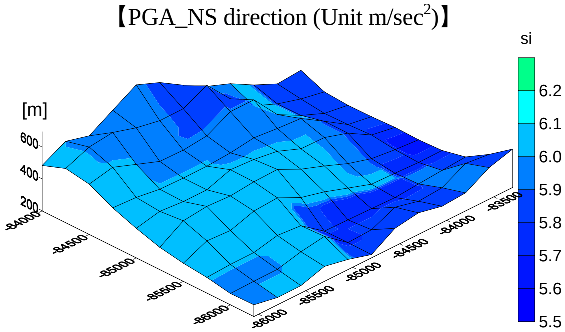
Fig. 5 - Distribution map of instrumental seismic intensity (si) in 250m grid cells by seismic micro-zoning survey.



【PGA_EW direction(Unit m/sec^2)】

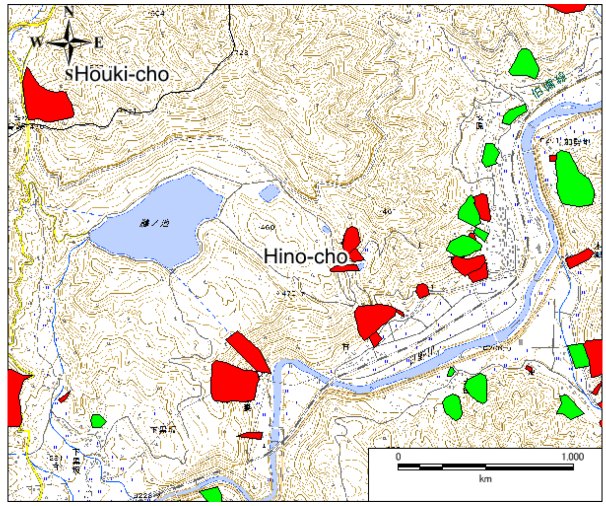


【PGA_NS direction (Unit m/sec^2)】



【Instrumental seismic intensity】

Fig. 6 - 3D view of surface peak ground accelerations (PGA) and instrumental seismic intensity (si) in 250m grid cells by seismic micro-zoning survey.



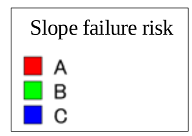


Fig. 7 - Risk assessment map of the earthquake induced slope failure on designated steep slope area by seismic micro-zoninng technique[11].

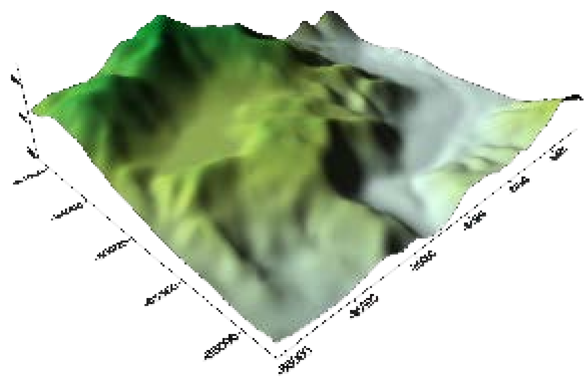


Fig. 8 - 3D geographic map of the analyzed area.

Fig. 6 shows the 3D view of 250m grid cells of PGA and si by seismic micro-zoning technique because of the comparison to the 3D-FEM results. Fig. 7 shows the earthquake induced slope failures risk assessment result that is investigated by si and the risk rank on the slope using slope failures metrics table shown in table 1[11].

