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SHAKE TABLE TESTS ON QUALITY EVALUATION PROCEDURE FOR AN UNSATURATION METHOD FOR LIQUEFACTION CONUTERMEASURES

H. Nakazawa[(1)], K. Nagao[(2)], K. Tabata[(3)], S. Maeda[(4)], A. Susami[(5)] and M. Jinguuji[(6)]

[(1)] *Research Fellow, National Research Institute for Earth Science and Disaster Resilience, nakazawa@bosai.go.jp*
[(2)] *Senior Researcher, Advanced Construction Technology Center, nagao@actec.or.jp*
[(3)] *Chief Researcher, National Research Institute for Earth Science and Disaster Resilience, tabata@bosai.go.jp*
[(4)] *Director, Sato Kogyo Co., Ltd., S.Maeda@satokogyo.co.jp*
[(5)] *Researcher, Sato Kogyo Co., Ltd., a.susami@satokogyo.co.jp*
[(6)] *Senior Researcher, National Institute of Advanced Industrial Science and Technology, m.jinguuji@aist.go.jp*

Abstract

Since an unsaturation or desaturation construction method for liquefaction countermeasures is inexpensive and simple, its introduction specially to housing sites have been examined after the 2011 off the Pacific coast of Tohoku earthquake. Although the mechanism of injecting air bubbles for unsaturation is almost understood, in-situ quality evaluation procedure of its introduction effectiveness has not been established yet. For the contribution to developing the quality evaluation procedure in situ, the authors conducted a shake-table test of saturated and unsaturated model grounds and performed field investigation by a dynamic cone penetrometer to recognize ground condition before shaking. The test and following consideration in this paper are based on the results of investigation using the dynamic cone penetrometer with a piezo drive cone (PDC) carried out at the experimental site for an unsaturation method and at a model ground in a container. The cone penetration tests obtained excess pore water pressure change and dynamic cone resistance, employed to evaluate the condition and variation of saturation of ground. In addition, the liquefaction behavior observed by accelerometers and pore water pressure transducers during shaking in the grounds is compared. Throughout the test results, the behavior of excess pore pressure change induced by cone penetration in the saturated and unsaturated grounds before shaking is identified. The consideration in this paper indicates the applicability of the quality evaluation procedure based on the mechanism of excess pore water pressure change.

Keywords: saturation condition, dynamic cone penetration, excess pore water pressure, shake table test

1. Introduction

It is commonly premised that liquefaction can occur in a sandy soil layer below groundwater level in fully saturated condition. However, since there is no technique and experience to directly obtain in-situ saturation degree, it has been pointed out that the soil layer below groundwater level is not always fully saturated when liquefaction occurs [1]. Besides, several studies have been made on characteristics of liquefaction of unsaturated soil and showed that liquefaction resistance increases with saturation decreasing [2]. In such circumstances, unsaturation or desaturation construction methods as liquefaction countermeasures have been developed.

In general, unsaturation construction methods are roughly classified into groundwater-level lowering and air injecting. Since lowering groundwater level causes intentional settlement during construction, the method may not suitable especially for housing sites. On the other hand, an air-injection method discussed in this paper is cost-effective and simple, and has been actively examined and introduced to a construction site on trial [3]. The mechanism of air injection contributing to liquefaction resistance improvement has almost clarified, while it is necessary to establish assessment procedure of its qualification by estimating saturation condition of the improved ground. To evaluate saturation condition of ground, the authors have performed dynamic cone penetration tests by the penetrometer with a piezo drive cone (PDC) and a variable energy dynamic cone penetrometer (VEDCP) for the model ground in a container [4]. This paper describes the following examination about a shaking test of saturated and unsaturated model grounds in a large soil container in order to investigate the behavior of pore water pressure change. Cone penetration tests with the observation of acceleration and power water pressure change were also performed in these grounds before shaking.

2. Shaking test program

In the examination described in this paper, the authors prepared the model grounds of saturated and unsaturated conditions, and cone penetration tests were performed after the preparation of these grounds and before the shaking test. The results of the cone penetration and shaking tests are explained in the latter chapters.

2.1 Properties and indices of soil for the model ground

Table 1 presents properties and indices of the soil for the model grounds in saturated and unsaturated conditions. The model grounds consisted of No.6 Iide silica sand. The grain-size distribution curve of the soil is shown in Fig.1. The table and figure illustrate that the soil is almost uniform with the mean grain size, D_{50}, of 0.299mm.

Table 1 - Properties and indices of No.6 Iide silica sand used for the model grounds.

