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ANALYTICAL EVALUATION OF REDUCING STRESS IN PILES WITH SOIL CEMENT IMPROVEMENT

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ABSTRACT

The authors have developed a new code for three-dimensional nonlinear analysis based on effective stress to assess the dynamic response of structures on liquefiable ground. The object of this paper is to study using the new code the effectiveness of some remediation methods as a means to protect a group pile foundation from soil liquefaction hazard. Four types of foundation supporting a rigid structure are considered: ① end-bearing piles in unimproved ground, ② end-bearing piles in the ground improved with sand compaction piles, ③ end-bearing piles and a "soil cement ring," ④ end-bearing piles and a "soil cement block." The study shows that the remedial measures of Case ③ and Case ④ reduce remarkably the magnitude of the internal forces in the piles, even though the size of the soil improvement is smaller than that of the other methods.

KEYWORDS

Liquefaction; nonlinear; pore water pressure; three dimension; finite element method; ground improvement; soil cement; pile; bending moment

INTRODUCTION

Ground improvement is often considered as a remedial measure to protect pile foundations from soil liquefaction hazard during earthquakes. Preliminary investigations show that such measure was effective during the Hyogo-ken Nanbu Earthquake of January 17, 1995. Among many ground improvement methods, the sand compaction pile (SCP) method is most frequently used in Japan because of its reliability and economy, although its use in urban areas may be precluded because of the noise and vibration it generates. Then a quieter, deep cement mixing method becomes a viable alternative to dynamic compaction. Because of its high cost, however, the deep cement mixing method can be applied to a limited area below a structure. A scheme has been proposed to improve a ring shaped area around the periphery of a structure as shown in Table 1 ③ (SC-ring method). In contrast, Yoshimi, one of the authors of this paper, has proposed a deep mixing method of block type (SC-block method) as shown in Table 1 ④ for a structure on piles. Thus, the piles and the soil cement block are expected to share earthquake loading: the overturning moment on the structure is supported by the piles, and the base shear is carried by the soil cement block (SC-block) and the piles. The SC-block method has three advantages: (1) Infinite combinations of the strength and volume of the soil cement offer a wide choice in design, contributing to a lower cost than a ring type improvement, (2) the bulky shape of the soil cement block permits greater variance in its strength thus requiring less strict quality control than a thin wall, and (3) the cement mixing method can be used in urban areas because it does not cause objectionable noise and vibration.

The object of this paper is to study by three-dimensional analyses the effectiveness of the ground improvement methods such as SCP, SC-ring and SC-block, as a means to protect a group pile foundation from soil liquefaction hazard.

LIQUEFACTION ANALYSIS

Usual approach to studying the seismic response of a pile foundation in liquefiable ground consists of two steps. First, a nonlinear response analysis is conducted to obtain the equivalent linear modulus of the ground without the structure and piles, which is a function of shear strains of the soil. Second, using this modulus, linear analyses such as substructure methods (Miura *et al.*, 1994), are used to calculate the response of the structure and piles. The results obtained by the method cannot express the nonlinear response of the surrounding ground caused by the vibration of the piles. On the other hand, the methods based on the Penzien model (Nomura *et al.*, 1991), and two-dimensional liquefaction methods (Fukutake *et al.*, 1990; Ohtsuki *et al.*, 1993) can deal with the above problem. For the Penzien model, it seems difficult to determine rationally nonlinear soil properties that can describe soil-structure interaction characteristics. In a two-dimensional liquefaction analysis, engineering judgment is needed to model a soil-pile-foundation system.

We have recently developed a new code for three-dimensional effective stress analysis called ***HiPER*** (Ohtsuki *et al.*, 1994) to assess the dynamic response of structures on liquefiable ground. The explicit finite element method by one point Gauss integration (Hallqueist, 1983) is applied to studying three-dimensional problems for considering a reduction in the CPU time and memory capacity on a supercomputer. In this method a simplified constitutive model is used to represent the nonlinear behavior of soil involving liquefaction. The proposed constitutive model consists of a stress-strain and a strain-dilatancy relationship: the modified

