PERFORMANCES OF FOUNDATIONS AGAINST LIQUEFACTION-INDUCED PERMANENT GROUND DISPLACEMENTS

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SUMMARY

The author conducted a case study on damage to foundation piles caused by the 1964 Niigata. He investigated into the cause and the process of the damage to the piles by taking liquefaction-induced permanent ground displacement into the consideration. He reached a conclusion that a permanent displacement of non-liquefied soil overlaying the liquefied soil was a governing factor of the damage to the piles. Furthermore, the author performed model tests on the characteristics of the external forces from the flowing liquefied soil on model piles under 1 G condition. He obtained the following conclusions from the model tests: The force from following liquefied soil on the model pile could be estimated as a drag force against an cylindrical object in a viscous flow. The external force from non-liquefied soil overlaying the flowing liquefied soil governs the deformation of the pile, and the deformation of the model piles can be simulated by a beam and soil spring model where the displacement of the non-liquefied soil is forced into the pile through the soil spring, as well as a drag force is also taken into the consideration.

INTRODUCTION

The liquefaction-induced large ground displacements have caused serious damage to foundation piles during past earthquakes, such as the 1964 Niigata and the 1995 Kobe earthquakes [1), 2)]. However, since the information and the knowledge on external forces from the flowing liquefied ground on foundations was not enough, the effect of this phenomena has not been taken into the consideration for earthquake resistant design of foundations.

The purpose of this study is to provide fundamental information about the permanence of foundations against liquefaction-induced ground displacement for the development of a rational design procedure based on a case study and model tests.

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CASE STUDY ON DAMAGE TO FOUNDATION PILE

Damage to Foundation Pile in The 1964 Niigata Earthquake

Twenty five years after the 1964 Niigata earthquake severe damage to concrete piles of the foundation of a building in Niigata City was found by the excavation of the ground for construction of a new building. Figure 1 shows schematic drawings of the damage to two piles and their deformations. The piles of No.2 is perfectly broken at the depth of about 2 m from the top of the pile and also many horizontal bending cracks are observed at the lower elevation of the pile. On the other hand, in the case of the pile of No.1 bending cracks are observed only at the upper elevation.

Figure 1: Damage to Foundation Piles and Deformation (the 1964 Niigata Earthquake)

