III-87 THREE-DIMENSIONAL MODEL TO PREDICT LIQUEFACTION-INDUCED PERMANENT GROUND DISPLACEMENTS BASED ON ENERGY PRINCIPLE

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INTRODUCTION

Recent studies have shown that liquefaction-induced permanent ground displacements have caused severe damage to earth structures and lifeline facilities. It is important, therefore, to predict the spatial distribution of ground movement resulting from liquefaction.

A three-dimensional model for predicting the pattern of ground movement is presented. It is an extension of the simplified two-dimensional model developed by Towhata et al. (1990) and is based on the principle of minimum energy. In the proposed model, the area is divided into two-dimensional finite elements and the total energy of the ground is expressed in terms of the unknown nodal displacements. Variational principle is employed to obtain the solution. To illustrate its validity, the model is used to analyze the ground displacements observed in Noshiro City during the 1983 *Nihonkai-Chubu earthquake*.

MODEL FORMULATION

The model employs the finite element shown in Fig. 1. The parameters B, H, and T correspond to the thickness of the unliquefied base, liquefiable layer, and surface unsaturated layer, respectively. The surcharge load, P, includes the weight of the surface layer. These parameters vary linearly with the coordinates x and y, i.e.,

$$B = B_o + a_1 x + b_1 y \quad H = H_o + a_2 x + b_2 y$$
$$T = T_o + a_3 x + b_3 y \quad P = P_o + a_4 x + b_4 y \qquad (1)$$

At any point (x, y, z) in the liquefied layer, the displacements along x and y-axes, denoted by u and v, respectively, are approximated by sinusoidal distributions in z direction:

$$u(x,y,z) = F(x,y)\sin\frac{\pi(z-(B_o+a_1x+b_1y))}{2(H_o+a_2x+b_2y)}$$
$$v(x,y,z) = J(x,y)\sin\frac{\pi(z-(B_o+a_1x+b_1y))}{2(H_o+a_2x+b_2y)} \qquad (2)$$

With the assumption that there is no slip between the surface unsaturated layer and the liquefiable layer, the functions $F(x,y)$ and $J(x,y)$ represent the displacements at the surface ($z = B + H$).

The surface unsaturated layer behaves like an elastic plate subjected to in-plane stresses and with an elastic modulus E. On the other hand, the stress-strain relation of the liquefiable portion is modeled by

$$\tau = G\gamma + \tau_r \qquad (3)$$

where G is the shear modulus and τ_r is the residual strength.

The settlement w at any point is related to the displacements u and v by the equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (4)$$

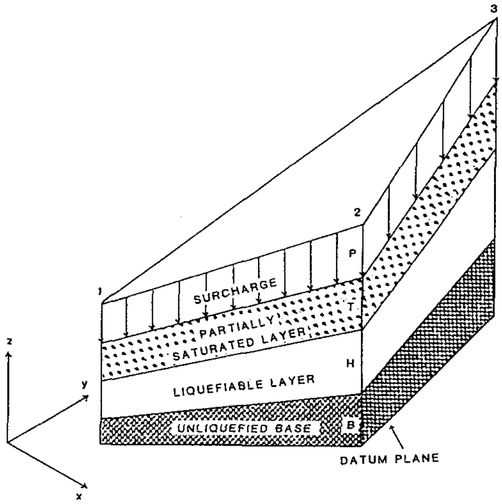

Figure 1: A finite element of the model ground

Since constant-volume condition is assumed, consolidation settlement should be considered separately.

The energy of each ground element consists of the strain energy and gravity components of the liquefied and surface unsaturated layers. For elements located at free boundaries of the study area, the change in potential energy due to the movement of such boundaries is also taken into account. Thus, the total energy in each element, represented by the functional Π_p, is expressed in terms of the unknown surface displacements $F(x,y)$ and $J(x,y)$, their derivatives, and the coordinates x and y.

The surface displacements within an element are represented by linear functions

$$F(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y$$
$$J(x,y) = \beta_1 + \beta_2 x + \beta_3 y \qquad (5)$$

These functions are then expressed in terms of the nodal displacements Fi and J_i and are substituted into the functional Π_p. By considering the variation of Π_p, the total energy is minimized, and the following expressions are obtained:

$$\frac{\partial \Pi_p}{\partial F_i} = 0 \quad \text{and} \quad \frac{\partial \Pi_p}{\partial J_i} = 0 \qquad (6)$$

These represent $2n$ equations (n is the number of nodal points) which can be written in a more familiar form

$$\{\mathrm{P}\} = [\mathrm{K}]\{\mathrm{U}\} \qquad (7)$$

Thus, the equation becomes a typical finite element problem where the displacement vector $\{\mathrm{U}\}$ is required.

