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EFFECT OF RIGIDITY OF NON-LIQUEFIED LAYER ON LIQUEFACTION-INDUCED LATERAL FLOW

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SUMMARY

Severe liquefaction near quay walls resulting from strong ground motion induces lateral flow, greatly damaging quay walls and the ground behind them, thereby aggravating the earthquake damage. In this study, analysis is conducted on damage of quay walls and the ground caused by liquefaction-induced flow, and an evaluation method for liquefaction-induced lateral flow is proposed considering the rigidity of the non-liquefied layer above the liquefied layer. At first, problems of treating soil with large Poisson's ratio, such as saturated sand deposit, by the finite element method are described. Selective reduced integration is introduced to the 2-dimensional finite element method as a solution to the problem mentioned above. The ground deformation analysis is applied to damage case studies to evaluate the effects of parameters, such as the thickness or the rigidity of the liquefied layer and the rigidity of the non-liquefied layer above the liquefied layer, on the lateral flow. The effect of the rigidity of the non-liquefied layer above the liquefied layer, such as the layer above the water level, is particularly clarified. A method is also proposed, in which the rigidity of the non-liquefied layer is expressed by the function of the distance from quay wall and the ratio of the rigidity of the non-liquefied layer and that of the liquefied layer. This method is applied to damage case studies to verify its applicability.

INTRODUCTION

When severe liquefaction occurs near quay walls by strong ground motion, liquefaction-induced lateral flow also occurs, significantly deforming the quay walls and the ground behind, thereby aggravating the earthquake damage. A variety of evaluation methods for lateral flow due to liquefaction have been proposed. According to Yoshida’s classification [1], these are roughly classified into two types: methods treating a liquefied layer as a solid with drastically reduced rigidity and methods treating a liquefied layer as a liquid. The former includes methods by Yoshida [2], Finn [3], Yasuda [4], while the latter include methods by Towhata [5], and Uzuoka [6]. Yasuda [7] proposed evaluation methods for lateral flow,

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modeling the characteristics of the ground during the flow by reduced rigidity caused by liquefaction, using the results of cyclic torsional shear tests of various soils. One of the evaluation methods is a 2-dimensional finite element method to determine the deformation of the ground by self-weight with reduced rigidity by liquefaction. This method is often used for practical use, because it is easy to treat and capable of explaining many phenomena. In this study, an evaluation method for flow due to liquefaction is proposed, in which the characteristics of liquefied and non-liquefied layers are considered. This method treats the liquefied ground as a solid.

At first, problems of treating soil with a large Poisson's ratio like saturated sand deposit by the finite element method are described. Selective reduced integration is introduced as a solution to the problem mentioned above in the 2-dimensional finite element method. Ground deformation analysis is adopted for damage case studies to investigate the effects of such parameters as the thickness or rigidity of the liquefied layer and the rigidity of the non-liquefied layer above the liquefied layer on the lateral flow. The effect of the latter, such as the layer above the water level, on the attenuation of deformation by the distance from quay wall is clarified.

Because a non-liquefied layer is affected by the significant nonlinearity and deformation of a liquefied layer in addition to its own nonlinearity, it is difficult to evaluate its rigidity during the flow. Since there have been few studies on the rigidity of a non-liquefied layer; rigidity is determined empirically so as to make damage examples accountable. Accordingly, nonlinear analyses in which nonlinearity is imparted to the non-liquefied layer are conducted to properly reproduce the flow damage at two sites. A method of evaluating the rigidity of a non-liquefied layer is then proposed based on shear strain estimated by the analysis mentioned above. In this method, the rigidity of a non-liquefied layer is expressed as a function of the distance from quay wall and the ratio of the rigidity of the liquefied layer estimated by the liquefaction resistance factor, FL. This method is applied to damage case studies to verify its applicability.

SHEAR LOCKING AND HOUR GLASS MODE

In treating the liquefaction-induced lateral flow, the assumption of undrained condition is often used. In this case, Poisson’s ratio of the liquefied layer is almost 0.5, and the liquefied layer is treated as an incompressive material with no volume change. The stress-strain relationship of an isotropic material with plain strain condition is indicated by elastic matrix D and Young’s modulus E as function (1).

$$D=\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \tag{1}$$

When Poisson’s ratio is 0.5, the denominator at the part of the coefficient reaches infinite. The simplest countermeasure is to be near 0.5, not 0.5. However, it is known that such treatment makes large errors in the 2 x 2 Gauss-Legendre integration mentioned in detail by Zienkeiwicz [8]. When Poisson’s ratio is almost 0.5, the apparent rigidity becomes very high, restricting the shear deformation. This phenomenon is known as shear locking. If the reduced integration is used in this case, shear locking can be avoided, but an unstable phenomenon known as the hourglass mode appears. Anti-hourglass stiffness is proposed to avoid this by Flanagan [9]. Yoshida [2] introduced this method to the flow analysis in the early years of liquefaction-induced flow research. Yasuda [7] used reduced integration and anti-hourglass stiffness to avoid shear locking and hourglass mode in their proposed method.

Selective reduced integration is one of the methods to avoid shear locking and hourglass mode. In selective reduced integration, restraint of shear deformation can be avoided by separating the deviatoric part from the total stiffness matrix and evaluating by reduced integration, while evaluating the dilatational by normal integration. This method was generalized by Hughes [10] to be applicable to anisotropic and nonlinear materials. In this study, selective reduced integration is introduced to the evaluation method of liquefaction-induced flow.