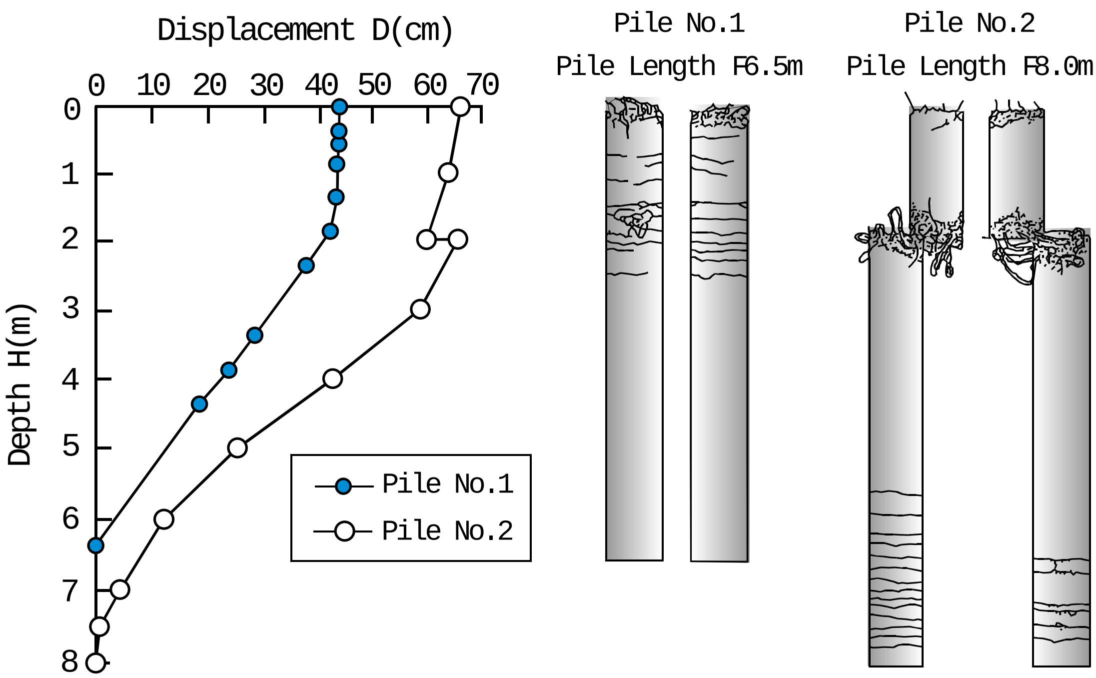


Figure 2 shows the soil condition in the neighborhood of the damaged building and the estimated liquefied soil layer. The pile of No.2 was penetrated about 2 m into non-liquefiable layer under the estimated liquefied layer, while the penetration of the pile of No.1 into the underlaying non-liquefiable layer is much shallower compared with that of the pile of No.2. It can be guessed that the damage at the lower elevation resulted from this difference of the penetration depth into the non-liquefiable layer.

The ground surface nearby the building displaced 1 to 2 meters as shown in Figure 3. The numerals at the top of the vectors are the magnitude of the horizontal displacements. The ground in the southern-west side in front of the building moved about 1.5 m towards the building, while and the ground displacement reduced to about 50 cm in the northern -east area behind the building.

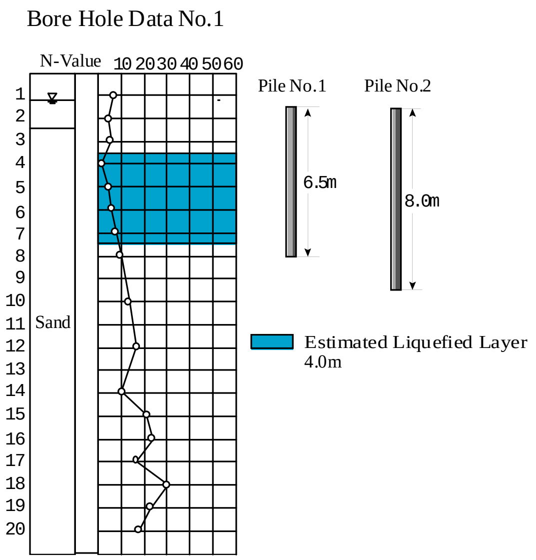


Figure 2: Soil Condition and Estimated Liquefied Soil

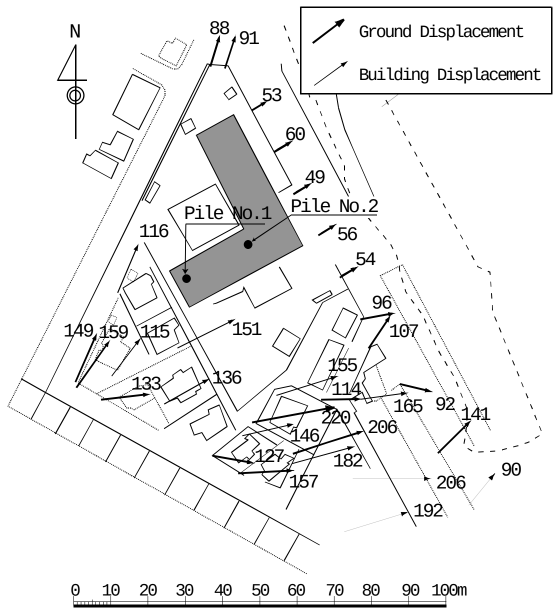


Figure 3: The Liquefaction-Induced Permanent Displacement of Ground Surface and the Building.

