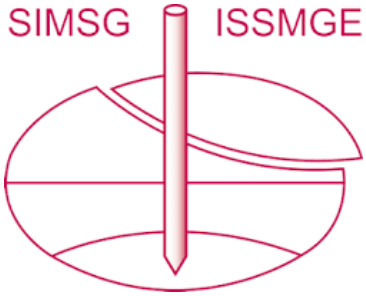
INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Stability analyses of embankment on soft clays against earthquakes

Analyses de stabilité d'endigage sur argiles molles en vue de tremblements de terre

S.Ohtsuka – *Department of Civil and Environmental Engineering, Nagaoka University of Technology, Japan*
E.Yamada – *Department of Geotechnical and Environmental Engineering, Nagoya University, Japan*

ABSTRACT: This study develops two stability methods of earth structures against earthquakes. One is a stability method against static repeated loads based on the seismic coefficient concept (Method A) and the other, a stability method which takes account of the acceleration time history exactly (Method B). The applicability of both are examined for embankment stability against enforced sine and irregular accelerations at bedrock. In conclusion, the embankment stability could be estimated with Method B depending on not only the acceleration time history, but also the dynamic properties of the embankment and ground. The result obtained by Method A coincides with that by Method B at long period in acceleration wave. It indicates the both methods work properly. The accuracy of conventional seismic coefficient method is discussed with numerical examples.

RESUME: Cette étude déploye deux méthodes de stabilité de structures de la terre pour le tremblement de terre. La première méthode de stabibilité pour les oppressions statiques répétées est basée sur le concept de coefficient séismique (méthode A) et la deuxième méthode tient compte de l'histoire exacte d'accélération (méthode B). L'application de deux méthodes est examinée par la stabilité de l'endidage pour le sinus renforcé et des accélérations irrégulières sur la roche. En conclusion, la stabilité de l'endidage évaluée avec la méthode B ne dépend pas que l'histoire de temps d'accélération mais aussi de propriétés dynamiques de l'endidage et du terrain. Le résultat obtenu de la méthode A est concordant avec celui obtenu avec la méthode B à une longue période d'accélération d'onde. Les résultats indiquent que les deux méthodes fonctionnent bien. La précision de la méthode de coefficient séismique conventionnelle est discutée avec plusieurs exemples.

1 INTRODUCTION

The seismic coefficient method has been adopted to estimate the stability of earth structures against earthquakes. It is simple and effective in design, however, it cannot consider both the acceleration time history of earthquake and the dynamic properties of ground and earth structure. It is because the seismic coefficient method considers a particular instant of successive motion of earth structure due to the prescribed acceleration time history.

This study firstly examines the effect of repeated load on the stability of earth structure, which changes its magnitude and direction as earthquake. Based on the seismic coefficient method, two load applications are considered. One is a constant load as employed in the conventional method and the other is a repeated load in a certain domain prescribed by earthquake. The effect of domain for possible load on the stability is investigated in detail with an embankment problem. It is conducted based on the shakedown analysis with the use of finite element method (Maier, 1969). The stability of structure is generally deteriorated by taking account of repeated change of load in earthquake.

Secondly, a failure definition of earth structure against a dynamic load is newly proposed and a stability method is developed. The proposed method can take account of the effects of the acceleration time history of earthquake and dynamic properties of the ground and earth structure. It could consider the effect of change in magnitude and direction of earthquake acceleration on the stability. The applicability of the proposed method is clarified through numerical analyses.

The conventional seismic coefficient method will generally give an underestimated safety factor for earthquake if the maximum acceleration intensity in earthquake is employed. It is a difficult task to determine an adequate design acceleration intensity for earthquake. This study discusses the accuracy of the conventional seismic coefficient method through the comparison of the results obtained by these two methods when the acceleration time history is prescribed.

2 SHAKEDOWN ANALYSIS BASED ON SEISMIC COEFFICIENT METHOD

2.1 *Load Domain and Shakedown*

The seismic coefficient method regards an earthquake as a static inertia force acting on earth structure. Defining a load factor α for an inertia force, the stability of earth structure is estimated by obtaining the limit load factor where the structure fails. However, the actual enforced acceleration of earthquake changes its direction and magnitude drastically with time. Even though the seismic coefficient method deals with an instant of enforced acceleration time history, it is still important to estimate the effect of repeated load in earthquake on the stability.