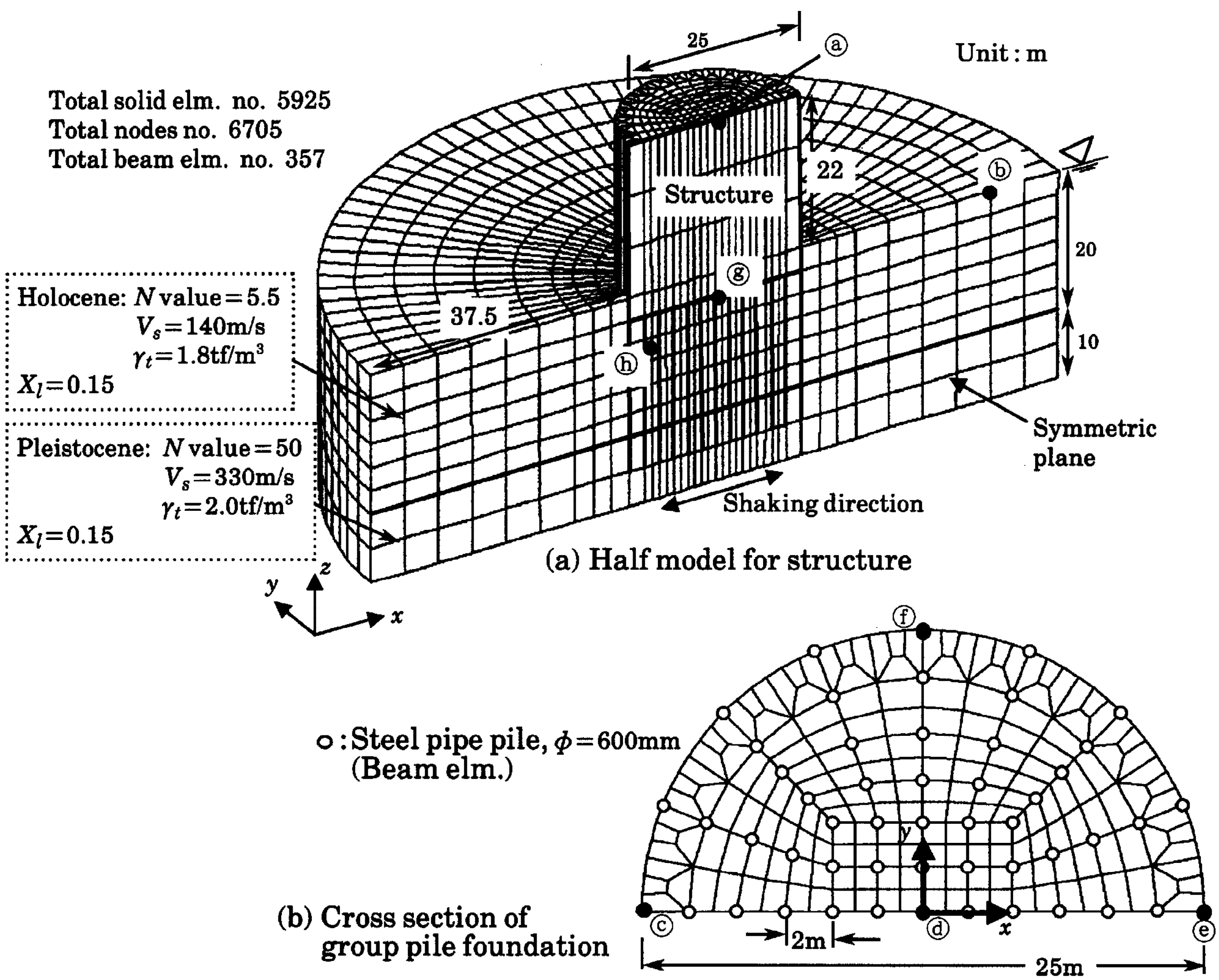


Fig. 1. Mesh model and material constants.

Ramberg-Osgood model (Tatsuoka, *et al.*, 1978) which is usually suitable for expressing the simple shear stress conditions, is extended to the three-dimensional problem (Fukutake *et al.*, 1991), and in addition a "bowl model" (Fukutake *et al.*, 1989, 1991) is used to describe the three-dimensional dilatancy characteristics. The applicability of the present method has been examined by comparing computed results with observed data (Fukutake *et al.*, 1992; Ohtsuki *et al.*, 1994).

Table 1. Pattern of soil improvement analyzed (shaded zone denotes improved area)

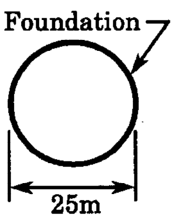
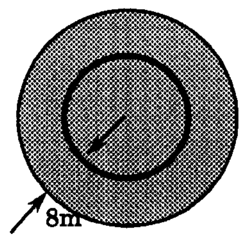
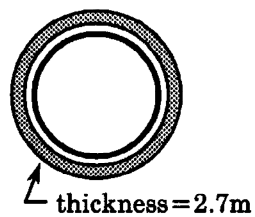
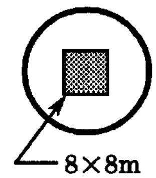
	① End-bearing piles in unimproved ground	② End-bearing piles in the ground improved by sand compaction piles (SCP)	③ End-bearing piles and soil cement ring (SC-ring)	④ End-bearing piles and soil cement block (SC-block)
Pattern of improvement (plan view, x-y plane)				
Improved area	0 m²	1320 m²	276 m²	64 m²
Improved area / Foundation area	0 %	269 %	56 %	13 %

