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# A SIMPLIFIED METHOD FOR ESTIMATING SEISMIC STABILITY OF EMBANKMENTS ON SANDY DEPOSITS

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## SUMMARY

This paper presents a simplified procedure which evaluate the seismic stability of embankments constructed on sandy liquefiable ground, without any complicated analysis. Evaluation was conducted on the basis of 42 field data on the embankments, some of which were damaged by earthquakes in the past several decades. Seismic stability analyses were performed by the sliding method, taking seismic force into consideration. The main concepts of the procedure are "critical N-value", "safety number", "average safety number" and "stability index". Critical N-value is defined as N-value of the ground that expresses boundary of seismic stability of the embankment, safety number as ratio of measured N-value to critical N-value, average safety number as average of safety number calculated from the ground water level to a certain depth. The seismic stability of the embankment can finally be estimated by comparison of the minimum average safety number (= stability index) with unity.

## INTRODUCTION

The major earthquakes that have occurred in the past several decades in Japan have caused serious damage to many embankments on liquefiable sandy ground. With this background, the seismic stability evaluation of earth structures such as river and road embankments has become necessary. It is desirable that comprehensive stability analyses be applied to each embankment section on the basis of detailed soil data obtained from in-situ and laboratory tests. This is, however, almost impossible and impracticable from the viewpoint of cost performance, because the total length of such embankments to be assessed is usually quite long. Therefore, it is required that a simplified procedure to evaluate the seismic stability of embankments be developed which can generally identify potentially dangerous sections of the whole embankments.

This paper presents a newly developed simplified procedure for seismic stability evaluation of embankments.

### Development of the procedure

The stability analysis method was applied to distinguish to the extent possible, which embankments had failed and which had not. Next, a comprehensive parametric study was performed on hypothetical embankment-ground models with various combination of embankment-ground conditions and design seismicity. From this study, critical N-values were summarized for various sandy soil types and design seismicity considered. This value can be used as basic index to evaluate whether an overlying embankment is seismically stable or not. Then, stability index, a factor to directly evaluate the seismic stability of an embankment was proposed.

Finally, the evaluation procedure mentioned above was converted to a handy table for seismic stability evaluation of embankments. With this table all the information that is required is soil type, N-value of the subsurface ground and design seismicity.

## Case Record of Seismically Damaged Embankments

Records of embankments that had been damaged by earthquakes were collected. Drilling data and SPT-N-value data were also obtained. It was determined that the subsurface ground consists mainly of sandy soil. The total number of damaged embankments was 42. All were river embankments 2 - 7 m in height. Settlement due to earthquakes ranged from 0 to 2 m.

## Seismic Stability Analysis

The circular arc method was combined with a modified version of the Fellenius method in the seismic stability analysis of the embankments.

In calculating factor of safety, the effects of earthquake were taken into account in two ways. One was to consider seismic force (Eq. (1)). The other deals with decrease in shear cyclic undrained strength due to excess pore-water pressure in sandy layer occurring during earthquakes (Eq. (2)).

$$F_{sd1} = \frac{\Sigma\,\{c \cdot \ell + (W - u_o \cdot b)\cos\alpha \cdot \tan\phi\}}{\Sigma\,(W \cdot \sin\alpha + k_h \cdot W \cdot y/R)} \quad \cdots\cdots\cdots\cdots \quad (1)$$

$$F_{sd2} = \frac{\Sigma\quad c \cdot \ell + \{W - (u_o + u_d) \cdot b\}\cos\alpha \cdot \tan\phi\}}{\Sigma\,(W \cdot \sin\alpha\,)} \quad \cdots\cdots\cdots\cdots \quad (2)$$

where, Fsd: factor of safety, c, $\phi$: effective stress shear strength parameters
W : weight of slice, $u_o$ : hydrostatic pressure,
$u_d$: excess pore-water pressure, $k_h$: horizontal seismic coefficient,
$\ell$ : length of sliding arc of slice, b: width of slice,
$\alpha$ : angle of sliding arc to the horizontal plane, y : vertical distance between the center of circle and the center of gravity of slice,
R : radius of sliding circle,

For each embankment two factors of safety were calculated by Eqs. (1) and (2), and the smaller one was finally adopted.

The procedure to compute factor of safety is shown in Fig. 1. In the figure, Meyerhof's formula was used to relate the N-value to the relative density $D_r^*$:

$$D_r^* = 21\sqrt{N/(\sigma_v' + 0.7)} \quad \cdots\cdots\cdots\cdots \quad (3)$$

in which $\sigma'_v$ is effective vertical stress in kgf/cm$^2$.

