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PROTECTION OF BURIED PIPELINES FROM LIQUEFACTION BY GROUND IMPROVEMENTS

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ABSTRACT

Effects of ground improvement by sand compaction piles(SCPs) on response behaviors of buried pipelines which are subjected to permanent ground displacement or buoyancy induced by liquefaction are investigated. Combining the programs for the simulation of SCP-improvement, the liquefaction analysis and the evaluation of the permanent ground displacement, the soil spring constants, input ground displacements and buoyancy are evaluated. The responses of pipeline are analyzed, which is based on the theory of a beam on an elastic foundation and the modified transfer matrix method. Results of numerical computations for the pipeline responses show that the SCP ground improvement is effective to prevent soil liquefaction and reduce responses of pipeline buried in SCP-improved ground.

KEYWORDS

pipeline, liquefaction, permanent ground displacement, sand compaction pile, buoyancy, 2-phase mixture theory, a beam on an elastic foundation, spring constant, joint

INTRODUCTION

The permanent ground displacement or buoyancy induced by soil liquefaction during earthquakes is one of the most important problems for aseismic design of structures in such grounds possible to be liquefied. There have been many studies about soil liquefaction (Hamada *et al.*, 1986; Miyajima, 1990; Yasuda *et al.*, 1992), and effective countermeasure is expected to be established. The sand compaction pile (SCP) method is one of such popular countermeasures and there are many examples which have been performed in Japan. However, the effects of SCP on soil liquefaction during past earthquakes have been verified in only several cases.

The purpose of this study is to clarify the effect of SCP method on behavior of the buried pipelines under soil liquefaction environment. The authors have developed the simulation program of SCP method and this program can evaluate the dynamic effect of SCP in considering the wave propagation for far field (Akiyoshi *et al.*, 1994a). They have also developed the liquefaction analysis program based on 2-phase mixture theory (Akiyoshi *et al.*, 1993). In this study they propose the 2-dimensional finite element analysis for the permanent displacement of the liquefied ground. Firstly the coefficients of subgrade reaction of the ground improved by SCP are evaluated by the numerical analysis using above SCP-simulating program and the liquefaction analysis of the ground(Akiyoshi *et al.*, 1994b). Then the permanent displacements of the liquefied ground are evaluated. The buoyancy forces are also evaluated according to the excess pore water pressure ratio. Thus the responses of pipeline subjected to permanent ground displacement or buoyancy induced by liquefaction are investigated by the analytical method (Fuchida and Wang, 1993) which is based on the beam theory on an elastic foundation using the modified transfer matrix method technique.

SIMULATION OF SCP AND LIQUEFACTION ANALYSIS

The authors developed the program "WAP3"(Wave Accumulation Process in 3-dimension : Akiyoshi *et al.*, 1994a) which simulates the process of improvement by sand compaction piles. In WAP3, the decrement of the void ratio and increment of the stiffness of the sandy soils are assumed to be caused by the strain accumulation for the wave propagation due to the vibration in compaction and static compulsory insertion of the casing pipe, using the fine content of sand, the vibrating forces, the spacing and the compacting time of SCPs as the parameters. The liquefaction analysis of the improved ground model is carried out by "NUW2"(Non-linear u-w analysis in 2-dimension : Akiyoshi *et al.*, 1993) which is based on the two-phase mixture theory and Iai's constitutive equation (Iai *et al.*, 1992). The shear modulus and the excess pore water pressure ratio of the improved ground during soil liquefaction are evaluated by NUW2. For the details about WAP3 and NUW2, readers are referred to the papers (Akiyoshi *et al*, 1993, 1994a and 1994b).

ANALYSIS OF PERMANENT GROUND DISPLACEMENT

To evaluate the permanent ground displacement induced by liquefaction, the authors propose a simplified analytical procedure, in which it is assumed that the permanent ground displacement occurs due to the shear deformation of the ground by the gravity force. In this finite element static analysis the potential head of the inclined ground is added to the gravity force as the external one. In addition to it, the shear modulus of the liquefied ground is assumed to be reduced according to the excess pore water pressure ratio calculated by NUW2. Figure 1 shows the relation between the reduction rate of the shear modulus and the excess pore water pressure ratio. In the process of numerical analysis, the external force including potential head loaded to the ground is divided in the several steps. It is assumed that the buoyancy to the pipeline is also related to the excess pore water pressure ratio(EPWP) as shown in Fig.2. In Fig.2 the buoyancy is maximum for the condition of perfect liquefaction (EPWP=1.0) and zero for the condition of no liquefaction (EPWP=0).

