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# THRUST ON PILE FOUNDATION FROM THE FLOW OF LIQUEFIED GROUND WITH SURFACE NON-LIQUEFACTION LAYER

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## SUMMARY

Several types of structures have been suffered from structural damage induced by liquefaction in destructive earthquakes. Since the flow slide of liquefied ground sometimes induces extraordinary thrust to underground structures, pile foundations for bridges and buildings and pipeline networks are severely damaged. The aim of this study is to investigate the mechanism of the damage to structural pile foundation induced by the flow slide of liquefied ground, and a series of model tests were conducted. Three types of model sloping ground with a pile foundation were shook on the shaking table. In the standard case the sloping ground with a surface non-liquefaction layer was prepared; the flat ground with surface non-liquefaction layer and the sloping ground without non-liquefaction layer were also prepared. The vibration behaviors of the ground and pile foundation were observed, and the thrust on the pile foundation from the liquefied ground were monitored through the measurement of bending moment along a pile. As a result of comparative examination of the observed behaviors, the significant combined effect of surface non-liquefaction layer and flow slide of liquefied ground on the damage to pile foundation was clarified.

## INTRODUCTION

In destructive earthquakes, many structures are severely damaged due to the liquefaction of grounds. On riverside, seaside or port and harbor area, liquefied ground often flows toward river or sea; the lateral displacement of the ground sometimes exceeds a few meters and rarely reaches ten meters (Hamada et al. [1]). The sloping liquefied ground with low shear stiffness is driven laterally by the gravity force. In port and harbor area the lateral flow is usually induced by the failure of retaining structures at water edge (Inagaki et al., [2]). Since the 1968 Niigata Earthquake, the damages to pile foundations for bridges and buildings by the flow of liquefied ground have been reported in many large earthquakes in Japan (e.g. Hamada et al. [1]). And the mechanism and the counter measure to this type of damage have been

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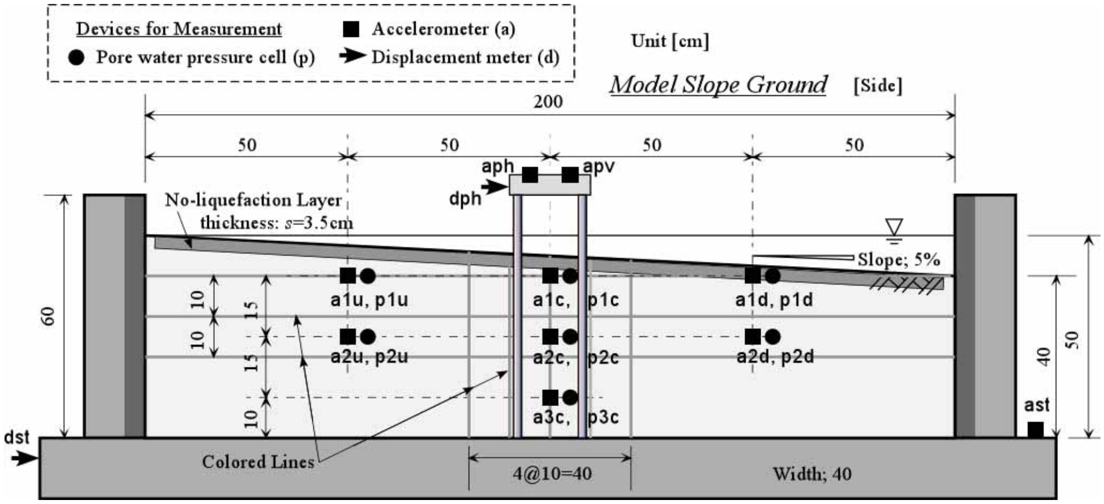


Fig.1. Model sloping ground and pile foundation for shaking table test.

investigated; Hyogo-Ken Nambu Earthquake road bridge earthquake counter measures committee [3], and Hamada et al. [4].

In the analyses of the thrust on pile foundation, liquefied ground is modeled as viscous continuum or solid elasto-plastic continuum; e.g. Uzuoka et al. [5]. An appropriate model for simulation of lateral flow and the evaluation of thrust on underground structures, however, has not been well established yet. Experimental investigations by means of shaking table tests have been conducted by many researchers in order to clarify the mechanism of the damage on pile foundation. However, the effect of the surface non-liquefaction layer has not been taken in consideration sufficiently in their investigations. On the other hand, in the reality of lateral flow of liquefied ground, the grounds are usually covered with solidified thin surface layer due to plants' rooting or artificial solidification for pavement. If the surface layer is impermeable, the liquefaction phenomenon would be enhanced extending the duration time. Moreover, since the surface layer would not lose its stiffness even in the process of lateral flow, pile foundations must be subjected to extraordinary thrust from the surface layer.

In this study a series of shaking table tests were conducted on the model sloping ground with surface non-liquefaction layer, where a model pile foundation is placed at the center of the sloping ground. We are aiming to reveal the mechanism of the damage to pile foundation induced by the lateral flow of liquefied sloping ground, with special attention to the interaction between the pile foundation and the ground through the surface non-liquefaction layer.

## MODEL SHAKING TABLE TEST

Figure 1 shows the model sloping ground and pile foundation prepared for shaking table test. Details of the model pile foundation is depicted in Fig. 2. The model pile foundation consists of four steel pipes and a rigid footing box made of steel plates of 10.13kg in mass. The steel pipes were welded to the container base and tightly connected to the footing box with two screws for each. The accelerations in horizontal and vertical directions, and horizontal displacement of the footing were monitored during shaking. One of the pipes on upstream side, that is the left hand side in the figure, has nine pairs of strain gauges for monitoring the bending moment along the pile.