Mechanical and physical properties of sandy soils were assumed as in Table 1, and those of clayey soils were assumed as follows: unit weight $\gamma_t = 1.5$ tf/m$^3$, shear strength parameters $\phi = 0°$ and $c_u = q_u/2 = 0.2 + N/40$ (kgf/cm$^2$) (after Ohsaki's formula).

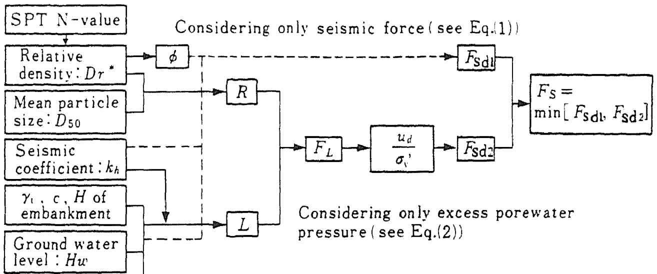
The assumed properties of the embankment material were the same for properties of the embankment material were the same for all soil types as follows: $\gamma_t$ = 1.8 tf/m$^2$ C = 2.0 tf/m$^2$ and $\phi = 25°$

To estimate dynamic shear strength ratio, R, of sandy soil, the empirical methods of Tokimatsu and Yoshimi were used.

In addition, excess pore-water pressure ratio $u_d/\sigma'_v$ was expressed as follows:

$$\begin{aligned} u_d/\sigma'_v &= F_L^{-7} \quad (F_L \geqq 1) \\ u_d/\sigma'_v &= 1 \quad\;\; (F_L > 1) \end{aligned} \quad \cdots\cdots\cdots\cdots \quad (4)$$

where $F_L$ is liquefaction resistance factor.



cf) $R$ : Dynamic shear strength ratio[4)]
$L$ : Shear stress ratio during earthquake
$F_L$ : Liquefaction resistance factor

Fig. 1 Flow Chart to Compute Factor of Safety

Table 1 Properties for Sandy Soils

(a) Mechanical properties

| SPT N-value | $\phi'$ (°) | $c'$ (tf/m$^2$) |
|---|---|---|
| N≦10 | 30 | 0 |
| 10<N≦30 | 35 | 0 |
| 30<N | 40 | 0 |

(b) Physical properties

| Soil type | $\gamma_t$ (tf/m$^3$) | $\gamma_{sat}$ (tf/m$^3$) | $D_{50}$ (mm) |
|---|---|---|---|
| Sandy silt | 1.6 | 1.8 | 0.04 |
| Fine grained sand | 1.75 | 1.95 | 0.15 |
| Medium sand | 1.8 | 2.0 | 0.35 |
| Coarse grained sand | 1.8 | 2.0 | 0.6 |

Fig. 2 shows the relationship between the factors of safety and observed amount of settlement for 42 embankments. There is a general tendency that factor of safety Fsd to decrease as settlement D increases, although the data of graphs show considerable scatter.

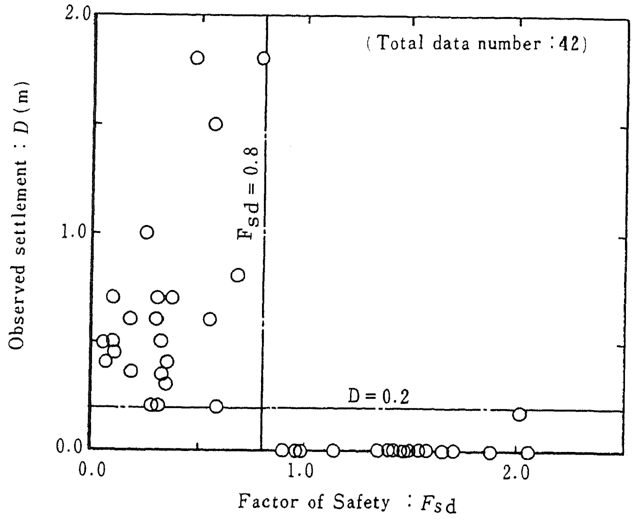
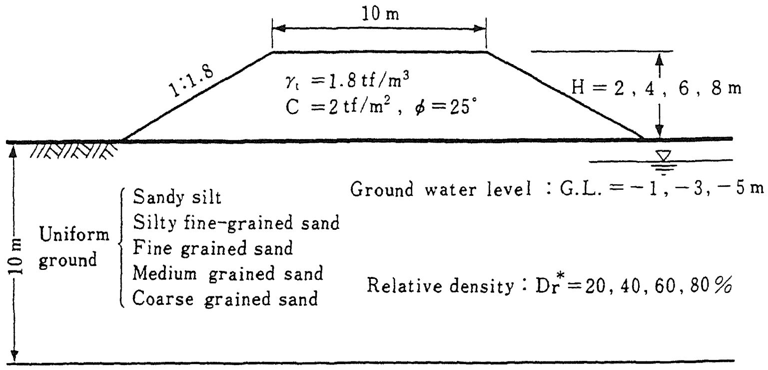


