NUMERICAL SIMULATIONS FOR DEVELOPMENT OF LIQUEFACTION COUNTERMEASURES BY USE OF PARTIALLY SATURATED SAND

K. MITSUJI [1]

[1] *Assistant Professor, Dept. of Architecture and Building Science, Tohoku University, Sendai, Japan*
Email: mitu@archi.tohoku.ac.jp

ABSTRACT:

The objective of this paper is to demonstrate the advantage of utilizing partially saturated sand for liquefaction countermeasure using the numerical analyses. To be specific, seismic response of liquefiable ground including partially saturated sand layer are investigated through numerical analyses, where the increase of liquefaction strength of partially saturated sand is considered. Three types of the ground model are prepared for the numerical analyses. Numerical analyses for each ground model are conducted in the two cases of different saturation of the sand layer. Therefore, two cases of the ground model consisting of the completely saturated sand layers, and the ground model where the completely saturated sand layers are replaced with the partially saturated sand layers are considered. That can discuss the effects of the partially saturated sand for liquefaction. Results show the advantage of utilizing the partially saturated sand for the reduction of seismic response of the ground. As a result, it can point out that utilizing the partially saturated sand can lead to the development of the new countermeasure for liquefaction.

KEYWORDS: Liquefaction, partially saturated sand, effective stress analysis, liquefaction countermeasure

1. INTRODUCTION

It is well known that liquefaction resistance of partially saturated sand increases more than that of saturated sand in the laboratory tests. The saturation effects of soil for liquefaction have been pointed out by the results from laboratory tests such as simple shear test, torsional shear test, tri-axial compression test, and so on. Sherif [1] showed that liquefaction potential for soils decreases with low saturation by the results of torsional simple shear tests. Chaney [2] also indicated the saturation effects of partially saturated Monterey sand increased liquefaction strength using cyclic tri-axial tests. Yoshimi [3] conducted the undrained cyclic shear tests on partially saturated sand, and mentioned the beneficial effect of partially saturated sand for liquefaction resistance. Tsukamoto [4] also pointed out the saturation effects of partially saturated sand for liquefaction with respect to the velocity of longitudinal and shear wave velocities.

However, the saturation effects of partially saturated sand have been examined only in the laboratory tests. Therefore dynamic behavior of the ground including partially saturated sand layer during earthquake may not be completely understood, particularly when concerning the severe seismic excitation causing ground liquefaction. If the effects of increasing liquefaction resistance due to lower saturation are verified for observation in the actual site or in-situ test, and numerical simulation of seismic response of ground, the effective use of the advantage of partially saturated soil can lead to the development of the new and beneficial countermeasure for liquefaction. Recently some researchers start investigations on the development of the inventive countermeasure for liquefaction by use of this strong point of partially saturated sand [5][6][7]. This paper discusses the efficiency of utilizing partially saturated sand for liquefaction countermeasure through the numerical analyses using the one-dimensional effective stress analysis for the ground models including partially saturated sand layer.

2. LIQUEFACTION CHARACTERISTICS OF PARTIALLY SATURATED SAND

Liquefaction resistance of partially saturated sand is sensitive to the slight change of the saturation. Theoretical relationship between the degree of saturation and the B-value derived by Lade [8] is shown in Figure 1.

Skempton defined B-value as pore-pressure coefficient, and expressed by the compressibility of soil skeleton and fluid (gas and water) in the void [9]. The B-value takes one when concerning the completely saturated soil. Figure 1 indicates that the relation between the B-value and the degree of saturation shows strong non-linearity, and the B-value is suddenly dropped by decrease of the saturation.
Yoshimi [3] conducted undraied cyclic shear tests on partially saturated soil with hollow cylindrical torsional shear apparatus, and discussed the effects of degree of saturation to liquefaction resistance. Figure 2 illustrates the relation between the degree of saturation and liquefaction resistance ratio of Toyoura sand under the condition that Dr (relative density) =60%, effective stress $\sigma_c' = 98\,kPa$, and number of cycles to DA (double amplitude of shearing strain)=5% Nc=15. Liquefaction resistance of partially saturated sand in case of 70% of the degree of saturation is about three times as much as that of the completely saturated sand. Results of Figure 1 and Figure 2 show that utilizing the partially saturated sand can possibly leads to the effective countermeasure for liquefaction.