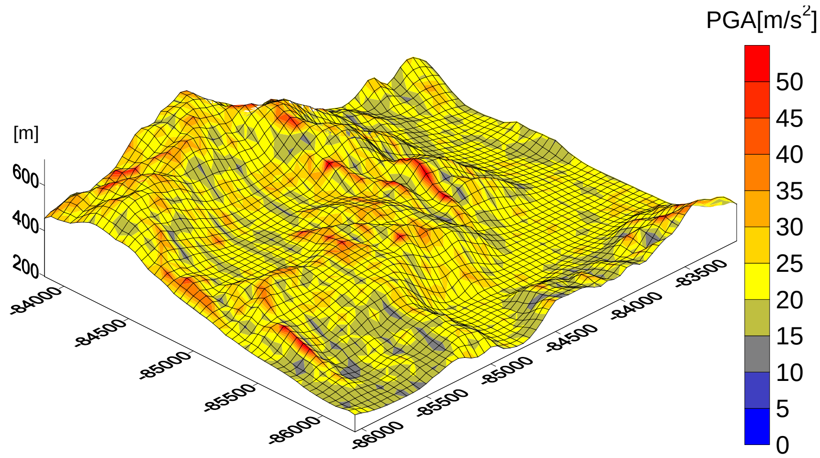
3.2 Risk assessment examples by 3D FEM seismic response analysis

The 3D-FEM seismic response analysis by BESSRA[2] is investigated in the area shown in the bottom graph of Fig. 3. The area is divided into 50x50m grid cells and the seismic motions of each grid cells are calculated. Input motion of the calculation is represented by the wave at KiK-net Hino (top of Fig. 3) obtained from the risk assessment by seismic micro-zoning technique in chapter 2.1. Fig. 8 shows the 3D geographic map in the area with view point at south-west corner.

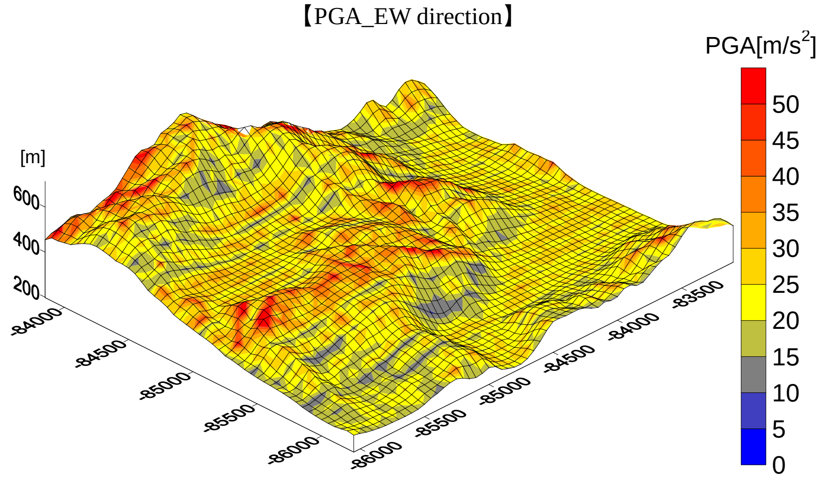
Fig. 9 shows the 3D view of the surface PGA and si of 50m grid cells. These figures indicate the higher PGA and si of the 3D-FEM analysis results than Fig. 6 by seismic micro-zoning technique. The reasons are as follows:

1) The 3D-FEM grid cells ground model is made on assumption that the each layer thickness ratio of the ground model to seismic bed rock is coincident with the layer thickness ratio of the KiK-net reference point.

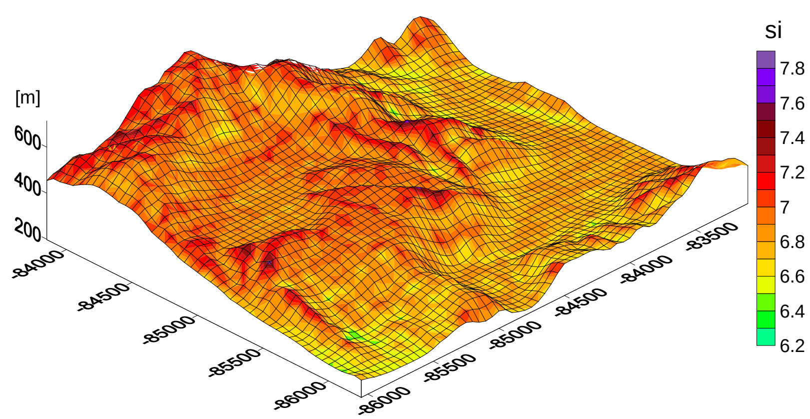
2) The 3D-FEM analysis by BESSRA can consider 3D topographic effect; however the analysis by seismic micro-zoning technique cannot consider the effect because of using 1D seismic response analysis. Therefore, very high values of PGA and si appear at the part of the mountain ridge in Fig. 9 with the 3D-FEM analysis result by BESSRA[2].



