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EXPERIMENTAL AND NUMERICAL STUDIES ON THE CHANGE IN GROUND STIFFNESS BEFORE AND AFTER LIQUEFACTION

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SUMMARY

It is possible, at present, to simulate liquefaction of ground due to earthquake with reasonable accuracy using an effective stress analysis. One of the key issues in liquefaction analyses is how to make a model that can take into consideration ground stiffness reduction before liquefaction. Yet, the process of ground stiffness recovery after liquefaction is also important issue. The change of soil stiffness has been studied with undrained cyclic triaxial tests or shaking table tests [1]. Based on the experimental results, a number of well-performed constitutive models have been proposed. Among those constitutive models, some elastoplastic models based on a nonlinear kinematical hardening rule have been well used in liquefaction analyses, mainly for clean sands. Unfortunately, those models cannot predict the change in ground stiffness well for soils of fine grains and gravels. In this study, in order to clarify the ground stiffness change during liquefaction, shaking table tests, undrained cyclic triaxial tests and effective stress analyses are conducted for three kinds of geomaterials. Decomposed granite, clean sand called Kasumigaura-sand and crushed stone called gravel are used in the series of tests and simulations. The experimental results are compared with the results of effective stress analyses. It is found that the change in pore water pressure during liquefaction is well simulated for Kasumigaura-sand and gravel. On the other hand, for decomposed granite, simulation results of the change in excessive pore water pressure in liquefaction process cannot express the experimental results well. It is also found that from laboratory tests, the change in ground stiffness in the process of primary liquefaction is largely affected from the performance of the excessive pore water pressure.

INTRODUCTION

The liquefaction phenomena are intimately related to excessive pore water pressure and ground stiffness. The effective stress analyses are usually used for analyses of liquefaction phenomena. Recently, the various effective stress analyses is proposed and modified by many researchers. The liquefaction analysis method LIQCA [2] proposed by Oka, et al. was applied the simulation of shaking table test in 2001[3]. The results of simulation using LIQCA are compared with the results from the experimental tests (see

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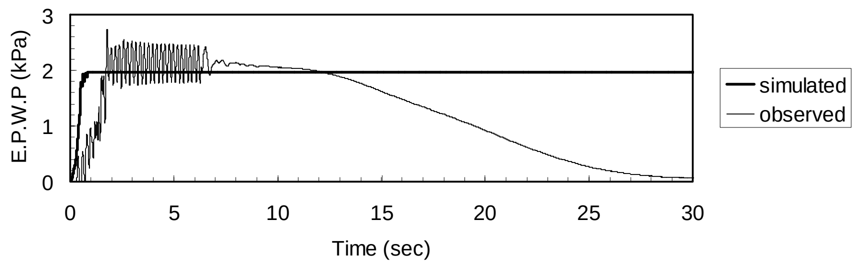
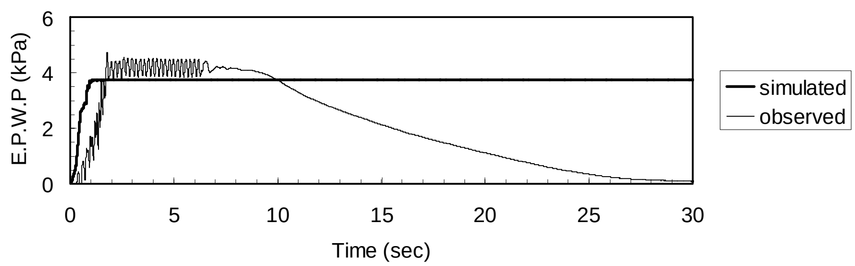
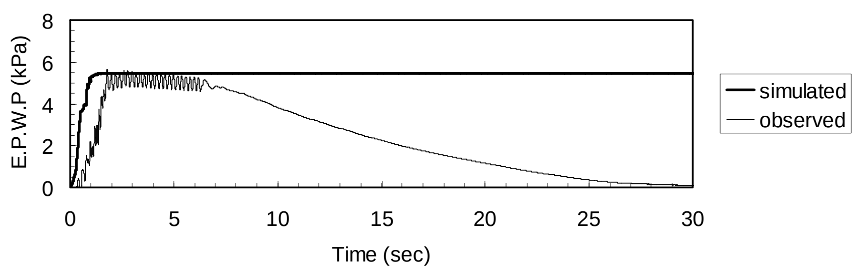
Figure 1). There exists much difference in excessive pore water pressures between simulated and experimental result after liquefaction. In simulated results, the excessive pore water pressure is almost constant after liquefaction. In experimental results, however, the excessive pore water pressure shows the reduction after liquefaction. For the reason of this difference, it is difficult to simulate the excessive pore water pressure reduction and the regaining of the ground stiffness after liquefaction using solid mechanics. From this reason, the excessive pore water pressure reduction may take place much later than observed one in simulation. In order to simulate liquefaction phenomena more appropriately, it is important to understand the behavior of ground stiffness and excessive pore water pressure during and after liquefaction.