ANALYSIS OF BURIED PIPELINES

To evaluate the responses of pipelines subjected to permanent ground displacement or buoyancy, the pipeline–soil system is replaced with a beam on an elastic foundation and a pseudo static analysis is adopted.

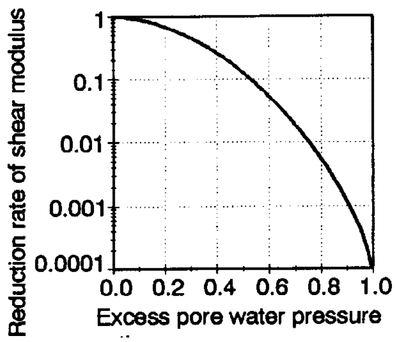


Fig.1 Reduction rate of shear modulus

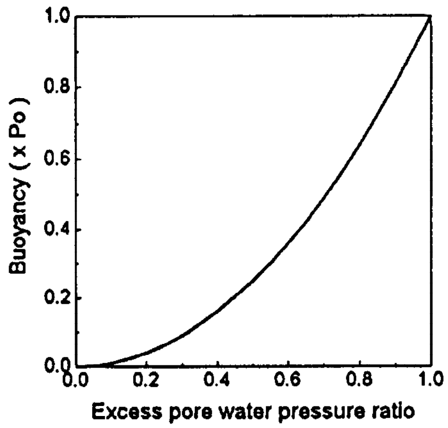


Fig.2 Buoyancy versus excess pore water pressure ratio

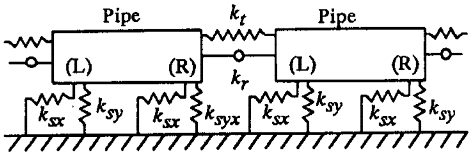


Fig..3 Modeling of a pipeline–soil system

Replacing the stiffness of liquefied ground around a pipeline with a coefficient of subgrade reaction, the pipeline is modeled as the pipeline–soil spring system as shown in Fig.3. The pipeline segments are connected by an axial joint spring k_t and a rotational one k_r. The joint and soil springs are assumed to be bi-linearly elastic and the inertia and damping forces are neglected under the static load assumption. For solving the governing equilibrium equation in the lateral direction and minimizing the accumulative errors in the numerical computations, a modified transfer matrix (MTM) method is adopted. For the details of the MTM method, readers are referred to the report (Fuchida and Wang, 1993). Using this analytical method, the solution of the physical quantities of a buried pipeline can be obtained.

Fig.4 shows the total analytical flow of this study. Firstly the model ground is improved by WAP3 . The liquefaction analysis of the improved ground is performed by NUW2 . According to the shear modulus and the excess pore water pressure ratio of the improved ground, the analysis for the permanent ground displacement is conducted. Through these stages, the input parameters for the analysis of the pipeline such as lateral ground displacement, buoyancy and coefficients of subgrade reaction are evaluated. The computer code. for the analysis of the pipeline is named PIPE . Finally the analysis for the responses of the pipeline buried in the liquefied ground is executed by the program PIPE .

EXPERIMENTS OF GROUND MODEL

Fig.5 is the schematic model used in the shaking table tests for the permanent displacement of the ground improved by SCP. In the sand box (length:1500×width:1000× height:1000mm), the loose saturated sand layer was made by dropping dry sand in water as thickness 500mm over a fully compacted base layer. The surface and bottom planes of the layer was inclined as 10%. The sensors for hydro pressure and acceleration were arranged in the sand layer at the depths of 100 mm from the surface. The 4 and 8 SCPs of the length of 400mm were built up by squeezing and vibrating the casing pipes, which process was similar to that of the field. Stiffness of the sand deposit at the midpoint of 2 SCPs was measured by cone–penetration–test