Density of soil particles	ρ_d	(g/cm^3)	2.651
Maximum grain size	D_{max}	(mm)	0.850
Fine content (<0.075 mm)	F_c	(%)	0.7
Mean particle size	D_{50}	(mm)	0.299
Uniform coefficient	U_c		1.778
Minimum density	ρ_{dmin}	(g/cm^3)	1.413
Maximum density	ρ_{dmax}	(g/cm^3)	1.744
Maximum void ratio	e_{max}		0.876
Minimum void ratio	e_{min}		0.520

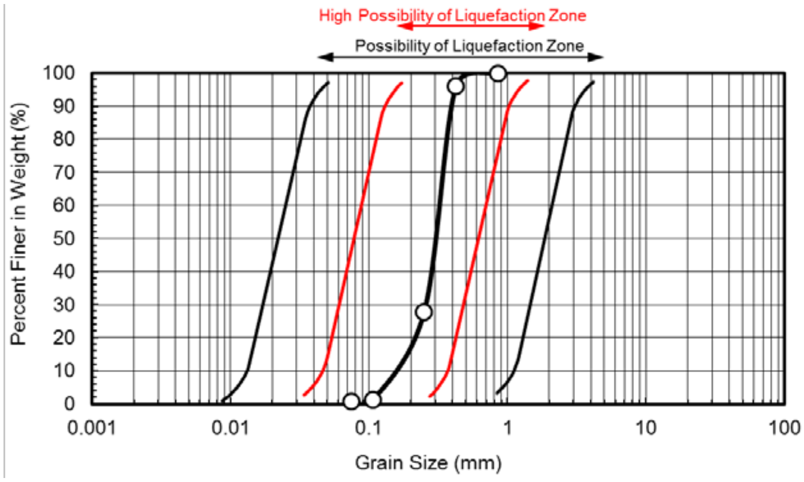

Fig.1 - Grain size distribution of No.6 Iide silica sand used for the model grounds.

This soil is very liquefiable because its liquefaction resistance, Rl, is about 0.170 obtained from undrained cyclic triaxial tests for the specimen with the relative density, D_r, of 60%.

2.2 Preparation of the model grounds

The model grounds were prepared in a soil container. As shown in Photo 1, the container of 4m long, 1.3m wide and 1.5m deep was divided into two parts to set the grounds with different saturation conditions.

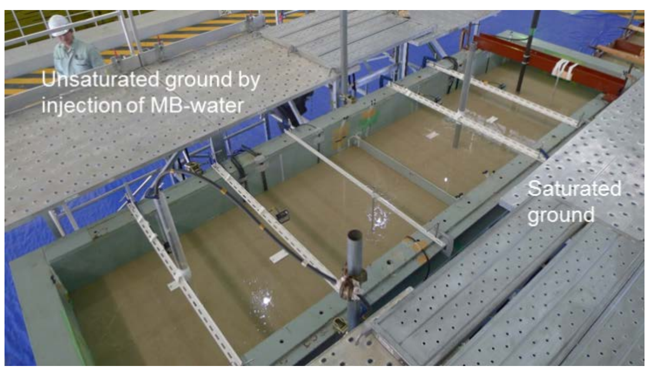

Photo 1 - The model grounds prepared in the container divided by two parts to set different saturation conditions.

Figure 2 presents the section of the model grounds. The grounds were prepared by air pluviation of the silica sand, reaching 1.2m thick. After its preparation, it was confirmed that D_r on average was 57% calculated by the volume of used sand. After the grounds reaching to 1.2m thick, pore water was injected into the grounds from the bottom of the container. For the saturated model ground, tap water was injected from the bottom to the surface under constant water head. For the unsaturated model ground, mixture of micro-air bubble and water (MB water) was injected to the ground. MB water is used for an MB-water construction method as liquefaction countermeasures. The MB-water contained air bubbles with diameter ranging between 10 and 100μm. The MB-water was pressurized to about 220kPa at its generator. This pressure level was decided based on previous researches and experiences. The pressurized MB-water was supplied from the generator to the unsaturated ground. Since it was possible that the pressure of the MB-water at the injection holes could become too high for the ground, 6cm-long 3/8-inch flexible tube covered a part of the injection holes to adjust the pressure appropriately [3]. After the injection, a time-domain-reflectometry soil-moisture meter obtained about 90% in S_r in the unsaturated ground in the case that S_r in the saturated ground was assumed as 100%.