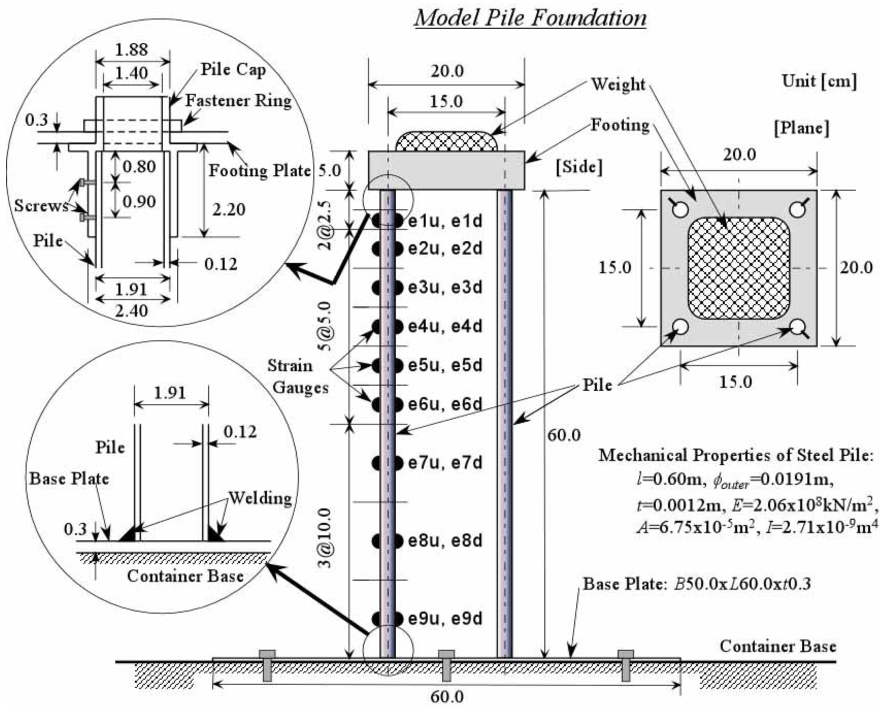


Fig.2. Model pile foundation

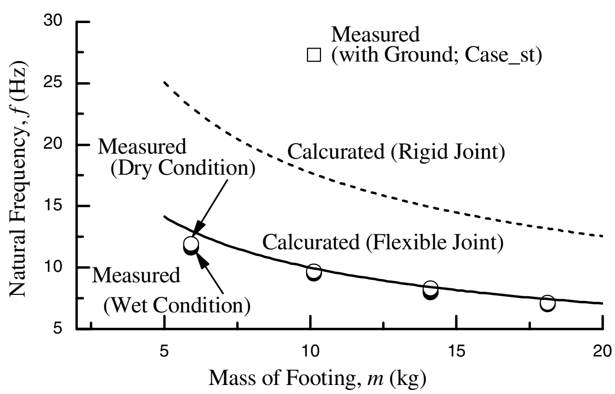


Fig.3. Natural frequency of model pile foundation

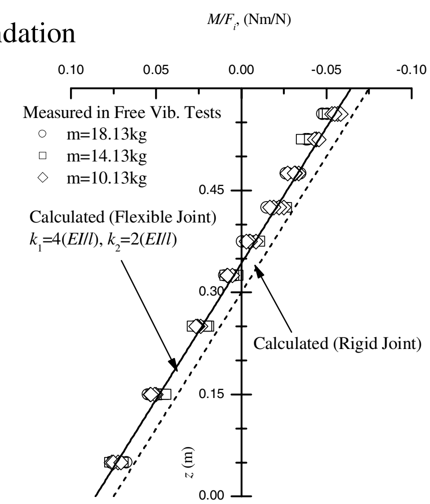


Fig.4. Distribution of bending moment

Figure 3 shows the natural frequency of the footing with the variable mass of footing. The natural frequency was determined from the time history of acceleration at the footing during free vibration of the foundation in wet and dry conditions: with and without water in the container. First the natural frequency was calculated by mass-beam model based on the assumption of perfectly rigid joint of the piles to the footing and the container bottom. As shown in the figure, the calculated natural frequency by broken line is much higher than the measured ones. In the distribution of the bending moment along the pile shown in Fig. 4, the calculated distribution is shifted from the measured one. The discrepancies between the measured and calculated values suggest the flexibility of the joints of the piles. Then the mass-beam model was modified for flexible joint; rotational springs were employed at the joints (see Fig.5). The rotational flexibility of the joints were determined through the trial and error calculations so as to reach good accordance between the measurement and the calculation in both of natural frequency and bending

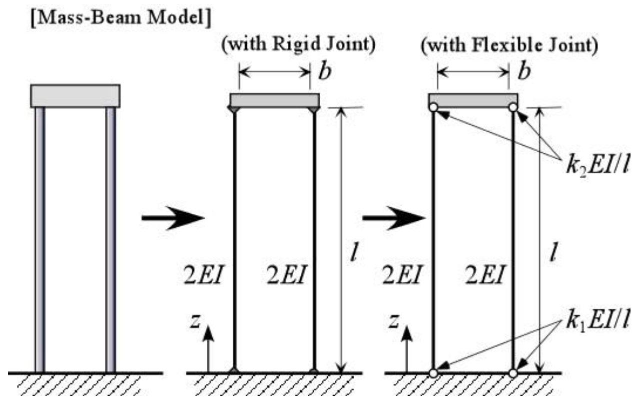


Fig.5. Mass-Beam Model for vibration behavior of pile foundation

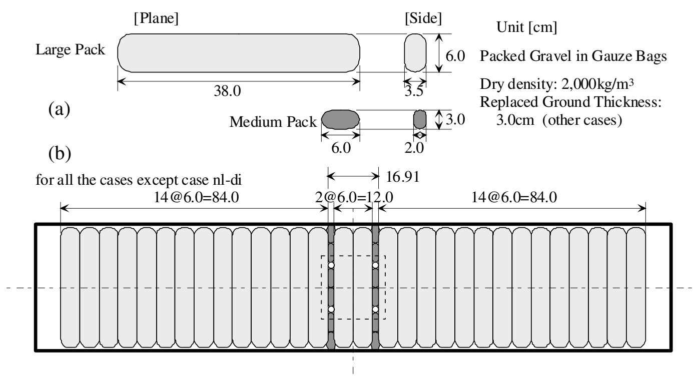


Fig.6. Surface non-liquefaction layer;
(a) densely packed gravel bags,
(b) arrangement of gravel bags over ground surface.

moment; see Figs. 3 and 4. The total bending moment $M_t$ which was directly measured consists of two components; one is due to external force from ground $M_e$, and the other is due to inertial force on the pile foundation $M_i$. The second component $M_i$ can be calculated from the inertial force, that is mass times the acceleration of the pile footing, through the modified mass-beam model. The bending moment due only to the external force $M_e$, was calculated by subtracting $M_i$ from $M_t$.