By regarding an earthquake as a possible static inertia force in a load domain Δ, a load factor α is defined for the load domain as Figure 1. The stability of earth structure can be estimated by the limit load factor where the structure does not shake down. The structure is safe if it finally gets to be elastic (shakedown) against any repeat of possible load in domain $\alpha\Delta$, even though there existed finite plastic deformation due to repeat of loading (Koiter,1960).

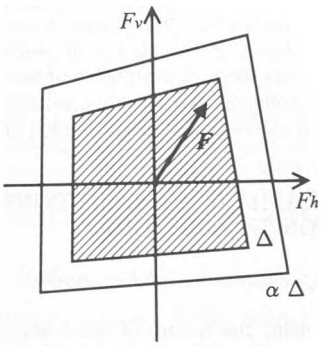


Figure 1. Load domain.

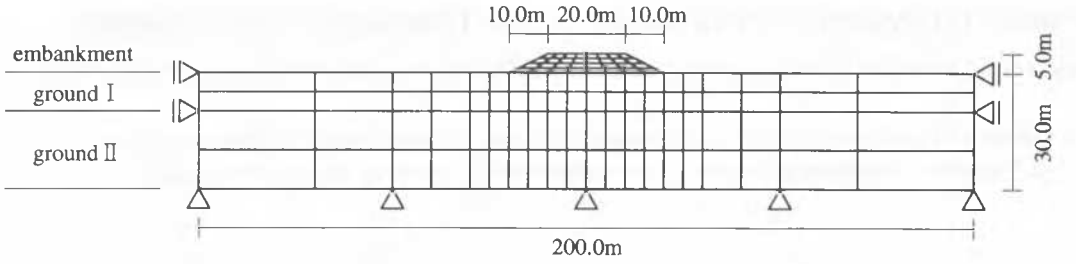


Figure 2. Finite elements and boundary conditions.

Table 1. Soil constants.

E	1000.0 kN/m^2	ν	0.33333
γ_t	19.6 kN/m^3	γ_w	9.8 kN/m^3

$$c_u = \begin{cases} \text{embankment} & & 70.7\text{kN/m}^2 \\ \text{ground I} & 0 \le z \le 10\text{(m)} & 141.1\text{kN/m}^2 \\ \text{ground II} & 10 \le z \le 30\text{(m)} & 212.1\text{kN/m}^2 \end{cases}$$

z : depth from ground surface

Table 2. Safety factor against load domain on inertia force.

case	horizontal acceleration (m/s^2)	F_s
case1	a_x=4.90	1.358
case2	$-0.98 \le a_x \le 4.90$	1.358
case3	$-1.96 \le a_x \le 4.90$	1.358
case4	$-2.94 \le a_x \le 4.90$	1.265
case5	$-3.92 \le a_x \le 4.90$	1.125
case6	$-4.90 \le a_x \le 4.90$	1.012

2.2 *Effect of Repeated Change in Inertia Force*

The effect of repeated change in magnitude and direction of horizontal inertia force on embankment stability is investigated through numerical analyses. Figure 2 and Table 1 show the boundary conditions and soil constants employed here. The embankment and soils are modeled as elasto-perfectly plastic materials with the von Mises shear strength. The load domains in Table 2 are considered in computation. The case 1 deals with a constant inertia force and corresponds to the conventional seismic coefficient method. On the other hand, the cases 2–6 consider the effect of change in inertia force. The maximum acceleration in each case is set as the same as a_x=4.9m/s^2. The limit load factor indicates the safety factor of earth structure against the load.

The results are exhibited in the same table. In case 1, the safety factor is obtained as 1.358. On the other hand, the safety factor reduces up to 70% of case 1 by considering the change in inertia force. It reveals the necessity of considering the change in inertia force in evaluation of seismic stability. It is noted that the conventional seismic coefficient method tends to overestimate a safety factor in this view point.

3 SEISMIC STABILITY ANALYSIS CONSIDERING ACCELERATION TIME HISTORY

3.1 *Failure Definition and Stability Analysis*

In a static problem, the failure of earth structure is defined as the state where the deformation is indefinite against the constant load. It is, however, difficult to define the limit state of earth structure against a dynamic load in the same way.