Numerical Analysis of the Damage

The damage to the foundation piles was simulated by using a numerical model shown in Figure 4, where the displacement of the non-liquefied soil layer overlaying the liquefied soil was forced to the pile through the soil springs. In this numerical model, the stiffness of the estimated liquefied soil was neglected. The $p-\delta$ curve of the soil spring of the non-liquefied layer was determined according to the procedure of Specifications of Highway Bridges [3]. Furthermore, it was assumed that the input displacements of the overlaying non-liquefied layer are uniform along the depth and that the magnitudes of the displacements were same with the observed deformation at the pile tops because the pile deformation at the top became nearly equal to the input ground displacements due to large reduction of the pile stiffness in the numeral analysis.

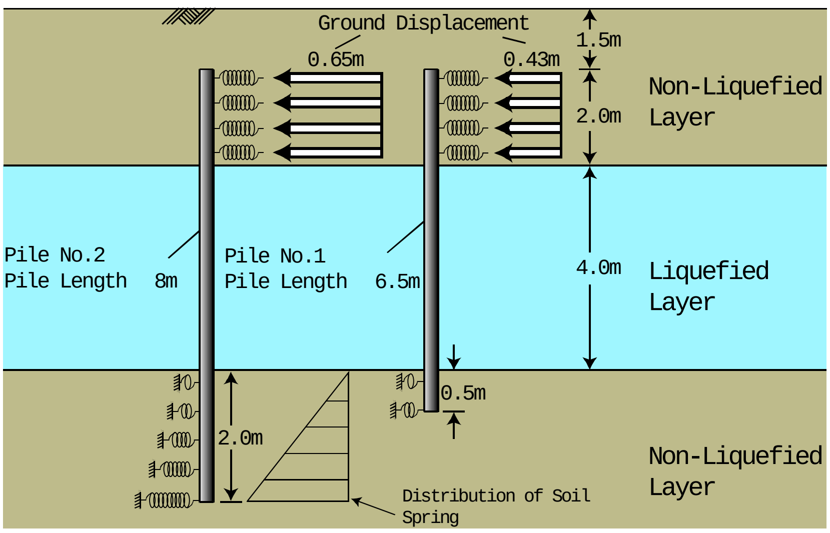
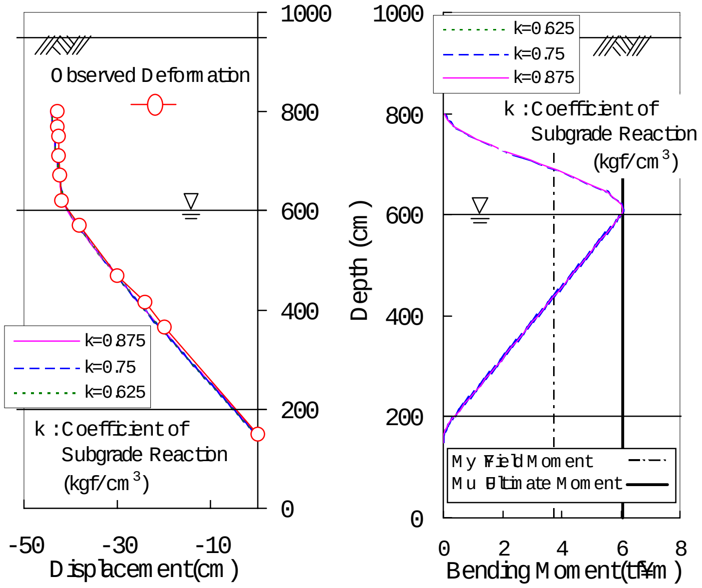


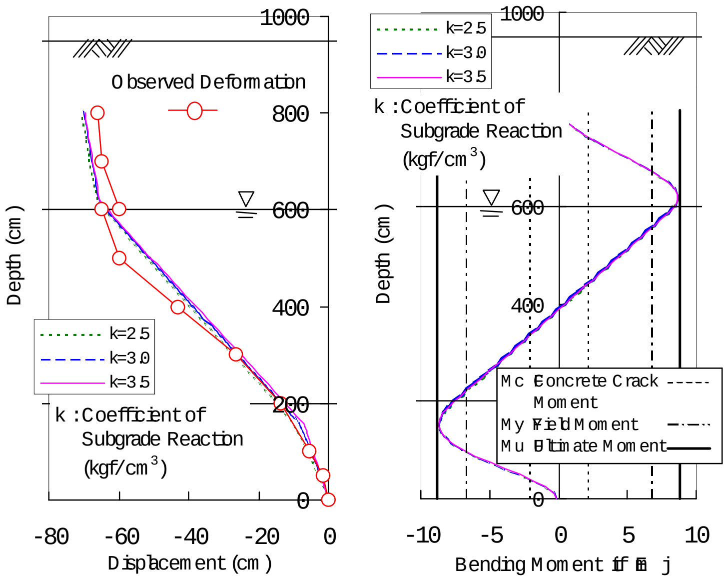
Figure 4: Numerical Model for Analysis of the Damage to Foundation Piles

