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ESTIMATION OF DIFFERENTIAL SETTLEMENTS DUE TO LIQUEFACTION

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ABSTRACT

In the present study, a new method to estimate differential settlements due to liquefaction of ground is proposed. The method is based on the Monte Carlo Simulation, taking into account the spacial variability of geotechnical properties of subsoil profile. Typical examples of the results by the proposed method are shown to discuss the application of the present method in practice.

KEYWORDS

Differential settlements; Liquefaction; Monte Carlo simulation

INTRODUCTION

Among various types of damage due to liquefaction of ground, differential settlements of foundation ground have a direct impact on large structures such as runways of airports and highways. Differential settlements due to liquefaction, however, are a less understood subject up to date. In this study, a numerical method to estimate the differential settlements for large area of ground is newly developed.

PROPOSED METHOD

Monte Carlo Simulation

Differential settlements depend on the variability of the subsoil properties. In this study, a stocastic model of soil properties, considering the spacial correlation of soil properties, is used. SPT-N values, thickness of soil layers and maximum shear stress are given as random variables relevant to the settlements. Monte Carlo simulation is adopted to compute differential settlements due to spacial variability of subsoil properties. Settlements of each soil layer is estimated from the SPT-N values, thickness of liquefaction soil layers and maximum shear stress at each trial of Monte Carlo simulation. The effect of the three-dimensional distribution of the settlement of the deep layer is taken into consideration through the use of Green's function (i.e., response function) of the subsoil profile.

SPT-N Values and Thickness of Soil Layers as Random Variables

Soil properties relevant to settlements of the ground such as SPT-N values and thickness of soil layers have natural spacial variation. Therefore we have to take the variation and the spacial correlation of these soil properties into consideration in estimating differential settlements. Modeling of these properties are accomplished as follows.

Fig.1 shows ground model divided into small segments. When the center of two segments on the same level are denoted as I and J, the distance between the two segments is give as r_{ij}, and soil properties (SPT-N values and thickness of soil layers) are given as random variables X (variance σ), correlation coefficients τ_{ij} between I and J are given as Eq.(1).

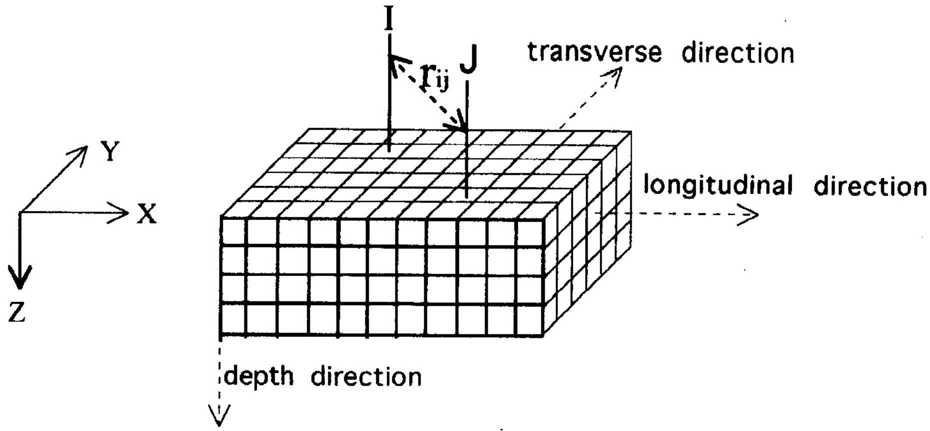

Fig.1 Ground model

$$\tau_{ij} = \frac{\mathrm{cov}[X_i, X_j]}{\sigma_i \sigma_j} \tag{1}$$

where cov[Xi,Xj] is covariance between Xi and Xj, and σ is variance of X. Among various types of functions representing the correlation function, we assume the following function.

$$\tau_{ij} = \exp\left(-\frac{r_{ij}}{b}\right) \tag{2}$$

where b is correlation distance parameter. The larger b is, the larger the area where the soil properties have strong correlation in lateral direction. Fig.2 shows an example of Eq.(2) with b=30m.