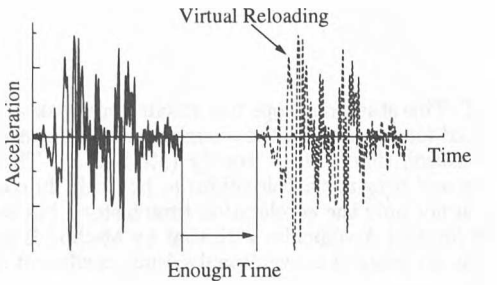


Figure 3. Imaginary repeats of earthquake.

Table 3. Rayleigh damping coefficients.

Rayleigh Damping ($C = \alpha M + \beta K$)
$\alpha = 0.3$, $\beta = 0.0$
M : Mass matrix, K : Stiffness matrix

In this study, an acceleration time history of earthquake is regarded as a successive load. Based on the shakedown concept, the failure of earth structure is judged by applying the earthquake load repeatedly (see Figure 3). The structure is safe if it finally settles to be elastic against the imaginary repeats of the prescribed dynamic load (Ohtsuka et. al., 1995).

The shakedown theorem for dynamic loads is proved by Ho (1972). The limit load factor for earthquake acceleration gives the safety factor of earth structure against the earthquake. The effect of change in magnitude and direction of acceleration is naturally considered in the analysis.

3.2 *Consideration on Safety Factor*

In a bearing capacity problem, the safety factor (load factor) gives the limit load by multiplying the prescribed load. But, the meaning of magnitude in safety factor is not so clear in the case of dynamic loads as earthquakes. It is examined through some examples.

The stability analysis is conducted on the embankment of Figure 2 with the proposed method. Table 1 exhibits the soil constants. The Rayleigh damping model is employed for simplicity. The damping coefficients are shown in Table 3. The sine acceleration wave with the period T = 2s is enforced at the bedrock of the ground. The maximum magnitude of sine wave is changed as shown in Table 4. The obtained safety factors are also exhibited in the same table. They are different, but the products of the maximum accelerations by the safety factors are found to be same. This implies that the safety factor obtained in the analysis denotes the limit load factor on acceleration intensity.

Table 4. Safety factor against seismic load.

a_x (m/s^2)	F_s	$a_x \times F_s$ (m/s^2)
0.98	11.031	10.810
1.96	5.515	10.809
2.94	3.677	10.810
3.92	2.758	10.811
4.90	2.206	10.809

4 SEISMIC STABILITY OF EMBANKMENT ON CLAYEY SOILS

The stability of embankment against earthquake is affected by 1) acceleration time history of earthquake and both 2) damping and 3) resonance property of earth structure. Those effects on seismic stability of embankment are investigated.

4.1 *Effect of Acceleration Wave Properties*

The stability of embankment in Figure 2 is investigated against a sine acceleration wave, which is enforced horizontally at the bedrock of the ground. The soil constants are shown in Tables 1 and 3. The intensity of maximum acceleration is set as a_x=2.94m/s^2.

The effects of both wave number n and period T of the sine wave on the safety factor are firstly examined through numerical analyses. Figure 4 shows the relationship between the safety factor F_s and wave number n. The safety factor is obtained to reduce with a wave number and settle to a certain value. It denotes the safety factor reflects the acceleration history. But, the effect of acceleration time history on safety factor converges with repeats of wave. The wave number n=25 is found to be enough to investigate the safety factor of embankment against the period of sine acceleration wave. In the case of long period, T=200s, the safety factor is constant regardless of wave number.

Figure 5 shows the effect of period in enforced sine acceleration at bedrock on the embankment stability of Figure 2. Two damping conditions are considered in the figure. The safety factor against enforced acceleration tends to reduce with the increasing period of acceleration and approaches to a certain safety factor. It is noted that the safety factor at long period coincides with that by the seismic coefficient method taking account of the change in acceleration wave. It sounds rational because the condition on the motion at long period in acceleration wave is approximate to assumptions in the seismic coefficient method. This fact assures that the proposed definition of failure is adequate for dynamic loads as earthquakes.

