SEISMIC DESIGN OF BRIDGE FOUNDATION AGAINST LIQUEFACTION-INDUCED GROUND FLOW

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SUMMARY

The liquefaction-induced ground flow inflicted serious damage to various engineering structures including highway bridges in the Kobe Earthquake of 1995. Although highway bridges did not suffer destructive damage due to liquefaction, liquefaction-induced ground flow caused large deformation of bridge foundations. This paper presents the influence of liquefaction-induced ground flow on highway bridge foundations by back analysis of damaged bridge foundations and shaking table tests. Based on those results, it was found that the ground flow force acting on bridge foundation may be estimated as the sum of the passive earth pressure of the surface non-liquefiable layer and 30% of the overburden pressure of the liquefiable layer, which has been incorporated into the Specifications for Highway Bridges in Japan.

INTRODUCTION

The Hyogo-ken Nanbu (Kobe) Earthquake, which occurred on January 17, 1995, caused extensive soil liquefaction over a wide area of offshore reclaimed lands and natural deposits [7]. Besides that, near the water's edge, liquefaction induced ground flow with the movement of quaywalls and seawalls. Aerial photogrammetry revealed that the maximum residual displacement due to ground flow reached 3 to 4m [1, 2]. Liquefaction and its associated ground flow exerted serious influence on various engineering structures. Although highway bridges did not suffer fatal damage due to liquefaction, liquefaction-induced ground flow caused large deformation of bridge foundations. For example, a pier of the Shin-Shukugawa Bridge that crosses a watercourse between reclaimed lands was moved toward the watercourse by approximately 1m, which resulted in rupture of bearings on the pier [9]. This pier was supported by cast-in-place concrete piles, 1.5m in diameter, and the piles were constructed in the reclaimed soil and supported by a diluvial sandy layer.

To estimate the influence of liquefaction-induced ground flow on bridge foundations, it was assumed that the layer near the ground surface which did not liquefy moved with the layer which liquefied, and both layers caused force to a bridge foundation. The ground flow force was estimated so that the displacement at pier top is consistent with the residual displacement of bridge foundation. From an experimental approach, a series of shaking table tests was also conducted. In this experiment, a quaywall and the ground behind it were modeled in a large container. Pile models were installed in the ground, and the force acted on piles were measured. Based on those results, seismic design against liquefaction-induced ground flow was incorporated into the Specifications for Highway Bridges [6, 8] in Japan.

2. GROUND AND BRIDGE PIER MOVEMENT DUE TO GROUND FLOW

The aerial photogrammetry was employed to estimate the ground movement vectors by comparing aerial photos taken before and after the earthquake [1, 2]. The residual horizontal displacements of bridge piers at the height

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of 1m above the ground level were also estimated by another survey conducted after the earthquake. The horizontal displacement vectors of the ground and bridge piers were found to include uniformly about 20cm component for the south-west direction. This displacement may be attributed to the base ground movement caused by fault movement or wide area ground movement. In the present study, this displacement is excluded from the result of aerial photogrammetry of the ground displacement and the residual displacement of bridge piers. The displacement vectors include also a certain degree of error because of the errors associated with aerial survey and photographic interpretation. The accuracy of measurement is estimated as ±30cm for the ground displacement and ±10cm for residual displacement of bridge piers, respectively [1].

Figure 1 shows the relationship between the residual horizontal displacement of bridge pier and the horizontal displacement of the ground on the Route 5 of the Hanshin Expressway. Although the considerable scatters exist, the residual displacement of bridge pier tends to increase as the ground displacement increases, in general. The residual displacements of piers with rigid foundations, i.e., caisson or diaphragm wall foundations, are smaller than those with pile foundations for a certain amount of ground displacement.

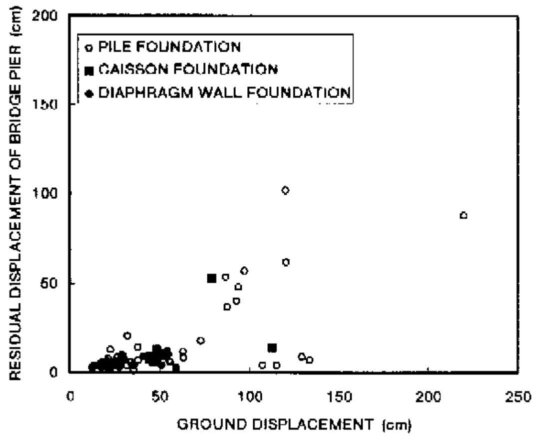


Figure 1 Relationship between Residual Horizontal Displacement of Bridge Pier and Horizontal Displacement of the Ground.

