Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.III)

4-2-8

PROBABILITY OF SLOPE FAILURES CAUSED BY EARTHQUAKES

Seiya TAZAWA[1], Yozo YUI[2] and Eiichi KURIBAYASHI[3]

1 Metropolitan Expressway Public Corporation, Minato-ku, Tokyo, Japan
2 Tokyo Engineering Consultants Co. Ltd, Chuo-ku, Tokyo, Japan
3 Toyohasi University of Technology, Toyohshi, Aichi, Japan

SUMMARY

This paper describes a method to evaluate probability of slope failures caused by earthquakes. As a typical example the method was applied to the slope failures occurred during the Japan's Nagano-ken Seibu Earthquake of September 14, 1984 with magnitude on Richter scale of 6.9. The volume of one of the biggest slope failures was estimated as 36 million cubic meters at the slope of Mountain Ontake.

In the method proposed hereby, static inertia forces in terms of equivalent seismic accelerations to apply to each solid mass assigned to square meshes, 200 by 200 meters for surface soil was assumed. The statistic variables were assumed as; the static inertia force, the cohesive strength of soils and the internal friction angle of soils.

Consequently, the probability of the failure strongly depends on slope angle in this analysis. In the examples of the three sites the highest probability of the failure reaches upto 100 percents in the residential area, the next upto 82 percents in the middle upper altitude of Mt. Ontake, and the lowest upto 43 percents in the non-residential area of the low altitude. The actual failures during the earthquake were observed in the most meshes with the probability of the failure of 20 percents or more in this analysis. Naturally, the residential area mostly reclaimed have higher risks than other in this analsis.

INTRODUCTION

An evaluation method of slope failures taking account of probability in earthquakes was discussed in this study. Slope failures or land slides have observed in mountaineous areas during or after heavy rain falls and strong ground motions. These failures are understood as geometric cycles or erosion cycles for the long history of the earth. The phenomena are frequently observed everywhere in mountaineous areas, and rerely bring large scale disasters, especially in Japanese islands.

In this study a probabilistic method was atempted to evaluate the slope failure at three sites including the failure of the slope of Mt. Ontake with the volume of the failure of its surface soil of 36 million cubic meters occurred during the Japan's Nagano-ken Earthquake of September 14, 1984 with magnitude on Richter scale of 6.9.

PROBABILISTIC ANALYSES OF SLOPE FAILURES

Probability of failure can be defined as follows,

$$P_f = P[R(x) < S(y)] \quad (1)$$

where P_f and P[ ] represent probability of failure, R(x) is resistantce of soil of slope, and S(y) is acting force during earthquakes.

The resistance of soil is assumed as statistical variables of shearing strengths of soil which are consisted of cohesion and internal friction with normal distribution in probabilistic sense. The acting force along the surface of the slope is assumed as a combined force of the grarity force and equivalent static seismic forces, acting on only horizontal direction, which are evaluated from an attenuation formula with a logarithmically normal distribution [5].

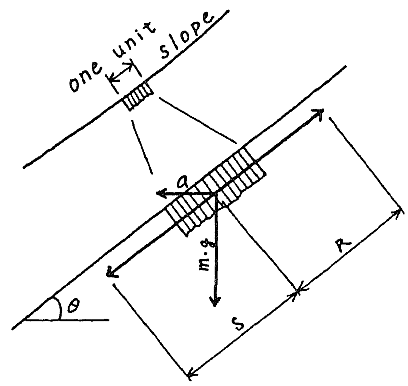


Fig. 1 Force and Strength for a Unit Area of Slopes

As shown in Fig. 1. the resistance of soil is expressed by the following strength function, R(x), and the acting force is expressed by the following forcing function S(y), respectively,

$$R(x) = C \cdot A \cdot g + m \cdot g \cdot \cos\theta \cdot \tan\phi \quad (2)$$

$$S(y) = m \cdot g \cdot \sin\theta + m \cdot a \cdot \cos\theta \quad (3)$$

where,

c: cohesive strength of soil,	in tf/m^2
ϕ: internal friction angle of siol,	in rad
g: gravity acceleration (9.80 m/sec^2),	
a: horizontal ground acceleration,	in m/sec^2
A: unit area injected to horizontal plane,	in m^2
m: weight of soil in unit area,	in t
θ: angle of slope to horizontal base line,	in rad