EVALUATION OF LIQUEFACTION-INDUCED FLOW CONSIDERING SELF-WEIGHT OF GROUND

Evaluation of liquefaction-induced flow by Static finite element method

Selective reduced integration is introduced to the 2-dimensional finite element method as a solution to the problem mentioned above. Ground deformation analysis is applied to damage case studies, while evaluating the effects of parameters, such as the thickness or the rigidity of the liquefied layer and the rigidity of the non-liquefied layer above the liquefied layer on the lateral flow. First, a representative soil layer is selected and modeled, and 1-dimendional equivalent linear analysis is conducted to obtain the equivalent shear rigidity. Liquefaction assessment is conducted for a liquefiable layer based on the response analysis results. When estimating the rigidity of the liquefied layer, the relationship between the liquefaction resistance FL and the shear rigidity during the liquefaction-induced flow found by Yasuda [7] based on cyclic torsional tests on many kinds of soils is used. The flow of the ground is evaluated by the analysis of self-weight, using a reduced rigidity during the flow for each soil element. Strictly speaking, it is necessary to subtract the deformation before liquefaction from that after liquefaction. However, because the deformation before liquefaction is much smaller than that after liquefaction, it can be ignored.

Summary of sites

Analyses are conducted for two quay walls and the ground at Higashinada, Kobe-city, damaged during 1995 Hyogoken-Nambu earthquake. There are caisson-type seawalls at Uozakihama, Higashinada, Kobe,

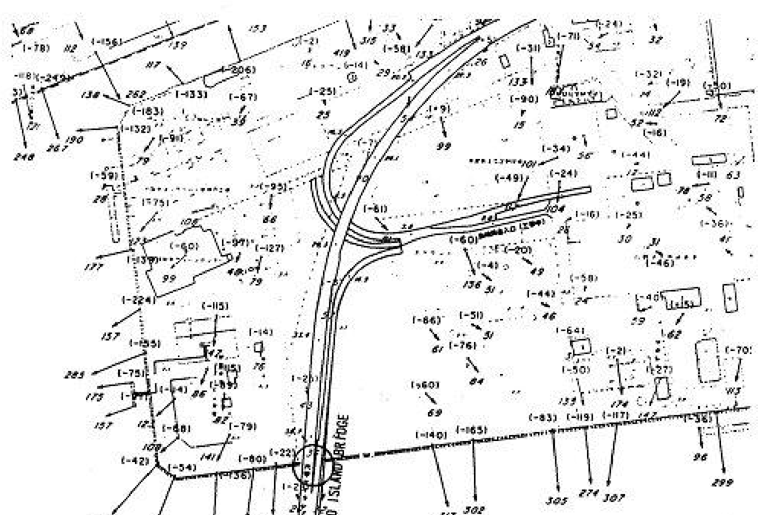
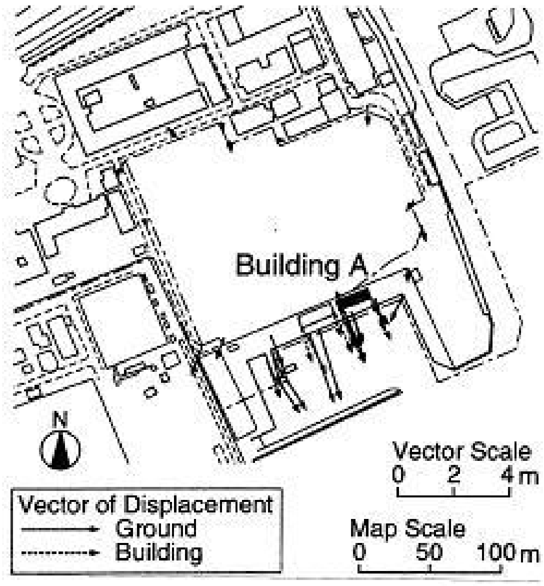


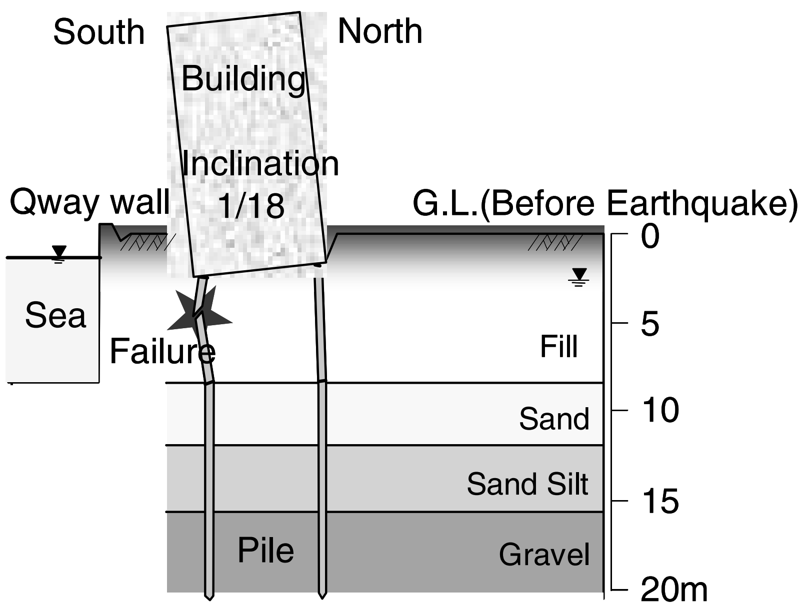
Figure 1: Displacement of Seawall and Ground at Site A

called site A, where Azuma [11] conducted damage analysis for the ground and the foundation structure of a highway bridge. It had been reclaimed from G.L.-20m by decomposed granite soil “Masado”. The deformations of the seawall at the site are shown in Figure 1, according to aerial photograph survey by

Hamada [12]. The seawalls moved toward the sea by about 2m to 3.5m. A shift of more than 50cm is observed even at a distance of 200m from the sea. There is a tilted building with the piles damaged by a lateral flow at another site of Higashinada, Kobe-city, called site B. Damage investigation was conducted here by Oh-Oka [13], and Tokimatsu [14]. Figure 2 shows the damage of the building and the ground deformation. The deformation at the quay wall is 1.5m and reduced sharply as the distance from the quay wall increased.