G.L=-0.2m



G.L=-0.4m



G.L=-0.6m

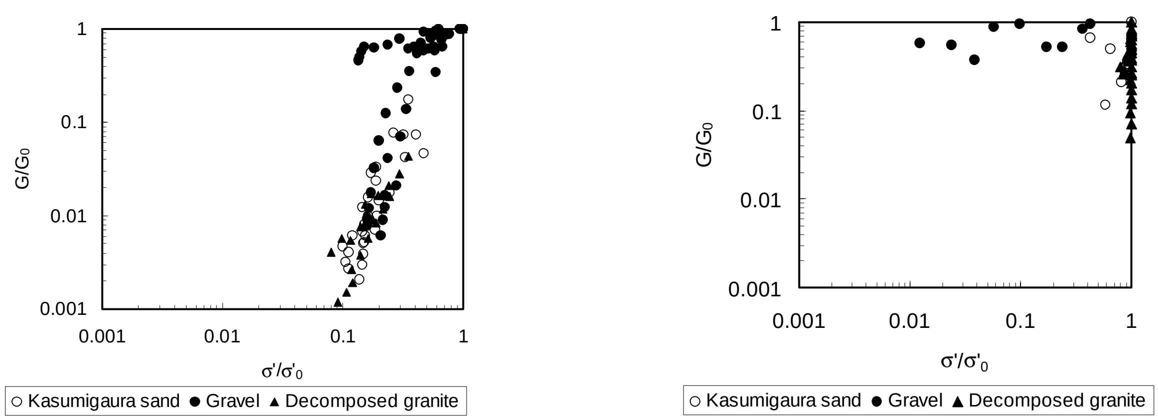
Figure 1 Excessive pore water pressure in simulation [3]

The aim of this research is to understand the ground stiffness in liquefaction process. Therefore, shaking table tests and cyclic triaxial tests are carried out using three kinds of material, Kasumigaura-sand, gravel and decomposed granite. Moreover, the constitutive model is modified to take into account the ground stiffness. The modified model is also applied to analyze the shaking table test. Using this model, simulation results of shaking tests are compared with the results of experimental tests. Finally, the discussions are focused to the change in ground stiffness during the liquefaction for three kinds of materials.

LABORATORY TESTS FOR UNDERSTANDING THE GROUND STIFFNESS CHANGE DURING LIQUEFACTION

Shaking table test and triaxial test for understanding the ground stiffness change before liquefaction

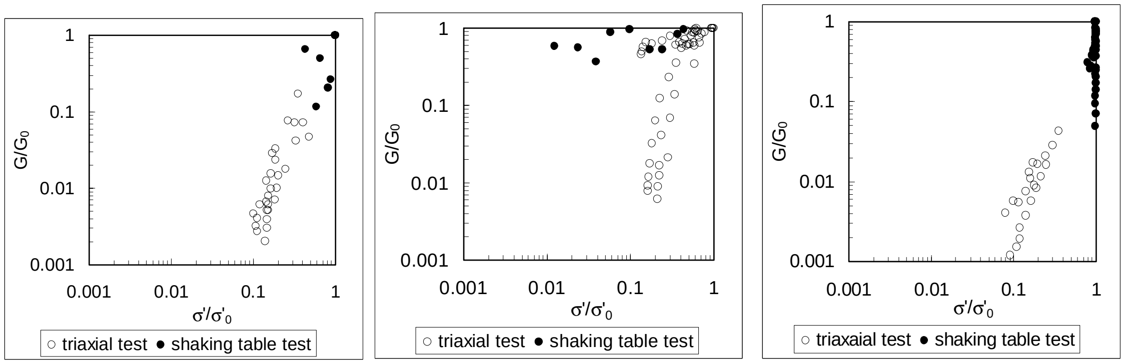
In this section, the behavior of shear modulus before liquefaction is verified by comparison the results between shaking table tests and cyclic triaxial tests. Firstly, the triaxial tests are conducted to express the soil stiffness reduction. Figure 2(a) shows the relationship between a ratio of shear stress reduction and a ratio of mean effective stress in cyclic triaxial test. In the case of triaxial tests, the behaviors of the shear modulus reduction have a similar tendency for three kinds of materials. Therefore, in order to understand difference of the shear modulus reduction during liquefaction, the results of triaxial tests are compared with the results of shaking table tests. Figure 2(b) shows the relationship between the ratio of shear modulus and the ratio of the mean effective stress reduction carried out with the shaking table test using three kinds of materials. In this figure, behaviors of the shear modulus reduction are described differently for three kinds of materials. From these two series of tests, the behavior of the shear modulus reduction shows much difference between triaxial tests and the shaking table tests. It is supposed that the reason of the difference is due to the boundary condition at the tests. In the case of triaxial tests, specimen is forced to a liquefied condition. Therefore, the behavior of shear modulus reduction shows the same tendency of behavior on three materials.