Table 2. Properties of virgin and improved soils

Holocene sand (decomposed granite soil)	N value = 8, Vs=170m/s G_0= 5300tf/m², ν=0.33	γ_t=1.8tf/m³ X_l=0.18
Holocene sand (decomposed granite soil) [Improved by SCP]	N value=18, Vs=250m/s G_0=11500tf/m², ν=0.33	γ_t=1.8tf/m³ X_l=0.24
Pleistocene sand	N value=50, Vs=330m/s G_0=22000tf/m², ν=0.33	γ_t=2.0tf/m³ X_l=0.25
Improved body of soil cement (SC-ring, SC-block)	q_u = 200tf/m² E=1.0×10⁵tf/m², ν=0.20	γ_t=2.0tf/m³

(Vs : S wave velocity, G_0 : Small-strain shear modulus, E : Young's modulus, ν : Poisson's ratio, γ_t : Unit weight, X_l : Lower limit of liquefaction resistance, q_u : Unconfined compressive strength)

MODEL FOR ANALYSIS

The model for analysis is a circular structure on 98 steel pipe piles as shown in Fig. 1. Four types of foundation supporting a structure are considered:

① End-bearing piles in unimproved ground [Unimproved],
② End-bearing piles in the ground improved by the sand compaction pile method covering a circular area of a radius of 20.5m [SCP],
③ End-bearing piles and a ring type soil cement covering a ring area of a thickness of 2.7m [SC-ring],
④ End-bearing piles and a block type soil cement covering an 8m square area [SC-block].

The ground improvement schemes of SCP, SC-block and SC-ring are expected to reduce the seismic shear force and bending moment in the piles. The SC-ring method is suitable for retrofitting of the existing structures. The physical and mechanical properties of the ground are also shown in Fig. 1 and Table 2. The tensile strength of the soil cement is tentatively assumed to be equal to its compressive strength. Figure 1(a) shows the mesh for the numerical analysis which consist of 5925 solid elements and 357 beam elements, and Fig. 1(b) shows the horizontal cross-section of the piles directly below the structure. The structure is assumed to behave as a rigid body during an earthquake. The bottom boundary of the model is assumed fixed. The vertical component of the ground nodes on the cylindrical boundary surface is also assumed fixed. The model is subjected to NS component of the 1995 Hyogo-ken Nanbu Earthquake at Kobe University for 10 seconds with a peak acceleration of 100 Gal.