a)Ground Deformation



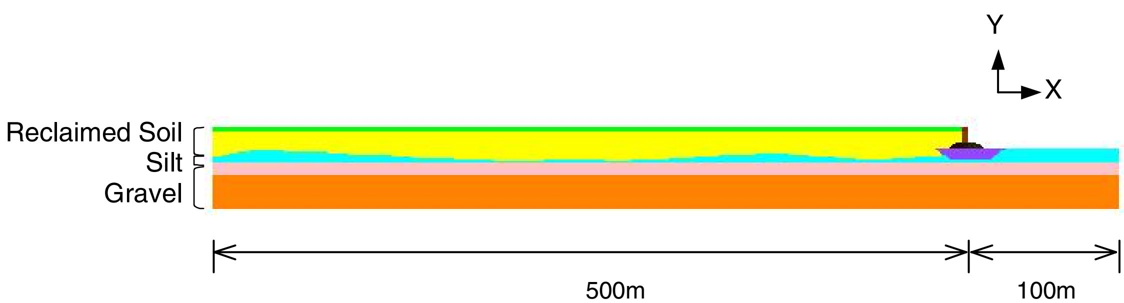
b) Damage of the Building

Figure 2: Ground Deformation and Damage of the Building at Site B

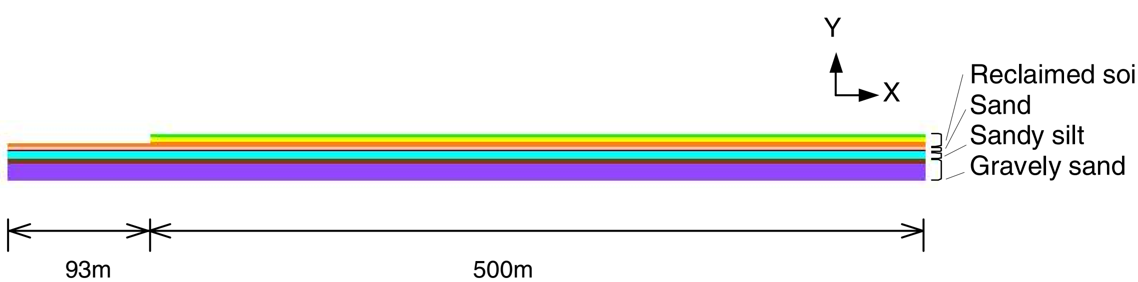
Soil profiles

It is not clear what kind of factors affect the liquefaction-induced flow and to what extent they affect it. Ground deformation analysis is applied to damage case studies to evaluate the effects of parameters, such as the thickness or the rigidity of the liquefied layer and the rigidity of the non-liquefied layer above the liquefied layer on the lateral flow (Miwa [15]).

Referring to the past researches and investigations by Azuma [11], Oh-Oka [13], and Sentoh [16], 2-dimensional finite element models are prepared. Figure 3 shows the model for each site. Table 1 shows the soil profiles and shear rigidity for flow analyses. The shear rigidity of the liquefied layer was evaluated from the relationship between FL and the reduction ratio of rigidity proposed by Yasuda [7] shown in Figure 4, where FL was obtained by liquefaction assessment from equivalent linear analysis. The rigidity of Site A is about 1/500 (Azuma [11]) and that of Site B is about 1/1000 (Miwa [15]). Because the non-liquefied layer is not only affected by its own nonlinearlity but also by severe nonlinearity and deformation of the liquefied layer, it is difficult to evaluate its rigidity during the flow. Since there have been few studies on the rigidity of a non-liquefied layer; rigidity has been determined empirically so as to make the damage accountable. The case where the rigidity of the non-liquefied layer is a hundred times the rigidity of the liquefied layer was set as a fundamental case. The rigidity is one fifth of the initial shear rigidity in site A and one tenth in site B. The rigidity of the non-liquefied layer is varied and analyzed. The cases of analysis are shown in Table 2. The initial rigidity is the rigidity in a very small strain level of 1×10^{-6} and corresponds to the rigidity from shear wave velocity by PS logging.



Ground A



Ground B

Figure 3: Analytical Model

Table 1: Soil Profile and Rigidity

a) Ground A

Ground A		Depth D(G.L.-m)	Factor of resistance from liquefaction F_L	Initial shear moduli G_0(kN/m^2)	Reduced ratio of shear moduli G_0/G_N	Shear moduli after liquefaction G_1 (kN/m^2)	Poisson ratio v	Effective unit weight γ'(kN/m^3)
Reclaimed soil	above water level	0-2.6	—	10368	1/3	3456	0.33	17.6
Reclaimed soil Below water level	above clay	2.6-18.6	0.79	10368	1/448	23	0.499	7.6
	above replacement soil	2.6-10.2	0.84	10368	1/374	28	0.499	7.6
Replacement soil	Ground	10.2-17.7	0.97	10368	1/133	78	0.499	7.6
	below sea bed	10.2-17.7	0.63	10368	1/752	14	0.499	7.6
Clay	Ground	18.6-23.6	—	828	—	—	0.45	5.6
	below sea bed	10.2-23.6	—	3207	—	—	0.45	5.6
Gravel 1	Ground	23.6-31.2	—	7331	—	—	0.33	7.6
	below quay wall	23.6-31.2	—	9774	—	—	0.33	7.6
	below sea bed	23.6-31.2	—	3008	—	—	0.33	7.6
Gravel 2	Ground	31.2-50.0	—	16541	—	—	0.33	7.6
	below sea bed	31.2-50.0	—	9398	—	—	0.33	7.6
Mound	Ground	6.2-10.2	—	1053	—	—	0.33	7.6
	below quay wall	6.2-10.2	—	1053	—	—	0.33	7.6
	below sea bed	6.2-10.2	—	182	—	—	0.33	7.6
Quay wall	above water level	0-2.6	—	1×10^{-6}	—	—	0.167	21.6
	below water level	2.6-6.2	—	1×10^{-6}	—	—	0.167	11.5