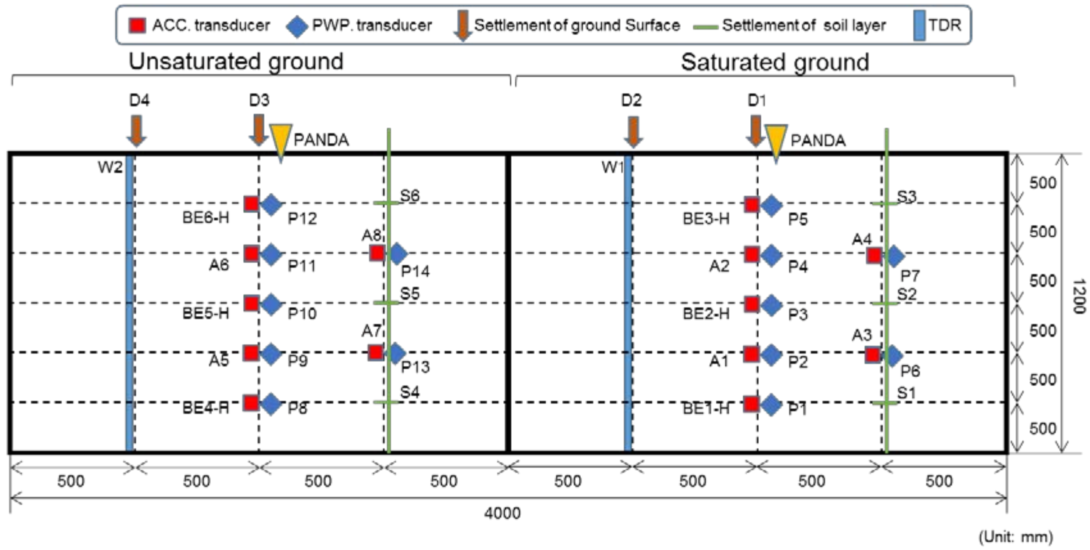

Fig.2 - Section of the model grounds prepared in the container and the locations of transducers and cone penetration points.

2.3 Measuring instruments

At the model grounds, as indicated in Fig.2, pore water pressure (PWP) transducers, accelerometers for acceleration (ACC) in the grounds, and displacement transducers for settlement of the ground surfaces and soil layer were placed. Figure 2 shows the distribution of the PWP and ACC transducers arranged at intervals of 20cm in the horizontal direction. Additionally, ACC transducers were installed at the depth of 20cm, 60cm and 100cm in vertical direction to measure P-wave velocity of both saturated and unsaturated model ground. This study mainly discusses the results obtained from these PWP and ACC transducers in the cone penetration and shaking tests.

2.4 Input motion of the shaking test

In the shaking test after the model preparation and the following cone penetration test, the model grounds were shaken horizontally in one direction of sinusoidal input motion with 5Hz frequency and 2-second durations of increasing, steady and decreasing processes, as shown in Fig.3. In this test, two shaking cases with different maximum acceleration settings were carried out. The double acceleration amplitude of the first case was 50gal, while that of the second case was 300gal.

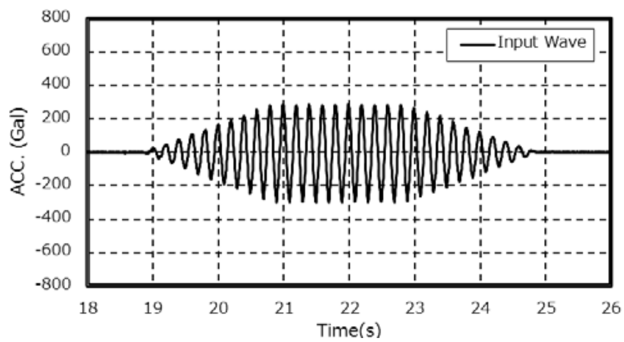

Fig.3 - Input motion of the shaking test.

3. Cone penetration tests

To investigate saturation condition of the saturated and unsaturated grounds before shaking, the cone penetration tests with a variable energy dynamic cone penetrometer (VEDCP) generally called as “PANDA” were conducted, as shown in Photo 2, obtaining dynamic cone resistance, q_{d}, as well as pore water pressure change by transducers in these grounds when its penetrating. The VEDCP cone was penetrated at the points from about 15cm of ACC or PWP transducer lines, as presented in Fig.2.

Photo 2 - Cone penetration test with a variable energy dynamic cone penetrometer in the container.

3.1 Penetration test program

Figure 4 presents the schematic diagram of a VEDCP test and Photo 3 shows its apparatus [5]. In a VEDCP test, extension rods with a cone (16mm in diameter and 90 degrees of the top angle) is penetrated by a 2kg-hammer blow with any energy input. For each hammer blow, the VEDCP provides the depth of cone penetration and the speed of impact, yielding q_{d} at each depth. A VEDCP can be operated by one man in a small space, and used with variable energy for cone penetration. It also needs a short period of test time and shows its results immediately after the test. The depth of cone penetration is measured by a retractable tape, and the speed of impact is acquired by the accelerometers in the anvil. q_{d} is calculated by the following:

$$q_d = \frac{1}{A} \frac{\frac{1}{2} M V^2}{1 + \frac{P}{M}} \frac{1}{x} \tag{1}$$

where A is the area of the cone, M is the weight of the striking mass, P is the weight of the struck mass, V is the speed of impact and x is the depth of cone penetration by the blow.

To estimate the saturation condition as well as conduct the VEDCP, measurements of elastic wave velocities were tried and that method was carried out by the almost same way as PS-logging in situ. P-wave and S-wave were generated by striking vertically and levelly to the small wooden plate put on the surface of model grounds by a small hand-held hammer, and then they were received by a set of ACC in the model ground, respectively.