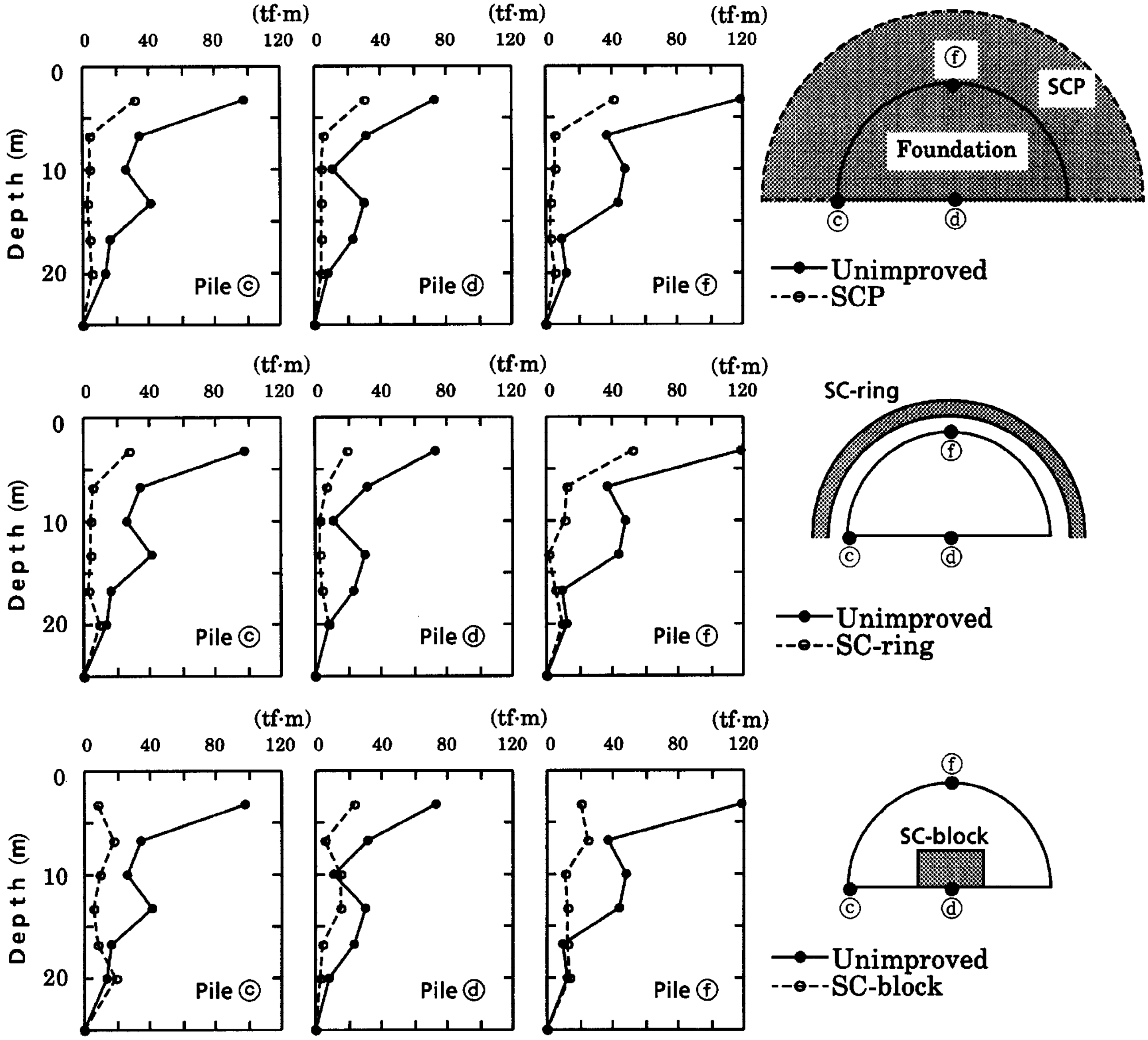


Fig. 2. Maximum bending moment in piles ⓒ, ⓓ and ⓕ

EFFECT OF REMEDIAL MEASURES

The maximum bending moment in three piles are shown in Fig. 2. It can be seen that in Piles ⓒ and ⓕ on the perimeter of the structure, the bending moment is remarkably reduced as a result of ground improvement with SCP and SC-ring, and that the SC-block method is even more effective. The fact that the volume of soil improved by the SC-block method is only 5% of that by the SCP method is expected to make the SC-block method economically competitive.

Figures 3 and 4 show the maximum shear force and maximum bending moment at pile top along the line of symmetry (see Fig. 5) and those in Pile ⓕ. The shear force and bending moment in the piles are significantly reduced as a result of the ground improvement, particularly toward the periphery of the structure. In the unimproved case, the distribution of shear force and bending moment is shaped like a bowl. In all four cases, Pile ⓕ sustains the largest shear force and bending moment. For the shear force of the unimproved case, the ⓔ/ⓓ and ⓕ/ⓓ ratios are 1.57 and 1.99, respectively; and for the bending moment of the unimproved case, the ⓔ/ⓓ and ⓕ/ⓓ ratios are 1.34 and 1.62, respectively. In reality, earthquake ground motions occur in all directions; thus all peripheral piles will be loaded in the same amount as Pile ⓕ.