b) Ground B

Ground B	Depth D(G.L.-m)	Factor of resistance from liquefaction F_L	Initial shear moduli G_0(kN/m^2)	Reduced ratio of shear moduli G_0/G_N	Shear moduli after liquefaction G_1 (kN/m^2)	Poisson ratio v	Effective unit weight γ'(kN/m^3)
Reclaimed soil	0-2	—	28125	1/100	281	0.333	7.8
Reclaimed soil	2-5	0.67	28125	1/1000	28	0.499	7.8
Reclaimed soil	5-8.5	0.67	52020	1/1000	52	0.499	7.8
Sand	8.5-10.2	0.9	72000	1/500	144	0.499	7.8
Sand	10.2-11.9	—	112500	1/50	2250	0.499	7.8
Sandy silt	11.9-16.3	—	24480	1/10	2448	0.499	6.9
Gravely sand	16.3-19.8	—	182590	1/2	91295	0.499	8.8
Gravely sand	19.8-30.5	—	220500	1/2	110250	0.499	7.8

Table 2: Analytical Case
a) Ground A

				Basic	Shear Moduli of liquefied layer	Thickness of liquefied layer	Shear Moduli of non-liquefied layer				
layer No.	layer		Depth D(G.L.-m)	A00	A01	A11	A21	A22	A23	A24	A25
1	Reclaimed soi labove water level		0-2.6	1/3	1/3	1/3	1/5	1/25	1/50	1/100	1/500
2	Reclaimed soil	above clay	2.6-18.6	1/448	3X1/448	1/448	1/448	1/448	1/448	1/448	1/448
3	Below water level	above replacement soil	2.6-10.2	1/374	3X1/374	1/374	1/374	1/374	1/374	1/374	1/374
4	Replacement soil	Ground	10.2-17.7	1/133	3X1/133	1/133	1/133	1/133	1/133	1/133	1/133
5		below sea bed	10.2-17.7	1/752	3X1/752	1/752	1/752	1/752	1/752	1/752	1/752
6	Clay	Ground	18.6-23.6	1	1	1	1	1	1	1	1
7		below sea bed	10.2-23.6	1	1	1	1	1	1	1	1
	thickness of liquefied layer					1/2					
	Poisson's ratio of liquefied layer	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999
	Integration	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI
	Domain	500m	500m	500m	500m	500m	500m	500m	500m	500m	500m

				Basic	Shear Moduli of a layer under liquefied layer	Small Model & Shear Moduli of non-liquefied layer			
layer No.	layer		Depth D(G.L.-m)	A00	A31	A51	A52	A53	A54
1	Reclaimed soi labove water level		0-2.6	1/3	1/3	1/3	1/5	1/50	1/100
2	Reclaimed soil	above clay	2.6-18.6	1/448	1/448	1/448	1/448	1/448	1/448
3	Below water level	above replacement soil	2.6-10.2	1/374	1/374	1/374	1/374	1/374	1/374
4	Replacement soil	Ground	10.2-17.7	1/133	1/133	1/133	1/133	1/133	1/133
5		below sea bed	10.2-17.7	1/752	1/752	1/752	1/752	1/752	1/752
6	Clay	Ground	18.6-23.6	1	1/20	1	1	1	1
7		below sea bed	10.2-23.6	1	1/20	1	1	1	1
	thickness of liquefied layer								
	Poisson's ratio of liquefied layer	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999
	Integration	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI
	Domain	500m	500m	500m	500m	100m	100m	100m	100m

Table 2: Analytical Case
b) Ground B

		Basic	Shear Moduli of liquefied layer			Thickness of liquefied layer		Shear Moduli of non-liquefied layer			
layer No.	layer	B00	B01	B02	B03	B11	B12	B21	B22	B23	B24
1	Reclaimed soil (above water level)	1/100	1/100	1/100	1/100	1/100	1/100	1/1000	1/50	1/10	1/5
2	Reclaimed soil	1/1000	1/1000	1/500	1/300	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000
3	Reclaimed soil	1/1000	1/1000	1/500	1/300	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000
4	Sand	1/500	1/1000	1/500	1/300	1/50	1/1000	1/500	1/500	1/500	1/500
5	Sand	1/50	1/50	1/50	1/50	1/50	1/1000	1/50	1/50	1/50	1/50
6	Sandy silt	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10
7	Gravely sand	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
8	Gravely sand	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
	Poisson's ratio of liquefied layer	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999	0.4999
	Integration	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI	SRI
	Domain	500m	500m	500m	500m	500m	500m	500m	500m	500m	500m

		Basic	Poisson's ratio of liquefied layer						Small Model & Shear Moduli of non-liquefied layer			
layer No.	layer	B00	B31	B32	B33	B34	B35	B36	B51	B52	B53	B54
1	Reclaimed soil (above water level)	1/100	1/100	1/100	1/100	1/100	1/100	1/100		1/50	1/10	1/5
2	Reclaimed soil	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000
3	Reclaimed soil	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000	1/1000
4	Sand	1/500	1/500	1/500	1/500	1/500	1/500	1/500	1/500	1/500	1/500	1/500
5	Sand	1/50	1/50	1/50	1/50	1/50	1/50	1/50	1/50	1/50	1/50	1/50
6	Sandy silt	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10	1/10
7	Gravely sand	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
8	Gravely sand	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
	Poisson's ratio of liquefied layer	0.4999	0.45	0.48	0.49	0.499	0.49999	0.49	0.4999	0.4999	0.4999	0.4999
	Integration	SRI				SRI	SRI	SRI	SRI	SRI	SRI	SRI
	Domain	500m	500m	500m	500m	500m	500m	500m	100m	100m	100m	100m