Figures 5 and 6 show the results of pile deformations obtained by the numerical analysis in comparison with the observed ones, and the maximum bending moment of the piles. The calculated pile deformation is in a good coincidence with the observed results. Furthermore, the calculated bending moment of piles well explains the damage to the piles shown in Figure 1. The bending moment of the pile No.2 in Figure 6 reaches over the ultimate bending moment at two elevations, while that of the pile of No.1 in Figure 5 reaches the ultimate strength only at the elevation.



(a) Displacement of Pile (b) Bending Moment of Pile

Figure 5: Numerical Analysis of the Damage to the Foundation Pile (No.1)



(a) Displacement of Pile (b) Bending Moment of Pile

Figure 6: Numerical Analysis of the Damage to the Foundation Pile (No.2)

MODEL TEST

Two kinds of model tests on the characteristics of the external forces on the foundation piles from the flowing liquefied-ground were carried out. In the first model tests (Model Test 1) whole part of the model ground is liquefied, while in the second test (Model Test 2) non- liquefied soil layer remains over the liquefied layer.

Model Test 1

Figure 7 shows the outline of the models of the ground and the pile. The model ground is 3 m long in the direction of the ground flow, 1 m width and 25 cm thickness. The material of the model ground is a beach sand with a mean grain size 0.19 mm and uniformity coefficient of 1.9. The uniform and saturated model ground was made by a water boiling from the bottom of the soil box and by mixing. After that, the model ground with a specific relative density was made through a densification by a preliminary shaking of the soil box. Then, the soil box was inclined with a specific gradient. Liquefaction and ground displacement were caused by a vibration of the soil box in the horizontal direction perpendicular to the direction of the ground flow. The time history of the ground surface displacement was measured by a camcorder, while the bending strain of the model pile, which was made by a polycarbonate pipe with a diameter of 26 mm was measured.

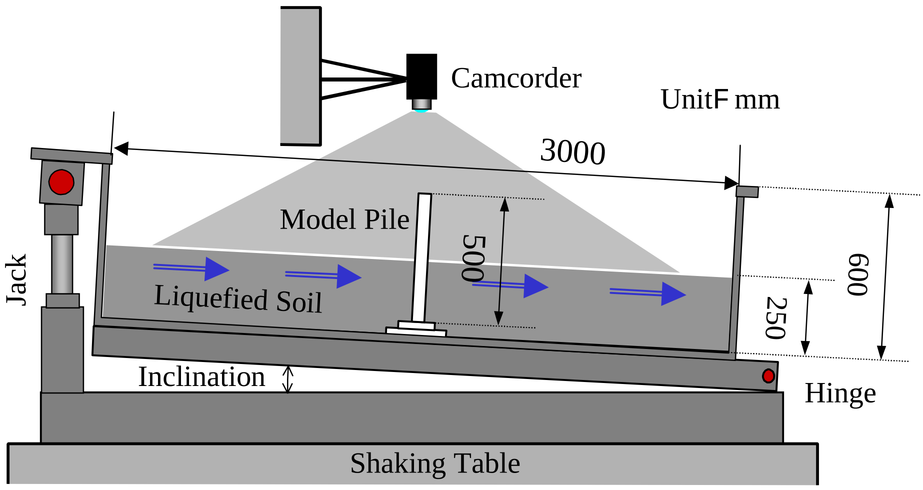
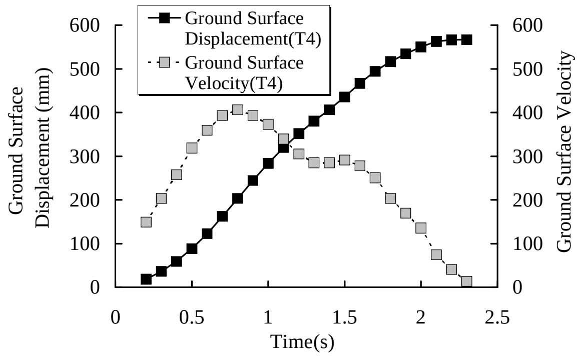
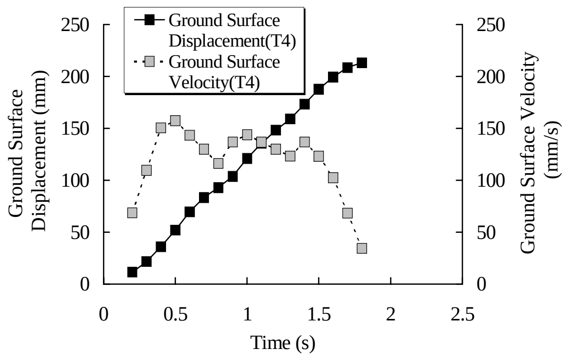