The relationship between the residual horizontal displacement of bridge pier and the distance from the water's edge is shown in Figure 2. The residual displacement rapidly decreases with the increase of distance from the edge of the water. The range in which prominent residual displacement occurred is limited to approximately 100m from the water's edge.

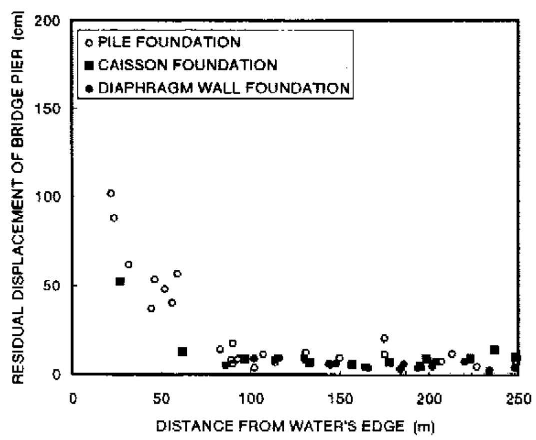


Figure 2 Relationship between Residual Horizontal Displacement of Bridge Pier and Distance from Water's Edge.

3. ESTIMATION OF GROUND FLOW FORCE BY BACK ANALYSIS

The force acted on a bridge foundation due to the liquefaction-induced ground flow was estimated by back analysis of bridges that suffered residual horizontal displacements [10]. The result for a bridge pier, which was located at the north edge of Rokko Island, is here presented. This pier was a 2-story steel rigid frame pier and was supported by cast-in-place concrete piles, 1.5m in diameter. The bearings on this pier were fixed for the watercourse-side girder and movable for the inland-side girder. The soils were composed of sandy artificial fill, alluvial clay and alternation of diluvial sand and clay. The residual horizontal displacement of this pier was 0.9m. The ground water level of the site was 3.3m below the ground surface, and the liquefaction was judged to occur in the sandy artificial fill below the ground water level.

In the estimation of the force acted on a bridge foundation due to the ground flow, it was assumed that the layer near the ground surface which did not liquefy (non-liquefied layer) moved with the layer which liquefied (liquefied layer), and both layers caused force to a bridge foundation [10]. Since the non-liquefied layer was considered to move toward the structure and exert force on it, the force equivalent to the passive earth pressure was assumed to act on a bridge foundation in the non-liquefied layer. The liquefied layer was considered to move fluidly around the structure, and the force corresponding to a certain portion of overburden pressure was assumed to act on a bridge foundation in the liquefied layer. This portion was estimated by back analysis of bridge piers with residual displacements.

In the analysis, as illustrated in Figure 3, a bridge foundation was so idealized that a rigid footing is supported by piles that are supported by soils, considering nonlinear properties of pile bodies and the ground [5]. Besides that, the soil resistance were ignored for the non-liquefied and liquefied layers that were considered to move when the ground flow occurred. The width for which the ground flow force applied was set as the width of structure for a pier and footing, and the projected width between the end piles for pile bodies. Figure 4 presents an overview of the analyzed foundation and the applied force.