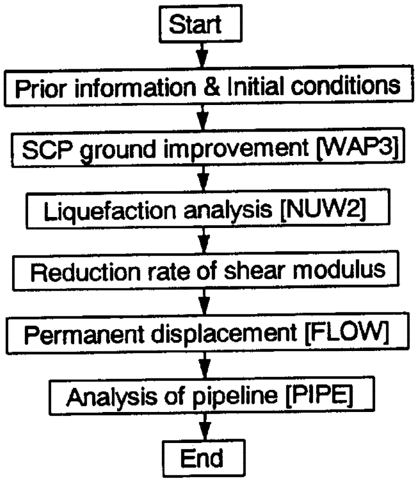
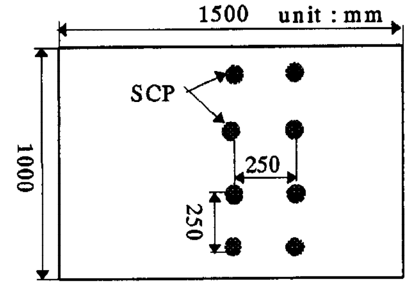
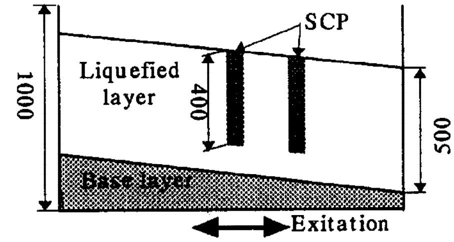


Fig.4 Total analytical flow



(a) Plan view



(b) Front view

Fig.5 Set up of SCPs and flow test

before and after improvement. The details of SCP model experiment are omitted here (see Akiyoshi *et al.*, 1994a, 1994b). The 28 pins with the spaces 200mm and the 5 sponge rubber columns with space 250mm are installed for the measurement of the displacements at the surface and the side wall, respectively. After the sand box was vibrated as the base acceleration 0.1G with 5Hz, the displacements of the ground model were measured. This ground model divided to the 360 elements is analyzed by the program FLOW . Figure 6 is the comparison of the ground surface displacement between the analytical results and the experimental ones of the ground model shown in Fig.5. In Fig.6, the solid lines show the analytical results and the symbol marks the experimental ones. The results by proposed analytical method agree well with the experimental results, which shows the accuracy of the proposed method.

CONDITIONS FOR NUMERICAL COMPUTATIONS

Figure 7 is the field scale ground model in which the surface layer is uniform, N–value 5, thickness 20m and the gradient 3%. In Fig.8 the distributions of the shear modulus of the ground improved by WAP3 for the different fine contents(F_C) are plotted with white symbols. The conditions used in WAP3 are the spacing of SCPs 6m, the vibrating time 20sec and the vibrating force 600N. Figure 8 shows that the effect of SCP improvement on the shear modulus becomes large as the fine content(F_C) is small.

Liquefaction analyses by NUW2 were executed for El Centro wave(1940) of maximum acceleration 0.1G. Figure 9 shows the coefficients of subgrade reaction versus the excess pore water pressure ratio and these coefficients are normalized by the initial one of unimproved ground model as the reference value. If liquefaction is assumed to occur for the excess pore water pressure ratio over 0.5, SCP ground improvement may be enough as letting the coefficient of subgrade reaction be about twice the initial one. Since the compacting time of SCP in Fig.9 is 20 seconds, the excess pore water pressure ratios of the most cases of SCP in the field in which the compacting time is longer than 20 seconds are expected to be below 0.5.