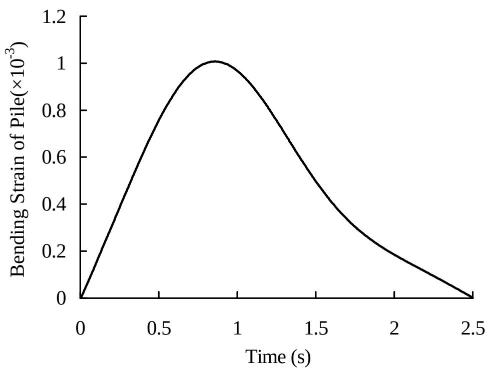
Figure 7: Models of Ground and Pile (Model Test 1)

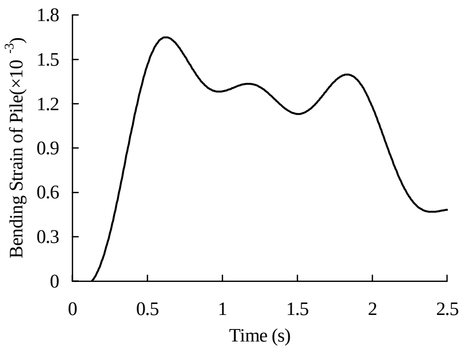
Figure 8 shows one example of the time histories of ground surface displacements measured by the camcorder, and the surface velocities which were calculated from the measured displacements, as well as the bending strains of the pile. Figure (a) shows the result of the test, where the relative density of the model ground is low, 24 %. In this case, the bending strain of the model pile has a mostly similar shape with that of the ground velocity. This suggests that an external force as a liquid acted on the pile during the ground flow. In the case of Figure (b) where the relative density of the model ground is higher, 43 %, a similarity can be also recognized between the time history of the bending strain of the pile and that of the ground velocity, but it should be noted that some residual strains remain after the ground flow ceases. This means that the whole part of the external force on the pile is not governed only by the drag force by the liquid flow. It can be guessed that in the case where the relative density of the model ground is larger the stiffness of the liquefied soil recovered its stiffness during the large deformation.





(a)-1 Ground Surface Displacement and velocity (b)-1 Ground Surface Displacement and velocity





(a)-2 Bending Strain of Pile (b)-2 Bending Strain of Pile

(c) Relative Density Dr = 24 % (c) Relative Density Dr = 43 %

Figure 8: Ground Surface Displacement and velocity, and Bending Strain of Model Pile (Model Test 1)

Model Test 2 and Numerical Analysis

Figure 9 shows the models of the ground and pile in Model Test 2, where non-liquefied soil remains over the liquefied soil. The test procedure is same with that Model Test 1. Fig 10 shows one of the test results, where the thickness of the liquefied soil and overlaying non-liquefied soil is 22 cm and 16 cm, respectively, and the relative density of the liquefied soil is 30 %. The bending strain of the pile increases with the increase of the ground displacement, but maintains mostly constant after reaching a maximum value. In this case, any significant similarity can not be found of the time history of the bending strain with the ground velocity as well as the ground displacement.