Covariance matrix [Cx] for random variable vector ($\{X\}^T=\{X_1,X_2, \cdot\cdot\cdot X_p\}$) of soil properties is given by Eq.(3)

$$[C_X] = \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2\tau_{12} & \cdot & \cdot & \sigma_1\sigma_p\tau_{1p} \\ \sigma_2\sigma_1\tau_{12} & \sigma_2^2 & \cdot & \cdot & \sigma_2\sigma_p\tau_{2p} \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & & & \cdot \\ \sigma_p\sigma_1\tau_{p1} & \sigma_p\sigma_2\tau_{p2} & \cdot & \cdot & \sigma_p^2 \end{bmatrix} \tag{3}$$

[Cx] can be transformed as Eq.(4). This is called LU transformation.

$$[C_X] = [C_X^*]\cdot[C_X^*]^T$$

where

$$[C_X^*] = \begin{bmatrix} c_{11} & & & & \\ c_{21} & c_{22} & & 0 & \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & & \cdot & \\ c_{p1} & c_{p2} & \cdot & \cdot & c_{pp} \end{bmatrix} \tag{4}$$

Based on the covariance matrix defined in Eq.(4), the random variables Xk of each point is given as Eq.(5) where a_k is a random variables which follows probability distribution function with mean 0.0 and variance 1.0. a_k is newly assigned at each trial of Monte Carlo simulation.

$$\begin{Bmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ X_p \end{Bmatrix} = \begin{Bmatrix} \overline{X}_1 \\ \overline{X}_2 \\ \cdot \\ \cdot \\ \overline{X}_p \end{Bmatrix} + [C_X^*]\begin{Bmatrix} a_1 \\ a_2 \\ \cdot \\ \cdot \\ a_p \end{Bmatrix} \tag{5}$$

where Xk is mean of random variables Xk. This procedure simulates random variation of SPT-N values and the thickness of soil layers with specified degree of correlation in lateral direction.

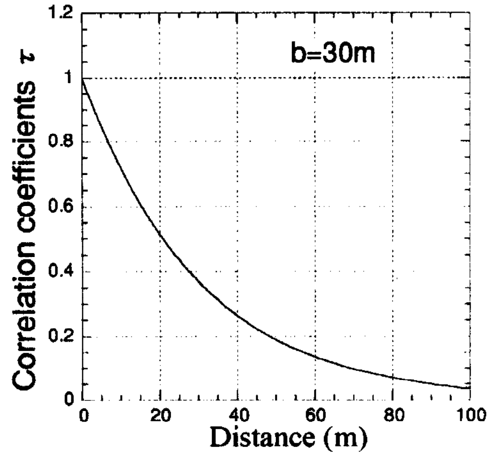

Fig.2 Correlation function (b=30m)