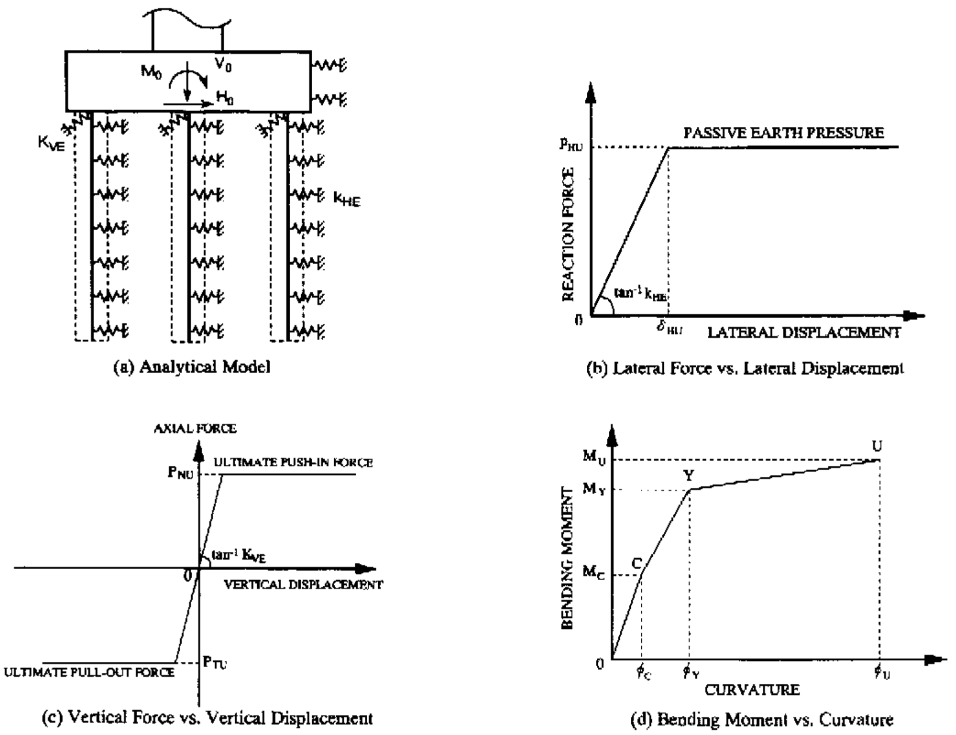


Figure 3 Idealization of Pile Foundation for Nonlinear Analysis.

Since how much portion of the overburden pressure of the liquefied layer acted on a bridge foundation was unknown, varying this portion parametrically and calculating the relationship between lateral force and displacement, the amount of force that was consistent with the residual displacement was estimated. The result is shown in Figure 5. The total force that caused the residual displacement of 0.9m to this pier was estimated as 2,256tf; 578tf for non-liquefied layer and 1,678tf for liquefied layer. The ratio of the force applied in the liquefied layer to the overburden pressure was calculated as 0.32 for this pier. Similar analysis was conducted for the four bridge piers on the Route 5 of the Hanshin Expressway, and the contribution factor of overburden pressure was estimated approximately as 0.3.

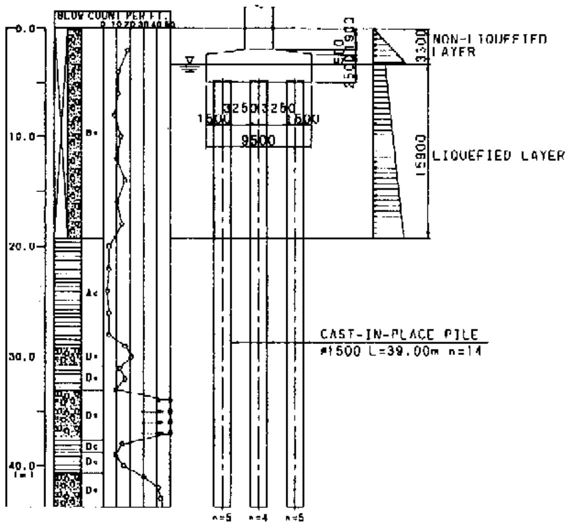


Figure 4 Overview of Analyzed Foundation and Applied Force.

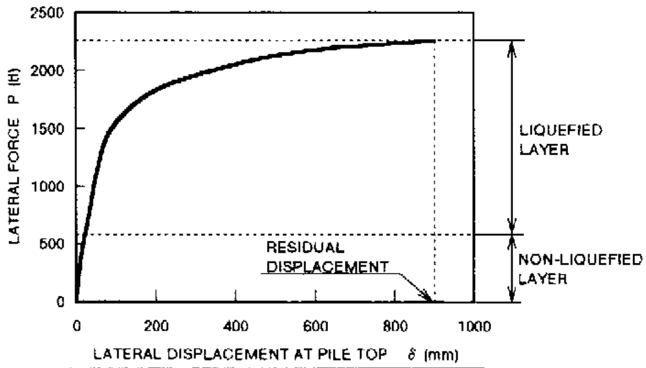


Figure 5 Relationship between Lateral Force and Displacement at Pile Top.

