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FIELD AND LABORATORY VERIFICATIONS OF QUALITY EVALUATION PROCEDURE FOR AN UNSATURATION METHOD FOR LIQUEFACTION COUNTERMEASURES

K. Nagao(1), S. Maeda(2), A. Susami(3), M. Jinguuji(4), N. Suemasa(5), H. Nakazawa(6) and K. Tabata(7)

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

Abstract

Since an unsaturation or desaturation construction method for liquefaction countermeasures, such as injection of the mixture of micro-air bubbles and water, is inexpensive and simple, its introduction specially to housing sites have been developed after the 2011 off the Pacific coast of Tohoku earthquake. The workability of the method is clarified, while the completion or quality of its construction is evaluated only by partially checking saturation conditions using soil-moisture meter, resistivity logging and so on employed at observation and/or injection boreholes. In order to develop evaluation procedure of saturation condition so as to assess the introduced effectiveness of an air-injection method, authors carried out field investigation using the dynamic cone penetrometer with a piezo drive cone (PDC) at the reclaimed site along the Tokyo Bay in Chiba Prefecture where many liquefaction phenomena were observed in the earthquake. A PDC recognizes pore water pressure change in its penetration, which can be informative to understand change of saturation condition influenced by air injection. The investigation obtained the difference between excess pore water pressure change induced by cone penetration before and after air injection, verifying its applicability as evaluation procedure of saturation condition. In other words, it can be said that PDC investigation is appropriate for assessment of the construction management of the method. However, the quantification of the quality of improved ground has still been difficult. Therefore, following the field test, authors performed further PDC investigation at the laboratory model ground prepared in a small container to understand response characteristics of pore water pressure influenced by PDC penetration. The results of this investigation shows that similar observation in the field test is obtained even in the model with smaller confining pressure than that in the field. Also, increase of the peak values of pore water pressure when PDC penetrating into air-injected ground is confirmed. While further consideration is needed to understand this mechanism, pore water pressure change obtained by cone penetration is probably able to explain saturation conditions and help assess the effectiveness of an air-injection method as liquefaction countermeasures.

Keywords: liquefaction countermeasures, micro bubble, field investigation, dynamic cone penetration, pore water pressure

1. Introduction

The 2011 off the Pacific coast of Tohoku earthquake caused extensive damages due to liquefaction in residential areas in the Kanto Plane. Particularly, in the metropolitan areas in the Kanto Plane, liquefaction caused unprecedented severe damages, yielding difficulty in people's life. Consequently, after the earthquake, many countermeasures against liquefaction for the ground of housing sites have been energetically developed.

The study described in this paper focuses on an unsaturation or desaturation construction method that is one of the effective liquefaction countermeasures. Generally, the unsaturation methods as liquefaction countermeasures are roughly classified into two types, which are groundwater-level lowering and air injecting applied to a liquefiable soil layer. This paper concentrates on the air-injection method using mixture of micro-air bubbles and water (MB water) to decrease saturation degree of a liquefiable layer. The construction work of this method is injecting MB water into a liquefiable layer so as to increase liquefaction resistance. The features of the method are more reducing cost and space, more simple and rapid construction, and more friendly for the environment than those of others. On the other hand, the method has limitation to applicable types of soil, and needs to establish reasonable indices to assess its introduced quality or effectiveness for construction management.

In order to develop estimation procedure of in-situ saturation condition so as to assess the introduced effectiveness of an air-injection method as liquefaction countermeasures, the authors conducted field and laboratory model tests in which saturation conditions of the models were evaluated by dynamic cone penetration tests with a piezo drive cone (PDC tests). A PDC captures change of pore water pressure, which can be informative to understand change of saturation conditions before and after MB-water injection and the saturation status. This paper describes the results of these tests and discusses the behavior of pore water pressure change induced by cone penetration to evaluate saturation condition and verify its applicability as the quality evaluation procedure for an air-injection construction method.