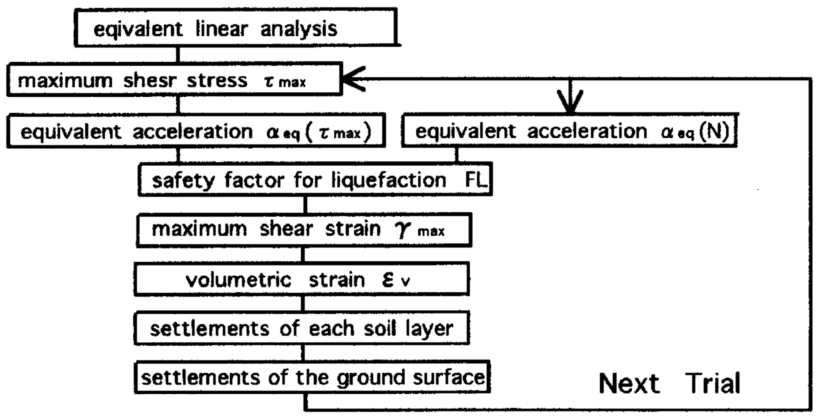

Fig.3 Procedure for estimate of settlements

Maximum Shear Stress τ_{max} as Random Variables

Maximum shear stress τ_{max} of each soil layers can be estimated by the equivalent linear analysis (Shnabel *et al*, 1975). The computation time becomes prohibitive, however if the equivalent linear analysis are performed at each trial of Monte Carlo simulation on whole points of model ground. To reduce computation time to a reasonable level, τ_{max} is also given as random variables in the present study. Average and variance of τ_{max} are estimated based on the representative results of the equivalent linear analysis.

ESTIMATION OF SETTLEMENTS

Each Soil Layer

Estimation of settlements of each soil layer and the ground surface is made based on a procedure shown in Fig.3. From the maximum shear stress τ_{max} and the SPT-N value assigned for each Monte Carlo trial, the safety factor for liquefaction FL is computed based on the liquefaction criterion used for the Japanese port and harbour areas (Ports and Harbours Bureau, Ministry of Transport, 1993).

Based on the obtained safety factor for liquefaction, maximum shear strain γ_{max} of ground can be obtained from Fig.4 (Ishihara *et al.*, 1992) in accordance with the density Dr of sand. Volumetric strain of soil element ε_v is obtained from the maximum shear strain γ_{max} based on Fig.5 (Ishihara *et al*, 1992). The settlements of each soil layer is obtained by multiplying ε_v with the thickness of liquefaction layer assigned for each Monte Carlo trial.

Ground Surface Settlements

When one area of ground settles, the other parts of ground also settles. The effect of three-dimensional distribution of the settlement of the deep layer has to be taken into consideration. For this we use Green's function (i.e., response function) relevant to settlements. The response function defines correlation between settlements of the ground at each point and settlement of the ground surface as shown in Fig.6.

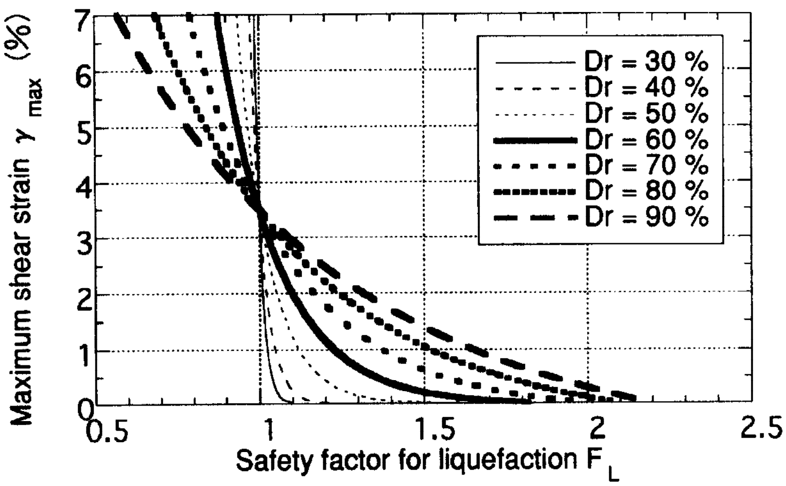

Fig.4 Relationship of maximum shear strain to safety factor for liquefaction (Ishihara,1992)