4. SHAKING TABLE TESTS

4.1 Methods of Experiments

A caisson type quaywall and the ground behind it were modeled in a large container (6m long, 2m wide and 2m deep), which was placed on a shaking table [11]. An overall view of experiment model is given in Figure 6. The quaywall model was 0.9m wide, 2m long and 1.3m high. The ground model was composed of three layers, that is, base layer, liquefiable layer and non-liquefiable layer. The base layer was of dense sand. The upper two layers were of loose sand, and were made by putting clean sand into the water. The liquefiable and non-liquefiable layers were distinguished by adjusting the water level. Two cases of tests, i.e., Case 1 and Case 2, were carried out, in which the thickness of liquefiable layer H_L and non-liquefiable layer H_{NL} was changed. H_L and H_{NL} were set as H_L =100cm, H_{NL} =50cm in Case 1 and H_L =50cm, H_{NL} =100cm in Case 2, respectively. The ground models had vertical lines on their sides so that ground deformation could be observed through the transparent glass of the container. These lines were made of colored sand. Photos 1 and 2 show the side views of experiment models.

Acceleration, displacement, pore water pressure and ground flow force were measured in the experiments, and instrumentation layout is presented in Figure 6. Displacements on the ground surface were measured by wire-reel type displacement meters. Displacement in the ground was measured by the underground displacement meter [11], which is of nine 2 mm thick stainless steel plates connected by hinges. These plates follow deformation of the ground. An accelerometer is attached to each plate, and the displacement is estimated from the change of gravity acceleration by incline of plate. The ground flow force meter [11] consists of nine separate polyvinyl chloride pipes and a rigid shaft that goes through pipes. Each pipe is 20cm long. A load gauge is installed between pipe and shaft so that the force acted on each pipe can be measured.

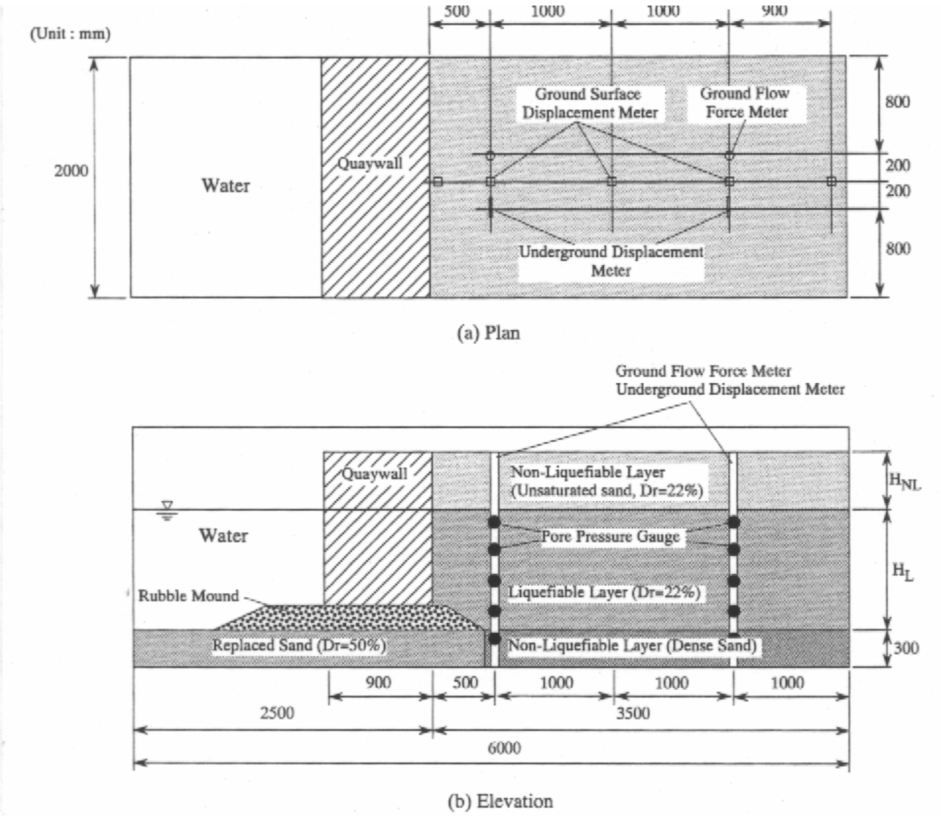
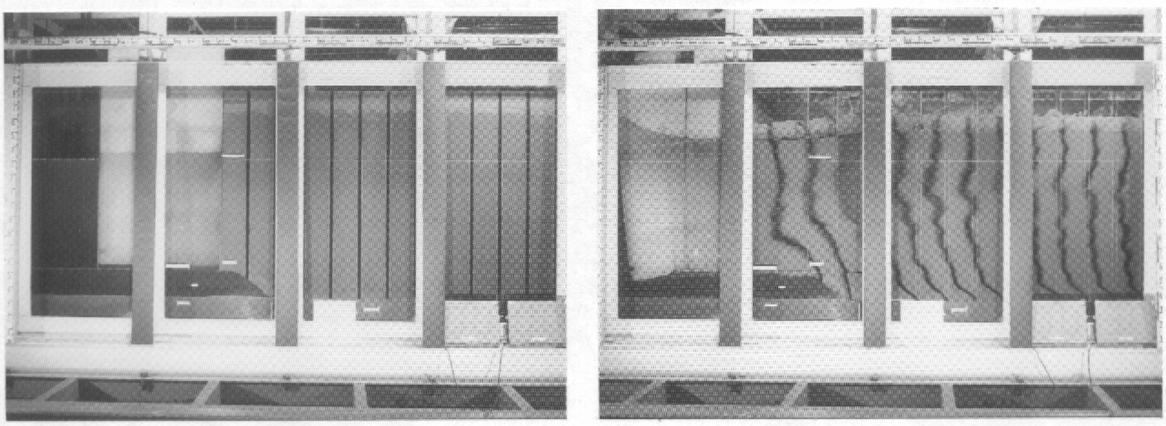


