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AN ENERGY-BASED MODEL TO PREDICT LIQUEFACTION-INDUCED DEFORMATIONS IN WATERFRONT AREAS

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ABSTRACT

This paper presents the development of a simplified model to predict the ultimate deformation of retaining wall and backfill soil due to liquefaction. In this model, which is based on the principle of minimum potential energy, the lateral displacements of liquefied ground are assumed to vary sinusoidally along a vertical section. The vertical displacements, on the other hand, are calculated as the sum of those resulting from constant-volume condition and post-liquefaction analysis. The total potential energy of the system consisting of sheetpile wall and backfill soil is then formulated and minimized using variational principle. Example calculations and comparison with the results of the more sophisticated finite element method prove the validity of the model. Finally, the method is implemented to predict the seismic deformations that will occur in a reclaimed area in Tokyo Bay.

KEYWORDS

ground displacements; liquefaction; seismic deformation; earthquake damage; waterfront areas; earthquake resistant; retaining wall; minimum potential energy; variational principle; predictive method

INTRODUCTION

Retaining structures at waterfronts, where the backfill soil inevitably is in large measure saturated, have frequently performed poorly during earthquakes with a number of spectacular failures. Most of these failures have resulted from large-scale liquefaction and the associated large deformations of the loose, saturated cohesionless soils in the backfill and/or in the foundation. This has been demonstrated recently by the catastrophic collapse of the retaining structures around two reclaimed islands in Kobe, Japan during the 1995 Hyogoken Nanbu Earthquake, which resulted in serious economic consequences for the stricken region. In port and harbor facility sites, as well as in newly reclaimed areas, where the backfill soil is highly vulnerable to liquefaction, the identification of zones of potentially large ground movements and the estimation of displacement patterns are essential in the design of future facilities and in the modification of existing ones.

The evaluation of permanent ground displacements has been the focus of research in recent years. At present, the techniques that have been developed to analyze ground displacements induced by earthquake motion range from empirical formulations to the more complicated non-linear finite element-based procedures. This paper presents a simple methodology to predict the ultimate deformations of retaining walls and backfill soil due to liquefaction using the principle of minimum potential energy. This method is formulated after an extensive study of the mechanism of liquefaction-induced ground displacements through laboratory tests and field observations. By considering only the soil parameters which play important roles in the phenomenon of lateral soil movement, it became possible to run an analysis with a limited number of input data and a short calculation time without sacrificing reliability.

BASIC THEORY

Towhata *et al.* (1992) developed a closed-form solution concerning the permanent displacement of liquefied ground with a simple slope for a free field case, i.e., superimposed and underground structures are absent. The model was formulated after a thorough investigation of the nature and mechanism of permanent displacements of liquefied ground through shaking table tests and in-situ investigations. Based on their findings, permanent displacements of liquefied ground are strongly affected by geological and topographical conditions and do not depend on the time history of earthquake motions. With this fact, a static analysis is sufficient to predict the ultimate displacement of liquefied ground. Consequently, it is implicitly assumed that the state of soil liquefaction continues for a sufficiently long period of time. The basic theory is discussed below.

The idealized ground consists of an unliquefied base at the bottom with elevation B, a liquefied layer with thickness H, and a surface unsaturated crust with thickness T. The liquefied ground is assumed to deform with a quarter-sinusoid distribution in a vertical section and is given by

$$u(x,z) = F(x)\sin\frac{\pi(z-B)}{2H} \tag{1}$$

where $u(x,z)$ is the lateral displacement at any point (x,z) and $F(x)$ is the unknown displacement at the surface, i.e., at $z=B+H$. The soil is assumed to flow under constant volume condition, and as liquid with zero stiffness. The surface unsaturated layer acts as a bar with a given Young's modulus. The total energy of the ground consists of the strain and gravity components of the liquefied layer and the surface unsaturated layer. The complicated computation is simplified by considering only the predominant components of the strain tensor. The magnitude of the displacement at the top of the liquefied stratum is derived by minimizing the potential energy of the ground using variational principle.