In convenience for the calculation, Eq.1. can be modified as follows,

$$P_f = P[R(x) - m \cdot g \cdot \sin\theta < S(Y) - m \cdot g \cdot \sin\theta] \quad (4)$$

then,

$$R(x) - m \cdot g \cdot \sin\theta = \frac{1}{\sqrt{2\pi} \cdot \sigma_x} \; e\,x\,p\left\{ \frac{1}{2}\left(\frac{x-\mu}{\sigma_x}\right)^2 \right\} \quad (5)$$

$$S(y) - m \cdot g \cdot \sin\theta = \frac{1}{\sqrt{2\pi} \cdot \nu \cdot y} \; e\,x\,p\left\{ \frac{1}{2}\left(\frac{\ln y - \lambda}{\nu}\right)^2 \right\} \quad (6)$$

where,

$\sigma_x = \sqrt{(A \cdot g \cdot \sigma_c)^2 + (m \cdot g \cdot \cos\theta \cdot \sigma_{\tan\phi})^2}$

$\mu_x = A \cdot g \cdot C + m \cdot g \cdot \cos\theta \cdot \tan\phi - m \cdot g \cdot \sin\theta$

$\nu = \sigma \ln a$

$\lambda = \ln a \cdot m \cdot \cos\theta$

σ_c: standard deviation of cohesion

$\sigma_{\tan\phi}$: standard deviation of friction

σ: standard deviation of acceleration

Assuming the variables of the forcing function are statistically independent to the variables of the strength function, the probability of the failure is expressed as follows,

$$P_f = P[R(x) < S(y)]$$

$$= \int_{-\infty}^{\infty} \left\{ R(x) - m \cdot g \cdot \sin\theta \right\} \int_{y}^{\infty} \left\{ S(y) - m \cdot g \cdot \sin\theta \right\} dxdy \qquad (7)$$

or

$$= \int_{-\infty}^{0} \left\{ R(x) - m \cdot g \cdot \sin\theta \right\} \int_{0}^{\infty} \left\{ S(y) - m \cdot g \cdot \sin\theta \right\} dxdy$$

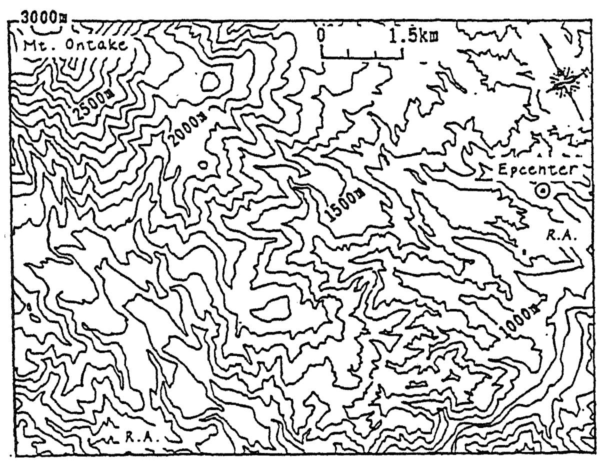
$$+ \int_{0}^{\infty} \left\{ R(x) - m \cdot g \cdot \sin\theta \right\} \int_{x}^{\infty} \left\{ S(y) - m \cdot g \cdot \sin\theta \right\} dxdy \qquad (8)$$

NUMERICAL EXAMPLES

The Japan's Nagano-ken Seibu Earthquake occurred in Nagano prefecture in central part of Japan. The epicenter is located at the location of N 35°39.3' and E 137°33.6', as shown in Fig. 2. It brought much damage such as 29 dead, 10 injury, 14 houses destroyed, 73 houses partially destroyed, 517 houses partially damaged and many slope failures including the slope failure of 36 million cubic meters at the slope of Mt. Ontake as shown in Fig.3. The material loss was estimated as 24.6 billion yen. The geograhical and geological conditions of the site, 8 km in North-South and 11 km in East-West, are shown in Fig. 2. and Fig. 4. respectively.