Figure 6 Overall View of Experiment Model.

In the experiments, liquefaction and its induced ground flow were generated by shaking the container on a shaking table. Sinusoidal waves with frequency of 5Hz were inputted in both Case 1 and Case 2 tests. For each case, the test was first conducted with acceleration level of 0.15G on the shaking table, and the acceleration level was then increased to 0.5G, after confirming that the excess pore water pressure induced by the first test disappeared. The duration of excitation was 5 seconds for both tests with 0.15G and 0.5G.

4.2 Experiment Results

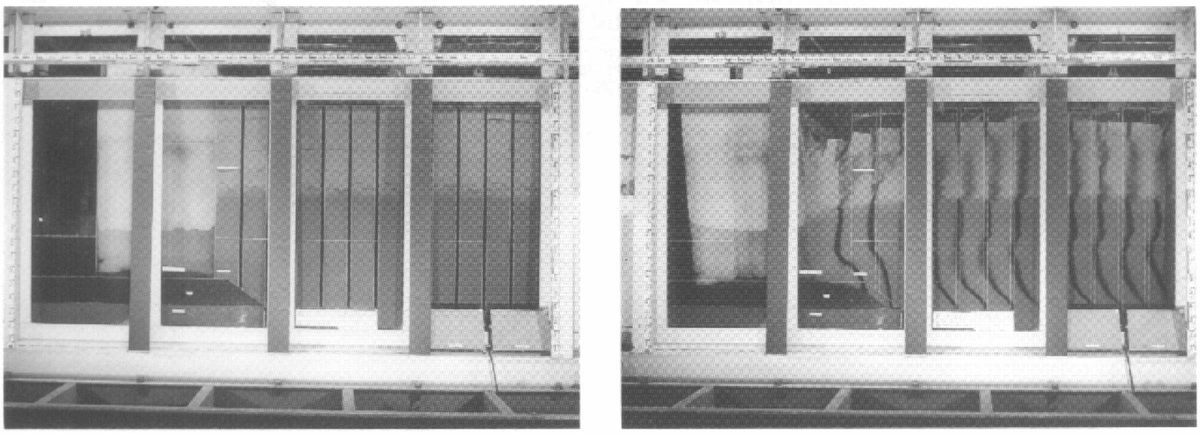
Photos 1 and 2 show the ground failure after 0.5G excitation for Case 1 and Case 2 tests, respectively. The quaywall was moved toward the water, and the liquefied layer with the overlain non-liquefied layer followed it.