2. Outline and understanding of the results from the field test

Prior to the laboratory model test, authors carried out a field test to investigate the workability and effectiveness of the method [1]. The experimental site of the test was located in Urayasu City, Chiba Prefecture along the Tokyo Bay in the metropolitan areas as shown in Fig.1. This site was enclosed by grid-shaped diagram walls. Around this site, serious liquefaction damages were observed in the earthquake.

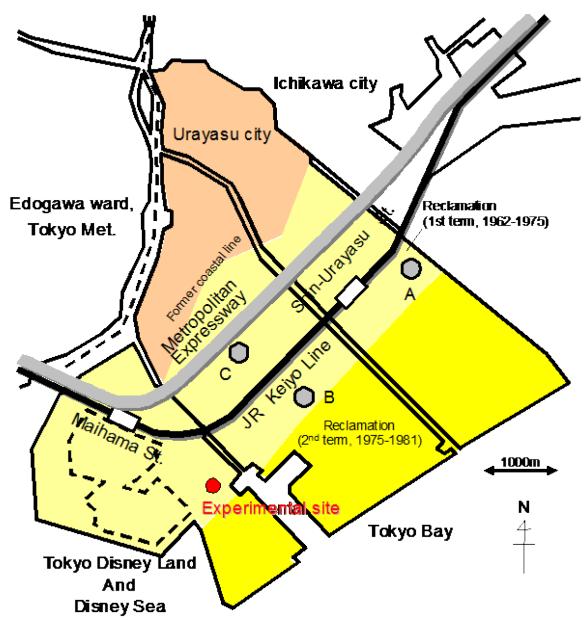


Fig. 1 - Location of the experimental site for the field test.

In the field test at this site, MB water was injected. Before and after the injection, PDC tests were performed as presented in Fig.2. Generally, a PDC test is employed for evaluation of liquefaction possibility because the test acquires response of pore water pressure at the cone and provides *N*-value, groundwater level, fine fraction contents and so on; in this study, a PDC test was carried out to observe change of pore water pressure at the cone when a PDC penetrates to ground. Before the test, authors anticipated that the pore water pressure induced by PDC penetration would become smaller in MB-injected ground than that in more saturated ground before MB-water injection because of compression of the void air introduced by MB water. However, as shown in Fig.3, the PDC tests obtained larger response of pore water pressure at the cone in the MB-water injected layers, which was the opposite observation to the authors' prior anticipation. To clarify this observation of pore water pressure responses, authors carried out laboratory model tests to investigate the behavior of pore water pressure change before and after MB-water injection in detail.

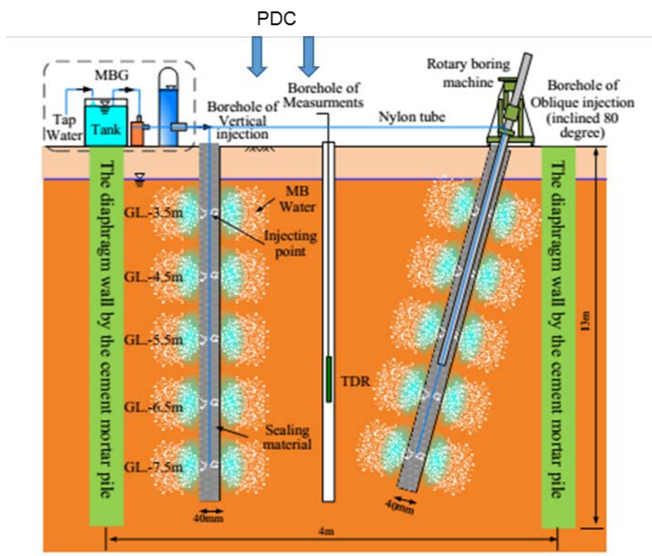


Fig.2 - Schematic diagram of the section of the experimental site where MB injection and PDC tests were performed.