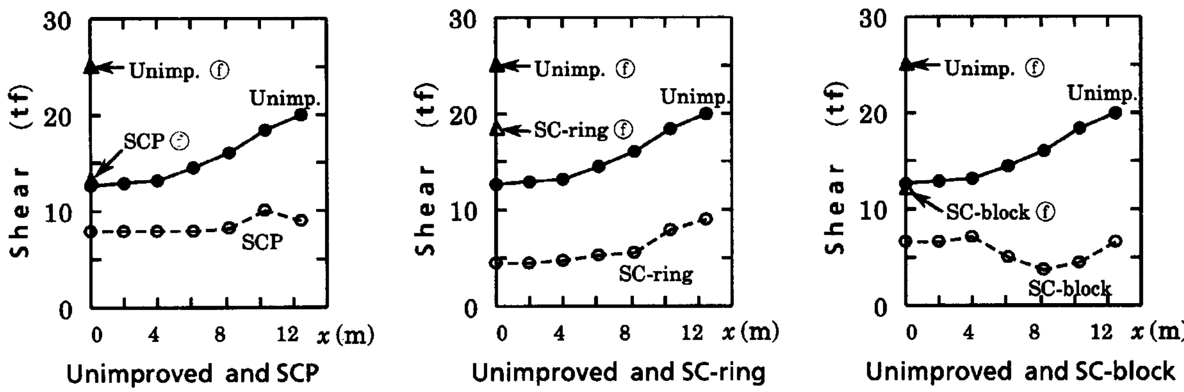


Fig. 3 Maximum shear force at pile top on the line of symmetry and Pile ⓕ

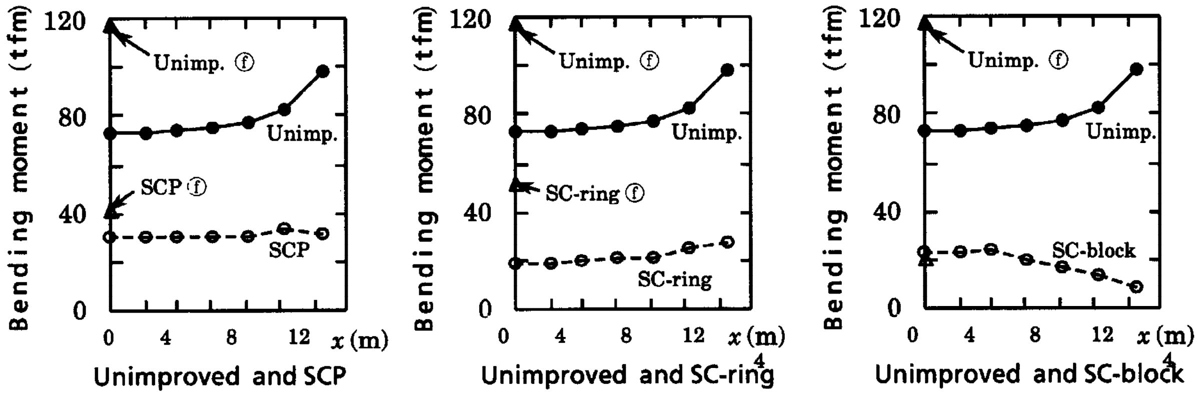


Fig. 4. Maximum bending moment at pile top on the line of symmetry and Pile ⓕ

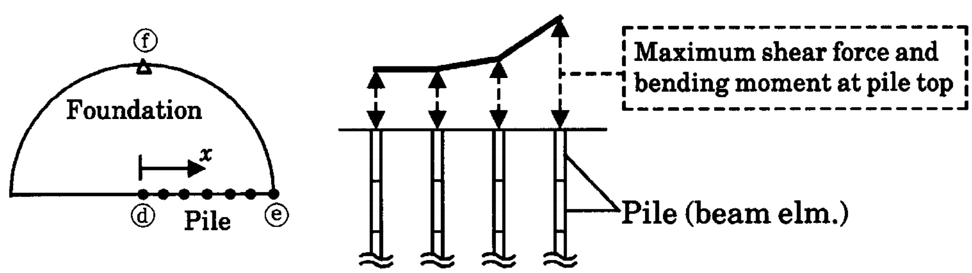


Fig. 5. Key sketch for Fig.3 and Fig.4

Figure 6 shows the relationship between bending moment M and axial force N at the top of Pile ⓒ. The axial force includes the self weight of the structure. In the SCP and SC-ring cases, the bending moment becomes smaller than the unimproved one, but the axial force does not differ so much. In the SC-block case, the bending moment reduces while the axial force increases. The reason is that the solid SC-block located in the center of the foundation excites the rocking mode of the structure.

As shown in Fig. 7, the horizontal displacements of the foundation (Node ⓖ) are reduced more than 50% as a result of the ground improvement. This suppression of the horizontal movement reduces the stresses in the piles.

Figure 8 illustrates the contour lines of excess pore water pressure ratios, P_w/σ_0', and the deformation of the ground which is magnified 50 times. The piles are not shown although they are present in all four cases. For the SC-ring case, the ground surrounded by the SC-ring generates 70% water pressure ratios. However the ground still retains sufficient stiffness to reduce the amplitude of the internal forces in piles.