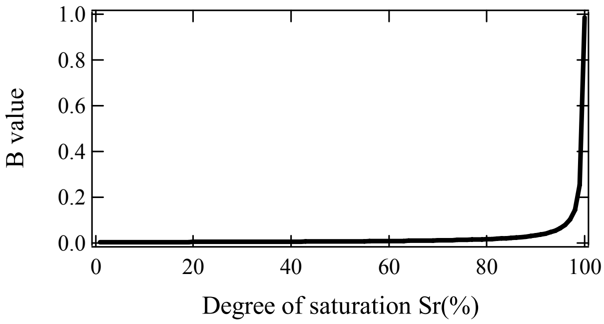


Figure 1 Theoretical relation between degree of saturation and B value (Lade and Hernandez)

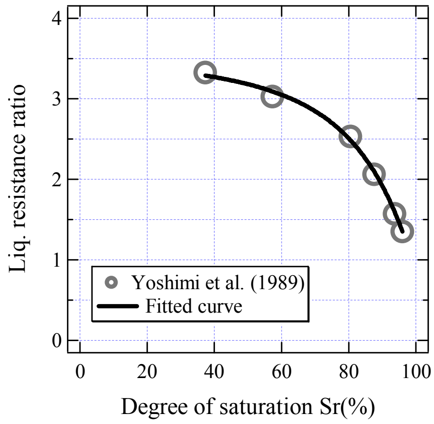


Figure 2 Liquefaction resistance ratio of partially saturated sand to completely saturated sand versus degree of saturation (Yoshimi et al.)

3. ONE-DIMENSIONAL EFFECTIVE STRESS ANALYSIS FOR LIQUEFIABLE GROUND

3.1. Numerical Simulation Using One-dimensional Effective Stress Analysis

In this section, we examine the seismic response of liquefiable ground including partially saturated sand layer. Comparing the results of the liquefiable ground including partially saturated sand layer to those consisting of the completely saturated sand layers, we also discuss the possibility of development of countermeasure for liquefaction. Computer code YUSAYUSA-2 [10][11] is adopted for the numerical simulation of one-dimensional effective stress analysis. First, the numerical simulation is conducted for the three types of liquefiable ground with saturated sand layer. Another numerical simulation is conducted with partially saturated sand layer instead of saturated sand layer. Results of both cases of the saturated sand layer and the partially saturated sand layer are compared, and the effects of partially saturated sand layer to the seismic response of the ground will be discussed.

3.2. Ground Model

Figure 3 shows the ground models for the numerical simulation. Three cases of the ground model are referred to Ohsaki [12], and depicted as the major types of soil deposits in alluvial plain area of Japan. Three kinds of stratum (Sand1, Sand2, Clay) are adopted as the element layers composing the ground models. Each ground model has the 20 meters depth for all cases. Sandy gravel layer below GL-20m is assumed the rigid bedrock. Water table is at GL-2m. In the Case-1, the ground model consists of two kinds of sand layer, which are named as Sand1 and Sand2. This case is considered most susceptible to liquefaction. In the Case-2, the alluvial clayey

layer is inserted between the soft sandy layer of Sand1 and the rigid sandy gravel layer. In the Case-3, Sand2 layer underlies Sand1 and Clayey layer, and the ground model consists of Sandy-Clayey-Sandy mixture. For the Case-1, the layer of Sand1 and Sand2 are liquefiable layer. For the Case-2 and Case-3, the layer of Sand1 is the only liquefiable layer, and Sand2 and Clayey layer are assumed to be "not liquefiable".
Physical parameters of each layer are shown in Table 1. Shear wave velocity is set up to vary along with the depth. This considers the experimental result in which shear modulus of soil is proportional to the root of the effective stress at the arbitrary depth.