A soil container of 200cm, 60cm and 40cm in length, depth and width, respectively, was made of steel plates and tempered glass plates on front and back. And the inside longitudinal ends were covered with foam rubber plates to prevent the excessive reflection of the vibration wave from the ends. The sand material for liquefiable sloping ground is siliceous sand with a mean diameter $D_{50}$ of 0.54mm, a uniformity coefficient $U_c$ of 2.11, a maximum dry density $\rho_{\mathrm{dmax}}$ of 1.745g/cm3, and a minimum density of $\rho_{\mathrm{dmin}}$ of 1.475g/cm$^3$. The sand material was dried in an oven, and pluviated through the slit of sand hopper which moved cyclically back and force. The sand was deposited under water uniformly, so as to create a saturated medium dense ground with a relative density $D_r$ of 50%. Its liquefaction strength was 0.17 in a series of undrained cyclic tri-axial tests; i.e. the shear-normal stress ratio of 0.17 was required to increase the excess pore water pressure to 95% of initial effective stress in 20 cycles of loading. During the preparation of the ground, accelerometers and pore water pressure meters were arranged as shown in Fig .1. Surface non-liquefaction layer consists of subangular gravel which was 6.3mm in $D_{50}$ and 3.55 in $U_c$; the gravel was densely packed into thirty narrow gauze bags and twelve small bags. The gravel bags were not connected one another and arranged on the surface of ground as shown in Fig. 6.

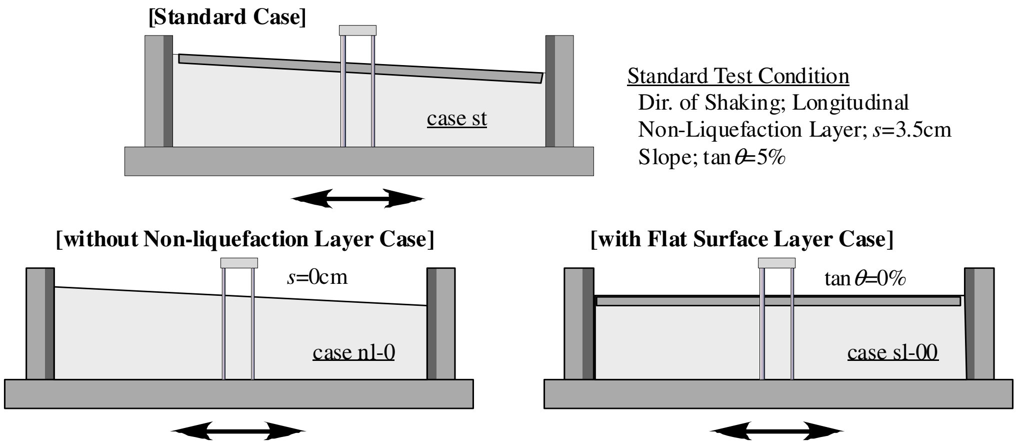


Fig.7. Selected three test cases; the standard case (Case st), the case without surface non-liquefaction layer (Case nl-0) and the case with flat surface (Case sl-00).

Three types of model grounds are shown in Fig.7. In the standard case (Case st) the slope of ground was 5% and the thickness of surface non-liquefaction layer was 3.5cm. In Case nl-0 surface non-liquefaction layer was not employed, and in Case sl-00 surface non-liquefaction layer was employed but the ground was flat to suppress the flow of liquefied ground. The natural frequency of the ground was about 40Hz in all the three cases, which was measured in a series of step loading tests of sinusoidal small shaking of 5Gal in amplitude. The natural frequency of the pile foundation was about 27.5Hz in the loading tests. Comparison between the behaviors in Case st and Case nl-0 would clarify the effect of surface non-liquefaction layer on the interaction. And the comparison between the behaviors in Case st and Case sl-00 would clarify the effect of slope and lateral flow.

Base input vibration was kept common for all the test cases; the sinusoidal acceleration was 150Gal in single amplitude and 4 Hz in frequency, and the duration time was 12s.

## TEST RESULTS

Figures 8 to 10 show the overall vibration behavior of the ground and pile foundation during shaking in all the three cases. Top graphs are time history of excess pore water pressure beneath the footing. In the standard test condition (Case st), liquefaction was initiated at 1.3s after shaking was started, and the liquefaction was retained for about 5s. And the excess pore water pressure began to reduce first at the deep part of the ground (p3c). After the end of shaking, the excess pore water pressure reduced to a hydrostatic state. This overall tendency was common and independent of the ground slope and the existence of the surface non-liquefaction layer.

Top second graphs are the time history of bending moment $M_e$ due only to external force from ground. While total bending moment $M_t$ tells the displacement of the footing and the deformation behavior of pile foundation, the bending moment due to external force $M_e$ tells the behavior of external force which is resulted from the interaction between ground and pile foundation.

Top third graphs show the lateral displacements of the liquefied ground at surface and depth of 15cm. This obstruction of the ground by the pile foundation causes the thrust on the pile foundation from the

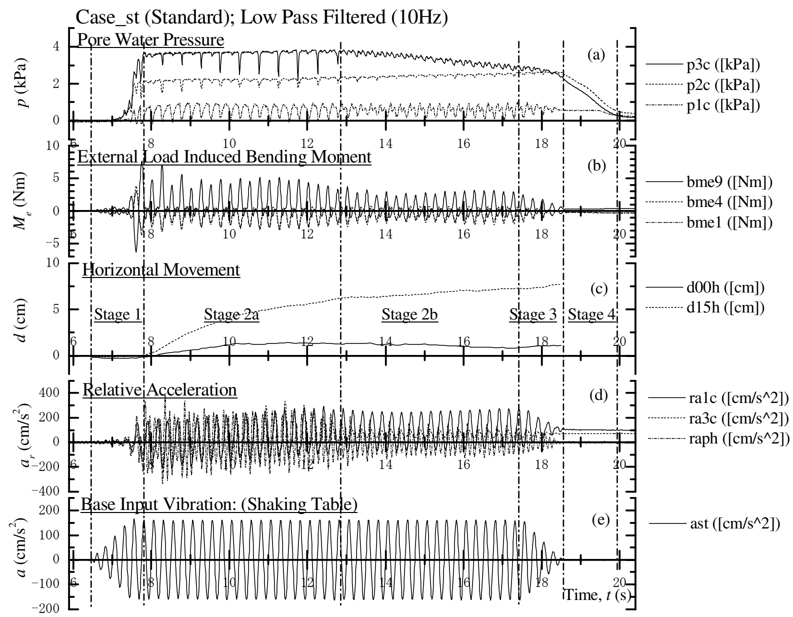


Fig.8. Behaviors of ground and pile foundation during shaking observed in Case st.