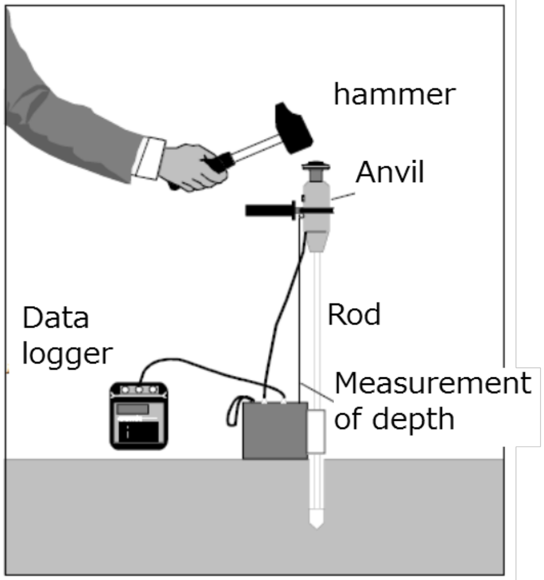

Fig.4 - Schematic diagram of a cone penetration test with a variable energy dynamic cone penetrometer (VEDCP).

Photo 3 - VEDCP apparatus; (a) hammer, (b) extension rod and (c) cone.

3.2 Test results of cone penetration and time histories of pore water pressure change induced by penetration

Figure 5 presents the distributions of P-wave velocity, V_p, S-wave velocity, V_s and q_d obtained from the saturated and unsaturated grounds before the shaking test. Though the tendency of V_s distribution shows that saturated and unsaturated conditions are almost similar, the remarkable difference in V_p distribution in a shallow depth can be seen and it is confirmed that V_p of the saturates case larger than that in the unsaturated case. However, the reason that V_p distribution of the saturated case showed the coincidence with unsaturated case in a deeper depth than GL.-60cm is unclear.

The q_d distributions both in the saturated and unsaturated grounds show the same tendency and indicates 0.5MPa or less above the level of 0.9m deep. Figure 5 also shows the depths of PWP and ACC transducers placed in the saturated and unsaturated grounds for reference later.

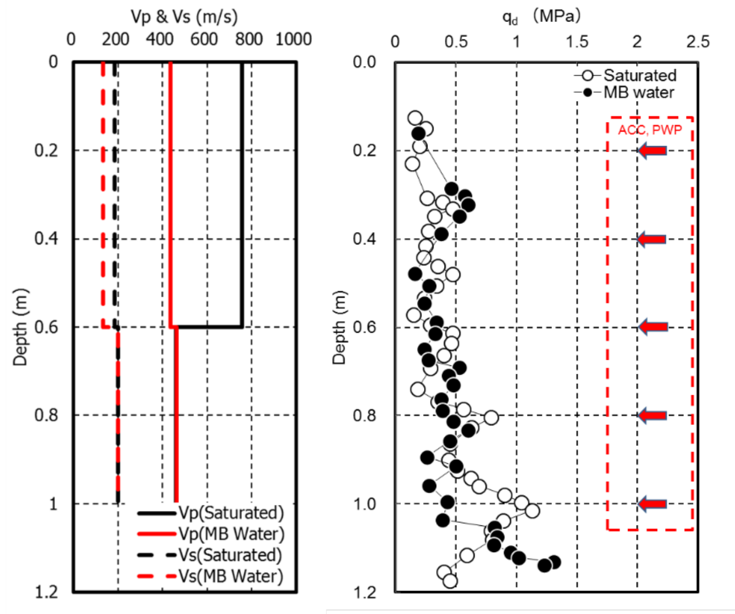

Fig.5 - Distributions of (a) elastic wave velocities and (b) dynamic cone resistance in the saturated and unsaturated grounds before shaking, and the depths of pore water pressure transducers and accelerometers.

To understand the change of pore water pressure induced by cone penetration, Figs. 6 and 7 present the change at 0.2m deep in the saturated and unsaturated grounds, respectively, as one example. In each figure, (a) and (b) show the results measured by ACC and PWP transducers. These figures also contain the areas surrounded by a broken line, representing the response caused by cone penetration when a cone reached at the closest depth of each transducer. In (a) and (b) in Figs. 6 and 7, the accelerations when a cone penetrating are about 20-40gal, while the pore water pressures are about 0.2-0.8kPa, illustrating there are no significant differences between the saturated and unsaturated conditions. With respect to the dissipation processes of pore water pressure shown in (b) and (c) in Figs. 6 and 7, the dissipation in the unsaturated ground seems slower than that in the saturated ground.