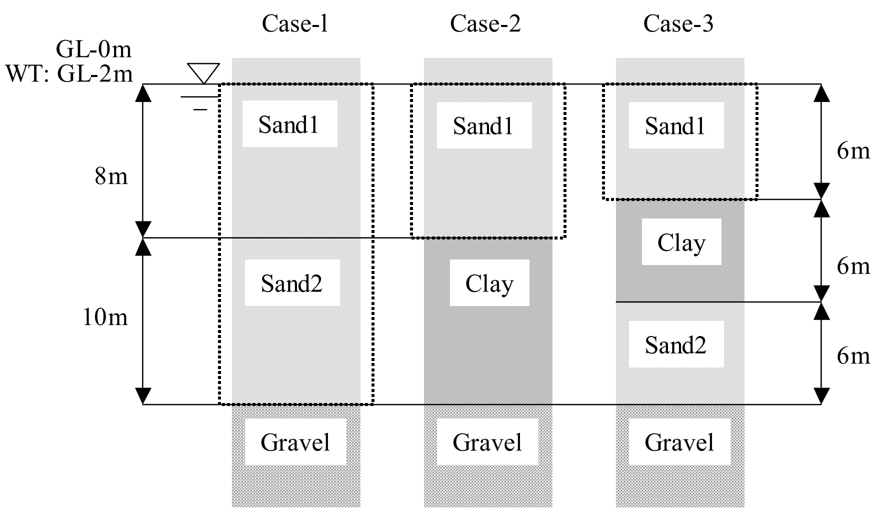


Figure 3 Schematic ground model for 1D effective stress analysis
Saturated sand layers in the dotted area are replaced with partially saturated sand layers in which liquefaction resistance doubles

Table 1 Physical parameters of each layer for numerical analysis

		Sand 1	Sand 2	Clay
Shear wave velocity	Vs(m/s)	120～220	220～250	200～225
Weight density	ρ(kN/m^3)	17.6	17.6	16.6
Angle of internal friction	ϕ (°)	25	30	
Cohesion	C(kN/m^2)			90～100
Coeff. of permeability	k(m/s)	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-8}

3.3. Parameters for Liquefaction

In the numerical simulation, the liquefaction resistance of saturated sand is defined by the shear stress ratio to the effective stress $\tau/\sigma'=0.18$, when reaching DA=5% at the 20th cycle. On the other hand, the liquefaction resistance of partially saturated sand is assumed to be twice as much as the saturated sand, which is $\tau/\sigma'=0.36$ when reaching DA=5% at the 20th cycle. Figure 4 shows one example of the liquefaction potential of the saturated and partially saturated sand model for the numerical simulation. YUSAYUSA-2 requires the two parameters of Bu and Bp relevant to the pore water pressure building up. Therefore, those two parameters are also related to the liquefaction potential. In carrying out the numerical simulation, we assume Bp=2.50, Bu=0.38 for saturated sand, Bp=0.08, Bu=0.03 for the partially saturated sand that correspond to the liquefaction potential of $\tau/\sigma'=0.18$ and $\tau/\sigma'=0.36$, respectively. It is also noted that the computer code Simmdl-2 [13] helps search for the suitable parameters Bp and Bu to the liquefaction potential.

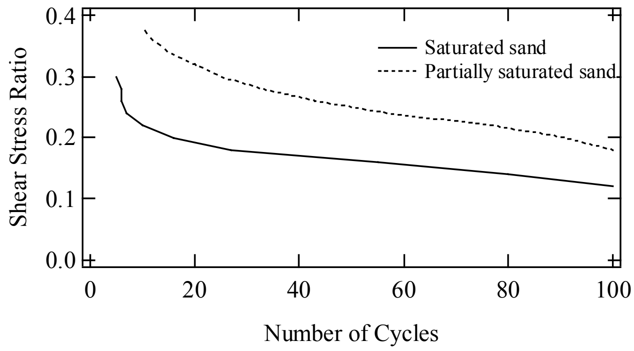


Figure 4 Example of liquefaction potential of saturated and partially saturated sand