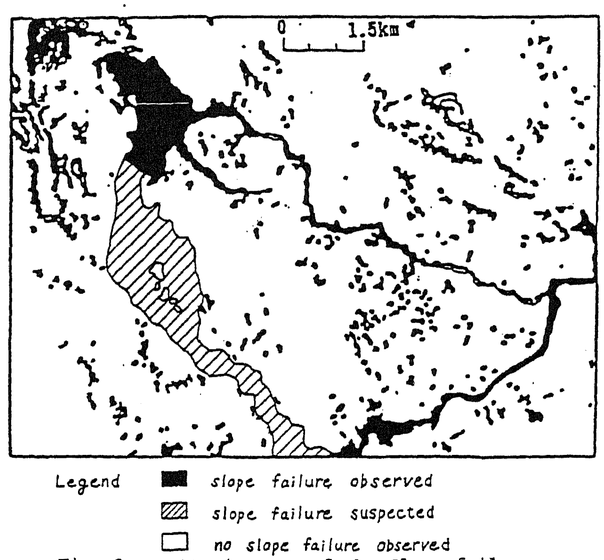
In this analysis unit weight of soil or rock was adopted as shown in Table 1., and the mean value and standerd deviation of the cohesive strength and internal friction anagle were adopted as shown in Table 2.

The probability of Eq. 4. was calculated by employing mesh data for each 200 meters of square meshes with the depth of surface soil of 5, 15 and



Legend R.A. : Residential Area

Fig. 2 Epicenter of the Japan's Nagano-ken Seibe Earthquake and the Severe Area



Legend
■ slope failure observed
▨ slope failure suspected
□ no slope failure observed

Fig. 3 Scattering Map of the Slope failure in the Severe Area

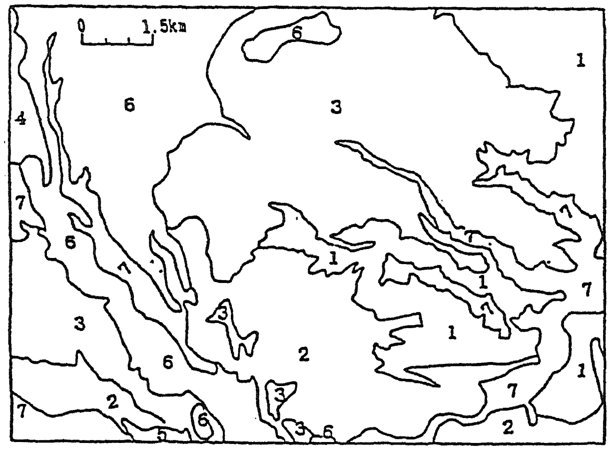
50 meters depending on the site conditions.

Consequantly, the distribution of the probability for each meshes was evaluted as shown in Fig. 5, and the relationship between the probability and the slope angle is shown in Fig. 6.

CONCLUSIONS

In comparison between the result of this analysis in Fig. 5, and the actual phenomenon in Fig. 3., there is apparently some defferences, especially the specific zone which is indicated as "slope failure suspected" in Fig. 3. The actual failure corresponds to the area with the probability of 20 percents or more in this analysis excepct the specific zone where would be another reason of the slope failure perceived.

In this anaysis the probability of the failure strongly depends on the slope angle as shown in Fig. 6. In this example of the three sites, the highest probability of the failurle reaches upto 100 percents in the residential area, the next upto 82 percents in the middle upper altitude of Mt. Ontake, and the lowest upto 43 percents in the non-residential area of the low altitude. The actual failures during the earthquake were observed in almost all of the meshes with the probability of the failure of 20 percents or more in this analysis. Naturally, the residential areas reclained have higher risks than other in this analysis.



note. Numerical figures correspond to the identification numbers for geology in Table 1.

Fig. 4 Geological Conditions in the Severe Area

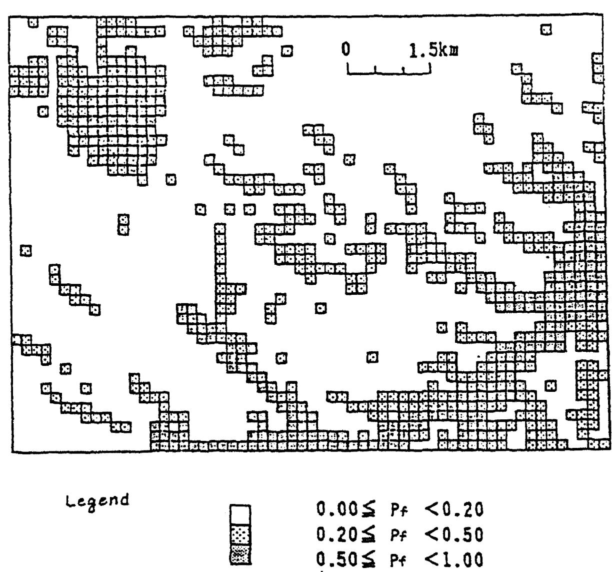


Fig. 5 Probability of the Slope failure in the Severe Area

Table 1 Unit Weight of Soil and Rock [1]