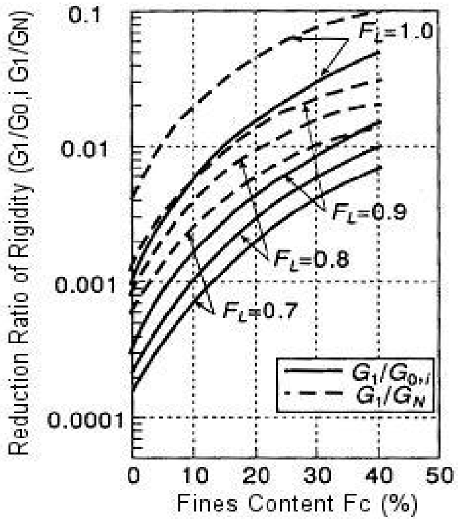


Figure 4: Relationship of FL and Reduction Ratio of Rigidity small resistance Condition in Liquefaction

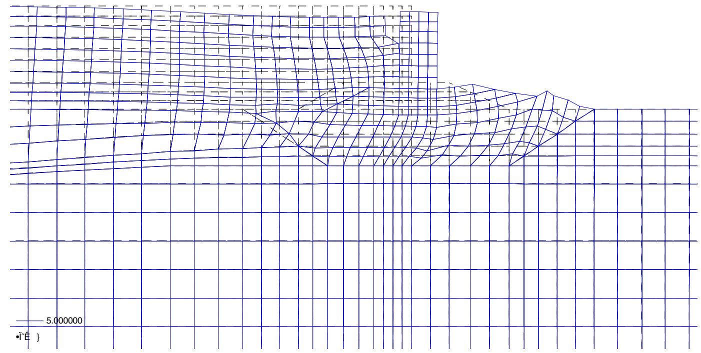


Figure 5: Example of Deformation of Ground by Analysis

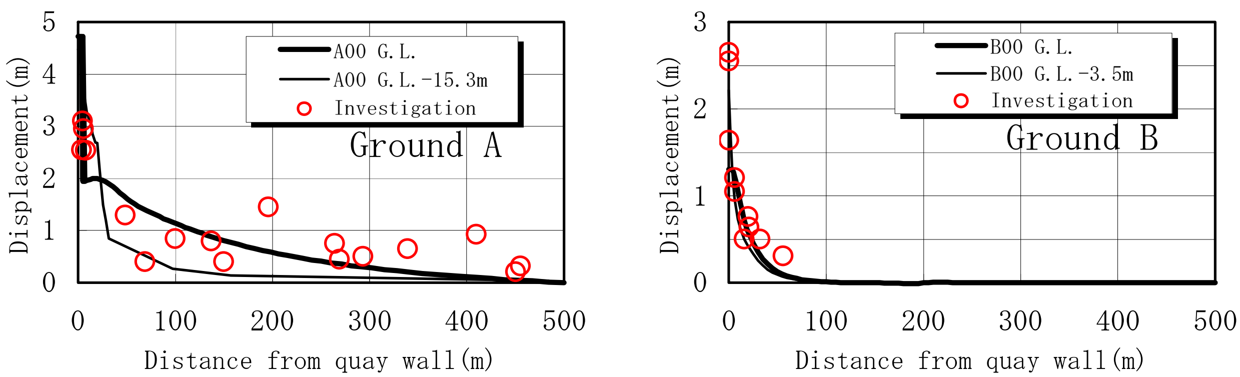


Figure 6: Relationship between Displacement and Distance from Quay Wall

An example of deformation of the ground evaluated by flow analysis is shown in Figure 5. Because of liquefaction of the ground behind the quay wall and softening of replaced sand below the caissons, the ground around the quay wall is severely deformed. The caissons move toward the sea influenced by the movement of the replaced sand and the mound. As the non-liquefied layer above the liquefied layer was separated from the caissons, the deformation of the caissons is larger than the ground. These results coincide with the investigation and result by Azuma [11], which explain the damage well.

From an aerial photograph survey, the displacement of the ground during the earthquake was determined. The relationship between the horizontal displacement and the distance from the quay wall evaluated from the fundamental case A00 and B00 is shown in Figure 6. The investigation results are also superimposed. The tendencies that the displacement continues over a long distance from the quay wall in site A and that the displacement sharply decreases near the quay wall in site B are expressed well and the volume of displacement near the quay wall agree well.

EFFECT ON LIQUEFACTION-INDUCED FLOW

Rigidity of layer under liquefied layer

It is found from the analysis that the rigidity of the layer under the liquefied layer decreased due to the appearance of nonlinearity during the strong ground motion, but the rigidity even in the reduced condition was sufficiently higher than that of the liquefied layer. It is clear that the effect of the rigidity of the layer under the liquefied layer on the flow is small.

Thickness of liquefied layer

The relationship between the horizontal displacement and the distance from the quay wall with respect to the thickness of the liquefied layer evaluated by the analysis are shown in Figure 7 compared with the fundamental cases. As the thickness of the liquefied layer increases, the displacement increases in proportion to the thickness or more, if other conditions are same. The distributions of the displacement normalized by the maximum displacement near the quay wall are almost the same in all cases. It is thought that the thickness does not affect the displacement attenuation from the quay wall.

Rigidity of liquefied layer

The relationship between the horizontal displacement and the distance from the quay wall with respect to the rigidity of liquefied layer evaluated by the analysis are shown in Figure 8. It is cleared that the rigidity of the liquefied layer strongly affects the displacement.