3.4. Dynamic Response Analysis

Dynamic response analysis is conducted by YUSAYUSA-2 using those parameters mentioned above. Soil deposits are modeled into a lumped mass model with shear spring and dashpot. Length of each element is one meter. Artificially simulated wave of BCJ-L2 [14] is adopted as the input motion of which maximum acceleration is scaled as 200cm/s^2 at the top of the sandy gravel layer (GL-20m). Time history of BCJ-L2 wave is shown in Figure 5. Step by step time integration is performed by Newmark-β method, where time increment is 0.01s. Parameter β for time integration takes 1/4 in this simulation. The numerical simulations are carried out in two cases for each ground model. One is the case that the sandy layer of Sand1 is postulated the completely saturated and highly susceptible to liquefaction. Another is the case that the sandy layer of Sand1 is assumed the partially saturated sand by soil improvement such as "bubble injection technique". For the Case-1, both sandy layers of Sand1 and Sand2 are assumed the partially saturated sand layers where the liquefaction potential is $\tau/\sigma' = 0.36$, and Bp=0.45, Bu=0.05. Comparing two cases for each ground model, the efficiency of utilizing the partially saturated sand for liquefaction countermeasure can be discussed. In the following, the simulation case considering the layers of Sand1 and Sand2 completely saturated is called 'the saturated sand case', and the simulation case considering the layers of Sand1 and Sand2 partially saturated, or only Sand1 partially saturated is called 'the partially saturated sand case'.

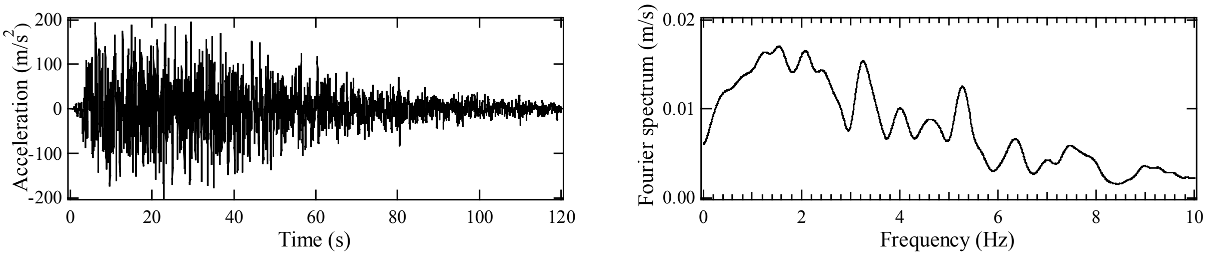


Figure 5 BCJ-L2 wave as input motion (Time history and Fourier spectrum) [14]

4. RESULTS AND DISCUSSIONS

4.1. Stress-strain Relation

Figure 6 shows the stress-strain relation of sand layer at GL-15m in the Case-1. The left figure illustrates the stress-strain relation in case of the saturated sand, and the right figure corresponds to that of the partially saturated sand. The stress-strain relation of the saturated sand indicates strong non-linearity, and shows the large shearing strain caused by liquefaction. In the case of the partially saturated sand, although the stress-strain relation shows non-linear hysteresis loop, liquefaction doesn't occur at this depth. Shearing strain is relatively small compared to that of the saturated sand. Therefore, converting the saturated sand layer into the partially saturated sand layer can lead to the control of liquefaction occurrence. Figure below the stress-strain relations in

Figure 6 shows the time history of the excess pore water pressure ratio of the sand layer at GL-15m for the saturated and partially saturated sand cases in the simulation case of the Case-1. Behavior of generating the excess pore water pressure is quite different, and it is not found that the excess pore water pressure generated enough to cause liquefaction.