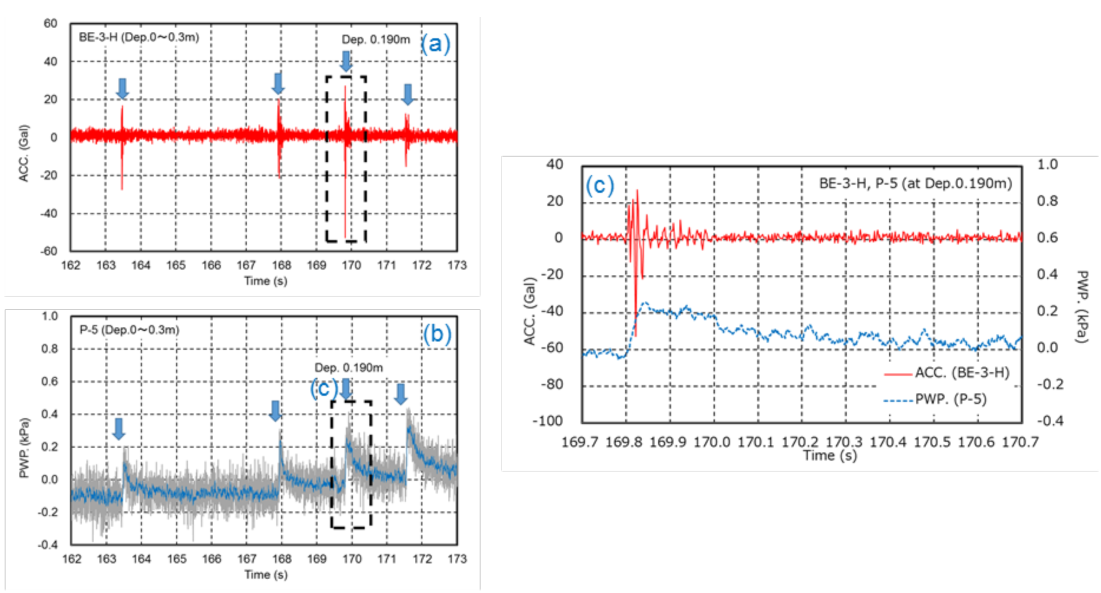

Fig.6 - Time histories of (a) acceleration and (b) excess pore water pressure at the depth of 0.2m in the saturated ground and (c) these enlarged diagram focusing the duration of cone penetration.

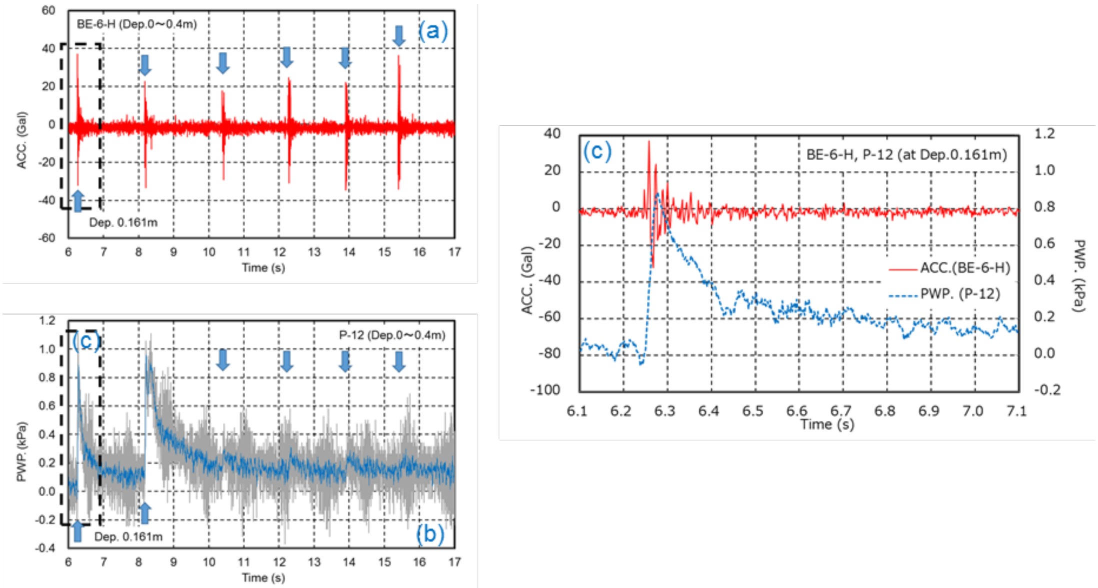

Fig.7 - Time histories of (a) acceleration and (b) excess pore water pressure at the depth of 0.2m in the unsaturated ground and (c) these enlarged diagram focusing the duration of cone penetration.

3.3 Response influenced by cone penetration of various saturation conditions

Figure 8 presents the distributions of q_d at the depths of transducers as well as the maximum accelerations (ACC) and the maximum excess pore water pressures (EPWP) obtained from each transducer. q_d is larger at the deep layer of the saturated ground, demonstrating the ground was somewhat denser than the unsaturated ground. Although ACC at most levels are similar in both grounds, ACC at the depth of 0.4m in the unsaturated ground is larger than that in the saturated ground even though both q_d are almost same. EPWP in the unsaturated ground become larger than those in the saturated ground except in shallow layer.