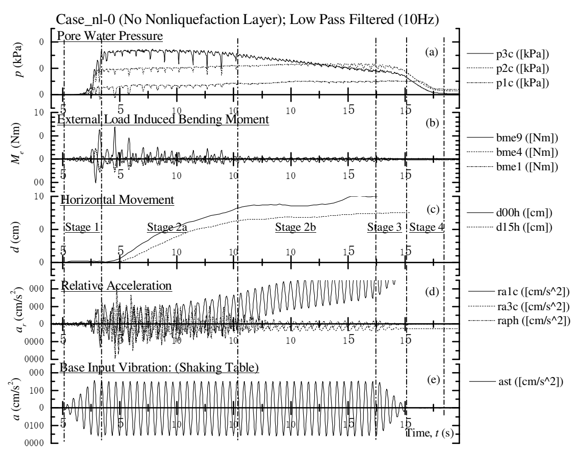


Fig.9. Behaviors of ground and pile foundation during shaking in Case nl-0.

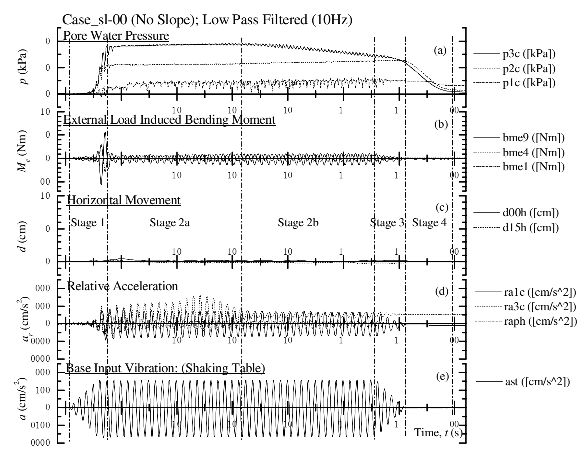


Fig.10 Behaviors of ground and pile foundation during shaking observed in Case sl-00.

ground. In standard test condition (Case st), the horizontal displacement became maximal not at ground surface but at intermediate depth, because the displacement of the surface layer was obstructed by the pile foundation. From the examination of the video image of the deformation of the ground, it was also suggested that a notable shear deformation and associated shear force was generated at the interface between the surface non-liquefaction layer and the ground.

The top fourth graphs show the time history of relative horizontal acceleration at the ground and the footing of pile foundation with respect to the shaking table; the relative acceleration tells the deformation behavior of ground and pile foundation as a result of not only base input vibration but also the interaction between ground and pile foundation.

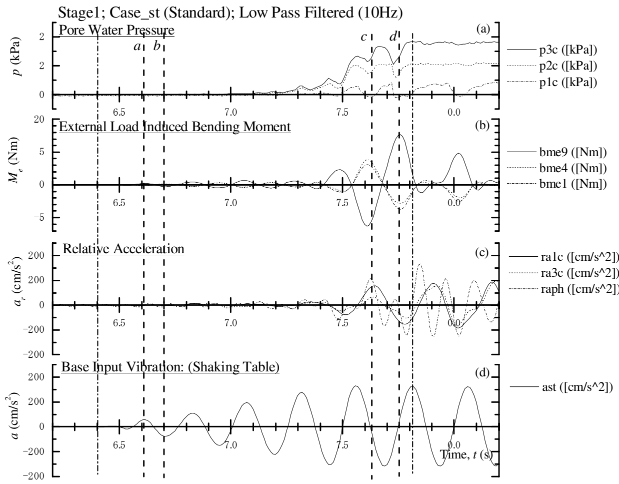

Fig.11 Behaviors of ground and pile foundation in Stage 1 of Case st

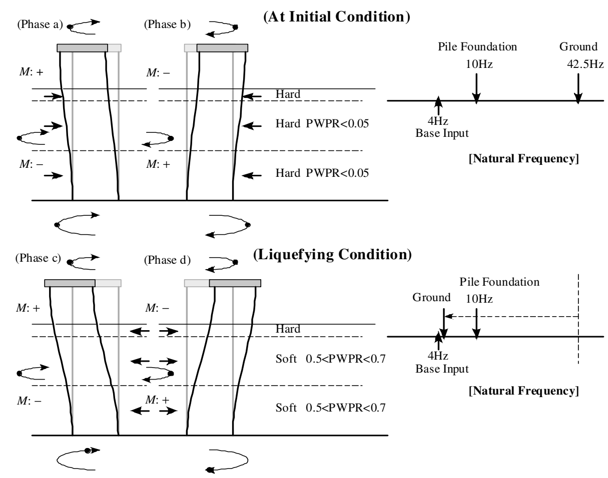

Fig.12 Illustration of deformation and external force in Stage 1 of Case st

The graphs at bottom are for absolute horizontal acceleration of shaking table as input base vibration.

For the detailed examination of the interaction between ground and pile foundation, we divided the shaking process into five stages according to the behaviors of base input vibration and pore water pressure as shown in Figs. 8 to 10.

Stage 1: until the initiation of liquefaction.
Stage 2a: until the start of reduction in pore water pressure.
Stage 2b: until the end of shaking with uniform amplitude.
Stage 3: until the end of shaking.
Stage 4: until the reach to hydrostatic condition.