【PGA_EW direction】



【PGA_NS direction】



【Instrumental seismic intensity】

Fig. 9 - 3D view of surface peak ground acceleration (PGA) and instrumental seismic intensity (si) in 50m grid cells by BESSRA 3D-FEM seismic response analysis results.

3.3 The actual slope failure damage at 2000 Tottori-Ken-Seibu Earthquake

The actual slope failure damages occurred at 2000 Tottori-Ken-Seibu Earthquake [12]. These actual slope failure damage points is superimposed on the risk assesment map of earthquake induced slope failure on designated steep slope area (FIg. 7). Fig. 10 shows the supeimposed figure of the slope failure damage points. Actual damage points and high risk slopes on assessment results corresponds well, although the high risk slopes are designated wider than the actual slope failure points.

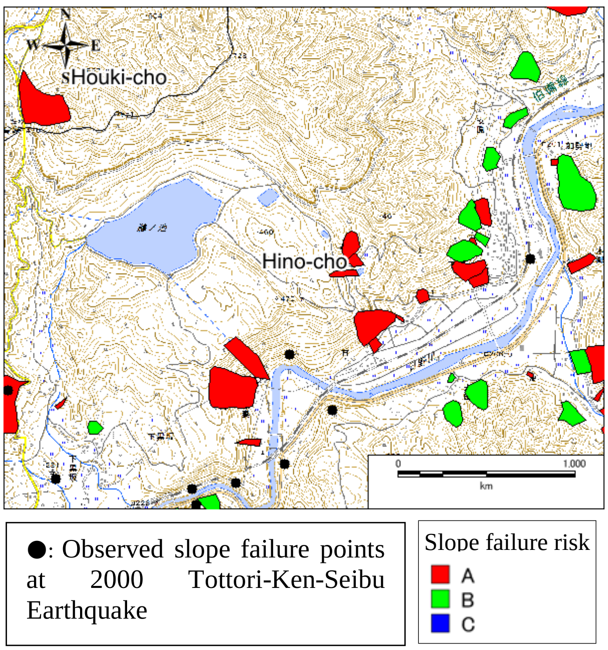


Fig. 10 - Distribution of the observed slope failure points at the 2000 Tottori-Ken-Seibu Earthquake with the assessed slope failure ranks on seismic micro-zoning.

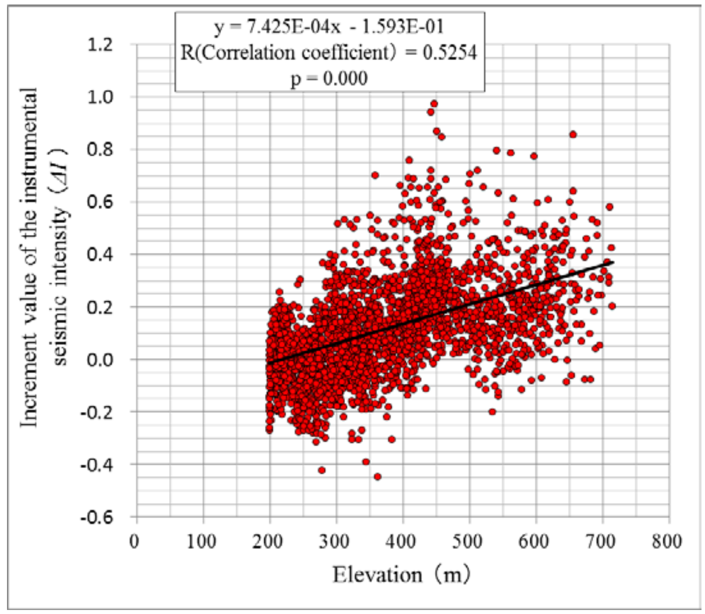


Fig. 11 - Correlation between the increment of the instrumental seismic intensity and the elevation of the 50m grid cells.