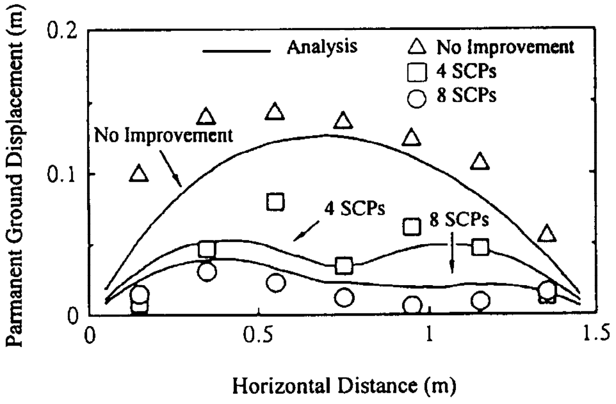


Fig.6 Comparison between analyses and experiments

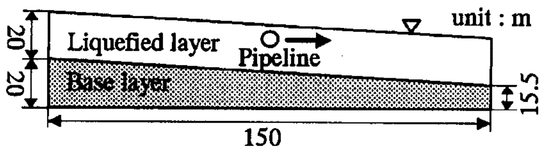


Fig.7 Field scale ground model

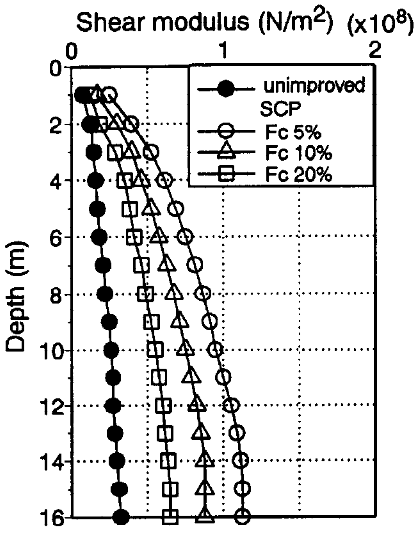


Fig.8 Improved shear modulus

RESPONSES OF PIPELINES

The followings are the investigations about the behaviors of the pipelines buried in above improved or unimproved grounds shown in Figs.7 and 8. The pipeline parameters used in the numerical computations are shown in Table 1. In addition to it, following parameters are used; the total length of the pipeline 100m; the length of one segment of the pipeline 5m; the depth of the buried pipeline 2m. Figure 10 shows the characteristic of the joint which is used as the aseismic joint in Japan and called with "S-type" joint. The distributed shape of the input ground displacement is assumed to be trapezoid. The numerical computations based on the load increment method are carried out and the input ground displacement is divided into 100 small increment.

In unimproved or improved ground the pipeline may be subjected to buoyancy induced by soil liquefaction during earthquakes. The buoyancy loading to the pipeline is obtained as 81 kgf/m (793.8 N/m) for the excess pore water pressure of unimproved ground 0.9 in Fig.9, by referring to the relation in Fig.2. Figure 11 shows the distributed responses of the continuous pipeline subjected to such buoyancy in both improved and unimproved grounds. The displacement, bending moment and shear force of the pipeline are represented in Fig.11 (a), (b) and (c), respectively. In Figure 11(a) maximum displacement of the pipeline reaches to

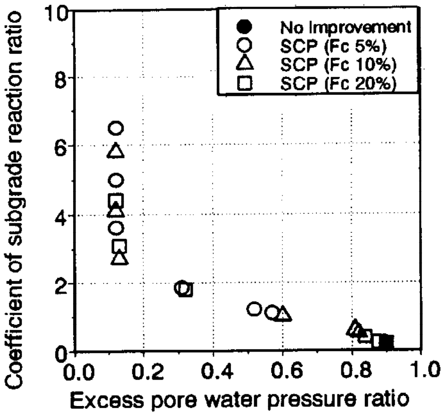
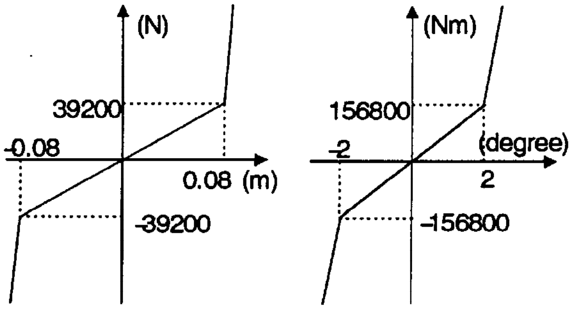


Fig.9 Coefficient of subgrade reaction ratio

Table1 Reference Pipe Parameters

Physical items	Values (unit)
Nominal diameter	500 (mm)
Outside diameter	528 (mm)
Thickness	9.5 (mm)
Total length	100 (m)
Young's modulus	1.57×10^{11} (N/m2)
Specific gravity	7.15