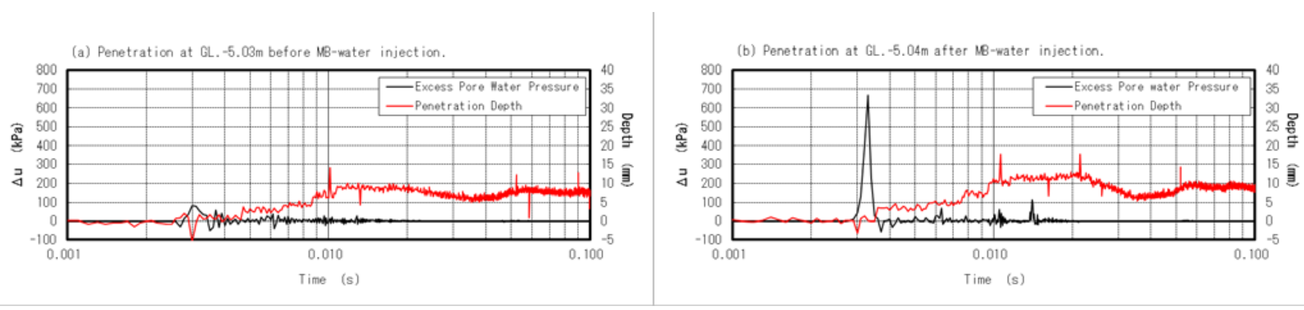


Fig.3 - Time histories of PDC penetration depth and excess pore water pressure measured at the cone (a) before and (b) after MB-water injection.

3. Laboratory model tests

3.1 Testing program

In order to obtain the behavior of pore water pressure influenced by various saturation conditions induced by MB-water injection, authors performed simplified PDC tests at model ground prepared in an acrylic container [2]. Figure 4 presents the schematic diagram of the test. The container of the model was 600mm long, 350mm wide and 400mm deep. For the ground of the model, Iide silica sand was used. Its particle density was 2.621g/cm^3, the maximum and minimum void ratios were 0.858 and 0.543, respectively, the mean grain size was 0.299mm and the uniformity coefficient was 2.2.