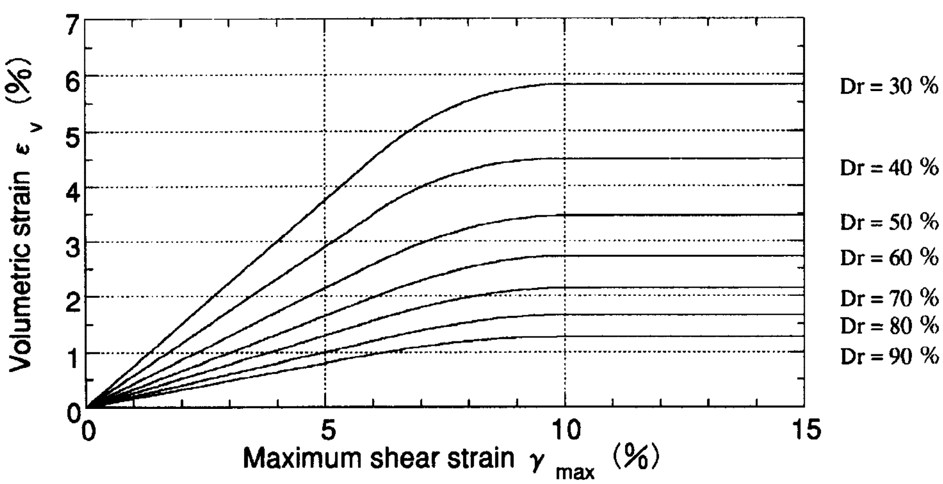

Fig.5 Relationship of maximum shear strain to maximum volumetric strain (Ishihara,1992)

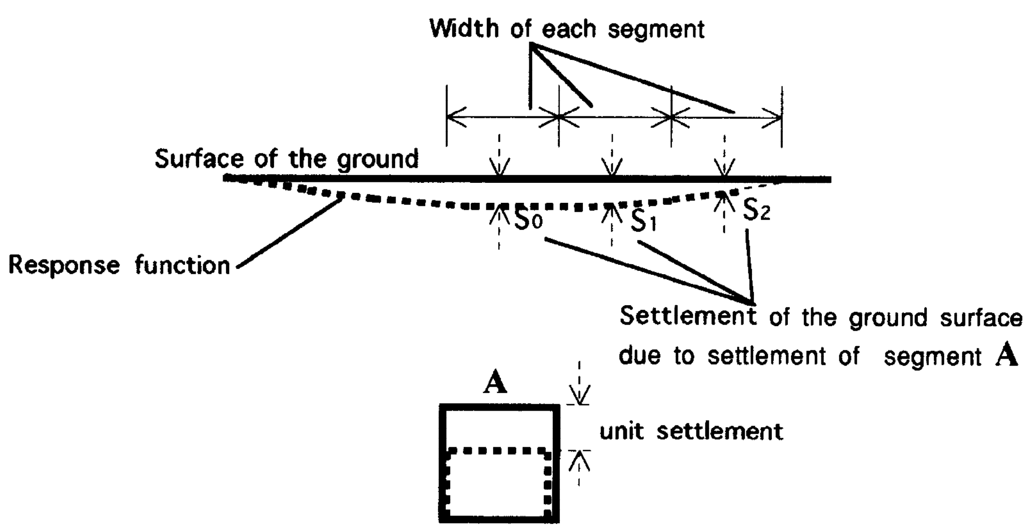

Fig.6 Response function relevant to settements

Table-1 Conditions for the simulation

The number of Monte Carlo trial		50 (times)
Size of segment		10m (transverse) × 10m (longitudinal) × 2m (depth)
Variance	SPT-N value	5.0 (times)^2
	Thickness of soil layer	1.0 (m)^2
	Maximum shear stress	0.15 (tf/m^2)^2
Maximum acceleration on baserock		200 (cm/s^2)