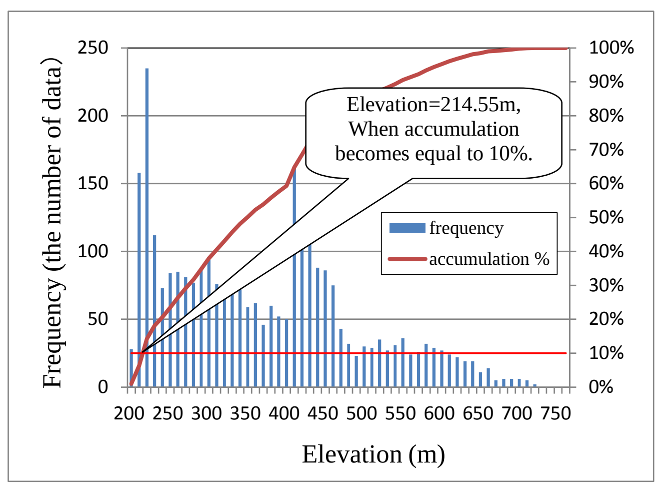


Fig. 12 - Frequency distribution of the elevation of 50m grid cells.

3.4 The new combined method of analysis with the assessment of earthquake induced slope failure

A new method is developed to consider the 3D topographic effect in the assessment of earthquake induced slope failure. The 3D-FEM analysis result by BESSRA is combined to the seismic micro-zoning technique. The method of the analysis is as follows:

a) Si correction factor regarding 3D geological effect (ΔI: the increment of si of the 50m grid cells) is introduced. ΔI is defined as the difference between the si value at the part of mountain ridge (I_{jma50}) and the si value at the reference grid cell of the alluvial plain ($I_{jma50(\text{The reference grid cell of alluvial plain})}$), which is expressed as follows:

$$\Delta I = I_{jma50} - I_{jma50\,(\text{The reference grid cell of alluvial plain})} \tag{1}$$

b) The correlation between ΔI and the elevation (ALT) of the grid cells is investigated from the 3D-FEM seismic response results by BESSRA. The correlation is shown in Fig. 11 and is concluded as follows:

$$\Delta I = 7.425 * 10^{-4} ALT - 1.593 * 10^{-1} \tag{2}$$

c) The elevation of the reference grid cell of the alluvial plain is decided by the cumulative frequency distribution of the surface grid cells elevation of the analyzed area. The 10% of low ranks of the cumulative frequencies of the surface grid cells elevation has been chosen as the reference grid cell (Fig. 12). The elevation of the cell is 214.55m.

d) The si of the 250m grid cells by the seismic micro-zoning technique (I_{jma250}) is corrected by the increment of si (ΔI). The corrected value (I_{jma50}') is delivered by the following equation:

$$I_{jma50}' = I_{jma250} + \Delta I \tag{3}$$

Fig. 13 shows the corrected instrumental seismic intensity by formula (3). Fig. 14 shows the corrected earthquake induced slope failures risk assessment result by seismic micro-zoning technique using this corrected instrumental seismic intensity (Fig. 13) and slope failures metrics table (Table 1). Black circle in Fig. 14 indicates the higher risk evaluation of the slope failure risk assesment than Fig. 10 because of taking into account of the 3D topographic effect by formula (3).