(a) Triaxial test (b) Shaking table test

Figure 2 Relationship between the ratio of shear modulus and the ratio of mean effective stress with different experimental test

Figure 3 shows the relationship between the ratio of shear modulus reduction and the ratio of mean effective stress, by which the results of triaxial tests and shaking table tests of each material. It is found that the reduction of shear modulus has much difference for the way of test on gravel and decomposed granite especially. In the case of Kasumigaura-sand, however, the behavior of the shear modulus reduction of the shaking table test is coincident to the behavior of triaxial test. As a conclusion, three kinds of materials show different behaviors respectively in the shear modulus reduction. It has to take account very carefully in determining the parameters necessary for the effective stress analysis from laboratory tests.



(a) Kasumigaura-sand (b) Gravel (c) Decomposed granite

Figure 3 Relationship between shear modulus ratio and mean effective stress ratio on each material.

Shaking table test for understanding the ground stiffness change after liquefaction

In this study, shaking table tests and cyclic triaxial tests were carried out for three kinds of materials. The physical characteristics of the materials are shown in Table 1 and the grain-size accumulated curves are shown in Figure 4.

Table 1 Physical property of materials

	Kasumigaura -sand	Gravel	Decomposed granite
ρ_{max} (g/cm^3)	1.762	2.058	1.958
ρ_{mim} (g/cm^3)	1.412	1.913	1.466
e_{max}	0.916	0.381	0.848
e_{min}	0.535	0.284	0.384
ρ_s(g/cm^3)	2.705	2.642	2.705

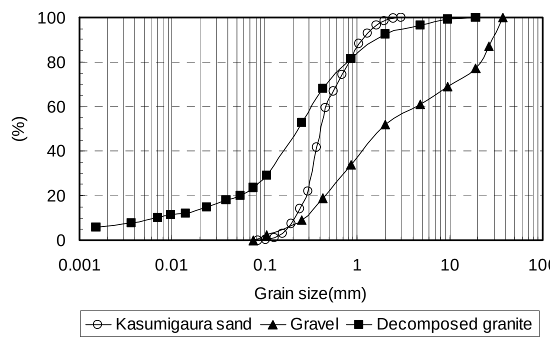


Figure 4 Grain-size accumulated curves

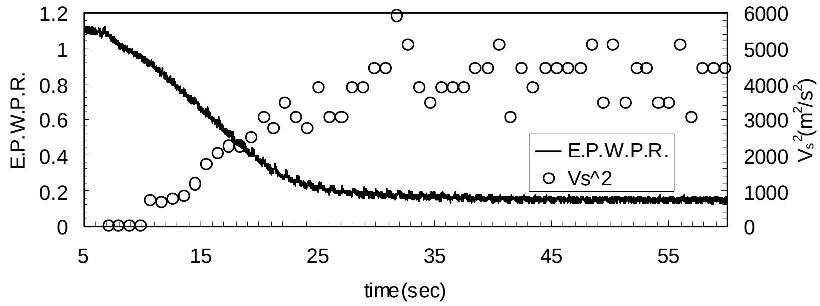
The size of shearing box that allows shear deformation of ground used in tests is 120cm in width and length and 80cm in height. In order to make the model ground evenly, soils are distributed within water carefully. Then three cases of shaking table tests with different materials were carried out. In order to understand the change of shear stiffness, the shear stress-shear strain relations and the effective stress passes were evaluated from the amplitude of vibration, the deformation and the pore water pressure in the tests results. Shear stress τ is calculated from equation (1):