The relationship between the safety factor and the period is affected by the damping coefficient. There exists a minimum safety factor at the period of around T=8s when the damping effect is small. Since the natural period of ground and embankment is 8.1s, the decline of safety factor is deduced to be caused by the resonance effect. When the damping effect is high, the resonance effect on the stability cannot be observed.

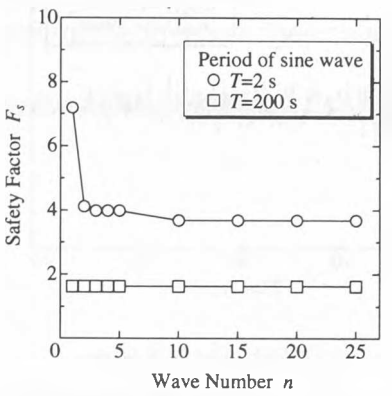


Figure 4. Safety factor ~ wave number relationship.

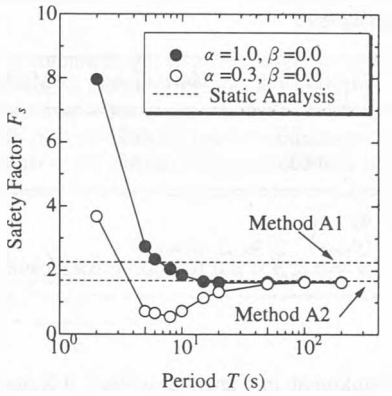


Figure 5. Safety factor ~ period relationship.

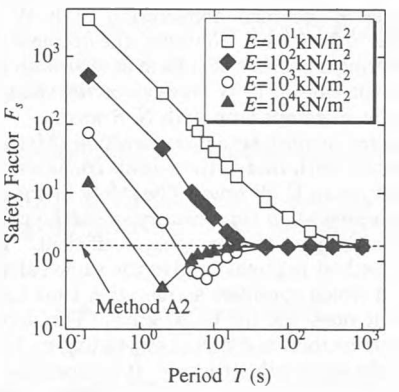


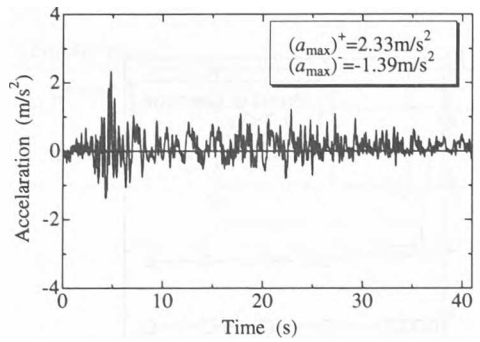
Figure 6. Effect of structural rigidity on safety factor ~ period relationship.

4.2 *Effects of Structural Rigidity on Embankment Stability*

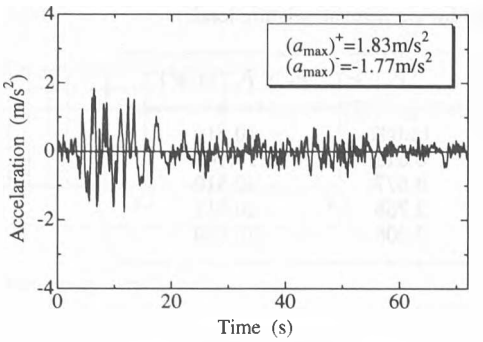
The dynamic property of earth structure is affected by its rigidity and geometrical condition. The effect of elastic modulus of embankment on the seismic stability is investigated. Figure 6 illustrates the relationship between the safety factor and period of sine acceleration wave. It is observed that the safety factor varies with the acceleration period. The relationship between the safety factor and the acceleration period depends on the magnitude of elastic modulus. When the elastic modulus, E is small, the safety factor monotonically reduces with the acceleration period. On the other hand, a drop of safety factor at a certain period of acceleration is observed when the elastic modulus, E is high. The figure suggests that the period at the minimum safety factor decreases with the elastic modulus. When the acceleration period is the same, the safety factor tends to decrease with the elastic modulus of the earth structure.