(a) Axial Joint Spring (b) Rotational Joint Spring

Fig.10 Characteristics of S-type joint

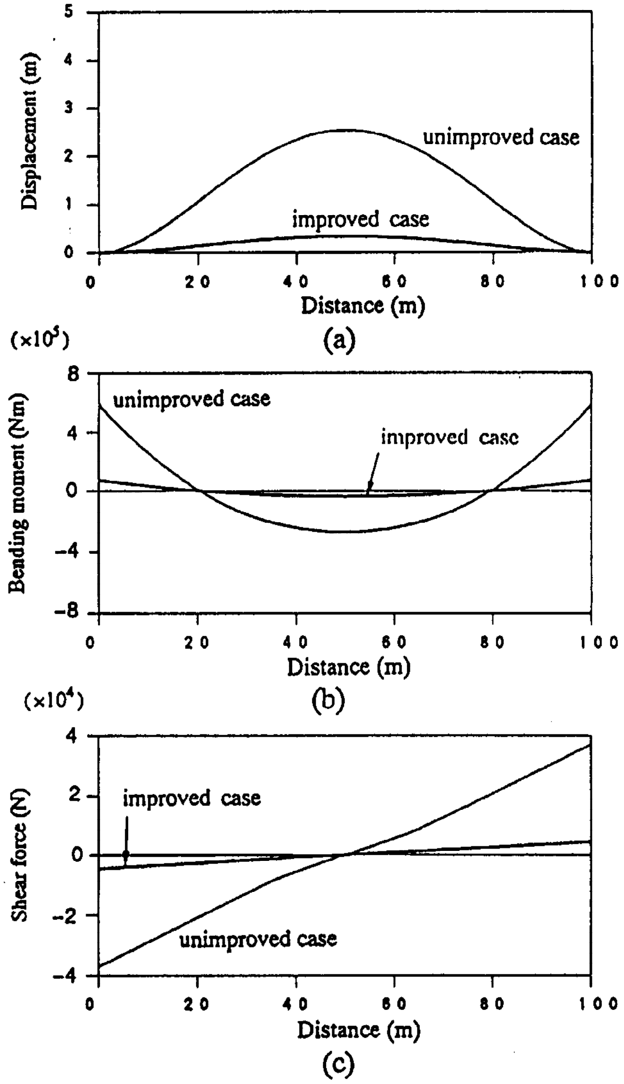
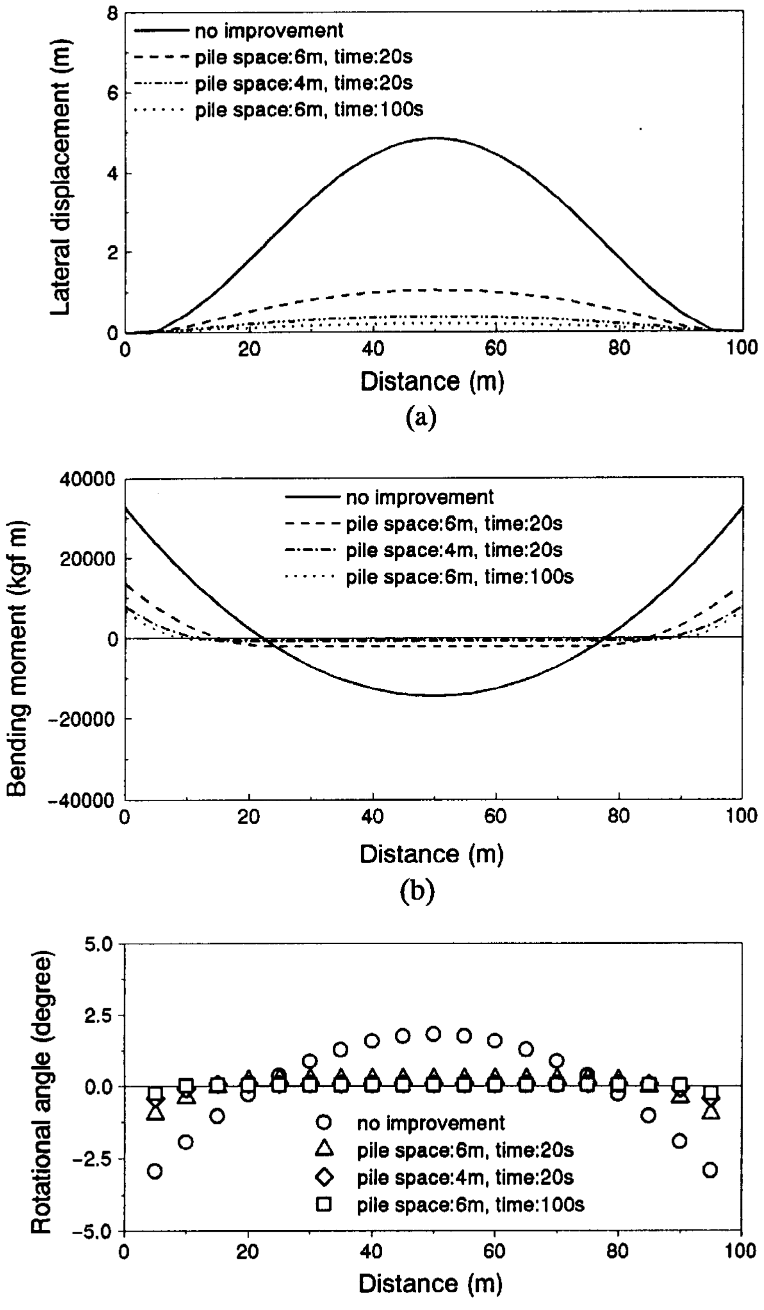