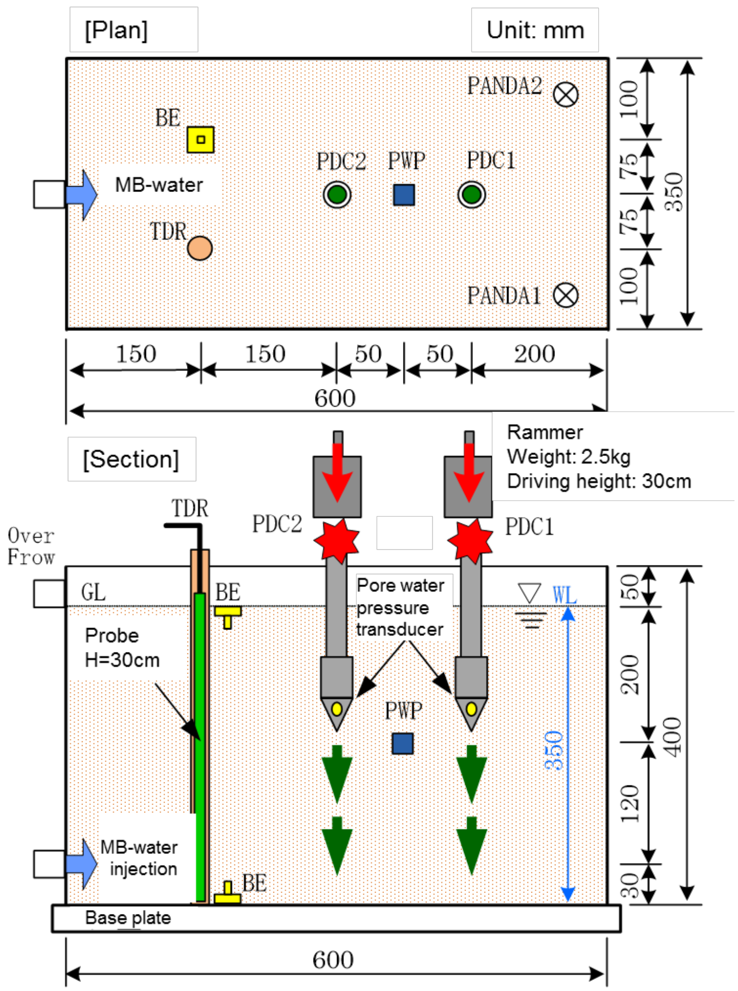


Fig.4 - Schematic diagram of the laboratory model test.

At first in the test, the ground was prepared by air pluviation of the silica sand with the thickness of 350mm and the relative density of approximately 60%. Then the ground was saturated by carbon dioxide gas from the bottom of the container, and de-aired water was injected into the ground to make fully saturated condition. Finally, de-aired water in the voids of the ground was replaced by MB water with the pressure of 400kPa from the bottom of the container.

For this model ground, time-domain-reflectometry soil-moisture meter (TDR), variable energy dynamic cone penetrometer (VEDCP) and simplified PDC tests were performed. TDR tests were performed to recognize saturation condition. TDR could obtain the average value of saturation degree for the ground because the length of its probe was 30cm nearly equal to the ground thickness. A VEDCP is a portable cone penetrometer for evaluating soil strength [3]. In the simplified PDC tests, the rod with a PDC was penetrated by a 2.5kg hammer freely fallen with the height of 30cm. Its dropping energy corresponds to 1/14 of field PDC investigation. In addition, pore water pressure was measured at the points in the ground indicated in Fig.4.

PDC and VEDCP tests were performed in the dry condition before saturation and the saturated condition before MB-water injection to the ground. Following these, both tests were also examined in the conditions after 30 and 90 minutes passed from MB-water injection. These are called as "MB-30" and "MB-90" cases in this paper, respectively. The PDC penetration points were located from about 3 to 5 cm of the pore water pressure transducer indicated in Fig.4.

3.2 Test results

In the case that the saturation degree, S_r, measured by TDR assumed as 100% for the ground in the saturated condition before MB-water injection, TDR-measured S_r decreased to 81% and 82% for the MB-30 and MB-90 cases, respectively, indicating MB-water injection made the ground unsaturate. Both S_r after MB-water injection were almost similar because the TDR probe may have captured S_r at the bottom of the container where bubbles less tended to disperse.

Figure 5(a) and (b) present the distributions of dynamic cone resistance, q_d, obtained from VEDCP tests and cone penetration depth from PDC tests. It can be seen that q_d increases with depth, while the cone penetration depth of PDC decreases in the surface layer of the ground. Except the surface layer, both indicate same tendencies, implying the model ground is almost uniform.