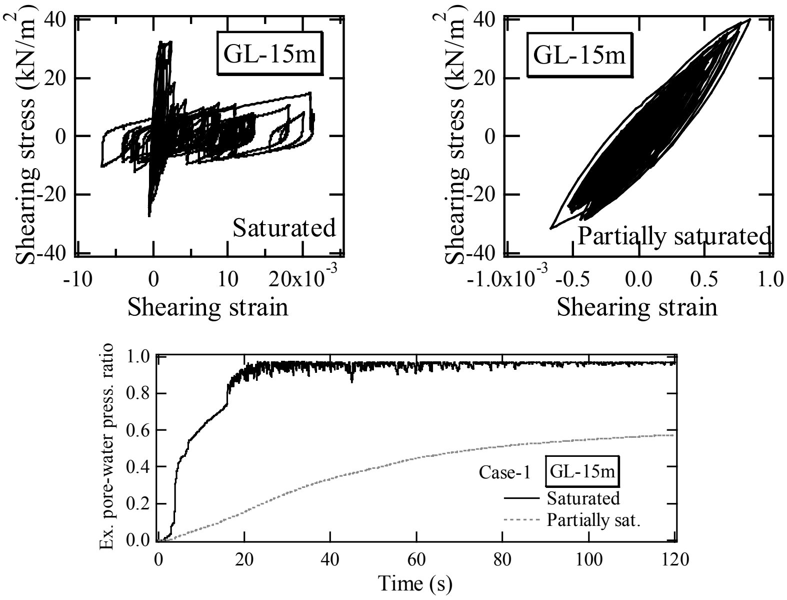


Figure 6 Stress-strain relation and excess pore water ratio of sandy layer at GL-15m (Case-1)

4.2. Time Histories of Response Acceleration and Excess Pore Water Pressure

Figure 7 shows the time histories of the response acceleration at the ground surface (GL-0m), and the excess pore water ratio at GL-6m for each simulation case. In order to focus the period of time around maximum acceleration, the response accelerations are shown during 0 to 30 (s). FortheCase-1, the response accelerations at the surface are reduced by the degradation of the shear modulus of sand layers resulted from liquefaction. For the Case-2 and Case-3, the response acceleration in the partially saturated case shows the large amplitude compared to that in the saturated case. In particular, from 5(s) to 13(s) in the partially saturated sand case, it can be seen that the response acceleration becomes large amplified. Comparison to the results of the excess pore water pressure ratio makes it clear that liquefaction doesn't occur in that period of time from 5 to 13 (s). This phenomenon is not found in the saturated sand case.
Concerning the time histories of the excess pore water pressure ratio, it should be noted that although the behavior of the excess pore water pressure ratio of the saturated sand case is similar for all the three cases, which of partially saturated sand case is quite different. For the Case-1, the excess pore water pressure ratio of the saturated sand case is almost the same as the partially saturated sand case, except after about 60(s) the pore water pressure begins to dissipate. For the Case-2 and Case-3, building up of the excess pore water pressure in the partially saturated sand case delays compared to that in the saturated sand case. In particular, the excess pore water pressure ratio of the Case-2 in the partially saturated sand case reaches to the level of liquefaction just before 30(s). Those results are attributed to the saturation effects of partially saturated sand for liquefaction.