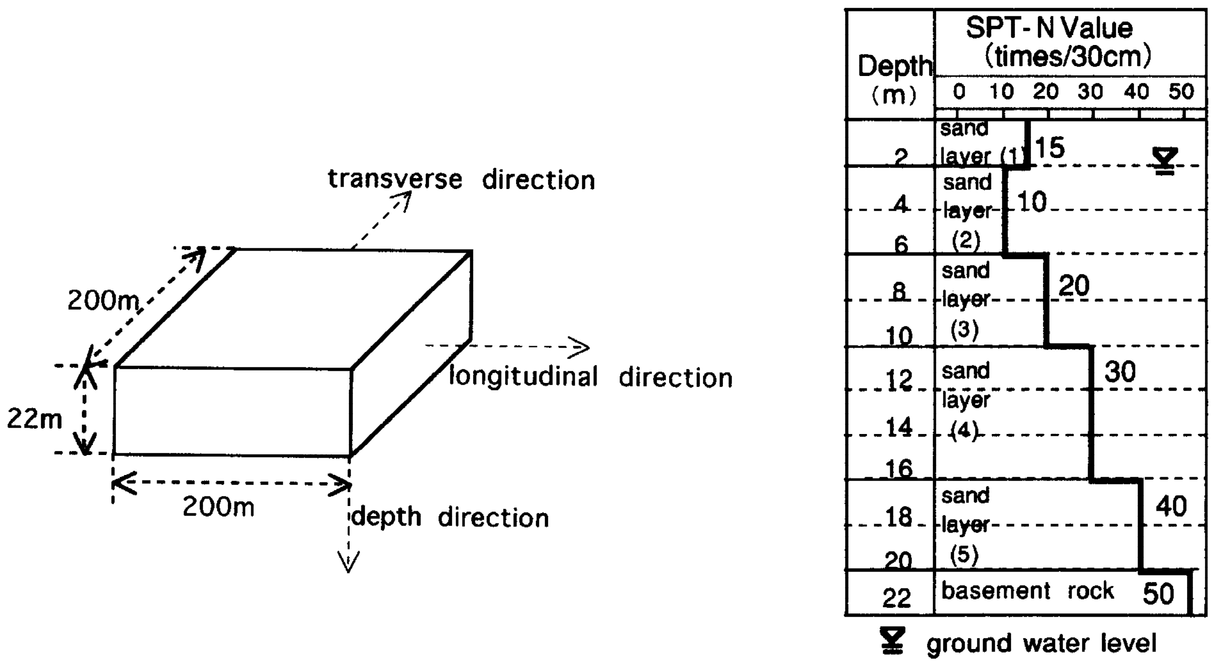

Fig.7 Area of the ground and Distribution of SPT-N value for the simulation

Settlements of the ground surface is calculated from sum of all effect of settlements at each layer. The function is calculated with FEM (Finite Element Method) calculation before the Monte Carlo simulation under the given soil properties.

COMPUTATION EXAMPLE

In order to demonstrate and discuss the application of the proposed method, computation examples are given bellow. The conditions for the simulation is shown in Table.1. The area and soil conditions (boring data) are shown in Fig.7. In this study we assume that the ground consists of horizontal stratification, so boring data is given at only one point. Typical examples of the results obtained by the present method are shown in Fig.8 and Fig.9.

Fig.8 shows distribution and contours of the ground surface at the first trial of Monte Carlo simulation with correlation distance b=25m. We can obtain these results at each trial and finally get average settlements, maximum settlements, average gradient, maximum gradient of the ground surface. Fig.9 shows distribution and contours of the ground surface with correlation distance b=100m. The results of Fig.8 and 9 are quite different. It is because of the difference in the parameter b.

From the proposed metohd, we can get some data indicating the ground which has strong possibility of liquefaction and differential settlements without many boring data.