$$\tau(z) = \int_0^z \rho \cdot a \cdot dz \qquad (1)$$

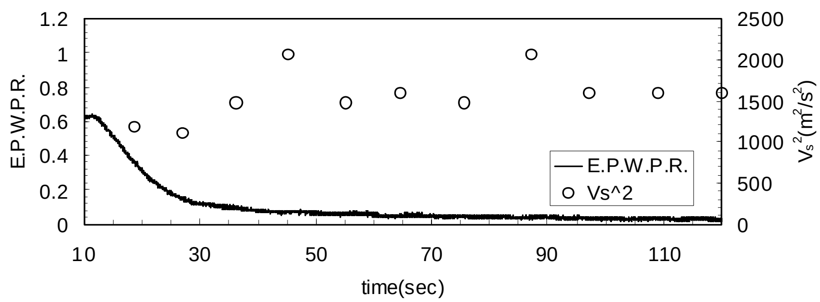
where, ρ is density, a is amplitude and z is vertical displacement. The shear strain γ is derived from equation (2):

$$\gamma = \left(\delta L_i - \delta L_j\right)/h \qquad (2)$$

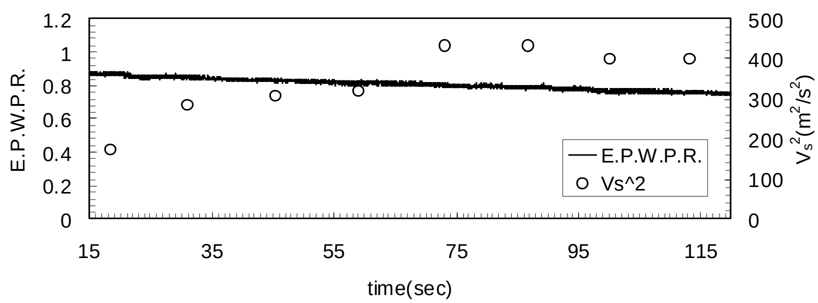
in which, δL_i and δL_j is the deformation of each layer and h is the thickness of the layer. In the tests, shear wave velocity in model ground was measured to understand the mechanism of ground stiffness reduction in the process of post-liquefaction by hammering method conducted immediately after liquefaction of the ground happened in shaking table tests.



(a) Kasumigaura-sand, G.L=-0.4m



(b) Gravel, G.L=-0.4m



(c) Decomposed granite, G.L=-0.4m

Figure 5 Time history of excessive pore water pressure ratio (E.P.W.P.R) and V_s^2

The time histories of excessive pore water pressure ratio $\Delta u/\sigma_0'$ and V_s^2 are shown in Figure 5. In the figure, it is found that the recovering of ground stiffness is related to the decreasing of excessive pore water pressure. In the case of Kasumigaura-sand, it was confirmed that the recovering of ground stiffness occurred with the excessive pore water pressure reduction. Moreover, the recovering of ground stiffness is started from the bottom layer to the upper layer. On the other hand, in the case of gravel, it could not observe the recovering of ground stiffness clearly, though the reduction of the pore water pressure occurred immediately. Furthermore, in the case of decomposed granite, the pore water pressure was almost remained unchanged, while the ground stiffness recovered a little. From these tests, the recovering of ground stiffness showed a different behavior in three materials used in the tests. Therefore, in order to analyze the recovering process of ground stiffness appropriately, a way of controlling ground stiffness is required by a modification of present models used in the effective stress analyses. It is, however, still needed to do further research on how to propose an appropriate modification based on the test results.

VERIFICATION OF THE MODIFIED CONSTITUIVE EQUATION IN GROUND STIFFNESS REDUCTION ON LIQUEFACTION PROCESS

Modification of constitutive model in liquefaction process

Up to now, most of effective stress analyses were related to the laboratory tests of sands. The effective stress analyses related to the laboratory tests of other materials, however, are seldom seen. As described in previous sections, it has been considered that the reduction of ground stiffness in liquefaction is different for each geo-material. The problem left to be solved for effective stress analyses is that the excessive pore water pressure increases much faster than the observed one in laboratory tests on the primary stage of liquefaction. Furuta, et al. [4] proposed a modified model that takes into consideration the reduction of ground stiffness a using logistic function.