(a) Original Form (b) After Excitation with 0.5G

Photo 1 Failure Mode of Case 1 Test (H_L =100cm, H_{NL} =50cm).

Deformation of vertical lines on the side of ground model indicates that lateral displacement of the ground increases from the bottom of the liquefied layer to the middle of it, and it is almost uniform for the upper part of the ground. Comparing the magnitude of ground deformation for Case 1 and Case 2, the former is larger than the latter. This may be attributed to the difference of the thickness of liquefied layer H_L.



(a) Original Form (b) After Excitation with 0.5G

Photo 2 Failure Mode of Case 2 Test (H_L =50cm, H_{NL} =100cm).

Figure 7 shows the normalized relationship between the ground flow displacement and the distance from the water's edge, where the ground flow displacement and distance are normalized by the residual displacement of quaywall and the height of quaywall, respectively. The measured ground flow displacements at reclaimed lands in the Kobe Earthquake are also shown in this figure [3, 4]. They are also normalized by the same way. It can be seen from the Figure 7 that the trends of ground flow displacement obtained from experiments agree with those estimated from the in situ measured data.

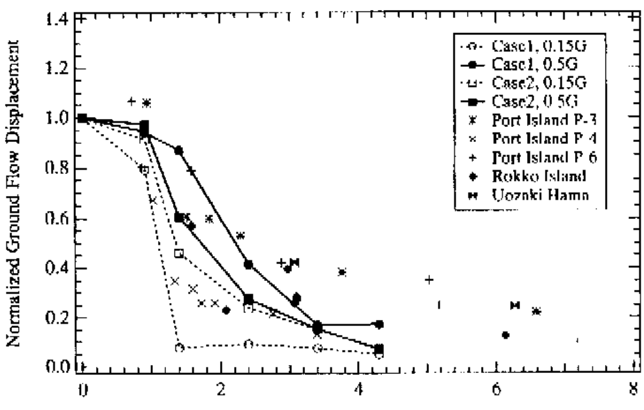
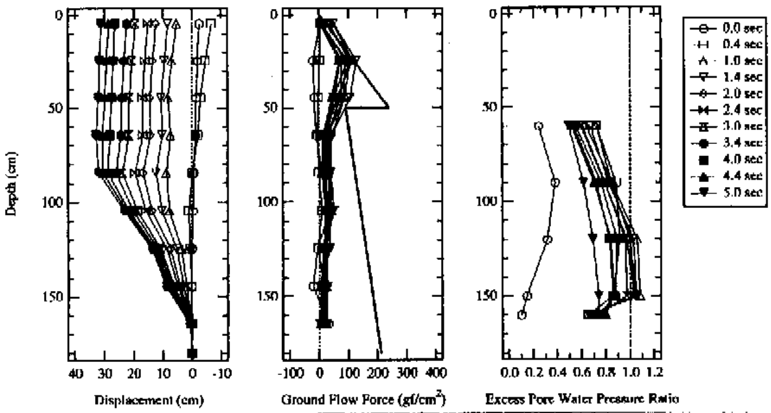


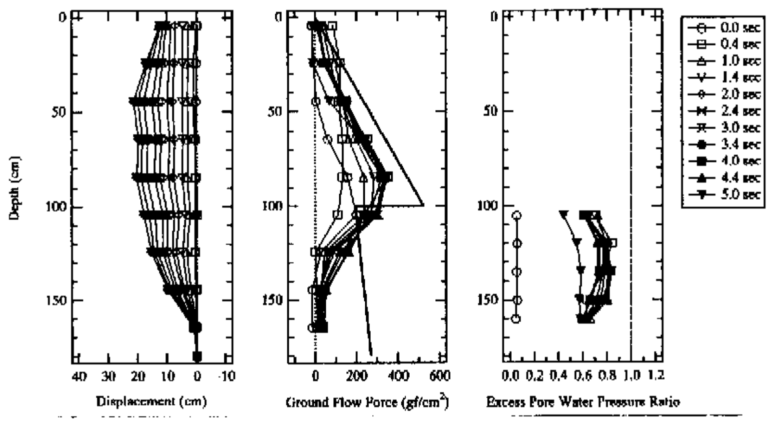
Figure 7 Normalized Relationship between the Ground Flow Displacement and the Distance from the Water's Edge.