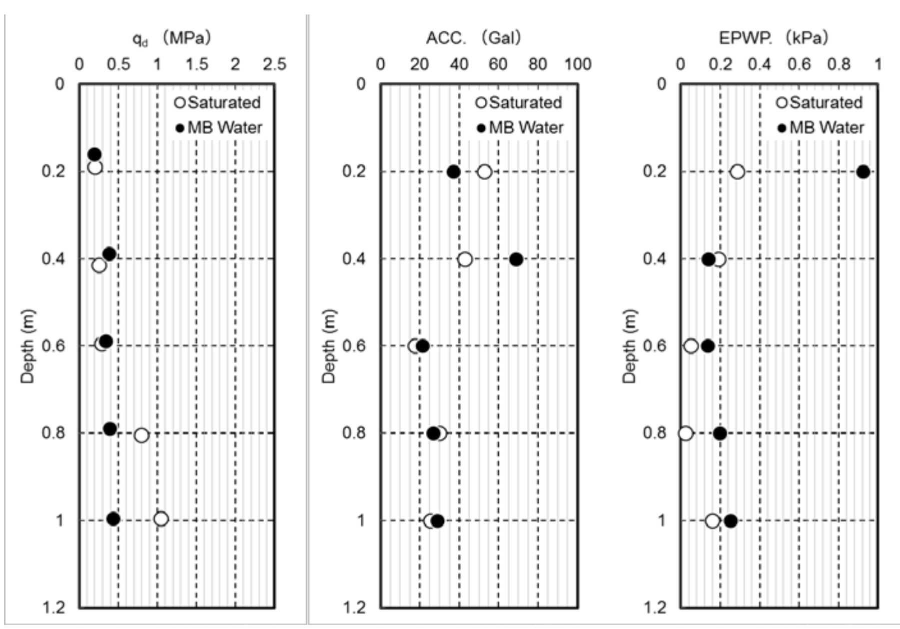

Fig.8 - Distributions of (a) dynamic cone resistance, (b) the maximum acceleration and (c) the maximum excess pore water pressure at the depths of transducers placed in the saturated and unsaturated grounds.

Figure 9 presents the distributions of corrected q_d, q_{d1}, excess pore water pressure ratio, $\Delta u/\sigma'_v$ and B-value of the model grounds calculated from V_p and V_s indicated in Fig.5. Here, q_{d1} is calculated by the following equation that is based on the Liao's proposed equation employing a conversion N-value, N_1, with effective overburden pressure, σ'_v, of 98kPa [6]:

$$q_{d1} = q_d \sqrt{\left(\frac{98}{\sigma'_v}\right)} \tag{2}$$

Additionally, on the estimated B-value shown in Fig.5, it was demonstrated that the ratio of the two velocities, V_p/V_s is expressed in the following equation, based on the theory of wave propagation through a porous medium,

$$\left(V_p/V_s\right)^2 = \frac{4}{3} + \frac{2(1+\nu_b)}{3(1-2\nu_b)(1-B)} \tag{3}$$

where ν_b is a skeleton Poisson's ratio, which recommended value was 0.35 in past study[7]. As a result, B-values in shallow depth were 0.8 for saturated ground and 0.67 for unsaturated ground respectively.

The tendencies of the q_{d1} distributions in both grounds are almost similar to those of the q_d distributions. Figure 9 also presents distributions of excess pore water pressure ratio, $\Delta u/\sigma'_v$, illustrating little difference between $\Delta u/\sigma'_v$ in the saturated and unsaturated grounds except at 0.2m deep, regardless of the different B-values in both saturation conditions.

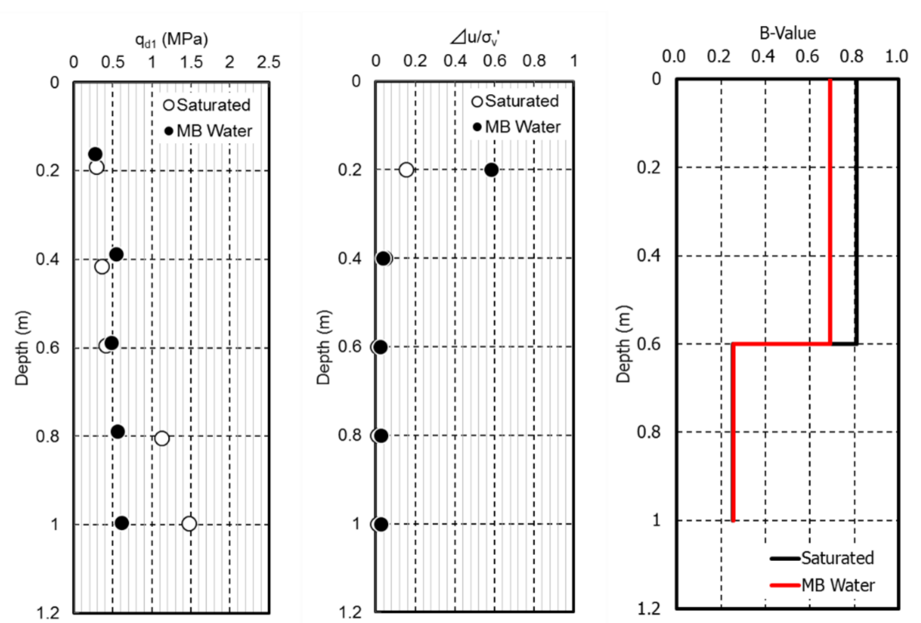

Fig.9 - Distributions of (a) corrected dynamic cone resistance, (b) excess pore water pressure ratio and (c) estimated B-values in the saturated and unsaturated grounds