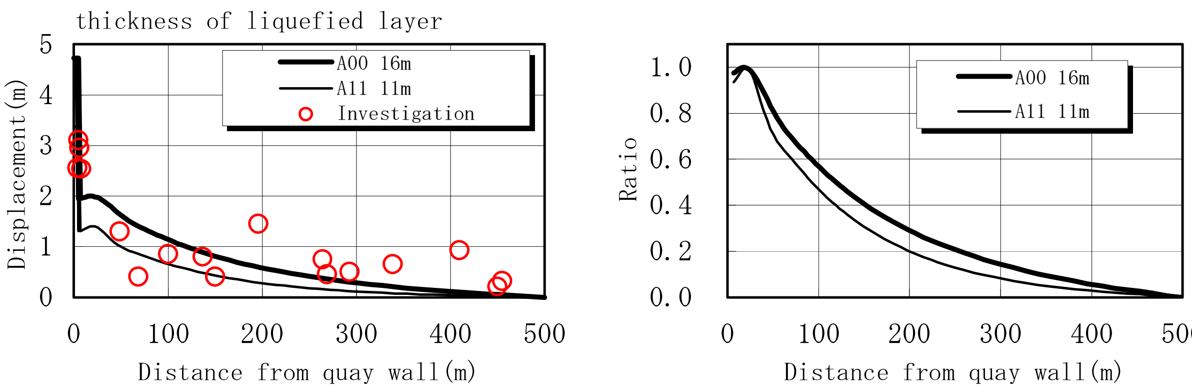


Figure 7: Relationship between Displacement and Distance from Quay Wall

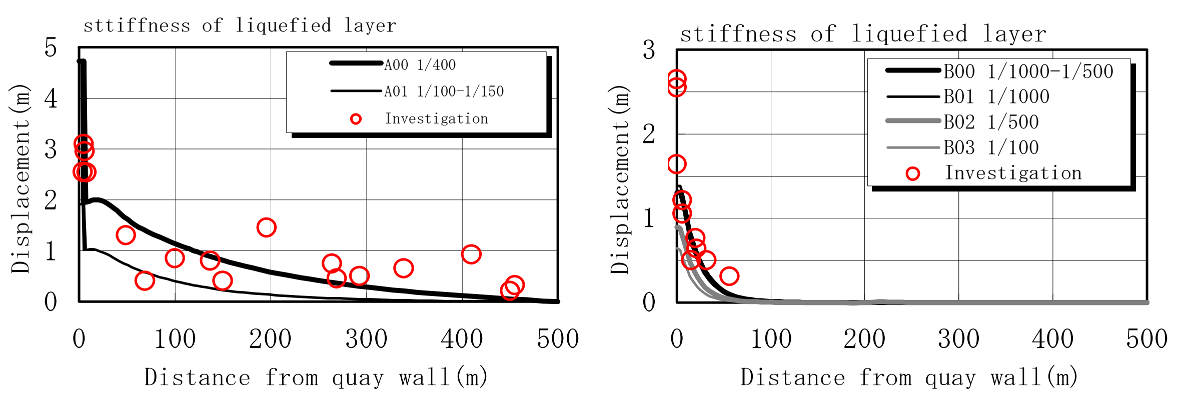
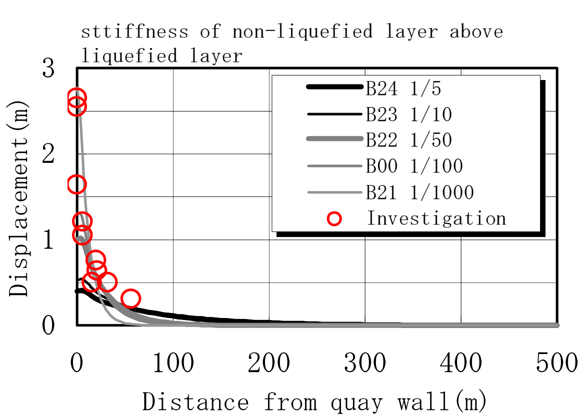


Figure 8: Relationship between Displacement and Distance from Quay Wall

Rigidity of non-liquefied layer above liquefied layer

Figure 9 shows the relationship between the horizontal displacement and the distance from the quay wall on the assumption that the rigidity of the non-liquefied layer is constant over the distance evaluated in the analysis. The rigidity of the liquefied layer is also assumed to be constant over the distance. The displacement at the ground surface near the quay wall decreases as the rigidity of the non-liquefied layer increases. When the rigidity becomes ten times higher, the displacement of the ground near the quay wall becomes twice as large. The degree of the effect is lower than that of the rigidity of the liquefied layer, which affects the horizontal displacement at a proportion of nearly 1:1. Conversely, at a distance of 50m or more from the quay wall, the displacement of the ground surface increases and becomes more far-reaching as the rigidity of the non-liquefied layer increases. In order to compare the attenuations of displacement, the displacements are normalized by the displacement at the quay wall. When the rigidity of the non-liquefied layer is the same as or ten times higher than that of the liquefied layer, the ground displacement settled within 100m to 200m. When the rigidity of the non-liquefied layer is one hundred times higher than that of the liquefied layer, the ground displacement reaches 400m to 500m. It is found that when the rigidity of the non-liquefied layer is high, the displacement of the ground surface near the quay wall is small because of its restriction. On the other hand, the attenuation is small and the displacement reaches over a long distance from the quay wall. It is clear that the attenuation characteristics of the ground displacement from the quay wall are affected by the rigidity of the non-liquefied layer above the liquefied layer.

The investigation revealed that the displacement reaches over a long distance, with the value at 100m from the quay wall being relatively large in Site A, whereas the displacement settles at 100m in site B. The two sites showed different characteristics of the ground displacement attenuation from the quay wall. When the rigidity of non-liquefied layer is assumed to be constant from quay wall throughout the distance, the analysis results agreed relatively well with the survey in the cases where the rigidity is 1/5 to 1/25 of the initial value at site A and 1/50 to 1/100 of the initial value at site B. These are 20 to 100 times higher than the rigidity of the liquefied layer at site A and 10 to 20 times higher at site B. Nevertheless, the analysis values on the assumption of constant rigidity from the quay wall do not necessarily agree well with the survey results throughout the distance. It is necessary to evaluate the rigidity of the non-liquefied layer according to the distance.