Identification	Unit weight, γ_t (tf/m^3)
1 Palaeozoic formation	2.6
2 Nohi rhyolites	2.7
3 Older andesite	2.6
4 younger rhyotiles	2.2
5 Takigoshi formation	2.0
6 younger andesite	2.6
7 recent sediment	2.0

Table 2 Mean Values and standard Deviations of Surface Soil [2], [3], [4]

Region	Cohesion, C		friction angle, $\tan\phi$		Area shared
	C	s.d.	ϕ	s.d.	
	tf/m^2	xC		xϕ	%
Mountaineous Area	20,000	0.400	0.577	0.300	90.75
River Side	1,480	0.487	0.239	0.460	8.64
Residential Area	5,304	0.295	0.342	0.082	0.61

ACKNOWLEDGMENTS

The authors would like to express their sincere appreciation to the many researchers who reported particularly detailed information on geography, geology, soil properties and the actual failure of the slopes in the severe area. This study was conducted by the support of the subsidy of Science Research Fund, Subject No. 58460156 provided by Ministry of Education, Science and Culture.

REFERENCES

1. H. Okura and K. Tanaka, "Develop on seismic slope stability map system, (Case study on Nagano-ken Seibu Earthquake of September 14, 1984)", Proceedings of the Tenth Symposium for Using computer, p165-p170, 1985
2. M. Matsuo, "Geotechnical Engineering, A Concept and its Application of Design of Reliability", Gihodo Press, p19-26, p55-104, 1984
3. K. Naruse, H. Honma, S. Tanifuzi, "Data Book on Civil Engineering", Morikita press, p195-232, 1962

4. E. Tanigchi, T. Kubota and T. Kuwabara, "Slop failure at Matsukoshi by the Naganoken-seibu Earthquake", Proc. Soil and Fundation, No.150, Nov., 1985
5. K. Kawashima, K. Aizawa and K. Takahashi, Attenuation of Peak Motions and Absolute Acceleration Response Spectra", Rep., PWRI, No.166, Sep. 1985
6. Keefer. D.K., Landslids caused by Earthquakes, Geological Society of America Bulletin, No.95, 1984
7. E. Kuribayashi and T. Nakazawa, "Research and Analysis of Landslide by Ground Motions", Proc., The Second Workshop on Joint Research on Earthquake Eng. between Japan and China, Toyohashi 1986

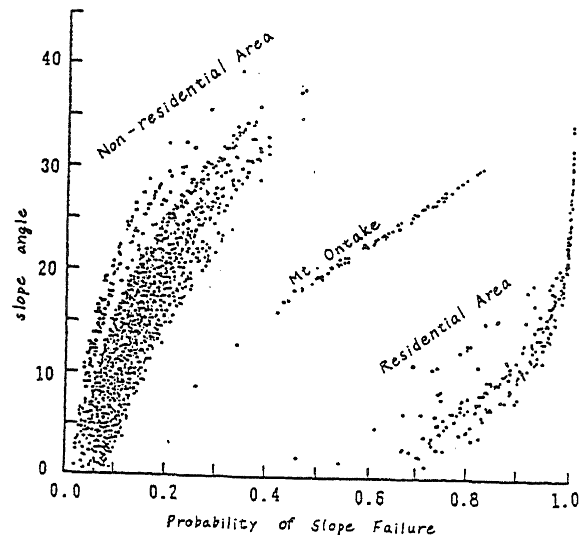


Fig. 6 Relationships between the Probability and the Slope Angle

note. All references are written in Japanese except 6 and 7

APPENDIX

Attenuation Formula in Reference 5, proposed by K. Kawashima, et al is

$$a=227.3\cdot 10^{0.308M}\cdot(\Delta+30)^{-1.201}$$

where,

M: earthquake magnitude on Richter scale

Δ: epcental distance, in km

a: peak ground acceleration, in gal

Distribution of the peak ground acceteration in this example in the right.