The relationship between q_{d1} and $\Delta u/\sigma'_v$ in Fig.9 is presented in Fig.10. It can be seen in this figure that $\Delta u/\sigma'_v$ becomes larger in smaller q_{d1}, especially in q_{d1} = 1MPa or less. It is considered that such relationship depends on the skeleton of soil; the relationship in the saturated ground is more scattered and $\Delta u/\sigma'_v$ depends on the density of ground, while q_{d1} and the distribution of $\Delta u/\sigma'_v$ in the unsaturated ground ranges within that in the saturated ground and its relationship is less scattered.

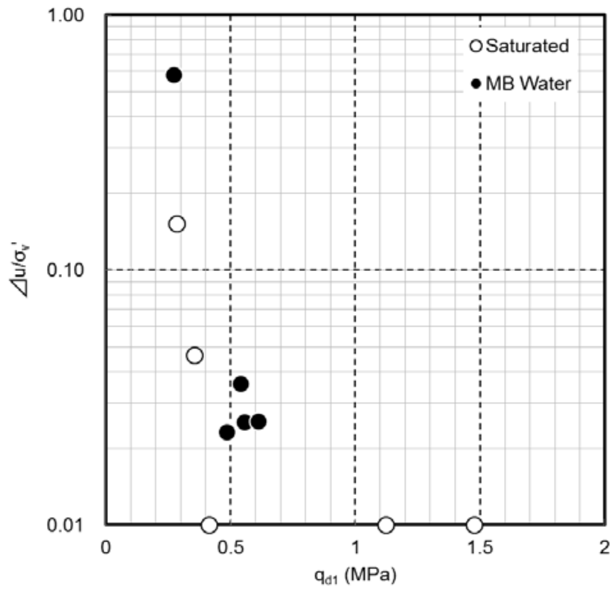

Fig. 10 - Relationship between corrected dynamic cone resistance and excess pore water pressure ratio in the saturated and unsaturated grounds.

Figure 11 presents the relationship between ACC and $\Delta u/\sigma'_v$. $\Delta u/\sigma'_v$ increases with ACC because shear stress increases in larger ACC in the ground. In this figure, it can be seen that increase ratio in the unsaturated ground is smaller than that in the saturated ground, implying difficulty of $\Delta u/\sigma'_v$ inducing.

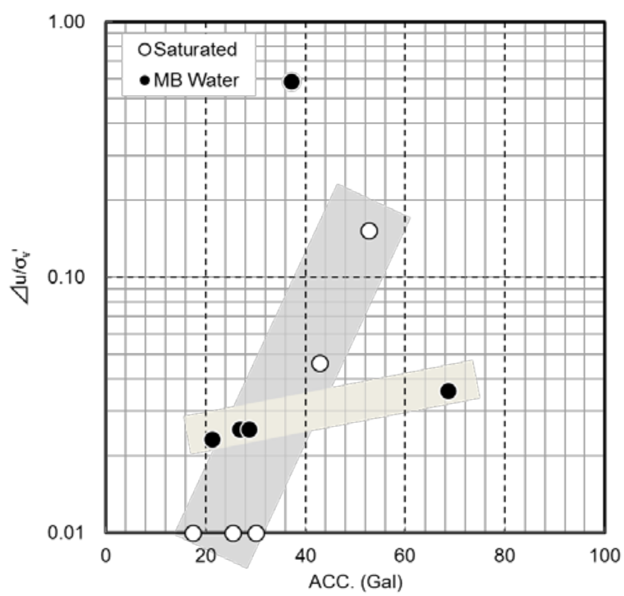

Fig.11 - Relationship between the maximum acceleration and excess pore water pressure ratio in the saturated and unsaturated grounds.

4. Shaking test results

In order to discuss the behavior in the saturated and unsaturated grounds, Fig.12 presents the time histories of the ACC transducers and EPWP in the second case of 300gal input motion in the shaking test. In the first case of 50gal input motion, increase of EPWP was very small and little difference between acceleration in the saturated and unsaturated grounds was observed. In the second case shown in Fig.12, the acceleration response and EPWP increase in both grounds were similar. This fact may indicate a possibility that the difference of *B*-values in both cases was not predominant in shaking test. However, it can be seen that EPWP dissipation in the unsaturated ground after shaking is earlier than that in the saturated ground.