The present approach introduces several modifications to the original model. Firstly, non-zero shear modulus of the liquefied soil is accounted for in the new analysis. For practical purposes, the amount of reduction in shear modulus as a result of liquefaction can be determined either empirically (e.g., a reduction of shear modulus to 1/1000 of the original value) or experimentally (e.g., Yasuda *et al.*, 1990).

Another major modification is the inclusion of retaining walls. When sheetpile walls are subjected to laterally moving ground, horizontal pressures are developed between the sheetpile and the ground, and consequently, bending moments and deflections develop in the sheetpiles. The retaining wall-liquefied soil model is shown in Figure 1. The basic differential equations governing the deflection of sheetpile wall are given by

(a) in the liquefied region:

$$EI\frac{d^4\rho_l}{dz^4} + k_{hl}\rho_l = k_{hl}F\sin\frac{\pi(z-B)}{2H} + q \tag{2}$$

(b) in the surface unliquefied region:

$$EI\frac{d^4\rho_s}{dz^4} + k_{hs}\rho_s = k_{hs}F + q \tag{3}$$

where EI is the rigidity of the sheetpile per unit length, F is the ground surface displacement at the pile-soil interface, ρ is the sheetpile deflection, k_h is the equivalent soil spring constant, q is the external lateral pressure and the subscripts l and s correspond to the liquefied and unliquefied layers, respectively. In the model, the coefficient of subgrade modulus in the liquefied soil is reduced by the same amount as the shear modulus.

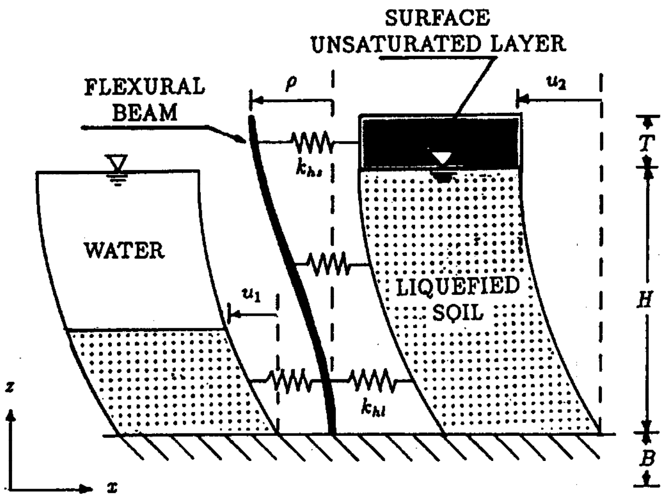

Figure 1: Retaining wall-liquefied soil system

Appropriate boundary conditions are employed to solve the above differential equations. The strain energy developed in the sheetpile can be expressed in terms of the pile deflection, ρ, and is given by

$$U_p = \int_B^{B+H+T} \frac{EI}{2} \left(\frac{d^2\rho}{dz^2} \right)^2 dz \tag{4}$$

where ρ is a linear function of F. In the application of the model, the whole ground configuration is subdivided into piecewise-linear segments and the energy is formulated in each segment. The energy developed in the sheetpile is incorporated to obtain the total energy of the system, and an equation is obtained which is a function of the unknown surface displacement $F(x)$, its derivative, and the coordinate x. The displacements of the sheetpile wall and the backfill soil are again calculated so that the potential energy of the system of the wall and the soil may take a minimum value. The details of the model formulation are presented elsewhere (Orense, 1992).

In the original energy model, the vertical displacements are computed by assuming constant-volume condition. In order to simulate the actual settlements, the calculated vertical displacements from the above-mentioned condition are added to the settlements resulting from consolidation and dissipation of excess pore water pressure. For this purpose, the consolidation components are obtained using the procedure for level ground proposed by Ishihara and Yoshimine (1992), where the settlements are determined from the correlations of volumetric strains with the factor of safety and the density of the sand deposit.

APPLICATION TO RECLAIMED AREA NEAR TOKYO BAY

The extensive damage caused by the 1995 Hyogoken Nanbu Earthquake on coastal areas and reclaimed islands emphasized the fact that liquefaction and associated ground deformations are major geotechnical hazards. Indeed, the estimation of magnitude and spatial distribution of permanent ground displacements induced by soil liquefaction is of prime importance for the seismic design and deformation analysis of structures.