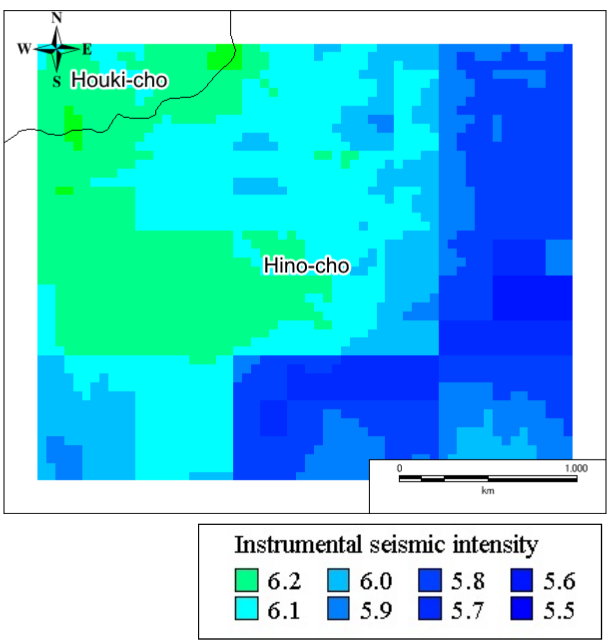


Fig. 13 - Instrumental seismic intensity distribution corrected by 3D topographic effect formula (3) (I_{jma50}').

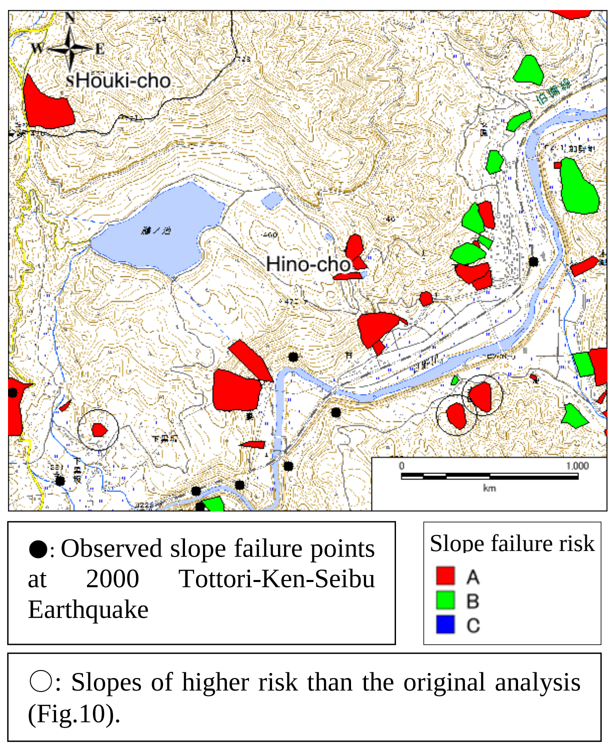


Fig. 14 - Risk assesment map of earthquake induced slope failure regarding 3D topographic effect.

4. Discussions

The new combined method of analysis with the assessment of earthquake induced slope failure is proposed. Considered from a different angle, the problem is how to evaluate the 3D topographic effect of the seismic motion.

The 3D topographic effect of the seismic motion has been investigated by many researchers after 1995 Hyogo-Ken-Nanbu Earthquake. Kurita et al. (2005)[13] and Asano et al. (2006)[14] studied the irregular topography effect on strong ground motion amplification. The calculation of seismic motion regarding the topographic effect is very difficult even in these days for prefectures or larger areas.

The seismic micro-zoning techniques are widely used to calculate surface motions of the scenario earthquake by dividing the target area into 250m grid cells in which 1D seismic response analysis is performed.

Fig. 15 shows the schematic figure of mountainous area with 1D seismic response analysis. The 1D ground analysis models naturally cannot be able to represent 2D or 3D ground structures in the mountainous area. That is because the 1D response analysis of the mountainous area is performed with very shallow engineering bedrock ground model. The new combined method of analysis with the assessment of earthquake induced slope failure is developed using 3D FEM seismic response analysis by BESSRA that can be able to consider 3D topographic effect. The 3D topographic effect is considered by using Formulas (1), (2), and (3).