Fig. 2 Relationships Between Observed Settlements and Computed Factors of Safety

## Critical N-value

In this part, a "critical N-value" is proposed. This is a basic factor for judging the seismic stability of an embankment by comparing with measured N-value in sandy deposit at a depth. The critical N-value of the sandy deposit is determined according to soil type, hypothetical earthquake intensity and depth. If measured N-value is lower than critical N-value, the overlying embankment is considered to be seismically unstable.

In order to determine critical N-value, a set of model studies were performed with the hypothetical embankment-ground model illustrated in Fig. 3. The studies consisted of more than a hundred cases of seismic stability analyses of the model, hypothesizing various combinations of the factor shown in Fig. 3. These factors are known to affect the seismic stability of embankment. From the model studies, a set of critical N-values was compiled. Then the sensitivity of the critical N-values to the factors was examined.



cf) The underlined indicates the standard value in a set of calculation.

Fig. 3 Hypothetical Analysis Model

The actual determination of critical N-value, which depends on soil type, and depth is a very complex. First basic critical N-value, defined as critical N-value for design seismicity Kh = 0.18 in fine grained sand, was determined. The corrections were made to determine the value for other soil types and design seismicity.

Safety Number

Safety number Ns which corresponds to factor of safety at each depth was defined as:

$$N_s = N/N_{cr} \quad \cdots\cdots \quad (5)$$

Average Safety Number

A comprehensive study was performed on how to determine the average safety number $\overline{Ns}$, considering such factors as:

(1) Maximum safety number $N_s$
(2) Safety number $N_s$ of non-sandy soils such as silt and clay (For such soils critical N-value Ncr could not be determined because it is not susceptible to liquefaction.)
(3) The depth range to which safety number applies.
(4) Correction for embankment height and ground water level

Stability Index

Stability index Is, which indicates the aseismicity of an embankments uses the minimum value of $\overline{Ns}$ from each depth. The standard for evaluating seismicity using Is was determined as follows:

| | |
|---|---|
| (Is) < 0.7: | Unstable.<br>Maximum settlement (as index of degree of damage) is 2 m. |
| 0.7 ≦ (Is) < 1.0: | Unstable.<br>Maximum settlement is 1 m. |
| 1.0 ≦ (Is) : | Little or no damage. |

Fig. 4 shows the relationship between stability index Is, calculated in this way to express damage and factor of safety determined by stability analysis. The two show good correspondence.

The use of Is to evaluate aseismicity of embankments is our simplified method of judging stability during earthquakes.

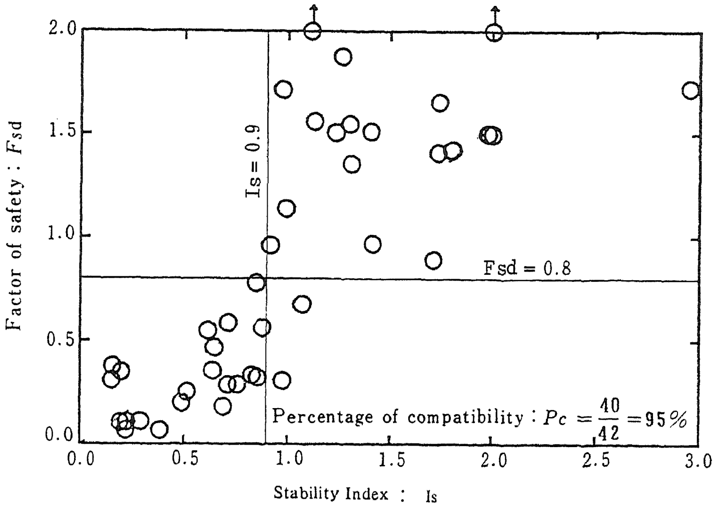


Fig. 4 Correlation Between Stability Index and Factor of Safety

Simplified evaluation table of seismic stability of embankement on sandy deposits

Table 2 is provided for convenience in using the simplified method of evaluating the seismic stability of embankments described in the previous chapter, blanks in order, stability values are automatically obtained.