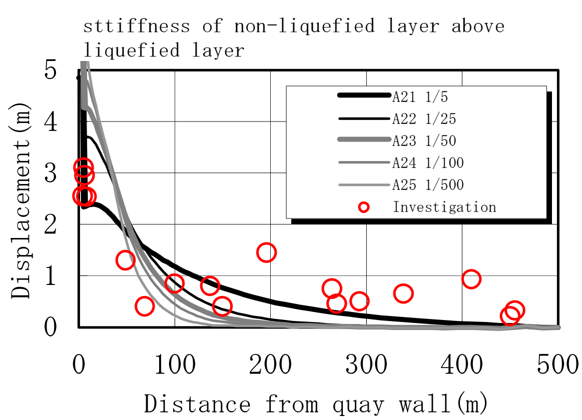


Figure 9: Relationship between Displacement and Distance from Quay Wall

EVALUATION METHOD FOR THE RIGIDITY OF NON-LIQUEFIED LAYER

Nonlinear analysis considering nonlinearity of non-liquefied layer

As mentioned above, it is expected that the strain and reduction ratio of the non-liquefied layer change depending on the distance from the quay wall. Taking notice of the rigidity of the non-liquefied layer, nonlinear analysis is conducted in which nonlinearity of the non-liquefied layer is considered and the rigidity of the non-liquefied layer in each element can be changed by the influence of deformation of the liquefied layer and so on (Miwa [17]). The nonlinearity of the non-liquefied layer is modeled into a hyperbolic curve model according to the dynamic deformation characteristic tests on decomposed granite soil, "Masado," taken from reclaimed land in Kobe city, the same area as the investigation sites shown in Figure 10 (Miwa [18]). Linear rigidities during liquefaction or earthquake are set beforehand equivalently for the liquefied layer and the layer under liquefied layer similarly to the above mentioned analysis.

The relationship between the horizontal displacement and the distance from the quay wall evaluated by the nonlinear analysis are shown in Figure 11 compared with investigation. The displacement distribution on the ground surface by nonlinear analysis is in the middle of the cases where the rigidity of the non-liquefied layer is assumed to be constant at 10 times and 100 times higher than that of the liquefied layer. It agrees with investigation better than the constant rigidity cases in regard to the attenuation characteristics. The relationship between the shear strain and the distance from the quay wall evaluated by the nonlinear analysis is shown in Figure 12. It is found that the strain distribution by the nonlinear analysis is close to the result of the most suitable case under the constant rigidity conditions. (The rigidity of the non-liquefied layer is 1/25 of the initial rigidity and 20 times that of the liquefied layer in Site A and 1/100 of the initial rigidity and 10 times that of the liquefied layer in Site B.) It is found that the reduction in the rigidity of the non-liquefied layer is large near the quay wall but decreases as the distance from the quay wall increases, and this tendency can be evaluated by the nonlinear analysis. Also, it is found difficult to evaluate the displacement under the constant rigidity conditions because of the change in the rigidity depending on the distance from the quay wall.

Evaluation method for the rigidity of non-liquefied layer

The possibility of evaluating liquefaction-induced flow in nonlinear analysis incorporating the nonlinear characteristics of rigidity for the non-liquefied layer is described above. However, analysis involving nonlinearity poses such problems as long calculation time. For this reason, linear analysis is conducted while setting stepwise reduction in the rigidity over the distance from the quay wall beforehand based on the nonlinear analysis. The proposed combinations of rigidities are shown in Table 3. The relationship between the horizontal displacement and the distance from the quay wall evaluated by the analysis is shown in Figure 11 compared with the nonlinear analysis. The rigidity reduction ratio is relatively large near the quay wall. Rigidities of 1/50, 1/25 and 1/5 of the initial value for up to 20m, 20-50m and beyond 50m, respectively, from the quay wall nearly express the survey results at site A. At site B, rigidities of 1/100, 1/50 and 1/10 of the initial value for up to 20m, 20-50m and beyond 50m, respectively, from the quay wall agree well with the survey results. It is found possible to express the tendencies of different attenuations at sites A and B by considering the changes in the rigidity depending on the distance from the quay wall. When expressed in terms of the ratio to the rigidity of the liquefied layer, the rigidity of the non-liquefied layer is 10, 20 and 100 times that of the liquefied layer up to 20m, 20-50m and beyond 50m, respectively, from the quay wall regardless of the difference of the ground. The relationship between the shear strain and the distance from the quay wall evaluated by the analysis are shown in Figure 12 compared with the nonlinear analysis results. In the case where the sets of rigidities are established beforehand depending on the distance from the quay wall, the results agree well with the nonlinear analysis. It is found that nearly the same results can be obtained by the proposed method without carrying out nonlinear analysis. It is found that the method in which the rigidity of the non-liquefied layer is set by the function of the distance from the quay wall and the ratio of the rigidity of the liquefied layer can express the different liquefaction-induced flow distributions at two sites.

Accordingly, the authors propose a practical method of evaluating the liquefaction-induced flow, in which the rigidity of the non-liquefied layer is set by the function of the distance from the quay wall and the ratio to the rigidity of the liquefied layer. A combination of the rigidities of the non-liquefied layer 10, 20 and 100 times the rigidity of the liquefied layer for up to 20m, 20-50m and beyond 50m, respectively from the quay wall, is in harmony with the two investigation sites.