Even prior to this earthquake, the Tokyo Metropolitan Government has been conducting comprehensive investigation to assess the seismic stability of reclaimed areas in Tokyo Bay. Because of the extent of the area to be examined, analysis using the finite element method is very costly. Due to economic considerations, the model presented above has been employed to analyze the seismic deformations of these waterfront areas in case of a major earthquake occurring near the site.

Site Description

The area analyzed consists of Aomi, Ariake and Daiba Districts, the locations of which are shown in Figure 2. Also shown in the figure are the 22 cross sections in both longitudinal and transverse directions which are

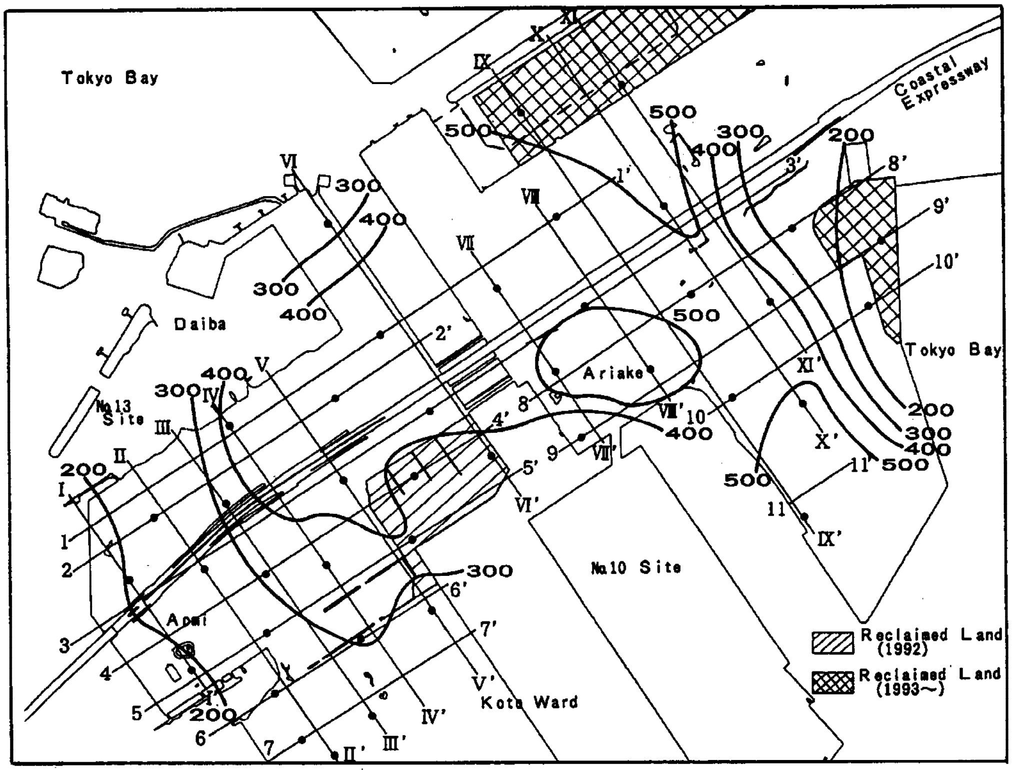

Figure 2: Site location and contours of surface accelerations

employed in the study. The soil profile in each cross section is estimated from several boring logs obtained in the area during past investigations. The area basically consists of backfill material, containing sand and clay, about 5~10 m deep underlain by soft Yurakucho layer (10~40 m depth) formed from sediments of deltaic and flood plain deposits of Arakawa and Edogawa Rivers. Reclamation of the area started about 300 years ago. Those in the No.13 site and Ariake District were reclaimed between 1961-1970.

Various retaining structures are employed in the waterfronts. These include sheetpile walls, anchored bulkheads, cantilever walls and sand mound with ripraps. In some sections, the foundations of these structures were improved through SCP and CDM methods.