In the application of the above model, the total stress in each element is computed by combining the stress components induced when subsoil liquefaction occurred and the initial static stresses in the surface layer given by

$$S_o = 1/2\, K_o \gamma_s t \tag{8}$$

where K_o is the coefficient of earth pressure at rest (assumed to be equal to 0.5 in this study), γ_s is the unit weight of the soil and t is the average thickness of the surface layer. Since sandy soil has no tensile resistance, the E of elements which show tensile principal stresses are reduced to only five percent of their normal values.

CASE STUDIES

The proposed method was used to simulate the ground displacements in Noshiro City. Since the soil parameters were not clearly known, values of $E = 10780\ kN/m^2$, $\nu = 0.3$ and $\gamma_s = 15.7\ kN/m^3$ were used for the surface layer. Moreover, the liquefied soil was assumed to behave like liquid, with $G = 0$, $\tau_r = 0$ and $\gamma_{liq} = 17.6\ kN/m^3$.

Analyses were made on the northern and southern portions of Noshiro City where large ground displacements were observed. In the analysis, fixed boundaries are assumed at the lowland areas where non-occurrence of liquefaction was observed. Similarly, cracks in the upper slope were modeled by free boundaries.

Figs. 2 and 3 show the calculated ground displacements in the northern and southern parts of the city, where the maximum permanent displacements obtained were 3.6 m and 6.6 m, respectively. Hamada et al. (1986) observed that the maximum displacements in these areas were approximately 3 m and 5 m for the northern and southern portions, respectively. Although the analyses slightly overestimate, the method shows good agreement with the measured data. Moreover, the spatial distributions are also consistent with those observed.

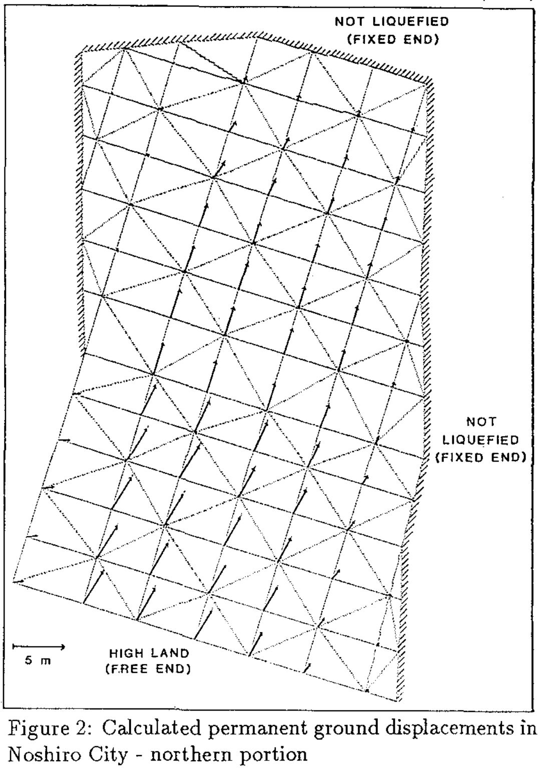

Figure 2: Calculated permanent ground displacements in Noshiro City - northern portion

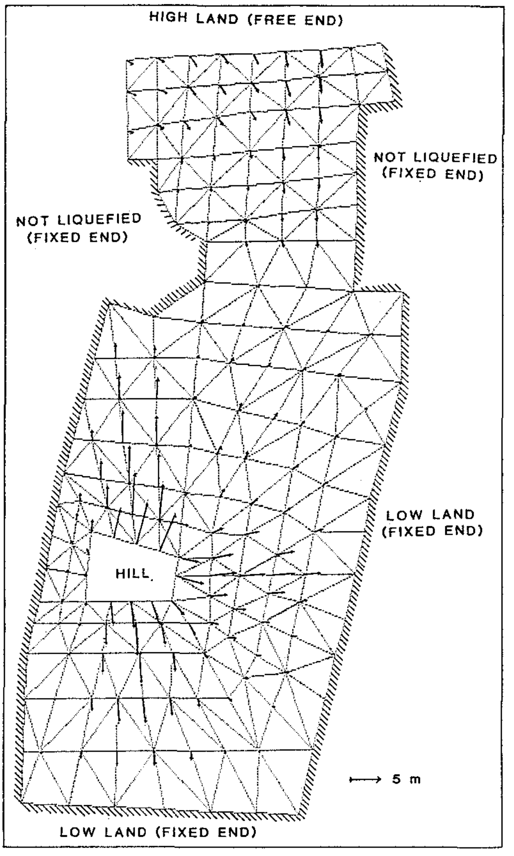

Figure 3: Calculated permanent ground displacements in Noshiro City - southern portion

CONCLUSION

A simplified numerical procedure based on energy principle is developed to predict the magnitude and spatial distribution of ground displacements induced by liquefaction. Based on the case studies illustrated, it is noted that the method can reasonably predict the resulting displacements.

REFERENCES

Hamada, M,, Yasuda, S., Isoyama, R., and Emoto, K. (1986), "Study on Liquefaction-Induced Permanent Ground Displacements," ADEP, Tokyo.

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