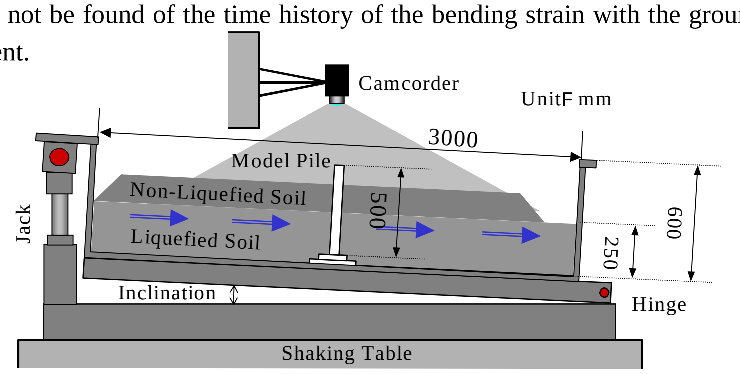
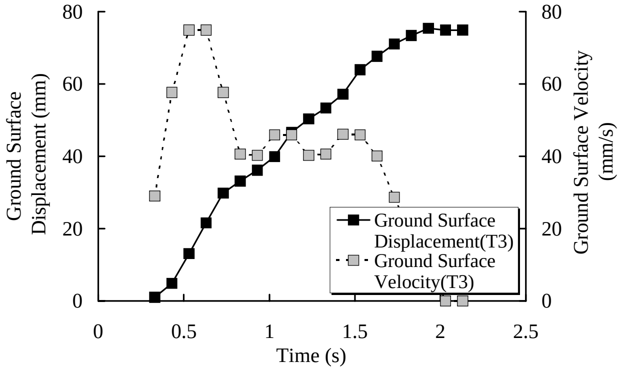
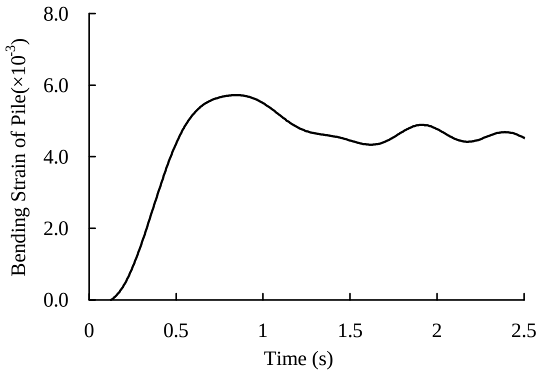


Figure 9: Models of Ground and Pile (Model Test 2)



(a) Ground Surface Displacement and velocity



(b) Bending Strain of Pile

Figure 10: Ground Surface Displacement, Velocity and Bending Strain of Model Pile (Model Test 2, Dr = 30%)

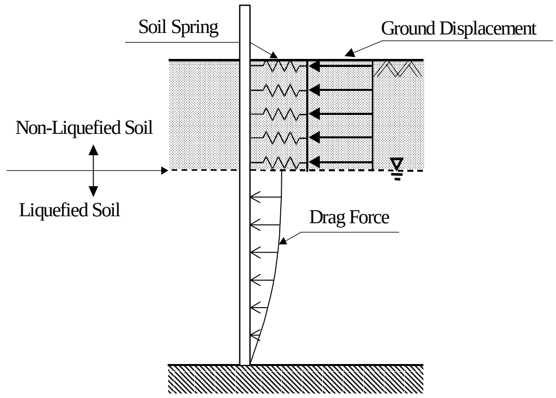
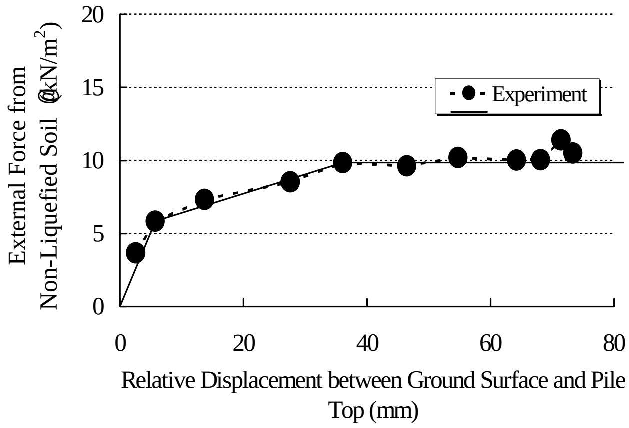