4.3 *Stability Analysis Against Actual Seismic Wave*

The acceleration time history of actual earthquake is an irregular wave as shown in Figure 7, which was obtained at Hachinohe in the Tokachi-oki Earthquake (1968) in Japan. The seismic



(a) Hachinohe N–S wave



(b) Hachinohe E–W wave

Figure 7. Acceleration time histories of Tokachi-oki Earthquake(1968).

Table 5. Safety factor against acceleration time histories of Tokachi-oki Earthquake.

	Method A1	Method A2	Method B
N–S wave	2.855	2.667	2.664
E–W wave	3.635	2.756	1.279

Method A1 : $a_x = a_{max}$
Method A2 : $(a_{max})^- \leq a_x \leq (a_{max})^+$
Method B : $\alpha = 0.3, \beta = 0.0$ (damping coefficients)

stability of embankment in Figure 2 against this acceleration time history is investigated.

Table 5 exhibited the obtained results. The conventional seismic coefficient method (Method A1) gives a larger safety factor for E–W wave than N–S wave. It is because the maximum magnitude of recorded acceleration in E–W wave is smaller than that of N–S wave. However, the decrease in safety factor by considering a possible change in acceleration (Method A2) is larger in the case of E–W wave since the change in acceleration is wider in comparison with N–S wave.

The safety factor against actual acceleration (Method B) is obtained to coincide with that of the seismic coefficient method in N–S wave, but not in E–W wave. The safety factor is clearly affected by the acceleration time history of earthquake and it will change depending on the damping coefficient. The seismic coefficient method happens to give the same safety factor with the method which considers acceleration time history for N–S wave, but it does not for E–W wave. The accuracy of seismic coefficient method is different depending on the conditions of earthquake and earth structure. It is concluded that an actual design acceleration intensity for the seismic coefficient method should be determined accounting for dynamic properties of earthquake and earth structure from the macroscopic view point.

5 CONCLUSIONS

The followings were concluded in this study.

1. The effects of repeated changes in direction of earthquake acceleration on the stability of earth structure were numerically clarified with the use of shakedown analysis based on the seismic coefficient method. The safety factor reduced to at most 70% of the conventional method in the case of clayey ground. It suggests the importance of taking account of change in acceleration in stability assessment against earthquake.

2. Based on the shakedown concept, the failure definition of an earth structure against an earthquake was newly proposed. The stability of earth structure was properly estimated to account for the effects of (a) acceleration time history of earthquake and (b) dynamic properties of earth structure such as damping and resonance.

3. In embankment stability against the enforced sine acceleration at bedrock, the safety factor was obtained to reduce monotonically with the period of enforced acceleration when the damping effect on wave was large. On the contrary, the decline of safety factor was appeared in the certain range of the period when the damping effect was low. It was concluded as the resonance effect of embankment against the enforced acceleration.

4. The safety factor at long period coincided with that by the seismic coefficient method taking account of the change in acceleration wave. This fact assured that the proposed definition of failure was adequate for dynamic loads as earthquakes since the condition on the motion at long period in acceleration wave was approximate to assumptions in seismic coefficient method.

5. The comparison of safety factors between the seismic coefficient method and the proposed method which took account of acceleration time history was conducted on embankment against the irregular acceleration enforced at bedrock. It denoted the accuracy of seismic coefficient method was different depending on the conditions of earthquake and earth structure. It was concluded that an actual design acceleration intensity for the seismic coefficient method should have been determined accounting for dynamic properties of earthquake and earth structure from the macroscopic view point.

REFERENCES

Ho, H.-Sh. 1972. Shakedown in Elastic-Plastic Systems Under Dynamic Loadings: *Journal of Applied Mechanics, Transactions of ASME*: 416–421.

Koiter, W.T. 1960. General theorems for elastic plastic solids: *Progress of solid mechanics*, Vol.2: North Holland Press.

Maier, G. 1969. Shakedown theory in perfect elastoplasticity with associated and nonassociated flow-laws: a finite element linear programming approach: *Meccanica*: Vol.4, No.3, 1–11.

Ohtsuka, S., Yamada, E. and Matsuo, M. 1995. Stability Assessment of earth structures against dynamic loads: *Proc. of 40th Geotechnical Engineering Symposium*: 265–270 (in Japanese).