Fig.11 Distributed responses of pipeline subjected to buoyancy

about 2.5 m but in the improved ground case, the maximum ground displacement is only about 0.3m. In Fig.11 (b) and (c), the bending moment and shear force of the pipeline buried in the improved ground decrease below 1/8 those in unimproved ground.

After the finite element analysis of the ground model in Fig.7 with 360 elements and 403 nodal points, the maximum input ground displacements for the analysis of the pipeline are obtained as 10.38m, 0.655m, 0.162m and 0.106m, for the unimproved case, SCP-improved case of the pile space 6m, compacting time 20sec, pile space 4m, compacting time 20sec and pile space 6m, compacting time 100sec, respectively. Figure 12 shows the distributed responses of the pipeline subjected to above ground displacements in both improved and unimproved grounds. The displacement, bending moment of the pipeline and joint rotational angle are represented in Fig.12 (a), (b) and (c), respectively. In Fig.12 (a) maximum displacement of the

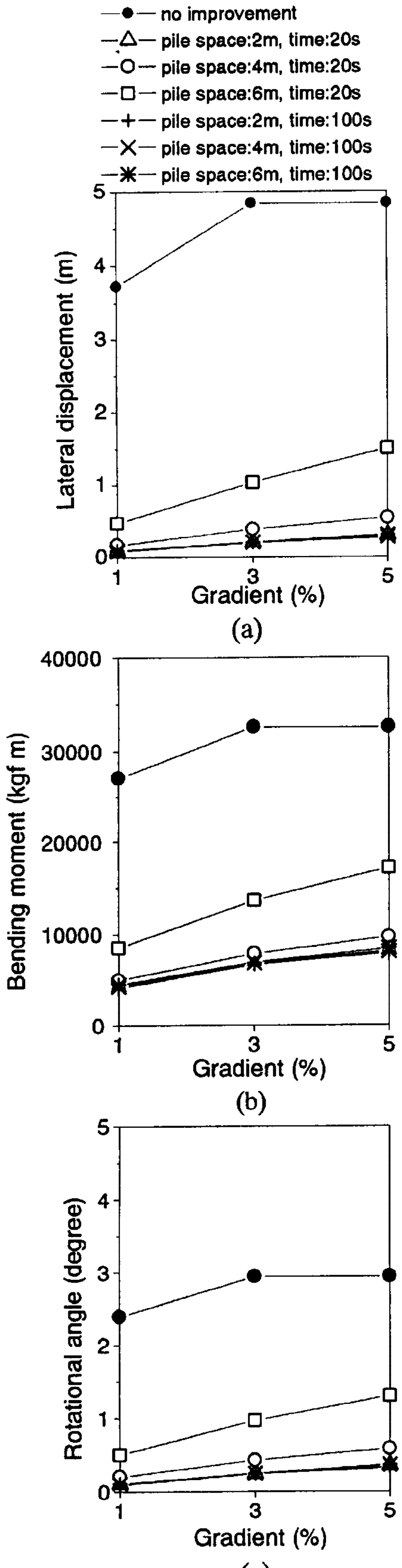


(a)

(b)

(c)