Table 2 Material parameters of Kasumigaura-sand

Model		Original model	Modified model
Initial void ratio	e_0	0.649	
Compression index	Λ	0.02	
Swelling index	K	0.002	
Initial shear modulus ratio	G_0/σ'_{m0}	1188	
Failure stress ratio	M_f	1.138	
Phase transformation stress ratio	M_m	0.91	
Hardening parameter	B_0	2500	5000
	B_1	50	50
	C_f	0	270
Reference strain parameter	γ^E_r	0.02	0.015
	γ^P_r	0.007	0.005
Dilatancy parameter	D_0	3.5	7.0
	n	2.5	2.4

Table 2 shows the material parameters of Kasumigaura-sand. These parameters, such as initial void ratio, compression index, swelling index, ratio of initial shear modulus, stress ratio at failure and phase-transformation stress ratio, are determined from the results of laboratory tests carried out by Furuta [1]. Figure 6 shows the comparison of hardening parameter calculated by the original model [5] and the modified model. The white dot shows the result of the modified model. It is found that the modified model contains the parameter concerning the reduction of stiffness. Moreover, the effect of modified model was confirmed by the liquefaction strength curve, a relationship between cyclic number N_c and stress ratio $\sigma_d/2\sigma'_c$, as shown in Figure 7. In this figure, it is known that the strength to the cyclic loading predicted by the modified model is higher than the one by original model. Figure 8 shows the comparison between the theoretical stress-strain relations and the effective stress paths from both models. The effective stress in the modified model decreased later than that of the original model. It means that the modified model has a capacity to analyze the ground ductile behavior in primary stage of liquefaction more accurately.

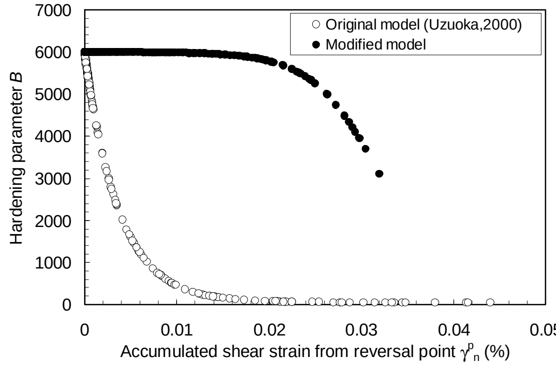


Figure 6 Comparison of hardening parameter

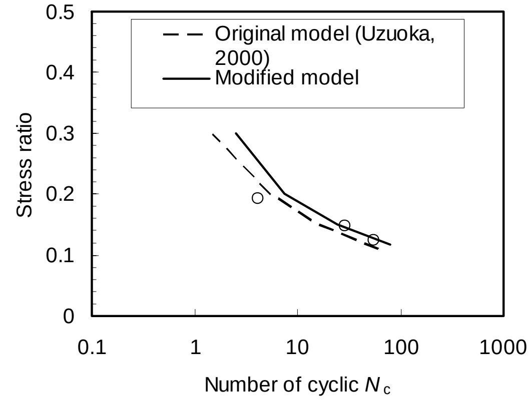
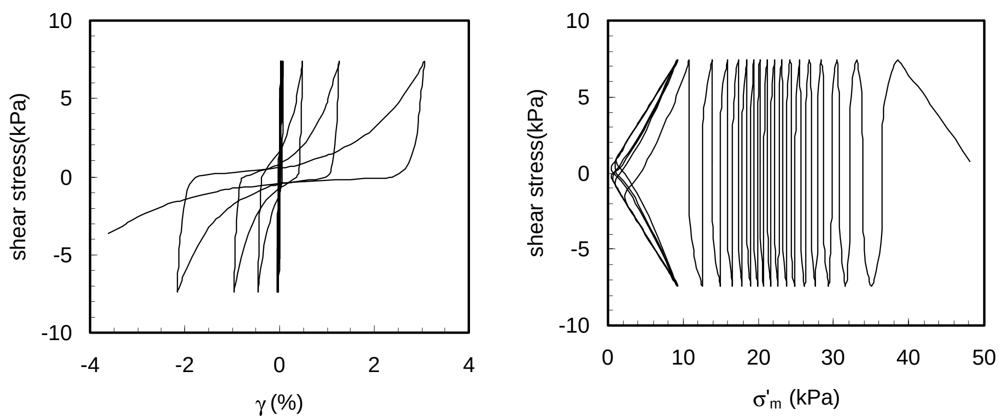
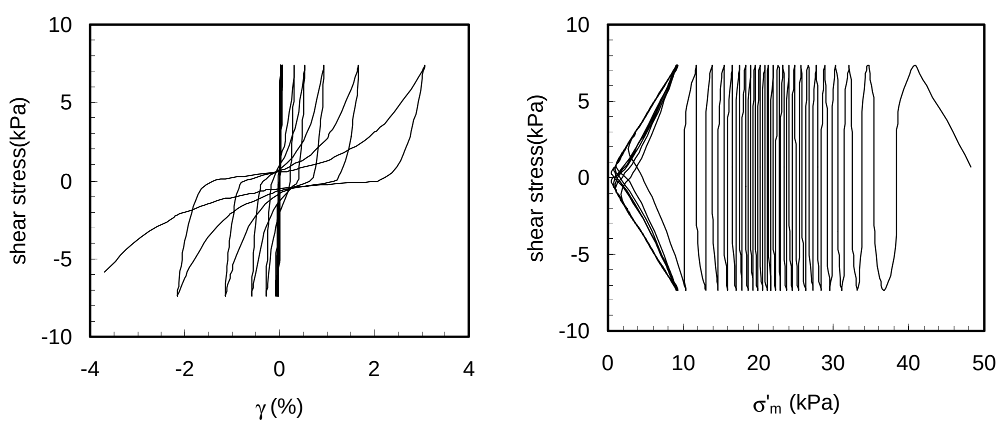