Figure 9 shows the excess pore water pressure ratio in Element ⓗ which is located midpoint between piles at a depth of 8.3m. In the unimproved case, the ground becomes completely liq-

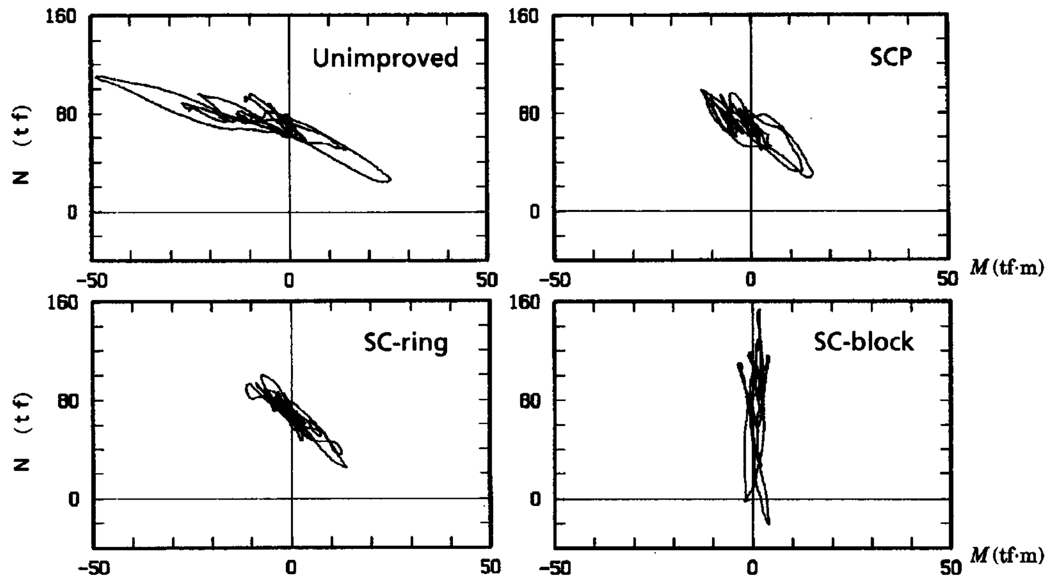


Fig. 6. Relation between bending moment M and axial force N at top of Pile ©

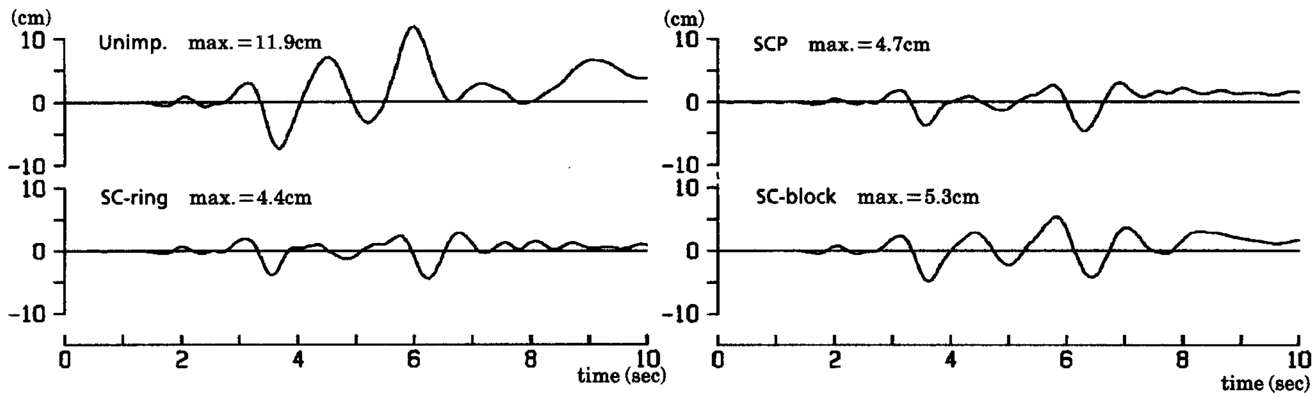


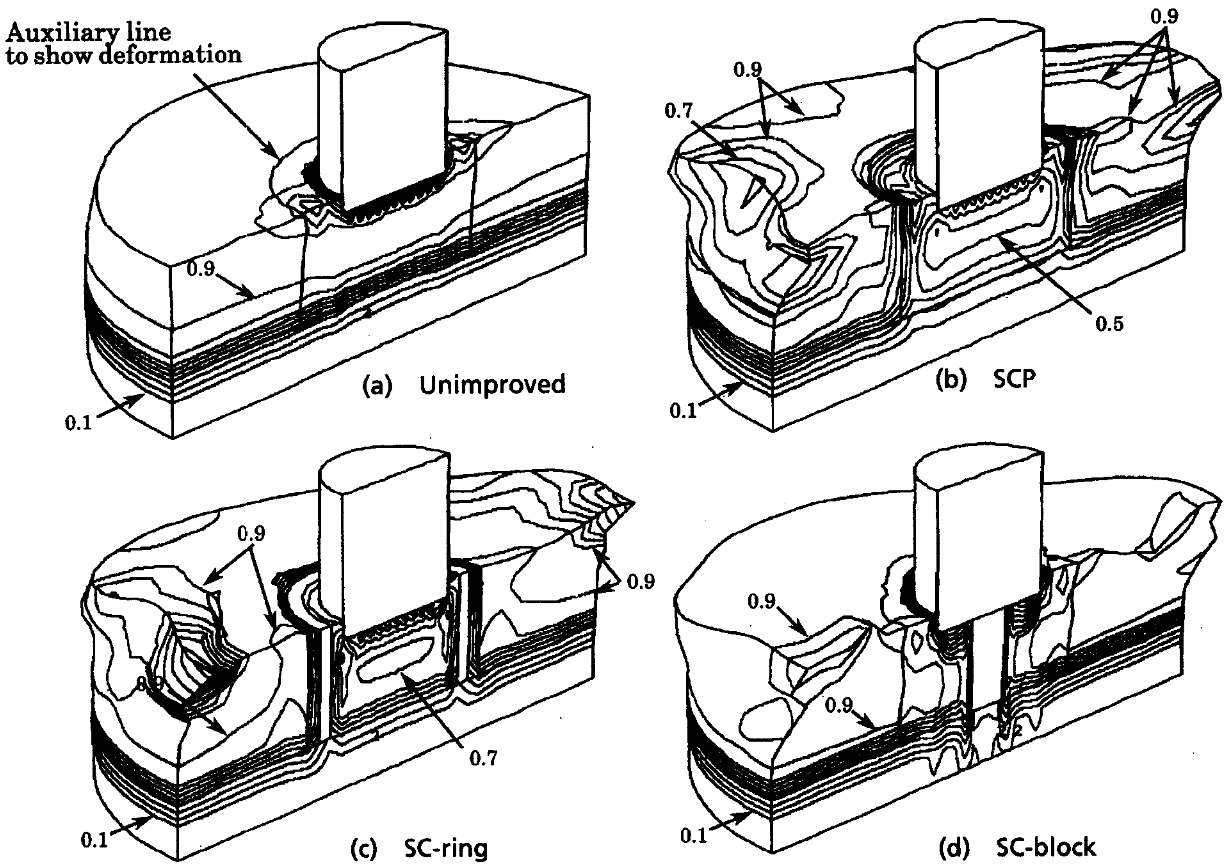
Fig. 7. Horizontal displacement of foundation (Node ⓖ)

uefied, but in the improved cases, P_w/σ_0' is suppressed. In the SCP case, the value of P_w/σ_0' is the smallest and it vibrates due to the cyclic mobility of the soil.

Figure 10 shows the horizontal accelerations at the top of the structure and at the ground surface together with the input waves at the bottom of the model. The acceleration of the SC-ring case and the SC-block case show rather large amplitudes at the top of the structure. Since the surrounding ground becomes liquefied in about 5 seconds, the acceleration response after 5 seconds becomes small in the unimproved case. On the other hand, the accelerations after 5 seconds for the SCP, SC-ring and SC-block cases are larger than the unimproved one, because the improved soil transmits wave energy to the surrounding ground.

CONCLUSIONS

On the basis of the three-dimensional numerical analyses of soil-pile-structure system with or without ground improvement, the shear force and bending moment in the piles can be significantly reduced by installing SCP, SC-ring or SC-block. The SC-block method is more effective than the SCP method even when the former occupies 5% of the volume improved by the latter. Thus, it may be tentatively concluded that the proposed SC-block method can be a viable and economical means to protect piles from soil liquefaction hazard. The SC-ring method is suitable for retrofitting existing structures, although the cost is higher than that of the SC-block method. Shaking table tests on a geotechnical centrifuge are underway to verify the analytical results (Ohtsuki, *et al.*, 1995).



(Deformation magnified 50 times, Pore pressure Contour spacing = 0.1)

Fig. 8. Deformation and contour lines of excess pore water pressure ratio (P_w/σ'_0) (Time = 10 sec).