Fig.12 Distributed responses of pipeline subjected to permanent displacement

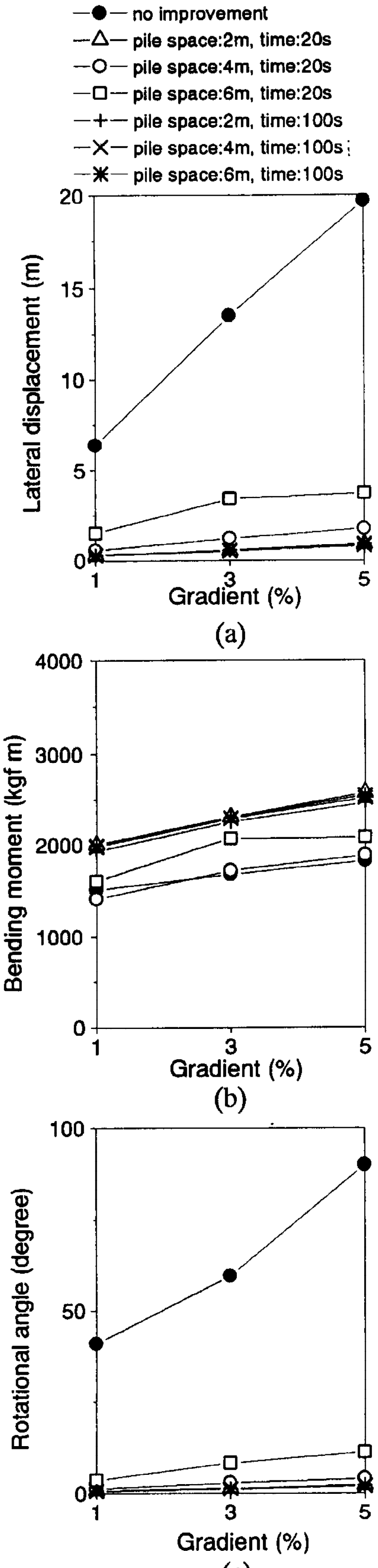


(a)

(b)

(c)

Fig.13 Responses of pipeline (S–type joint) versus gradient of the ground



(a)

(b)

(c)

Fig.14 Responses of pipeline (GM–type joint) versus gradient of the ground pipeline buried in unimproved ground reaches to about 5m, but in the improved ground cases the maximum pipeline displacements are reduced below about 1m. Since the improving condition is very loose, the pipeline displacement could be decreased below 1m in most usual SCP improvement in the field in which the vibrating time is more than 100sec and pile spacing is narrower than 2m. In Fig.12 (b) and (c) the bending moment and the joint rotational angle of the pipeline buried in the improved ground decrease below 1/8 those in unimproved ground. From these responses of pipeline, it can be considered that SCP ground improvement is an effective countermeasure against soil liquefaction.

Figures 13 and 14 show that the relation between the responses of the segmented pipeline and the gradient of the ground in which (a), (b) and (c) represent the lateral displacement, bending moment and rotational angle, respectively. Figure 13 shows the responses of S–type(seismic joint type) jointed pipeline and Fig.14 those of GM–type(gas mechanical type) jointed pipeline. The responses in the improved ground are less than that of the unimproved ground. Especially, for GM–type joint, the responses of pipeline are extremely reduced by SCP–improvement.

CONCLUSIONS

In this paper the effects of SCP ground improvement on the responses of the pipeline are investigated by the simulation of SCP method, the liquefaction analysis of SCP–improved ground and the analysis for permanent ground displacement and the pipeline. The result obtained are summarized as follows:

(1) SCP ground improvement is effective to prevent soil liquefaction and reduce responses of buried pipeline subjected to permanent ground displacement or buoyancy induced by liquefaction.
(2) Coefficient of subgrade reaction of SCP improved ground keep its initial value during excitation of it, but that of unimproved ground decreases because of soil liquefaction.
(3) Coefficient of subgrade reaction of improved or unimproved ground can be evaluated numerically and related to excess pore water pressure ratio estimated by WAP3 and NUW2.
(4) The accuracy of the proposed method as the analysis for the permanent ground displacement is confirmed by applying this method to the ground model of the experiment (shaking table test).
(5) Effects of SCP–improvement on shear modulus of the ground increase as fine constant of the ground becomes small.

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