Figure 7 Curve of liquefaction strength



(a) Original model



(b) Modified model

Figure 8 Comparison of theoretical stress-strain relation and effective stress path

Simulation of an element liquefaction test with modified model

The applicability of the modified model to ground ductility was confirmed with the theoretical result. In this section, therefore, the modified model is applied a simulation of one element ground model. The one element finite element mesh for a model ground is shown in Figure 9. The boundary condition in the model is that the displacement at the base is fixed while the displacements at the surface are assumed with identical-displacement restriction. For drainage condition, surface of the element is drained while others are impermeable. Figure 10 shows the input wave used in this analysis. The wave is a type of sweep wave with 25Gal in maximum acceleration and is inputted from the bottom of the ground. Figure 11 shows the comparison result of excessive pore water pressure ratio (E.P.W.P.R) between the original and the modified model. It is found that the excessive pore water pressure ratio of the modified model indicate lower value than that of the original model. From this finding, it was confirmed that the modified model can predict the ground ductility in the primary stage of liquefaction.

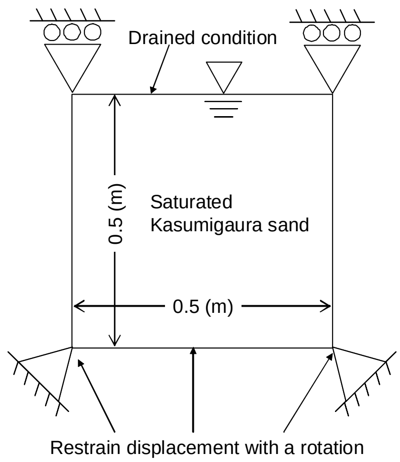


Figure 9 One-element finite element mesh and its boundary conditions

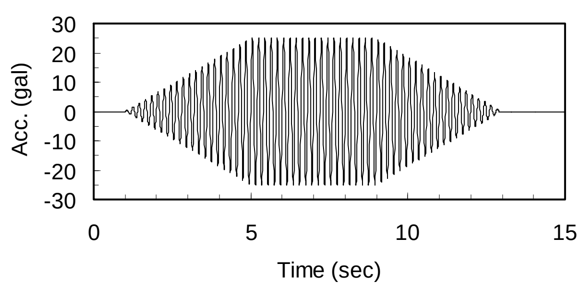


Figure 10 Input wave

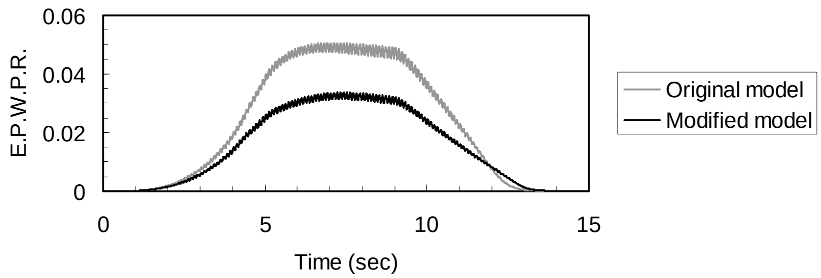


Figure 11 Comparison the results of original and modified model

Validation of the modified model using simulations of shaking table tests

In this section, the proposed model was verified with the results of simulations. For the verification of the model, the results of simulation of the shaking table tests using proposed model are compared with the results of shaking table test results. In comparisons, aforementioned three different soils were used for both shaking table tests and simulations. Material parameters used in simulations for the materials are shown in Table 3. The important issue in the simulations is that the parameters used in each simulation are determined from the results of shaking table tests using the same materials.