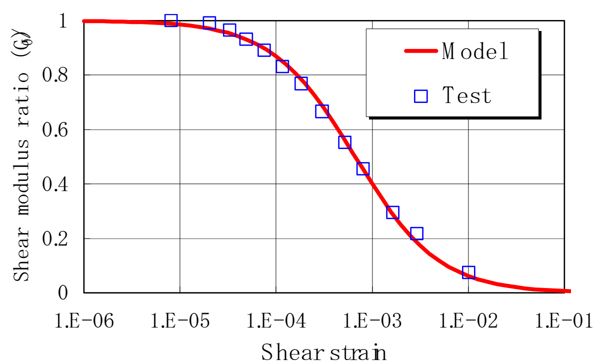
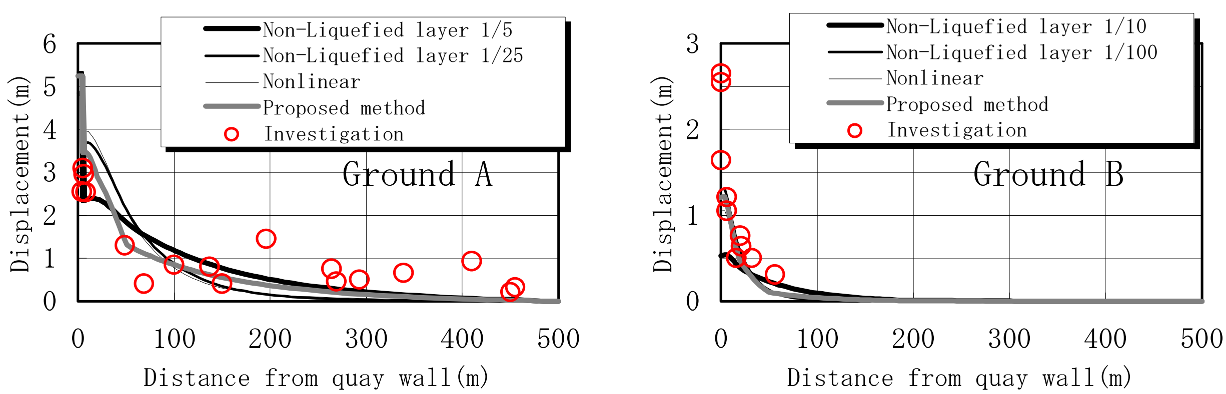
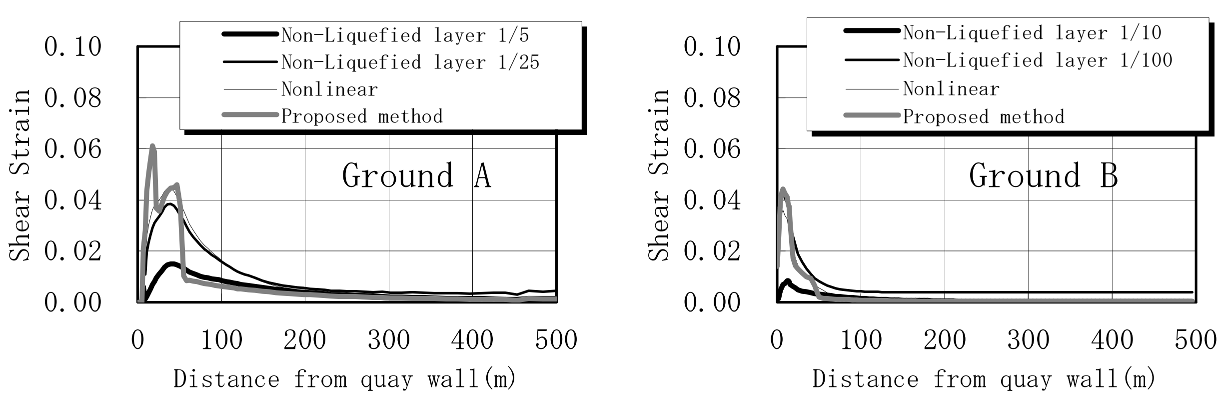


Figure 10: Nonlinear Characteristics of Non-Liquefied Layer



a) Site A **b)Site B**

Figure 11: Relationship between Displacement and Distance from Quay Wall



a) Site A **b)Site B**

Figure 12: Relationship between shear Strain and Distance from Quay Wall

Table 3: Combination of Rigidities

		Ground A			Ground B		
		Distance from quay wall (m)			Distance from quay wall (m)		
		- 20	20 - 50	50 -	- 20	20 - 50	50 -
Proposed method	Ratio of shear modulus between non-liquefied layer and liquefied layer	10	20	100	10	20	100
Nonlinear		Nonlinear			Nonlinear		

It should be noted that these cases are both limited to the damage during the 1995 Hyogoken-Nambu earthquake in lands reclaimed with Masado in Kobe City. Other cases should therefore be analyzed. Also, there is a possibility that the displacement may include components other than the flow, for example, movement of the whole deep soil structure in the same direction within a wide area. The attenuation characteristics of displacement should therefore be researched more in detail.

CONCLUSION

Ground deformation analysis was applied to damage case studies to evaluate the effects of parameters on the lateral flow. The authors proposed a method for evaluating liquefaction-induced flow. The following conclusions were obtained:

1) Selective reduced integration was introduced as a solution to the problem mentioned above to the 2-dimensional finite element method. Ground deformation analysis was applied to damage case studies to evaluate the effects of parameters, such as the thickness or the rigidity of liquefied layer and the rigidity of non-liquefied layer above liquefied layer, on the lateral flow.

2) It was clarified that the rigidity and thickness of liquefied layer strongly affect the displacement, but they are not considered to strongly affect the attenuation of the displacement from the quay wall.

3) It is clear that the attenuation characteristics of the ground displacement from the quay wall are affected by the rigidity of the non-liquefied layer above the liquefied layer.

4) A method of evaluating the liquefaction-induced flow is proposed, in which the rigidity of the non-liquefied layer is set by the function of the distance from the quay wall and the ratio to the rigidity of the liquefied layer. It indicates that the case considering nonlinearity of the non-liquefied layer expresses the damage more accurately than the case in which the rigidity of the non-liquefied layer is constant. The proposed method with the shear modulus varied depending on the distance from the quay wall also agreed well with the investigation.

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