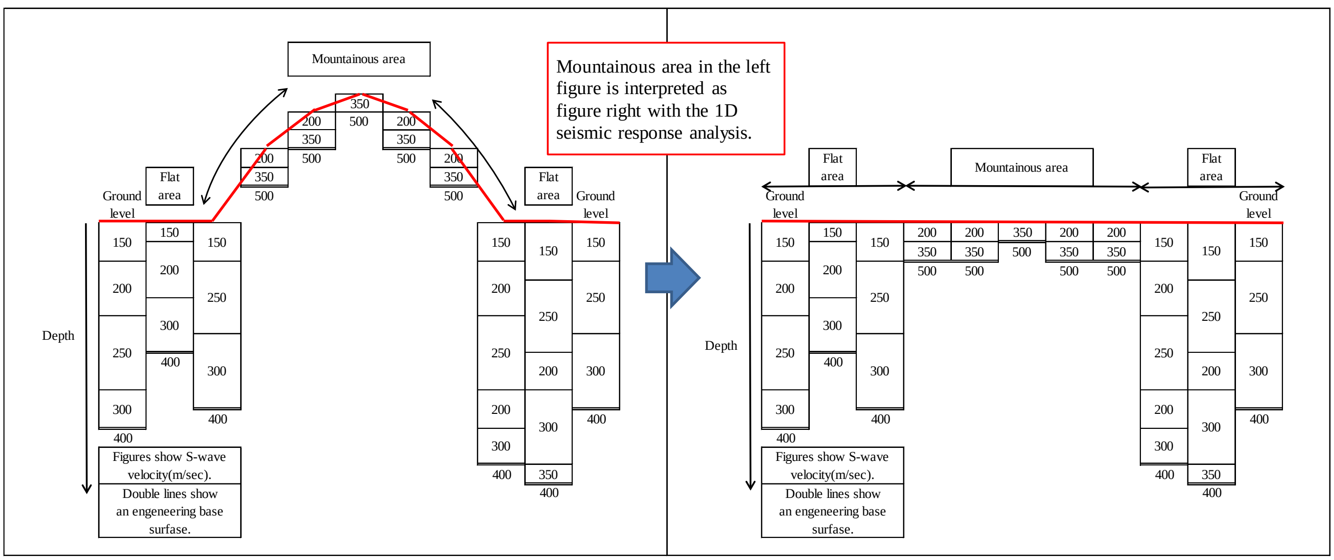


Fig. 15 - The schematic diagram of approximation when mountainous area is expressed approximately in 1D ground analysis model.

5. Conclusions

1) The seismic response analyses are performed by two methods in the same region and the same input motions, the one is seismic micro-zoning technique by 1D response analysis and the other is 3D-FEM seismic response analysis by BESSRA.

2) The assessment of earthquake induced slope failures is carried out widely by seismic micro-zoning technique. The results of the analyses are indicated by using the slope failures metrics table on table 1 in this paper. The actual slope failures damage records in 2000 Tottori-Ken-Seibu Earthquake are introduced

and the assessment of earthquake induced slope failures are compared with this actual slope damage records. Superimposed results of the analyses and actual damage records are well corresponded.

3) The methods of analyses are combination of the assessment of the earthquake induced slope failures by the seismic micro-zoning technique and 3D-FEM seismic response analysis. Formulas (1), (2), and (3) are developed to take into account the 3D topographic effect on assessment of the earthquake induced slope failures.

4) The results of the combined method are indicated in Fig. 14. These results agree well to the actual slope failure distribution.

5) These results reflect the future trend of the assessments of earthquake induced slope failures, and indicates the importance of the 3D topographic effect for these assessments.

6. Afterword

The comments for the analyses are as follows:

a) The 3D-FEM grid cells ground model assumes that each layer thickness ratio of the ground model to seismic bedrock is coincident with the layer thickness ratio of the KiK-net reference point. The reasons for the assumption are lack of geotechnical data for instance geological column data and also lack of dynamic property data of the slope in the mountainous region.

b) The dynamic properties of the 3D-FEM analysis by BESSRA referred to the average dynamic properties of the seismic micro-zoning study in Tottori prefecture. The stress and strain relationships are adopted to the Ugai-Wakai model[3]

7. Acknowledgements

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