Preliminary Calculations

Prior to the seismic deformation analysis of the whole area using the proposed method, preliminary calculations were made with the purpose of checking the validity of the model in comparison with the more elaborate finite element procedure. For this purpose, four cross sections in the study area were analyzed, namely No. 13 Site, Aomi, Toyosu N-S and Toyosu E-W sections. The Hachinohe record obtained during the 1968 Tokachi-oki Earthquake was used as the base acceleration with the maximum acceleration scaled to 300 gals. The soil profiles and soil properties are estimated from existing laboratory and field data.

The finite element procedure employed in this study is similar to that proposed by Kuwano and Ishihara (1988) where it is assumed that the deformation is due to the softening of the soil as a result of seismic shaking so that after the earthquake, the ground will deform to a new condition compatible with the new softened stiffness of the soil. Laboratory torsional shear tests were performed in which the in-situ stress conditions before and during the earthquake are simulated through static and dynamic response analyses to determine the softened parameters. Finite element analyses are then performed using the normal and reduced/softened moduli to calculate the earthquake-induced ground displacements. Figure 3 shows the result of the calculation using the finite element method for the No.13 site.

For the energy model, the distribution of acceleration within each cross section is obtained from two-dimensional seismic response analysis, and in portions where complete liquefaction is expected, the moduli of

Node No.	X (cm)	Y (cm)	Node No.	X (cm)	Y (cm)
1	0.0	11.5	9	1.6	12.1
2	0.6	11.3	10	0.0	6.7
3	4.1	7.7	11	0.1	4.2
4	4.2	7.4	12	0.4	5.1
5	2.5	10.1	13	0.1	7.5
6	3.8	9.1	14	0.3	3.7
7	3.0	12.5	15	0.1	3.6
8	2.7	12.2			