Table 3 Material parameters for liquefaction analysis

Material		Kasumigaura-sand		Gravel		Decomposed granite	
Model		Original model	Modified model	Original model	Modified model	Original model	Modified model
Initial void ratio	e_0	0.649		0.376		0.537	
Compression index	λ	0.02		0.003		0.02	
Swelling index	κ	0.002		0.0012		0.0011	
Initial shear modulus ratio	G_0/σ'_{m0}	1188		436		852	
Failure stress ratio	M_f	1.138		1.3		1.33	
Phase transformation stress ratio M_m		0.91		0.91		0.91	
Hardening parameter	B_0	2500	6000	1200	2000	2100	10000
	B_1	50	50	20	20	100	100
	C_f	0	270	0	220	0	280
Reference strain parameter	γ^E_r	0.02		0.05		0.004	
	γ^P_r	0.007		0.01		0.004	0.002
Dilatancy parameter	D_0	3.5	7.0	1.5	2.0	2.0	8.0
	n	2.5	2.4	2.0	2.0	4.5	4.5

Firstly, the results of Kasumigaura-sand are used for comparison. The time histories of excessive pore water pressure (E.P.W.P. in figures) obtained by the liquefaction analyses and the experimental tests are shown in Figure 12. The results from three different depths of the test ground on the shaking table were picked up, G.L.-20cm, G.L.-40cm and G.L.-60cm. From the results with Kasumigaura-sand, it can be seen that the proposed model can repress the increment in excessive pore water pressure more slowly than the one from the original model. Furthermore, the deeper the ground is, the more effective of the modification of the slowing down in the increment in excessive pore water pressure will be.