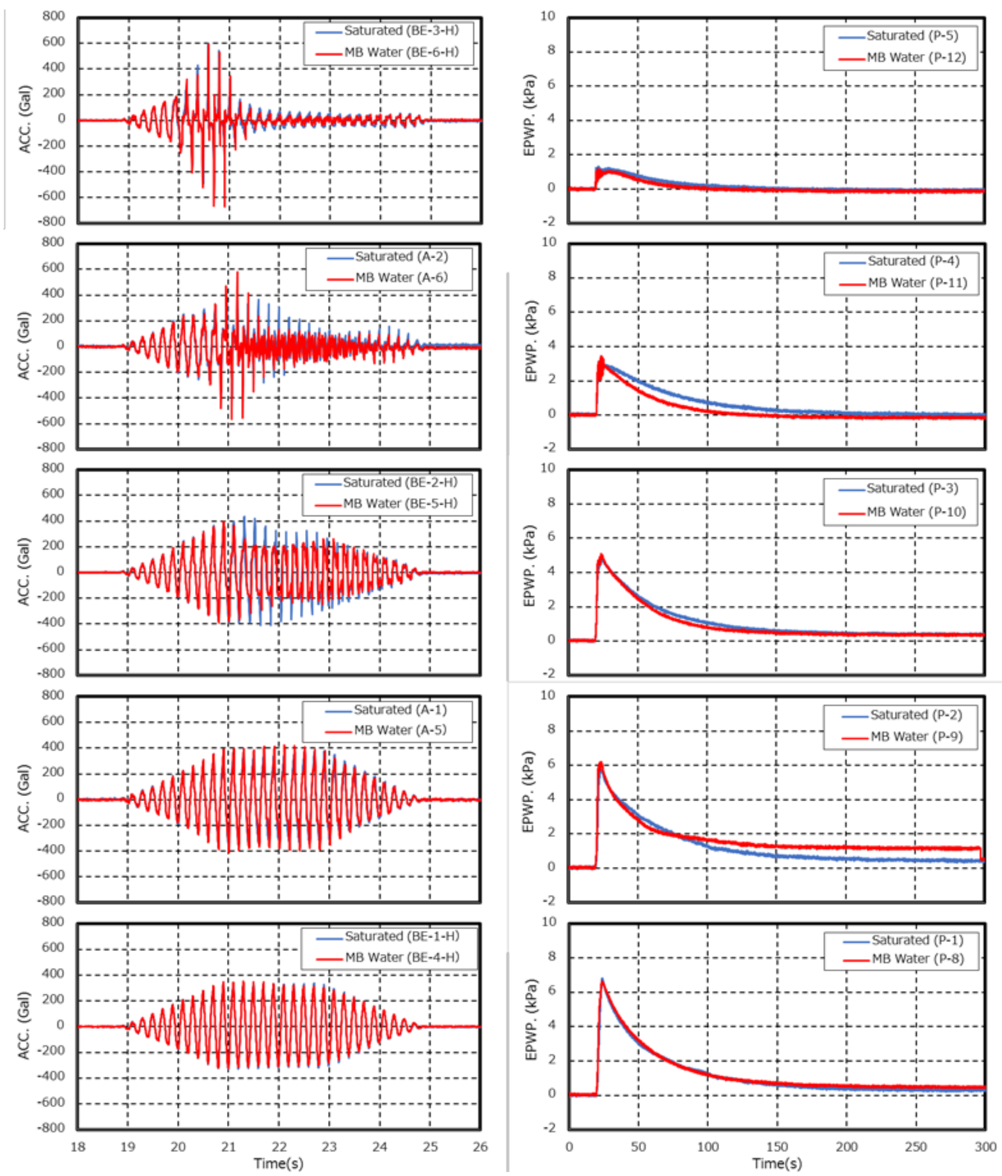

Fig.12 - Time histories of acceleration and excess pore water pressure at different layers in the saturated and unsaturated grounds obtained from the second case of 300gal input motion of the shaking test.

Throughout the results obtained from the test, the authors understand that assessment of the introduced quality of an unsaturation or desaturation construction method remains as a matter to be examined and discussed further.

5. Summary

In a field test performed prior to the test explained in this paper, difference between the change of excess pore water pressure measured at a PDC cone in saturated and unsaturated (MB-water injected) grounds was observed. However, in the cone penetration tests of the model grounds described in this paper, it can be seen that there was no significant difference between excess pore water pressures in the saturated and unsaturated (MB-water injected) model grounds when a cone penetrating regardless of a remarkable differences in the distribution of P-wave velocity. On the other hand, in terms of the relationship between the maximum acceleration and excess pore water pressure, difference between the behavior in the saturated and unsaturated grounds when a cone penetrating was observed and excess pore water pressure induced by cone penetration in the unsaturated ground was smaller than that in the saturated ground. In the cone penetration tests of the model grounds, the behavior of acceleration and excess pore water pressure was measured by the transducers placed at about 15cm from each penetration point. These results imply that such manner is probably able to clearly obtain desaturation effect and can be applied to in-situ investigation at a site.

In the cases of the shaking test, no significant difference between behaviors in the saturated and unsaturated grounds could be observed. This was derived from two reasons; one is that acceleration of the input motion was relatively larger than adequate input acceleration for the ground with the relative density in the test and the other is that *B*-values in both grounds might not be effective though the difference of *B*-value was recognized. Nevertheless, the dissipation process of excess pore water pressure in the unsaturated ground was different from that in the saturated ground. Such process after shaking needs to be considered further.

6. References

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