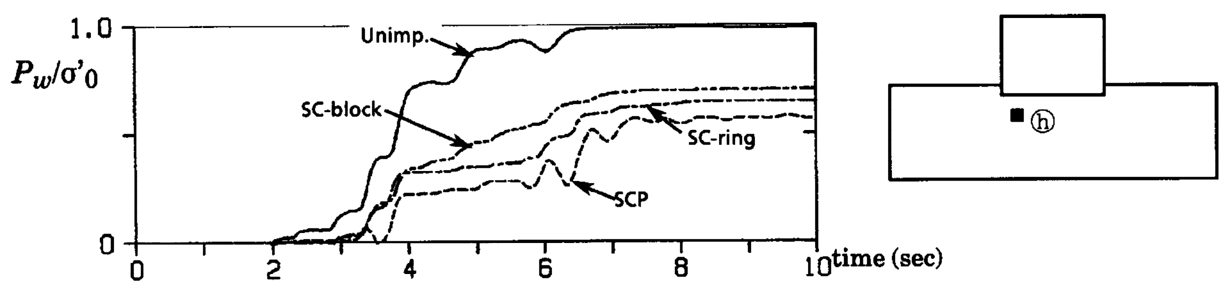


Fig. 9. Excess pore water pressure ratio in Element ⓗ (midpoint between piles, at a depth of 8.3m)

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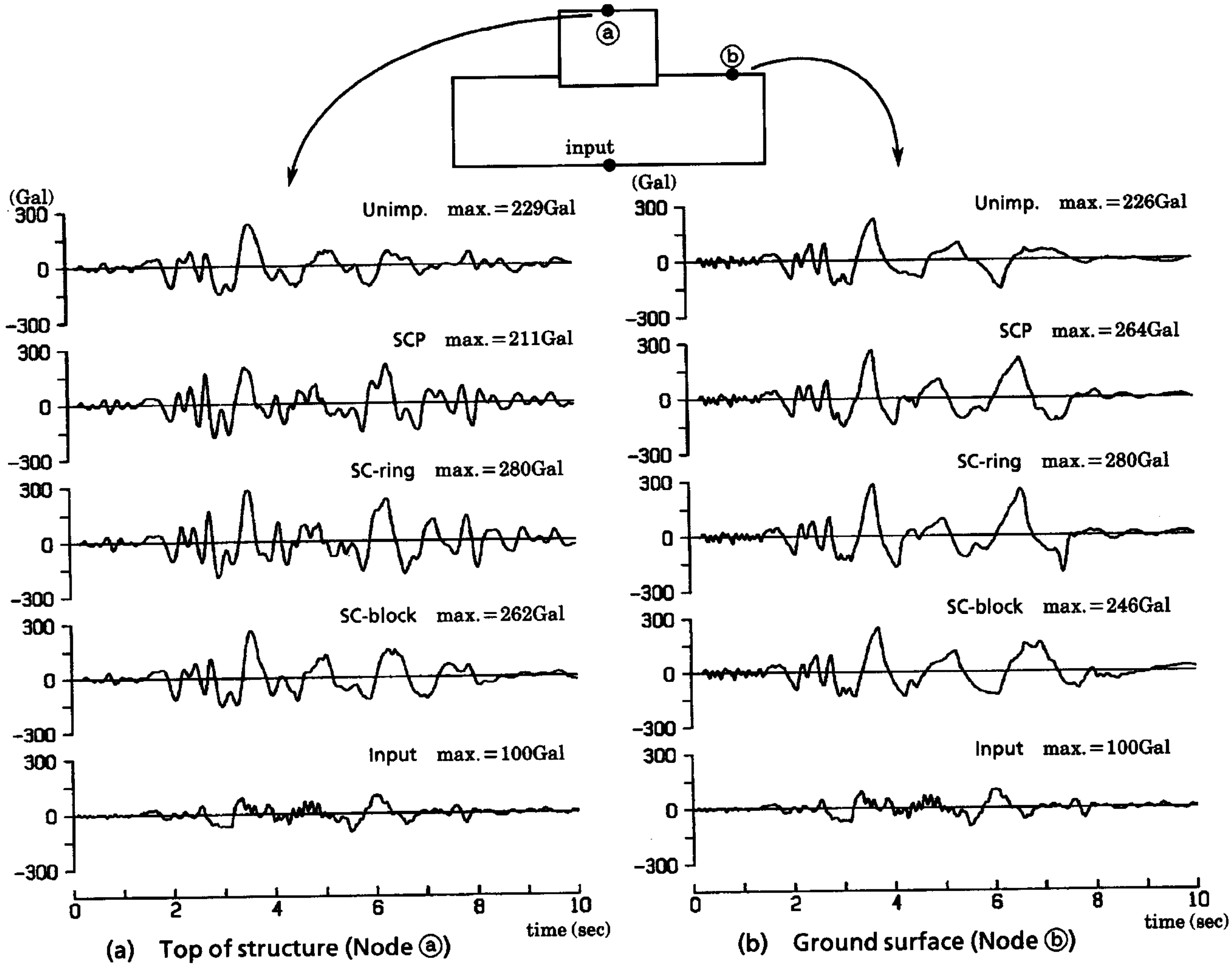

Fig. 10. Horizontal acceleration

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