vertical

horizontal

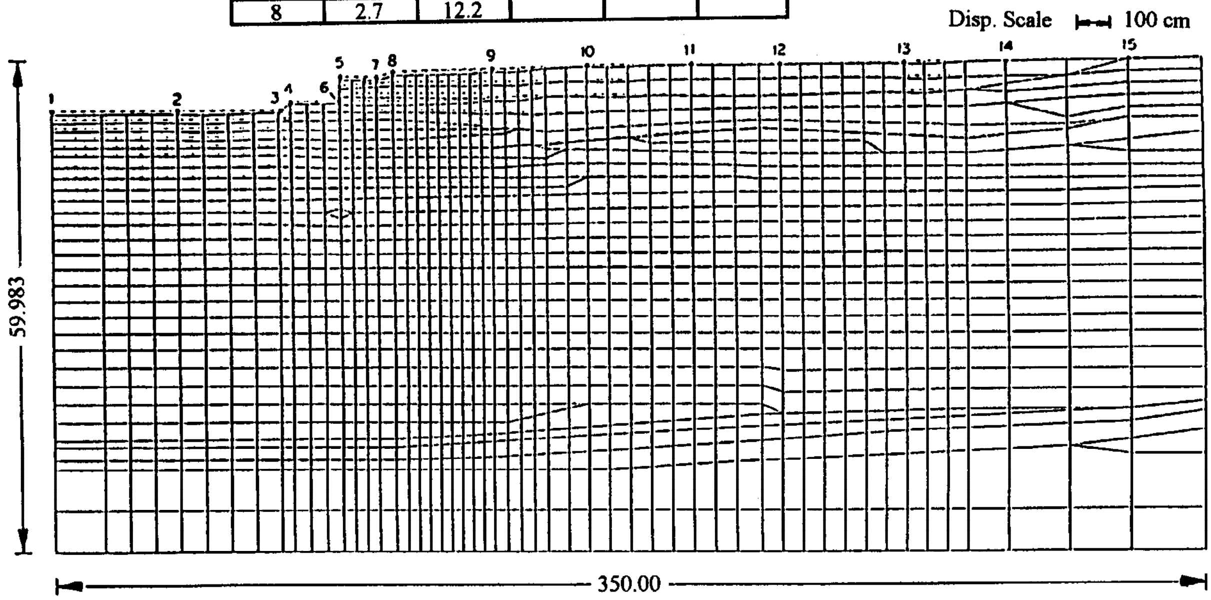

Figure 3: Result of calculation for No. 13 site using finite element method

Node No.	X (cm)	Y (cm)	Node No.	X (cm)	Y (cm)
1	0.0	3.8	9	7.6	18.9
2	1.3	5.3	10	7.3	19.1
3	1.8	5.3	11	6.0	14.6
4	2.8	5.3	12	4.5	12.3
5	4.3	7.9	13	3.1	10.4
6	5.6	10.7	14	2.4	10.2
7	6.5	14.6	15	1.2	10.1
8	7.1	18.6	16	0.0	10.1

vertical

horizontal

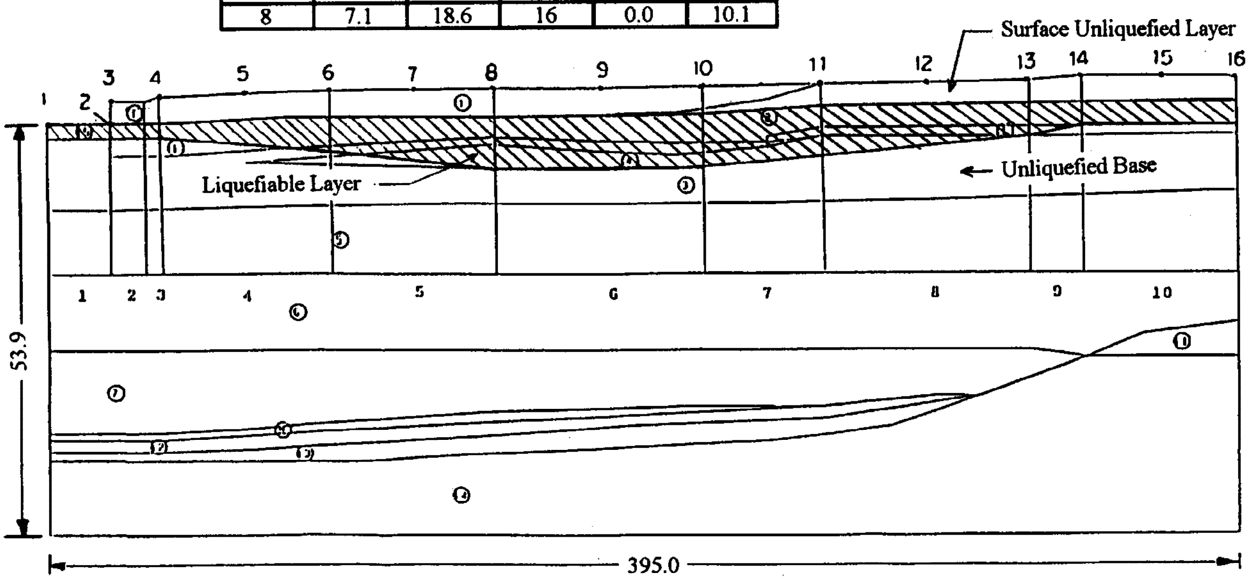

Figure 4: Soil profile and computed displacements for No. 13 site using energy model