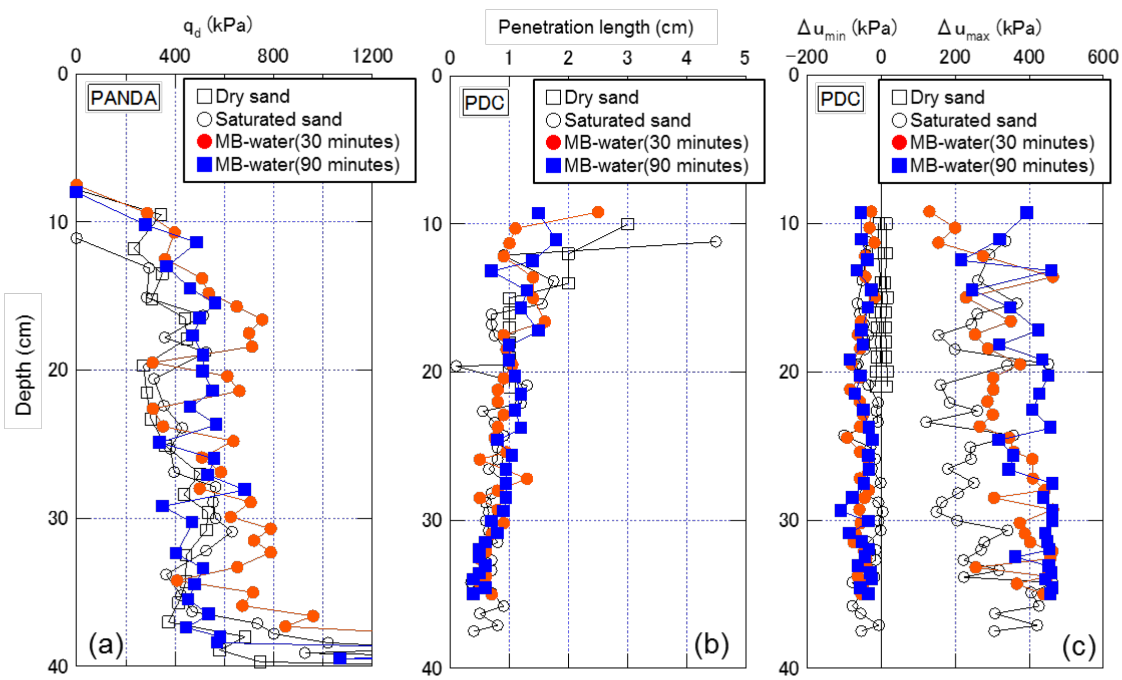


Fig.5 - Distributions of (a) dynamic cone resistance from VEDCP tests, (b) cone penetration depth from PDC tests and (c) the maximum and minimum pore water pressures measured by PDC.

Figure 6 presents the time histories of pore water pressure change measured at a PDC in the dry, saturated and MB-water injected conditions. These time histories were obtained at the depth of 21cm from the surface where the pore water pressure transducer was placed as indicated in Fig.4. Even in the dry condition in Fig.6(a), pressure change ranged between +/-15kPa, which could be derived from the inertial force induced by hammer falling when the cone penetrating. With respect to the saturated and MB-water injected conditions, the maximum pressures, Δu_{max}, obtained in the MB-30 and MB-90 cases are larger than that in the saturated condition, and the minimum pressures, Δu_{min}, have similar tendencies. As shown above in Fig.5(c), the distributions of Δu_{max} and Δu_{min} are larger in the MB-water injected conditions than those in the saturated condition. These facts indicate that pore water pressure change measured by a PDC reflects MB-water injection to ground. In other words, a PDC is able to obtain the change of saturation condition.

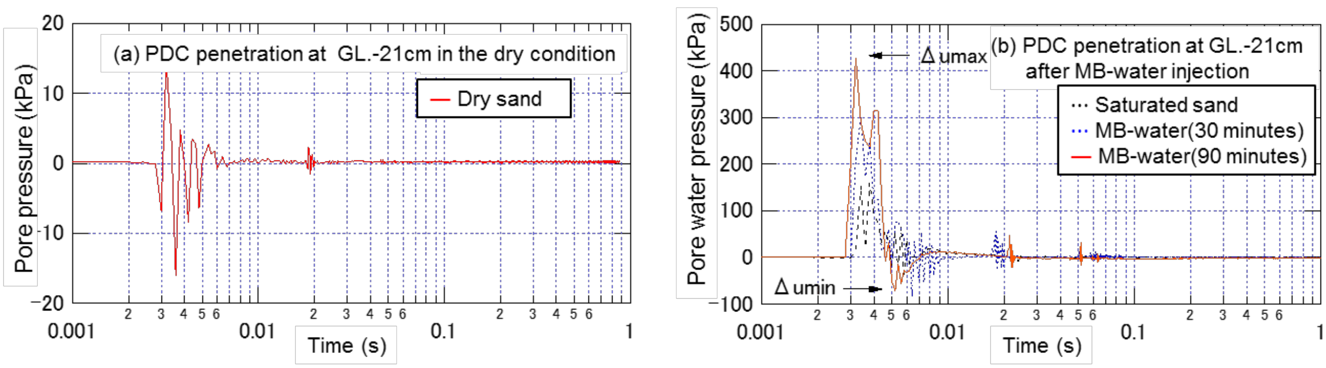


Fig.6 - Time histories of excess pore water pressure change measured by a PDC (a) in the dry condition before saturation and (b) in the saturated and MB-water injected conditions.