## DISCUSSION

In this section, first the behavior observed in the standard test condition (Case st) is examined in detail. Then, the interaction between ground and pile foundation is analyzed by the comparative examination of the behaviors of the three test cases conducted in this study, with an attention to the influence of surface non-liquefaction layer and lateral flow of the ground.

### Detailed Examination of Vibration Behavior

*In the Process to Liquefaction Initiation (Stage 1: Figures 11 and 12)*

At the early part of this stage, since the ground still maintains certain amount of stiffness with some excess pore water pressure of a fraction of initial effective stress, the ground vibration was rather small and the phase of vibration of the ground and pile foundation was almost same as that of the input base vibration (Phase a and b in Figs. 11 and 12). Here, due to the support by the ground, the vibration of pile foundation was fairly small compared with the case of the pile foundation standing alone.

With a continuous reduction in effective stress and associated stiffness of ground corresponding to a further increase in excess pore water pressure, the natural frequency of ground would have reduced more. Then the resonance condition was met just before the initiation of liquefaction, where the phase difference angle in vibration between shaking table and ground was about a half $\pi$. At the resonance the bending moment $M_e$ along the pile was fluctuated with notable amplitude in a few cycles (Phase c and d in Figures

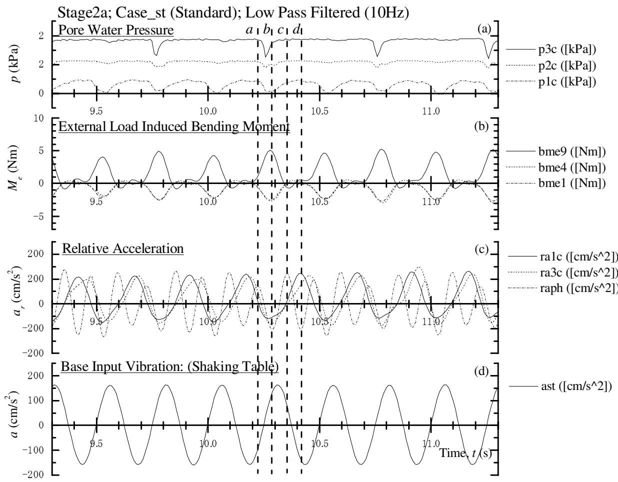


Fig.13. Behavior of ground and pile foundation in Stage 2a of Case st.

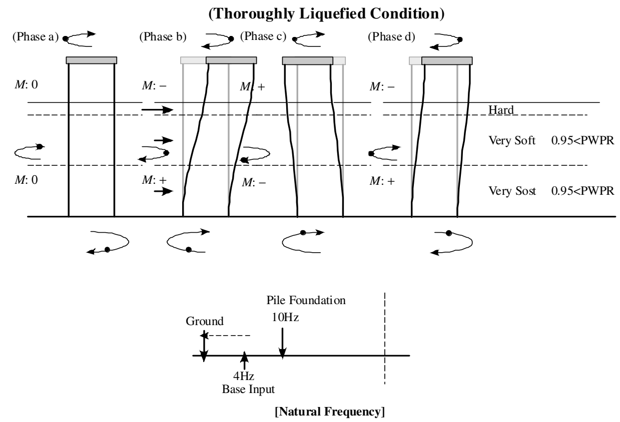


Fig.14. Illustration of deformation and external force in Stage 2a of Case st

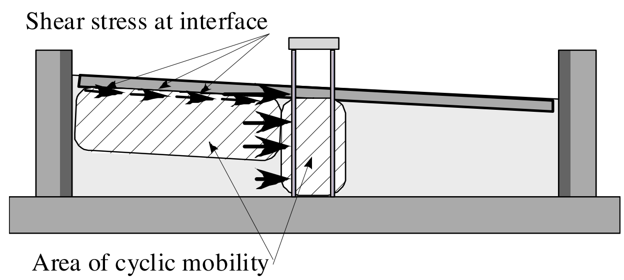


Fig.15 Illustrated external force regarding cyclic mobility in Stage 2a of Case st.

11 and 12). In this condition, the ground stiffness was small but the integrity of the ground was still maintained, so that the interaction between ground and pile foundation and the interactive force must have been enhanced instantaneously. The variation of relative acceleration of pile foundation (raph) indicates that the pile foundation vibrated twice in a cycle of input base vibration as a result of the interaction. The occurrence of the resonance was common feature in all the test cases conducted in this study.

*In the Full Liquefaction Stage (Stage 2a: Figures 13 and 14)*
In this stage the interaction between ground and pile foundation was emphasized by the fairly large vibration and flow of liquefied ground. The characteristic variation of the bending moment $M_e$ tells that the external force was intermittently applied to the pile foundation only in downhill direction in every cycle of shaking. That is, the external force became maximal when the pile foundation and ground both deflected in downhill direction at the same time; see Phase b in Figs. 13 and 14. This characteristic behavior of the external force suggests the significance of surface non-liquefaction layer in the interaction. It seems that due to the combined effect of vibration and flow, the surface non-liquefaction layer would contact with the pile foundation only when the ground deflected in downhill direction; only compressive force but not tension would be expected between them.

In this process the cyclic mobility of ground stiffness was perceived clearly in the sloping ground as shown in Figs. 13 and 14; the instantaneous reduction in the pore water pressure is the evidence of the cyclic mobility, and is followed by the increase in effective stress and mobilization of stiffness. This characteristic mechanical behavior is related to the dilatancy in granular materials like sand. The dilatancy causes an increase in volume in drained condition or a reduction in pore water pressure in undrained condition. The careful examination of the time history of excess pore water pressure indicated that the cyclic mobility occurred not only in the vicinity of the pile foundation but also near the interface with the surface non-liquefaction layer. Thus the pile foundation would have been subjected to two kinds of external forces: one directly from liquefied ground and the other from the surface non-liquefaction layer,

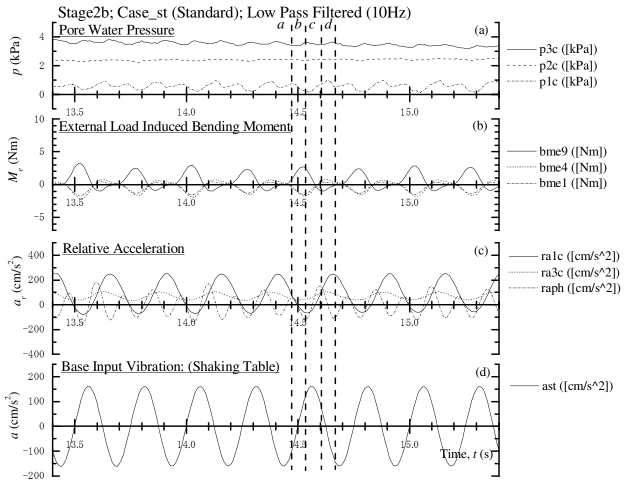


Fig.16. Behaviors of ground and pile foundation in Stage 2b of Case st.