Figure 11: Numerical Model for The Analysis of Model Pile

The test result was simulated by using a numerical model shown in Figure 11. In this numerical model, the displacement of overlaying non-liquefied soil is forced to the pile through the soil springs, while a drag force was applied from the flowing liquefied soil. The $p-\delta$ curve of the non-liquefied soil was determined based on the relationship of the relative displacement between the pile top and the ground surface with the external force from the non-liquefied soil, which was estimated from the measured bending strains, as shown in Figure 12.
The drag force on the pile from the flowing liquefied soil was estimated by the following Lamb's formula ;

$$f = \frac{4\pi\,\mu\,V}{\frac{1}{2}-\gamma-l_n\,\frac{\mathrm{Re}}{8}} \quad , \quad \mathrm{Re} = \frac{\rho\,V\,d}{\mu} \tag{1}$$

, where f, Re, μ, V, ρ, d are the force on the pile per unit length , Reynolds' number, coefficient of viscosity, the velocity of the flow, density of liquefied soil and diameter of the model pile, respectively. γ is the Euler number. The velocity measured at the ground surface was used for the analysis and the distribution of the displacement along the depth was assumed to have a 1/4 sinusoidal shape. The coefficient of viscosity was estimated as 60 pa·s from the measured ground surface velocity under an assumption where the flow of the liquefied model ground can be expressed as one-dimensional viscous flow. Figure 13 shows a good coincidence between the measured shear force of the pile and the analytical results.



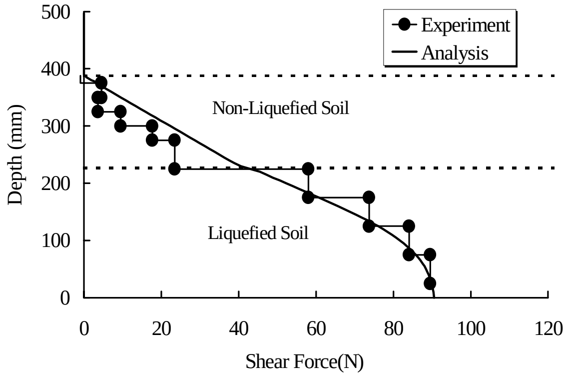


Figure 12: $p-\delta$ curve of Non-Liquefied Soil

Figure 13: Numerical Result of Shear Force of Model Pile in Comparison with Experimental Value

CONCLUSIONS

The followings were obtained on the characteristics of the external forces from the flowing liquefied-ground on the foundation piles by a case study on the damage during the past earthquake and model tests.

(1) According to the case study of the 1964 Niigata earthquake, the piles were broken at two elevations, where were the boundaries between non-liquefied soil and liquefied soil. This damage to the piles can be well explained by a numerical analysis, where the displacement of non-liquefied soil overlaying the liquefied soil is forced to the piles through the soil springs.

(2) According to a model test, where the whole part of the model ground was liquefied, the time history of the bending strain of the model pile is similar to that of the ground velocity. This suggests that a drag force was applied on the pile from the flowing liquefied soil.

(3) A model test, where non-liquefied soil remained over liquefied soil suggested that the displacement of the non-liquefied soil and a drag force of the liquefied soil governed the deformation of the model pile. This was confirmed by a numerical analysis, where non-liquefied ground displacement and the drag force were taken into the consideration.

REFERENCES

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