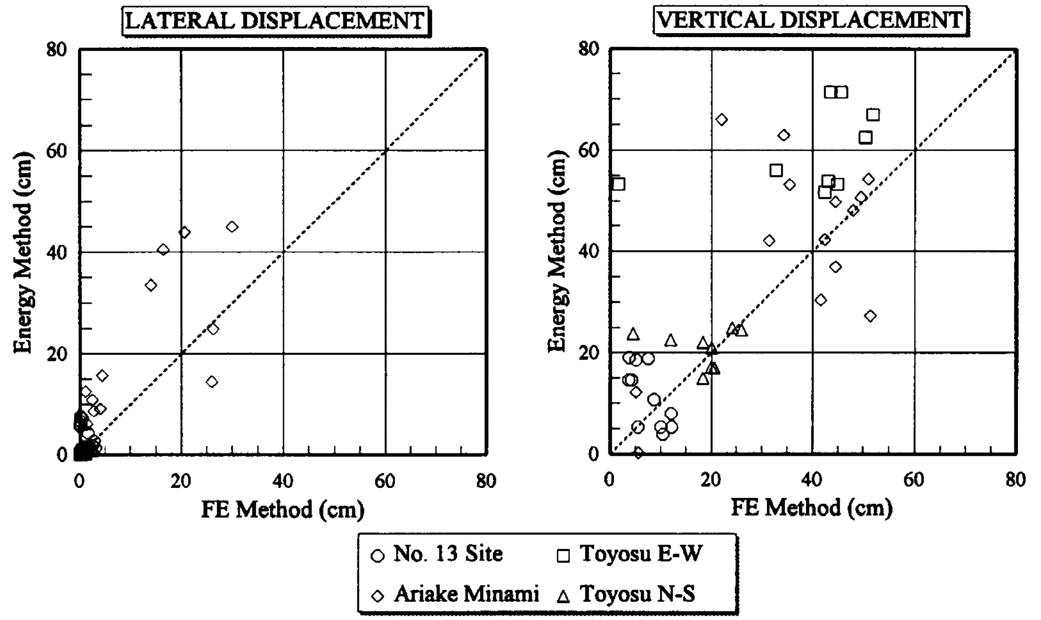

Figure 5: Comparison of results obtained by finite element method and energy model

the liquefied ground are reduced to 1/1000 of the original values. The soil profile as well as the calculated displacements are shown in Figure 4.

For the four cross sections considered here, the comparison between the proposed method and the finite element results are shown in Figure 5. It can be seen from the figures that although the energy method gives generally higher magnitudes of lateral movement and settlement as compared to the more detailed finite element method, there is a good correlation between the results obtained. Moreover, although the magnitude of the lateral displacements are smaller compared to the settlements, both methods predict the same pattern of ground deformations.

Analyses Using the Energy Model

The procedure employed in this study is shown in the flowchart of Figure 6. Initially, one-dimensional seismic response analyses using the program SHAKE are performed in 40 sites located all over the area (designated by dark dots in Figure 2) to determine the spatial distribution of ground surface accelerations. For this purpose, the base rock accelerations recorded in Hachinohe and Ofunato (1978 Miyagiken oki Earthquake) are employed with the maximum base accelerations scaled to 300 gals. At each site, the greater of the two surface accelerations from the two input motions is considered. The contours of the computed peak surface accelerations (in gals) are also shown in