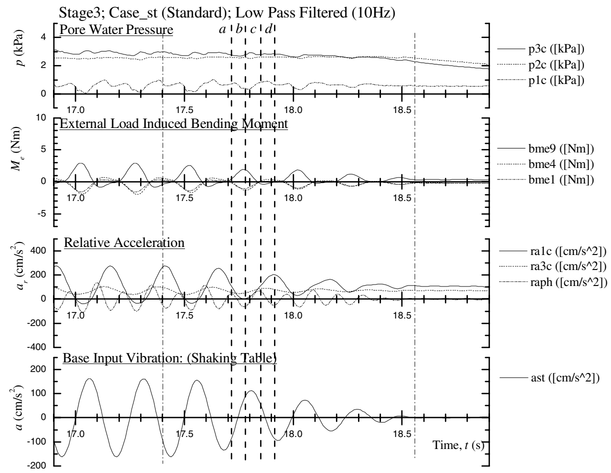


Fig.17. Behaviors of ground and pile foundation in Stage 3 of Case st.

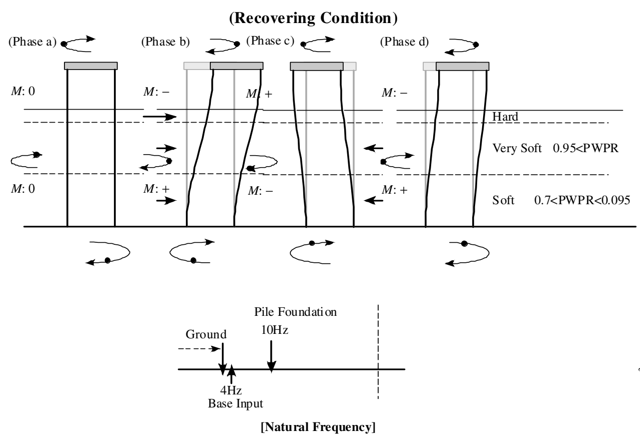


Fig.18. Illustration of deformation and external force in Stages 2b and 3 of Case st

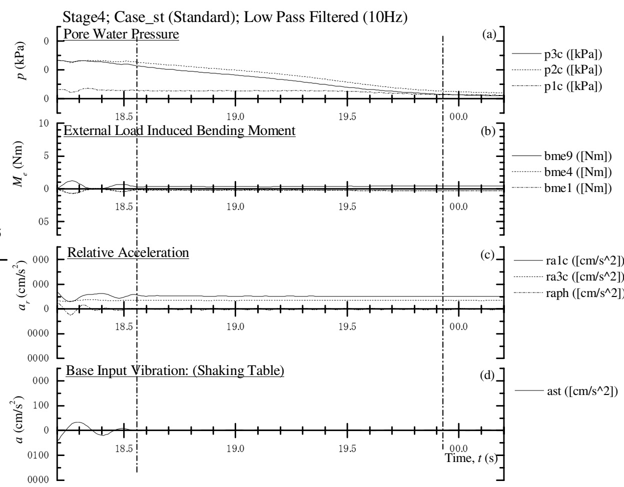


Fig.19. Behaviors of ground and pile foundation in Stage 4 of Case st.

as shown in Fig. 15. The cyclic mobility occurs when ground moves in downhill direction, but it did not occur every cycles of shaking regularly. It was interesting that the intensity of external force on the pile foundation was related to the amount of the instantaneous decreased in pore water pressure.

*In Partial Liquefaction Stage (Stage 2b and 3: Figures 16, 17 and 18)*

In this stage following the full liquefaction stage 2a, the stiffness of ground was partially recovered especially at the deep part of the liquefied ground, and the vibration amplitude of ground gradually reduced as shown by the oscillating relative acceleration (ra1c) in Fig. 16. According to this change in ground vibration, the intensity of external load was also reduced as shown by the bending moment $M_e$ in the figures. In this process the external force was applied not only in downhill direction but also in uphill direction with small amplitude as shown in Figs. 16, 17 and 18, while the direction of external force was restricted in downhill direction during full liquefaction (Stage 2a).