Figure 7 shows the time histories of pore water pressure obtained by the transducer when a PDC reached at the depth of 21cm from the surface where the transducer placed in the ground. It can be seen that there is not much difference between the positive peak values of pore water pressure in the saturated and MB-water injected conditions. On the other hand, regarding pore water pressure changes after the PDC penetration, pore water pressure tends to remain negative, and the negative pressure in the MB-90 case builds up earlier than that in the MB-30 case. This reason is hardly understood because both saturation degrees obtained by TDR are similar, as explained previously. However, it can be said that the difference of pore water pressure changes from saturation conditions are confirmed.

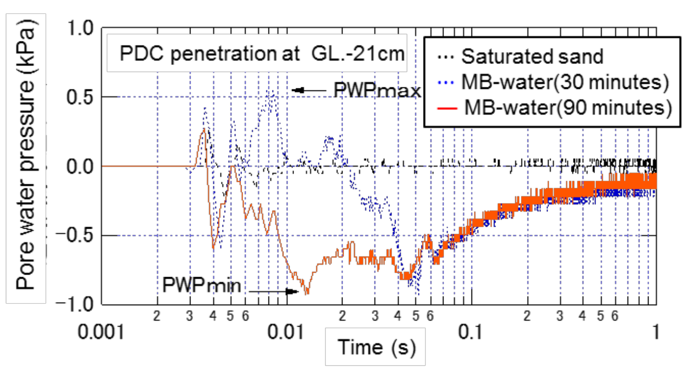


Fig.7 - Time histories of pore water pressure obtained by the transducer when PDC penetrating in the saturated and MB-water injected conditions.

3.3 Evaluation of saturation conditions by P-wave velocity

Besides understanding pore water pressure change obtained by PDC penetration as described above, the authors also examine the evaluation of saturation condition by P-wave velocity measurement in an additional laboratory model test [4].

There are several reports on characteristics of liquefaction resistance in unsaturated sandy soil. It is well known that liquefaction resistance of soil increases with S_r decreasing [5]. Moreover, as shown in Fig.8 presenting relationship between increase rate of liquefaction resistance, R_u/R_s, of partially saturated soil and P-wave velocity, V_p, R_u/R_s increases with V_p decreasing and becomes about two times larger than that of fully saturated soils at V_p = 450m/s [6]. In this figure, the data were obtained by a triaxial test apparatus equipped with bender elements for elastic wave velocity measurement, and R_u and R_s referred to cyclic strengths of partially saturated and fully saturated soils, respectively. Based on these facts, V_p is able to imply saturation condition with respect to liquefaction susceptibility of fully and partially saturated soils.