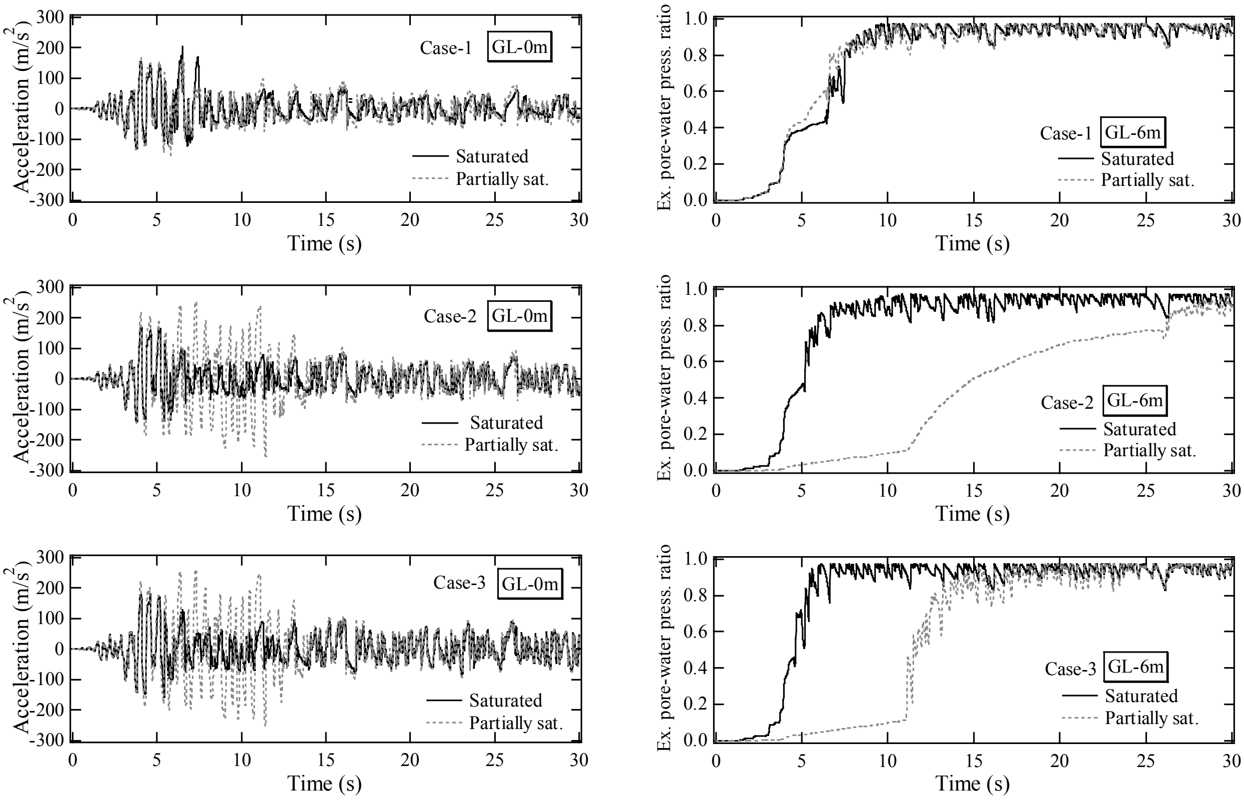
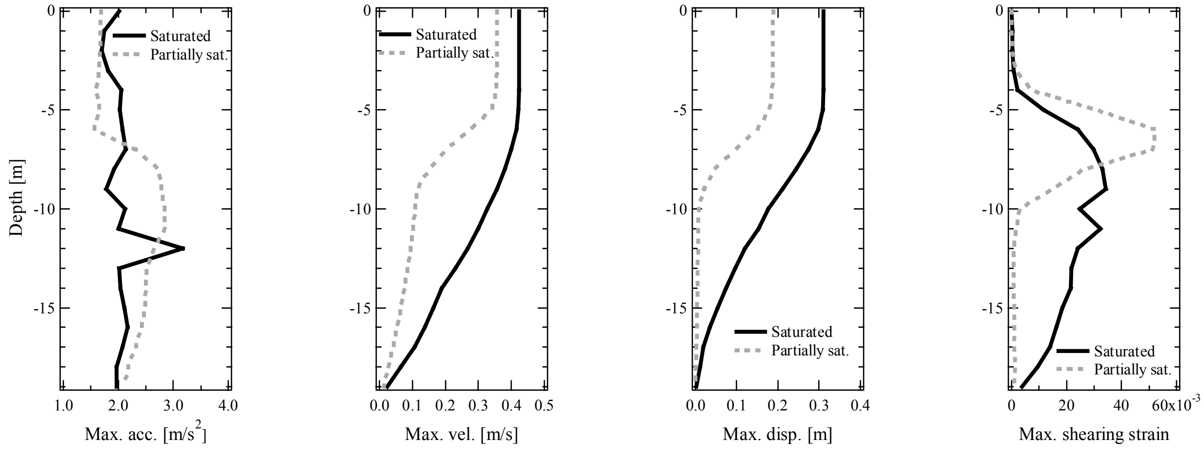


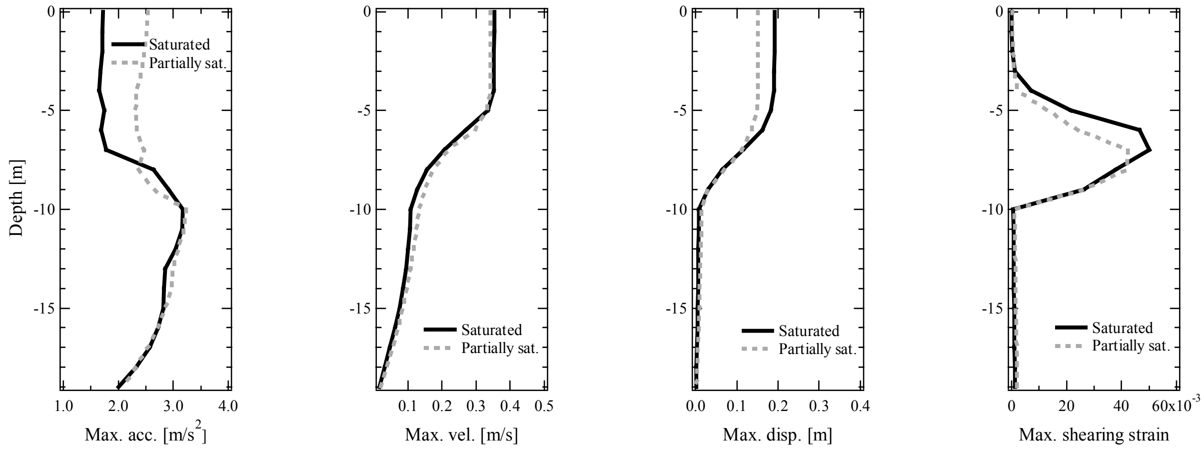
Figure 7 Time histories of acceleration and excess pore water pressure ratio