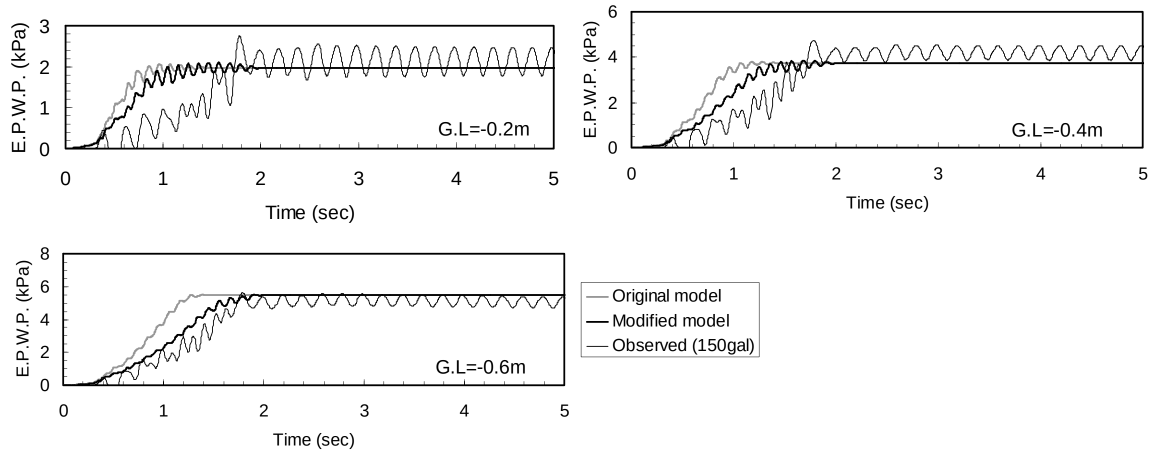


Figure 12 Comparison of E.P.W.P. on Kasumigaura-Sand

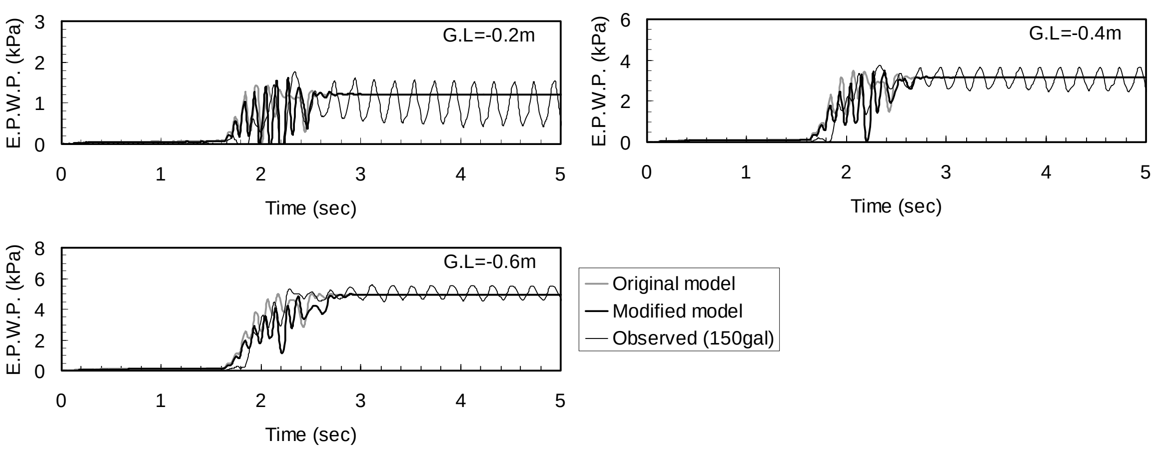


Figure 13 Comparison of E.P.W.P. on Gravel

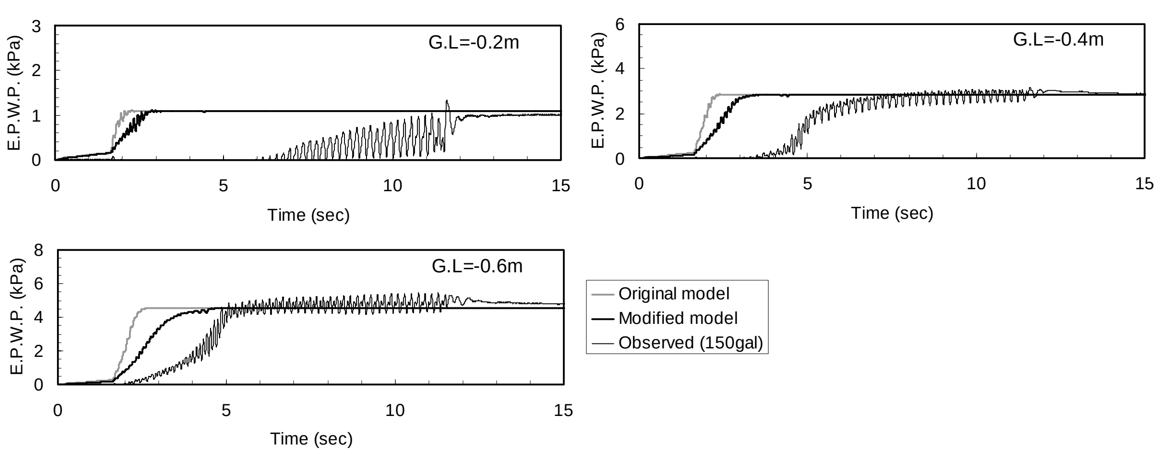


Figure 14 Comparison of E.P.W.P. on decomposed granite

Moreover, the same simulations were carried out to verify the proposed model on other materials, that are, decomposed granite and gravel. In the same way, the behaviors of three different depths of the test ground are computed for the time histories of E.P.W.P. for these geo-materials. The results are shown in Figures 13 and 14, respectively. In the results with gravel, it is found that there is little difference in each depth between original and proposed models. It is supposed that due to a very high permeability of the gravel, the new proposed model dose not affect E.P.W.P. obviously.

It can be seen that, however, for decomposed granite, there is clear difference of the change in excessive pore water pressure before liquefaction between original and new models. The increasing tendency of the change in excessive pore water pressure is clearly verified in the direction of depth, the same result as Kasumigaura-sand.

From the series of simulated results, validity of the proposed model to liquefaction analysis is verified except for decomposed granite. Furthermore, the importance of appropriate determination of parameters is confirmed. In this study, for instance, parameters for the simulation of Kasmigaura-sand are determined from the results of shaking table test using the same material.

CONCLUSIONS

In this paper, a modified constitutive model was proposed for the explanation of the reduction in ground stiffness caused by liquefaction. In order to verify the effectiveness of the proposed model, results of shaking table tests and cyclic triaxial tests using three kinds of geomaterials are presented, firstly. In the case of conventional compression triaxial tests, there is no much difference in different kind soils in the reduction of ground stiffness during liquefaction process. On the other hand, different soils show quite different pattern in the reduction of ground stiffness behaviors in the shaking table tests. The results of shaking table tests are used for verifying the modified constitutive model through boundary value problem, in which the real behavior of soils in gravitational stress field can be simulated. Therefore, comparisons between shaking table tests results and simulations were carried out. In new model, logistic function is introduced in for expressing slowly reduction of ground stiffness. As the result, in simulations, some improvements in describing the soil behaviors are confirmed by using the proposed function with the results of shaking table tests. Although, improvement is still needed in simulating the reduction of ground stiffness before and after liquefaction in the future research.

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