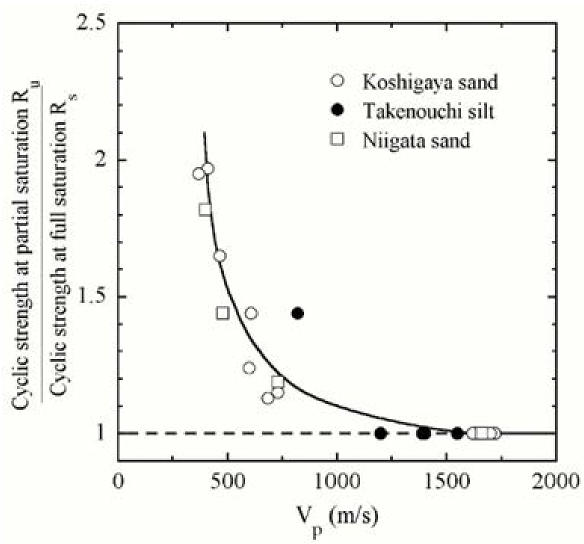
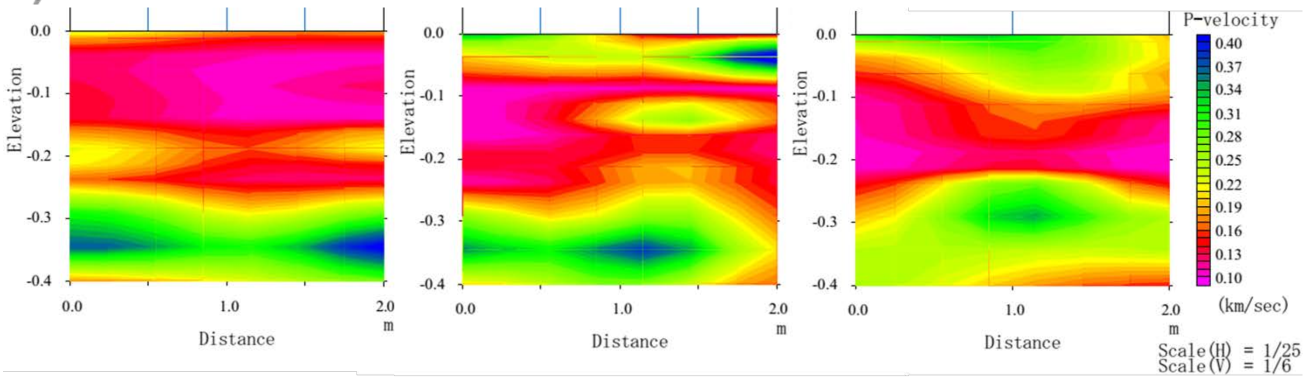


Fig.8 - Relationship between increase rate of liquefaction resistance of partially saturated sandy soil and P-wave velocity.

In the additional test, a VEDCP was used for the vibration source of V_p [4]. A VEDCP cone with extension rods and anvil was dropped by a hammer, generating vibration in the model ground and the vibration was received by several seismometers placed on the ground surface. From this measurement system, 2-dimensional V_p distributions could be drawn in the cases of dry, saturated and MB-injected conditions as shown in Fig.9. The 2-D V_p distributions obtained from the additional test indicate that the velocity of P-wave generated by dynamic cone penetration can be effective to evaluate roughly saturation conditions two-dimensionally.



(a) Dry condition (b) Saturated condition (c) MB-water injected condition (S_r=90%)

Fig.9 - 2-D distributions of P-wave velocity at (a) dry, (b) saturated and (c) MB-water injected conditions in the additional laboratory model test.

4. Summary

In order to develop estimation procedure of saturation condition, the authors focus on pore water pressure change when PDC penetrating into ground. In a field test, it is found that the peak value of pore water pressure induced by PDC penetration in the MB-water injected condition is different from that in the saturated condition. To clarify this fact, authors conducted a laboratory model test. In this laboratory test, the change of pore water pressure was observed by a PDC and transducers placed in the model ground. The test shows that similar behavior observed in the field test is obtained even in the laboratory model with smaller confining pressure than that in the field. Also, increase of the peak values of pore water pressure when PDC penetrating into the MB-injected ground is confirmed. While further consideration is needed to understand this mechanism, pore water pressure change obtained by cone penetration is probably able to explain saturation conditions and help assess the effectiveness of an air-injection method as liquefaction countermeasures. Besides, it is thought that estimation of desaturation effect becomes easier by interpretation of two-dimensional distribution of the degree of saturation as well as understanding the mechanism of PDC penetration.

5. Acknowledgements

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