4.3. Distribution of Maximum Response in Ground

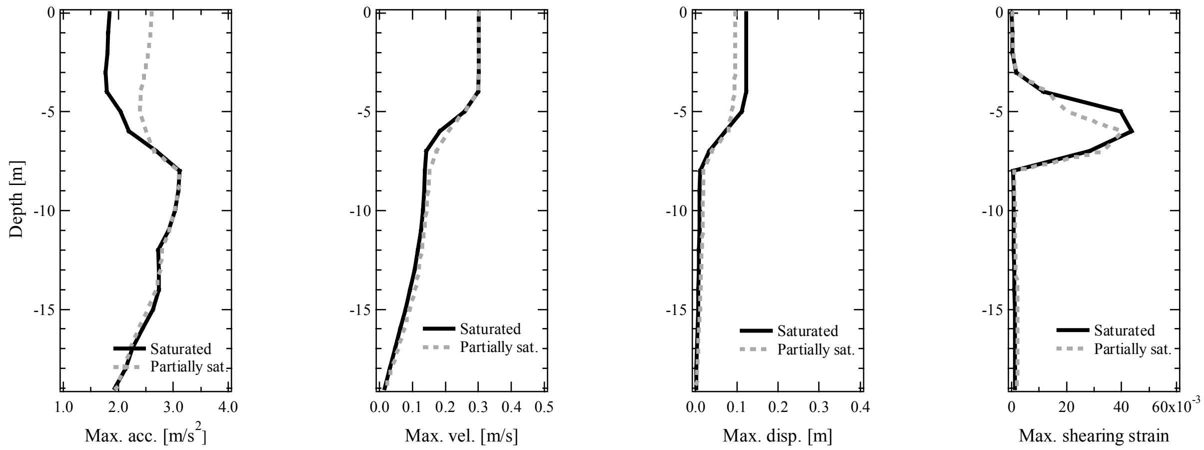
Figure 8 shows the maximum response distributions in the ground for each case. Concerning the maximum acceleration at the ground surface, both cases of saturated sand and partially saturated sand have the slight difference due to liquefaction. Even when replacing the saturated sand layer to the partially saturated sand in all the layers above GL-20m, liquefaction occurs in the layers of Sand1 (from GL-10m up to GL-2m). Below GL-15m in the layers of Sand2, liquefaction doesn't occur in the partially saturated sand case.
Therefore, the maximum response acceleration becomes less than the saturated sand case. The maximum response velocities and displacements have the same tendency that the responses increase in the layer of Sand1 above GL-10m. In the partially saturated sand case, the responses are highly reduced with respect to response velocities and displacements. Shearing strain for the saturated sand case is quite large from GL-20m up to about GL-5m due to liquefaction. On the other hand, the shearing strain decreases in the layers of Sand2 (from GL-20m up to GL-10m) in the partially saturated sand case. However, the layers of Sand1 are liquefied from GL-10m up to about GL-5m even if the saturation effects of the partially saturated sand layers are considered. It should also be noted that replacing the saturated sand layers with the partially saturated sand layers in the deeper area is effective to reduce the maximum responses of the ground.
For the Case-2 and Case-3, the maximum responses indicate almost the same distribution patterns. The response accelerations are decreased in the upper layers of Sand1 due to the degradation of the shear modulus caused by liquefaction in the saturated sand case. In the partially saturated sand case, the response accelerations in the upper layers become larger than the saturated sand case, because the shearing moduli of the layers of Sand1 are not so great. With respect to the response velocity, displacement, and shear strain, the responses are reduced in the partially saturated sand case compared to the saturated sand case, although the amount of reduction is less than the Case-1. On the whole, it is worthy noted that the effects of the partially saturated sand for liquefaction are found out in the results of the seismic response analysis through one-dimensional effective stress analysis.