## CONCLUSION

This method requires further verification on the basis of more earthquake damage data. Nevertheless we believe that even though it is a simplfied method, it has wide applicability for determining stability of embankments on sandy ground during earthquakes. In the future, we would like to further expand its applicability to include embankments of ground where clayey soil is predominant.

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## Table 2 Table for Simplified Evaluation of Seismic Stability of Embankment on Sandy Deposit

Site:

1 Max. Seismic Coef. Ks =

Embankment Hight H = (m)

Ground Water Depth Hw = (m)

≪ Conditions of Application ≫
(1) The ground mainly consists of sandy deposits.
(2) Max. seismic coefficient of ground surface, Ks, is 0.1 ~ 0.3.
(3) Embankment height, H, is 2 ~ 6m.
(4) Ground water level below ground surface, Hw, is 0 ~ 2m.

| Depth from G.L. (m) | 2 Depth from W.L. L (m) | 3 Soil Type | 4 Standardized Critical N-value ($N_{cr}$) | 5 Correction Factor | 6 Corrected Critical N-value | 7 Measured N-value (N) | 8 Safety Number (Ns) | 9 Average Safety Number ($\bar{N}s$) |
|---|---|---|---|---|---|---|---|---|
| 1 | | | 3.4 | | | | | |
| 2 | | | 3.8 | | | | | |
| 3 | | | 4.1 | | | | | |
| 4 | | | 4.5 | | | | | |
| 5 | | | 4.9 | | | | | |
| 6 | | | 5.2 | | | | | |
| 7 | | | 5.6 | | | | | |
| 8 | | | 6.0 | | | | | |
| 9 | | | 6.4 | | | | | |
| 10 | | | 6.7 | | | | | |

≪ Remarks ≫ 1 $Ks = As_{max}/g$ ($As_{max}$: max. ground acc., g: acc. of gravity)
$Kh = 0.65 \times Ks$ (Kh: design seismic coefficient)
2 L is to be measured from the ground water level
3 Soil types and the corresponding mean grain size ($D_{50}$) are as follows:

| Soil type | Clay, silt | Sandy silt | Silty fine-grained sand | Fine sand | Medium sand | Coarse sand |
|---|---|---|---|---|---|---|
| $D_{50}$ (mm) | —— | 0.04 | 0.07 | 0.15 | 0.35 | 0.60 |

5 Correction factor
- Sandy silt : $\left(\frac{65Ks - 10.3}{41Ks - 5.3}\right)^2 =$
- Silty fine-grained sand : $\left(\frac{72Ks - 10.4}{41Ks - 4.3}\right)^2 =$
- Fine sand : $\left(\frac{85Ks - 10.5}{41Ks - 2.7}\right)^2 =$
- Medium sand : $\left(\frac{138Ks - 6.3}{41Ks + 6.6}\right)^2 =$
- Coarse sand : $\left(\frac{244Ks - 1.7}{41Ks + 24.3}\right)^2 =$

6 (Corrected Critical N-value) = (Standardized N-value) × (Correction Factor)
8 (Safety Number Ns) = (Measured N-value)/(Corrected Critical N-value).
For sandy soils, if calculated Ns is greater than 3.0, Ns should be equal to 3.0.
For clay and silt (except for sandy silt), Ns = 2.0
For depth above the ground water level, calculation of Ns is not needed.
9 At 1m underground $\bar{N}s_1 = Ns_1$
At 2m underground $\bar{N}s_2 = (\bar{N}s_1 + Ns_2)/2$
At Lm underground $\bar{N}s_L = (\bar{N}s_{L-1} + Ns_L)/2$
10 Stability Index: $Is = \min_{L} (\bar{N}s_L)$

10
Stability Index

Is =

⇨

| Is | Judgment | Final Result |
|---|---|---|
| Is < 0.7 | Maximum Settlement = 2m | |
| 0.7 ≦ Is < 1.0 | Maximum Settlement = 1m | |
| 1.0 ≦ Is | Stable | |