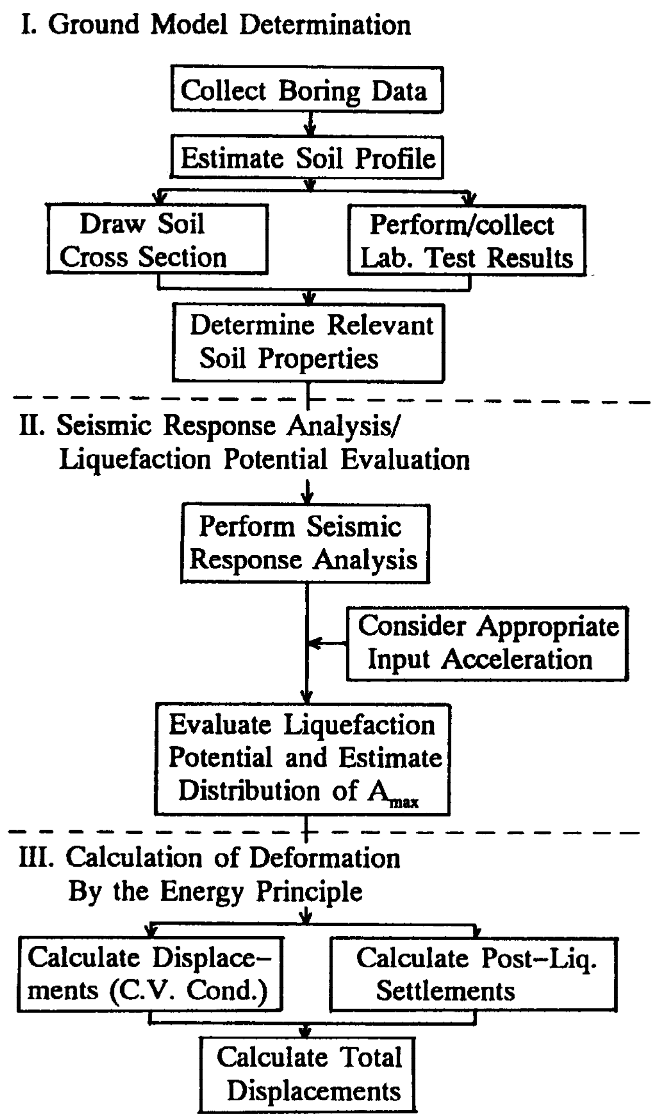

Figure 6: Flowchart of the model

Figure 2. Note that the maximum surface accelerations computed are about 550 gals in Ariake area and 450 gals in Daiba area.

In the application of the method, the liquefaction potential of the site is evaluated using the procedure adopted in the Specification for Highway Bridges adopted by the Japan Road Association (1990). For sites judged to have liquefied, the shear moduli are reduced to 1/1000 of the original values, as suggested by Yasuda *et al.* (1990).

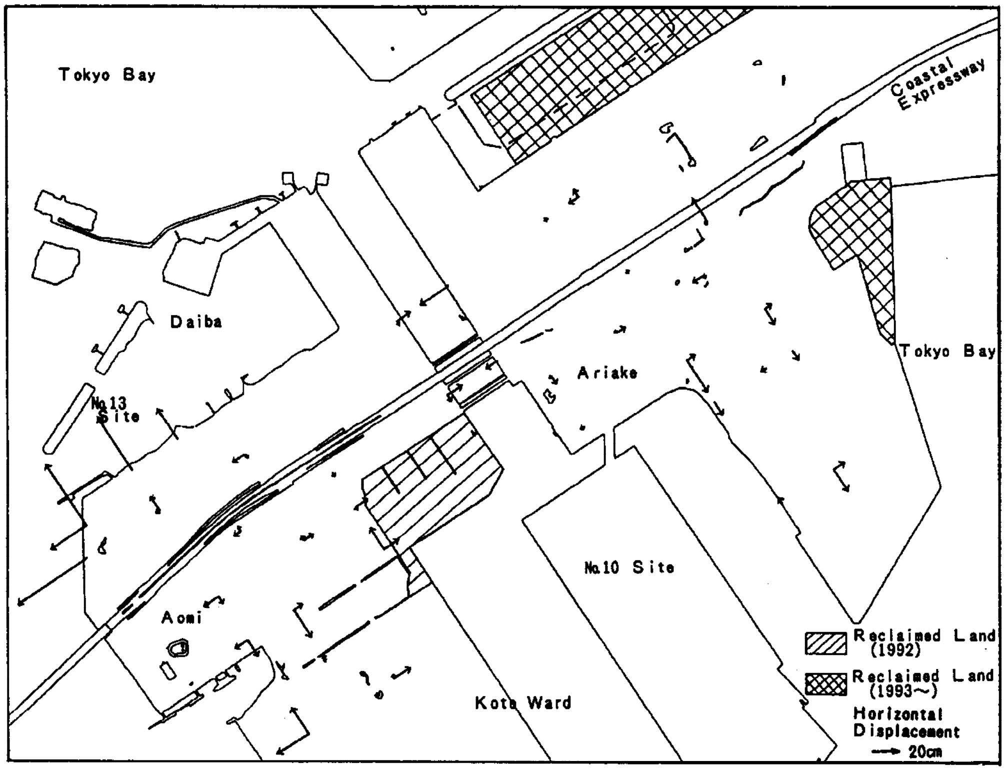

Figure 7: Calculated lateral displacements (values in cm)