(a) Distribution of maximum acceleration, velocity, displacement, and shearing strain of Case-1



(b) Distribution of maximum acceleration, velocity, displacement, and shearing strain of Case-2



(c) Distribution of maximum acceleration, velocity, displacement, and shearing strain of Case-3

Figure 8 Maximum response distribution in ground

5. CONCLUSIONS

On the assumption of replacing the completely saturated sand layers in the liquefiable ground with the partially saturated sand layers, the seismic response of the ground and lateral resistance of a pile are investigated through the numerical analyses. Calculations are carried out under the condition that liquefaction resistance of the partially saturated sand layer doubles compared to the saturated sand layer.
The one-dimensional effective stress analysis clarifies the reduction of the maximum response of velocity, displacement, and shearing strain in the ground due to the saturation effects of the partially saturated sand layer, while the maximum response of acceleration in some layers becomes more than in case of the saturated sand. Therefore, replacing the saturated sand layer with the partially saturated sand layer can control the liquefaction occurrence. That can lead to the development of the new and economical countermeasure for liquefaction.

REFERENCES

1. Sherif, M. A., Ishibashi, I., and Tsuchiya, C., Saturation effects on initial soil liquefaction, Journal of Geotecnical Engineering Division, ASCE, 1977, 914-917
2. Chaney, R. C., Saturation effects on the cyclic strength of sands, Earthquake Engineering and Soil Dynamics, ASCE, **Vol.1**, 342-358, 1978
3. Yoshimi, Y., Tanaka, K. and Tokimatsu, K., Liquefaction resistance of a partially saturated sand, Soils and Foundations, **Vol.29**, No.3, 157-162, 1989
4. Tsukamoto, Y., Ishihara, K., Nakazawa, H., Kamada, K. and Huang, Y., Resistance of partially saturated sand to liquefaction with reference to longitudinal and shear wave velocities, Soils and Foundations, **Vol.42**, No.6, 93-104, 2002
5. Ohtsuki, A., Fukutake, K., and Miyake, M., Preventive measure of liquefaction by decreasing saturation ratio – Part 3: Effect of partial saturation on decreasing residual settlement -, the 38th Japan National Conference on Geotechnical Engineering, 1979-1980, 2003 (in Japanese)
6. Nishigaki, M., Komatsu, M., Yoshioka, S., Uemura, K., Ouchi, M., and Sakue, M., A study on the development of preventive method for liquefaction during earthquake by creating unsaturated sandy ground, the 40th Japan National Conference on Geotechnical Engineering, 1313-1314, 2005 (in Japanese)
7. Mitsuji, K., Reduction of seismic response of liquefiable ground by use of unsaturated sandy soil and its effect to lateral resistance of single pile, the 12th Japan Earthquake Engineering Symposium, 714-717, 2006 (in Japanese)
8. Lade P. V. and Hernandez S. B., Membrane penetration effects in undrained tests, Journal of Geotecnical Engineering Division, ASCE, 1977, 109-125
9. Skempton, A. W., The pore-pressure coefficients A and B, Geotechnique, **Vol.4**, No.4, 143-147, 1954
10. Ishihara, K., and Towhata, I., One-dimensional soil response analysis during earthquake based on effective stress method, Journal of the Faculty of Engineering, **Vol. XXXV**, No.4, The University of Tokyo, 656-700, 1980
11. Yoshida, N., and Towhata, I., YUSAYUSA-2 Version 2.10, 2003
12. Ohsaki, Y. and Sakaguchi, O., Major types of soil deposits in urban areas in Japan, Soils and Foundations, **Vol.13**, No.2, 255-270, 1973
13. Yoshida, N., and Towhata, I., Simmdl-2, 2003
14. The building center of Japan, http://www.bcj.or.jp/download/wave.html