Distributions of ground displacement, ground flow force and excess pore water pressure ratio in the ground were measured at 50cm and 250cm from the quaywall, and results of the former case are shown in Figure 8. Near the quaywall, the surface non-liquefied layer was moved toward the water with the underlain liquefied layer, while the ground deformation far from the quaywall was mainly concentrated in the liquefied layer.

The ground flow force generated in the non-liquefied layer is larger than that in the liquefied layer. In the figures, the passive earth pressure and overburden pressure are shown for the non-liquefied and liquefied layers, respectively. In case of 50cm from the quaywall, ground flow force in the non-liquefied layer almost reached the passive earth pressure, and it was smaller than the overburden pressure in the liquefied layer. In case of 250cm from the quaywall, however, the ground flow force was small and did not reach the passive earth pressure in the non-liquefied layer. It should be noted that the excess pore water pressure ratio for Case 2 did not exceed 1.0, which signifies that the complete liquefaction did not occur, nevertheless, large ground flow force was induced in the surface non-liquefied layer.



(a) Case 1 (H_L =100cm, H_{NL} =50cm)



(b) Case 2 (H_L =50cm, H_{NL} =100cm)

Figure 8 Distribution of Displacement, Ground Flow Force and Excess Pore Water Pressure Ratio at 50cm from Quaywall.

5. SEISMIC DESIGN AGAINST LIQUEFACTION-INDUCED GROUND FLOW

When the liquefaction-induced ground flow that may affect seismic safety of bridge is likely to occur, this influence has become to be considered in the revised Specifications for Highway Bridges [6, 8] in Japan.

The case in which the ground flow that may affect seismic safety of bridge is likely to occur is generally that the ground is judged to be liquefiable and is exposed to biased earth pressure, e.g., the ground behind a seawall. The effect of liquefaction-induced ground flow is considered as the static force acting on structure. This method premises that the surface soil is of the non-liquefiable and liquefiable layers, and the forces equivalent to the passive earth pressure and 30% of the overburden pressure are applied to the structure in the non-liquefiable layer and liquefiable layer, respectively, as shown in Figure 9. Since the magnitude of ground flow decreases as the distance from the water's edge increases, modification by distance is incorporated in the estimation of the ground flow force. Modification by the degree of liquefaction is also established.

The seismic safety of a foundation is checked by confirming the displacement at the top of foundation caused by ground flow does not exceed an allowable value. The allowable displacement of foundation may be taken as two times the yield displacement of foundation. In this process, the inertia force of structure is not necessary to be considered simultaneously, because the liquefaction-induced ground flow may take place after the principal ground motion ends.

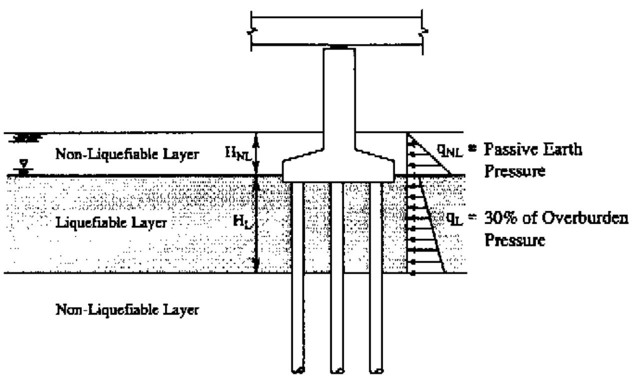


Figure 9 Idealization of Ground Flow Force for Seismic Design of Bridge Foundation

6. CONCLUSIONS

1. According to back analysis of damaged bridge foundations by ground flow in the 1995 Kobe Earthquake, the ground flow force acting on bridge foundation can be approximately estimated as the sum of the passive earth pressure of the surface non-liquefiable layer and 30% of the overburden pressure of the liquefiable layer.
2. Characteristics of ground flow displacement and force obtained from shaking table tests are consistent with those observed from the Kobe Earthquake.
3. Based on back analysis and shaking table tests, a simple design method against liquefaction-induced ground flow for bridge foundations has been developed.

7. REFERENCES

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