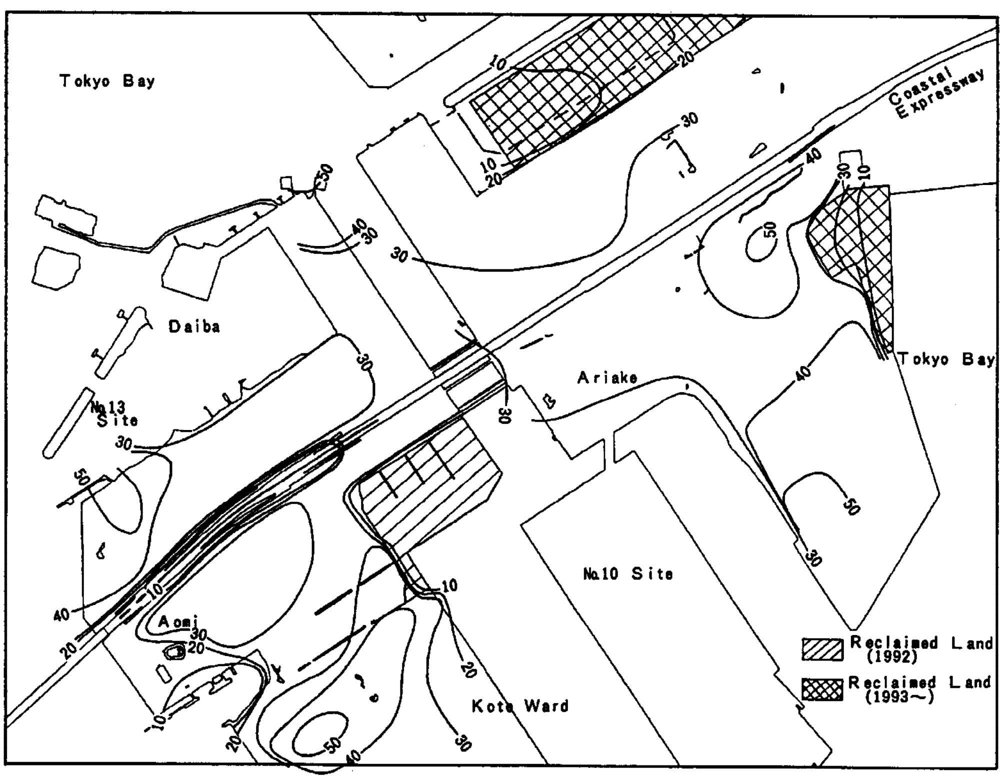

Figure 8: Calculated settlements (values in cm)

The calculated lateral displacements at various selected points are shown in Figure 7. It can be seen that large lateral displacements of the retaining structures in the order of 30-60 cm would occur in the northern section of No. 13 site and in Daiba area. This can be traced to the thick liquefiable layers (8-10 m thick) in these portions which are inclined towards the retaining structures. Although displacements in the order of 20-30 cm are evident in a number of locations in Aomi and Ariake Districts, the displacements are generally in the order of a few centimeters. In addition, the calculation shows no movement of the retaining walls. In the newly reclaimed sites (shaded portions in the figure), no lateral movement is noted since complete liquefaction does not occur in this region.

The contour lines of equal settlements are shown in Figure 8. Settlements in the order of 40-50 cm are noted in the No.13 site, while those in the Daiba and Aomi areas are in the order of 30-40 cm. These large settlements predicted are largely due to the thick liquefiable deposit existing in these areas. In the newly reclaimed portions, the calculated settlements are generally less than 10 cm because of the low liquefaction potential of these areas.

The analyses presented above clearly show the critical locations where large lateral displacements and settlements are expected when a large scale earthquake would occur near the area. Based on these results, a more detailed investigation is recommended in these critical areas and suitable countermeasures be applied to mitigate the damage.

CONCLUDING REMARKS

A model to predict the permanent ground displacements of retaining wall-liquefied soil system is developed based on the principle of minimum potential energy. Although the model is quite simple, the example calculations show that the proposed method can reasonably predict the resulting displacements comparable to that of finite element method. Thus the technique can serve as an economical and practical tool to predict the potential seismic hazards to ports and harbor facilities induced by the lateral flow of liquefied soil.

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