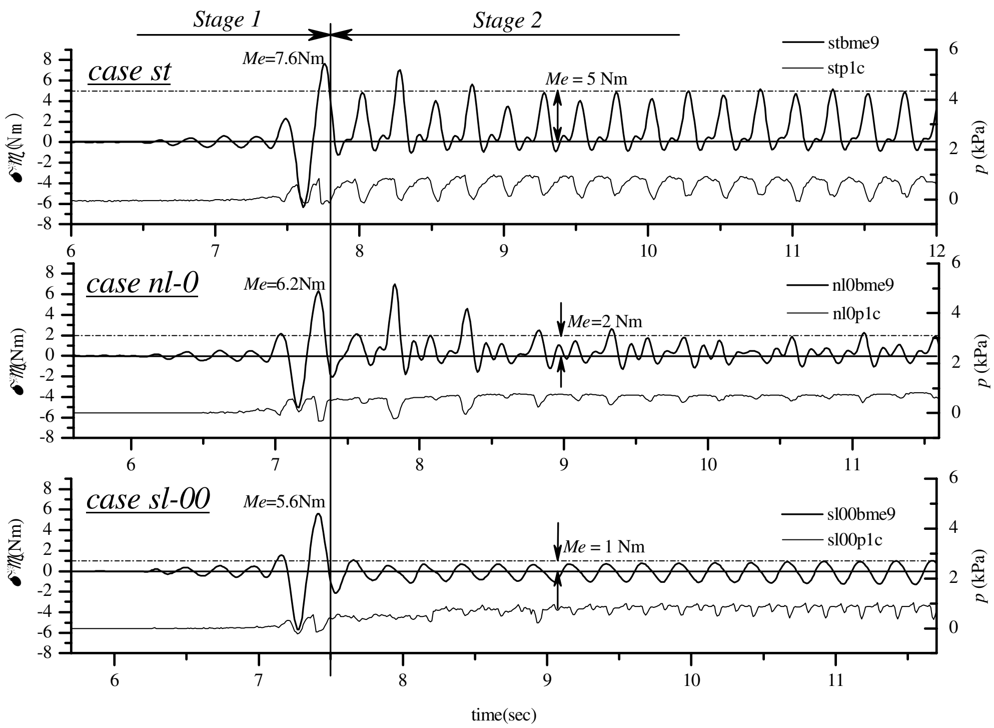


Fig.19. Comparison of behaviors of ground and pile foundation observed in Case st, Case nl-0 and Case sl-00.

*In the Process to Hydrostatic State (Stage 4: Figure 18)*

The flow of the liquefied ground was terminated at the end of shaking. In this process deformation of ground was not susceptible and the bending moment indicated almost constant value. The intensity of residual external force was less than one tenth of that during liquefaction. The viscousity of the liquefied ground was expected to play an important role in this stage; however, the amount of the residual force was much smaller than the expectation. In this test program employed, the duration of the shaking was rather long, and the flow of liquefied ground, that is the horizontal displacement of the ground, was almost finished with in the shaking process shown in Fig. 8. It can be said that the residual external force would depend on the duration time of shaking, and would have become larger if the duration time is shorter.

**Effects of Surface Non-liquefaction Layer and Flow of Ground**

Shown in Fig. 19 are the time histories of excess pore water pressure $p$ at (p1c) and external force induced bending moment $M_e$ at (e9u and e9d) in the three test cases conducted in this study. From the comparative examination of the behaviors observed in the three test cases, the following characteristic effects of the surface non-liquefaction layer and the flow of liquefied ground on the interaction between the ground and the pile foundation could be found.

*Resonant vibration just before Initial Liquefaction*

The resonant response of the ground and the associated large external force on the pile foundation were recognized just before liquefaction was attained in Stage 1, commonly in all the cases, as shown in Fig. 19. In this stage the application of the large external force was only in a few cycles but the intensity was comparable with those in full liquefaction stage (Stage 2a). The maximum bending moment $M_e$ was 7.6, 6.2, and 5.6 Nm in Case st, Case nl-0 and Case sl-00, respectively. The influence of surface non-

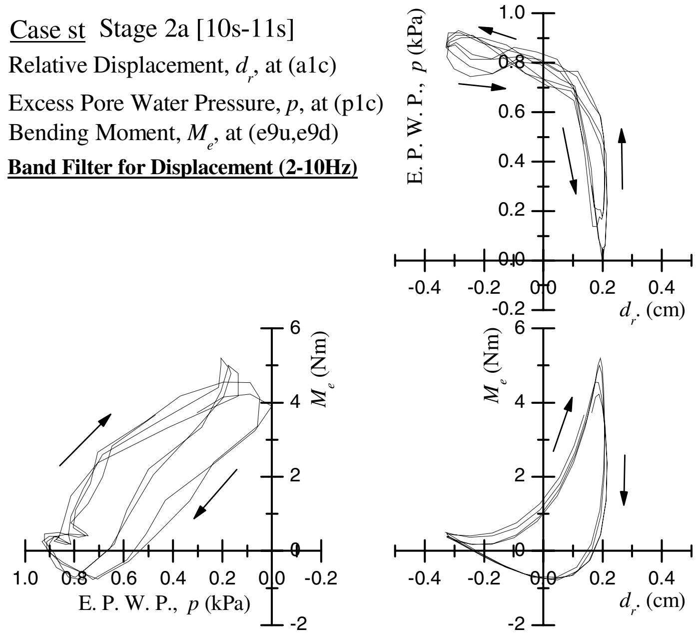


Fig.20. The relationship between relative horizontal displacement, excess pore water pressure, and bending moment during full liquefaction (Stage 2a) in Case st.

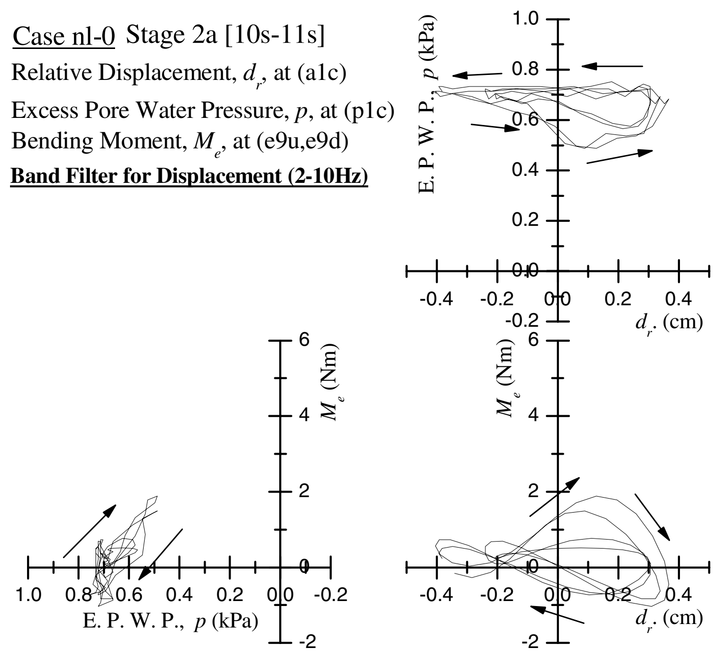


Fig.21. The relationship between relative horizontal displacement, excess pore water pressure, and bending moment during full liquefaction (Stage 2a) in Case nl-0.

liquefaction layer and lateral flow was rather small, and it seems, however, that the external force was enhanced by the surface non-liquefaction layer and the lateral flow.