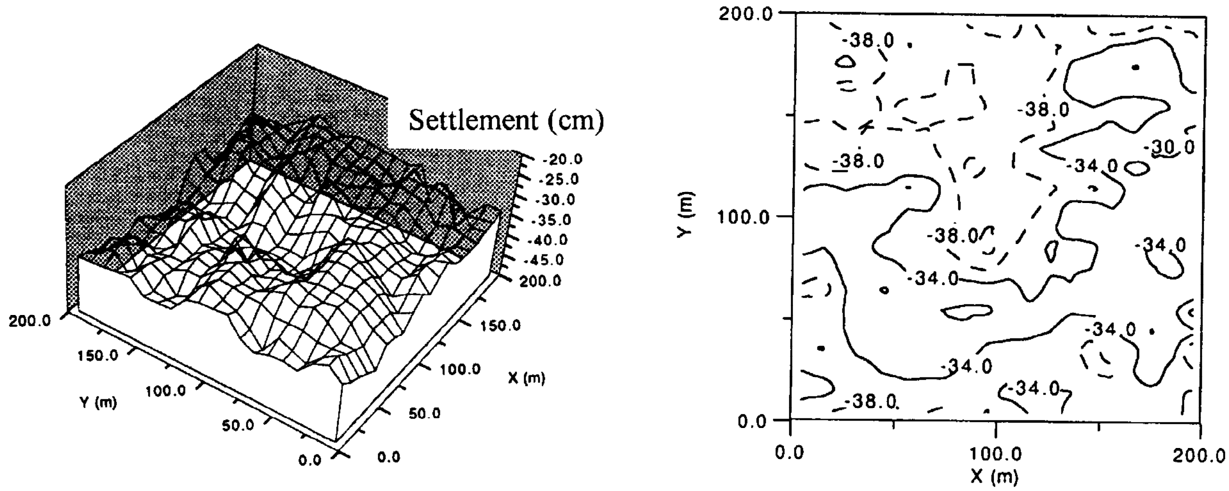

Fig.8 Distribution and Contours of settlements of the ground surface at the first trial (b=25m) (unit : cm)

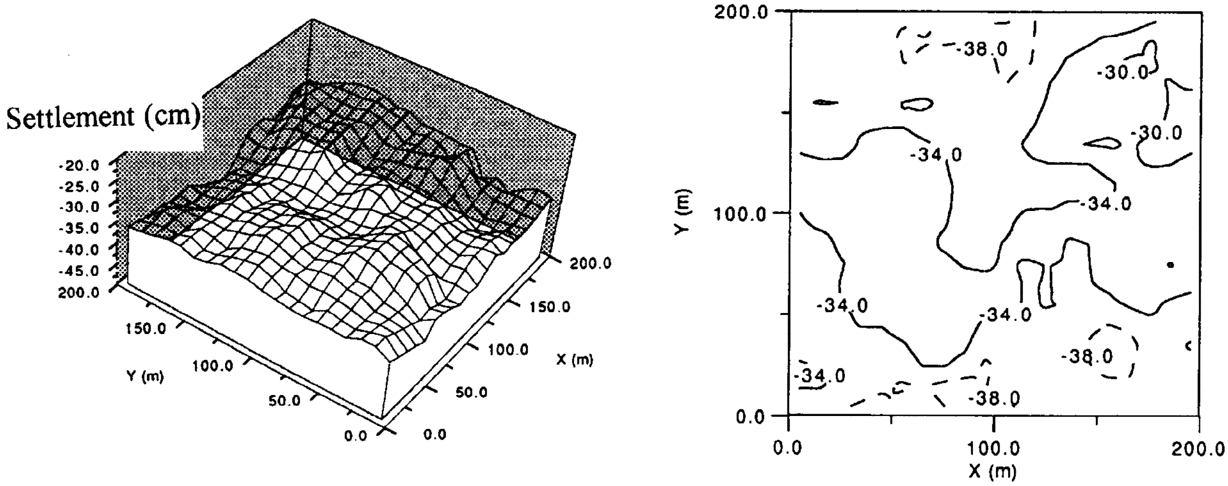

Fig.9 Distribution and Contours of settlements of the ground surface at the first trial (b=100m) (unit : cm)

CONCLUSIONS

a) In the present study, a new method to estimate differential settlements due to liquefaction of ground was proposed. The method is based on the Monte Carlo simulation, taking account the spacial variability of ground. b) Typical examples of the results by the proposed method were shown to discuss the application of the present method in practice. These results show that the correlation distance b, the key parameter relevant to the spacial correlation of soil properties, has an important effect on the computed differential settlements.

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