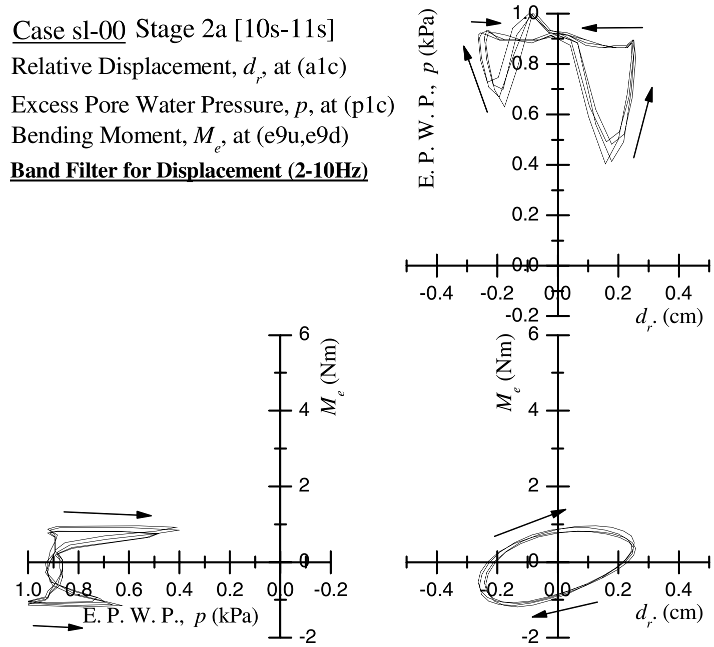


Fig.22. The relationship between relative horizontal displacement, excess pore water pressure, and bending moment during full liquefaction (Stage 2a) in Case sl-00.

*Flow of Liquefied Ground*

In the cases of sloping ground (Case st and Case nl-0) the flow of liquefaction ground began at the initiation of liquefaction; however, in the case of flat ground (Case sl-00) the horizontal flow displacement was negligibly small, and the ground was just vibrated responding to the base input vibration; see Figs. 8, 9 and 10. Without surface non-liquefaction layer (Case nl-0) the horizontal displacement was maximal at the surface and exceeded 10cm. In the contrast, with the surface non-liquefaction layer (Case st) the displacement was not more than 2cm at surface and became maximal at intermediate depth, because the displacement of the surface layer was obstructed by the pile foundation.

*Cyclic Mobility*

The cyclic mobility of the stiffness of liquefied ground, which was induced by a decrease in pore water pressure and associated regain in effective stress, was recognized in all the test cases. However, the intensity of the instantaneous decrease in excess pore water pressure was larger in sloping ground; and also enhanced by the surface non-liquefaction layer.

Shown in Figs. 20, 21 and 22 are the relationships between the bending moment $M_e$. the relative horizontal displacement of the ground with respective to the pile foundation $d_r$, and the change in excess pore water pressure $p$. In the standard condition (Case st), characteristic behaviors due to the cyclic mobility is shown; the relationship between $d_r$ and $p$ is clearly nonlinear and an abrupt drop in p at large $d_r$ is recognized. The relationship between $p$ and $M_e$ is rather linear; this indicates that the external force to the pile foundation is directly related to the drop in $p$ and associated the cyclic mobility of shear stiffness of ground. Though this characteristic behavior can be also seen in the case of sloping ground without surface non-liquefaction layer (Case nl-0), the drop in $p$ and the intensity of $Me$ are fairly small compared with Case st. In the case of the flat ground (Case sl-00), the behavior is free from the effect of the cyclic mobility and is clearly different from the cases of sloping ground (Case st and Case nl-0).

*External Force on Pile Foundation during Liquefaction*
With surface non-liquefaction layer (Case st) the external force was applied only in downhill direction; otherwise external force fluctuated in both directions (Case nl-0, Case sl-00). In average, the maximum bending moment $M_e$ was about 5, 2 and 1 Nm in Case st, Case nl-0 and Case sl-00, respectively.

As explained in the previous subsection, the liquefaction flow in the sloping ground has a decisive effect on the cyclic mobility of the shear stiffness of ground and the application of external force on the pile foundation. The effect of the surface non-liquefaction layer is important as shown in the comparison between Case st and Case nl-0 in Figs. 20 and 21.

*Residual External Force on Pile Foundation*
The residual external force was rather small compared with that during liquefaction in the case with surface non-liquefaction layer (Case st). Without surface non-liquefaction layer (Case nl-0), the residual external force was further small. In the flat ground (Case sl-00) the residual force was negligible due to the lack of the flow of liquefied ground, as shown in Figs. 7, 8 and 9.

## CONCLUSIONS

From the observation of the interactive vibration behavior of ground and pile foundation in a series of model shaking table tests, the mechanism of the thrust on pile foundation was investigated. The significant effects of flow of liquefied ground and surface non-liquefaction layer can be summarized as follows:

- Resonant vibration behavior of ground was recognized just before the initiation of liquefaction in all the test cases. In this condition, notable external force was applied in a few cycles. The effects of surface non-liquefaction layer and the liquefaction ground flow on the external force were rather small.

- In the case of sloping ground, the external force was applied from liquefied ground to pile foundation, mainly in downhill direction. Since the flow of liquefied ground has decisive effect on the external force during liquefaction, in the case of flat ground the external load was sinusoidal and the amplitude was rather small compared with those in the sloping grounds. In the sloping ground with surface non-liquefaction layer, the intensity of external force was rather large compared with that in the sloping ground without surface non-liquefaction layer.

- The external force was strongly related to the cyclic mobility of ground stiffness; the external force synchronized with the instantaneous decrease in excess pore water pressure. The cyclic mobility was observed clearly in the cases of sloping ground; the stiffness of ground was mobilized only when the liquefied ground displaces in downhill direction. The intensity of the external forces was strongly related to the amount of a decrease in excess pore water pressure.

- When hydrostatic condition was attained after vibration, residual external force on pile foundation was perceptible in sloping ground. However, the intensity of the residual external force was rather small and not so important compared with the intensity of the external force on the pile foundation during liquefaction.

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