# A countermeasure to liquefaction by reducing the degree of saturation of in-situ sandy soils

## Un contremesure à la liquéfaction par la réduction du degré de saturation des couches sablonneuses souterraines

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## ABSTRACT

Following were observed in a series of field and laboratory tests,: (1) after sand compaction, the primary wave velocity and the degree of saturation of in-situ sandy soil decreased due to the injection of air bubbles into the ground; (2) the liquefaction strength of partially saturated sand before and after sand compaction was much higher than that of fully saturated sand; (3) the effects of the size and roundness of soil particles and relative density on the relationship between degree of saturation and primary wave velocity were minor, but the effect of the confining stress on that relationship was significant; (4) for all tested sand, primary wave velocity increased rapidly with increasing degree of saturation from 90 to 100%. Based on these test results, a method to inject air bubbles into the ground is thought to be an effective method to reduce the disaster due to sand liquefaction.

## RÉSUMÉ

Les observations suivantes ont été effectuées lors d'une série d'essais sur le terrain et en laboratoire : (1) après compaction du sable, la vitesse de propagation de l'onde primaire et le degré de saturation des couches sablonneuses souterraines diminue avec l'injection de bulles d'air dans le sol ; (2) la résistance à la liquéfaction du sable partiellement saturé avant et après compaction est beaucoup plus grande que celle du sable entièrement saturé ; (3) les effets de la taille et de l'arrondi des particules des sols et de à l'aide densité relative sur le rapport entre le degré de saturation et la vitesse de propagation de l'onde primaire sont mineurs, mais l'effet de l'effort limite sur ce rapport est significatif ; (4) dans tous les essais sur les sables, la vitesse de propagation de l'onde primaire augment rapidement avec l'élévation du degré de saturation de 90 à 100%. Su la base de ces résultats d'essais, une méthode d'injection de bulles d'air dans le sol semble une méthode efficace pour réduire les risques des catastrophes dues à la liquéfaction du sable.

Keywords : liquefaction, degree of saturation, primary wave velocity, sand compaction

## 1 INTRODUCTION

A countermeasure to liquefaction by reducing the degree of saturation of in-situ sandy soils has been studied in recent years by several researchers (Okamura et al (2003), Nabeshima et al (2007), Hatanaka et al (2006, 2008)). For completing this countermeasure, it is necessary to develop a method for reliably estimating the degree of saturation (Sr) of in-situ sandy soils and to establish a useful correlation between the degree of saturation and the liquefaction strength. In the present study, primary wave velocity (Vp) was investigated as an index property to estimate the degree of saturation of in-situ soils. In previous studies, useful Vp-Sr correlations have been observed in laboratory tests using Toyoura sand and de-aired tap water under limited confining stress condition (Ishihara et al., 1998; Yongnan et al. 1999, Tsukamoto et al., 2002; Tamura et al. 2002;). However, the applicability of such a correlation to other kinds of in-situ sands with different sizes and shapes of soil particles, relative densities, confining stress and conditions of pore water remains unknown. The present study investigates the effects of the size and roundness of soil particles, relative density, pore water characteristics and the confining stress on the correlation between P-wave velocity and the degree of saturation of sand.

This paper also presents a case study to show the possibility to reduce the degree of saturation by injecting air bubble into the sandy soils and also to indicate the effect of the degree of saturation on the liquefaction strength of in-situ sandy soils based on a series of laboratory test on high-quality undisturbed samples recovered by in-situ freezing sampling.

## 2 SOIL PROFILES OF SAMPLING SITE AND SOIL IMPROVEMENT BY SCP METHOD

A method to reduce the degree of saturation of in-situ sandy soils by injecting air bubbles into the ground was found possible based on a study on the engineering properties of in-situ sandy soils improved by sand compaction pile method (SCP method)(Hatanaka et al, 2008). In that study, the P-wave velocity was found to be drastically reduced after sand compaction due to the air injecting into the ground in performing the sand compaction as shown in Figures 1 and 2. Figures 1 and 2 indicate the soil profiles of the sampling site and the results of P-wave velocity obtained by performing P-S wave-logging tests before and after sand compaction, respectively. As shown in Figures 1 and 2, the upper soil layer to a depth of about 6 meters is fine sand fill, while the lower part to a depth of about 10 m consists of fine alluvial sand. The groundwater level is at a depth of about 0.7 m. Sixteen sand piles were made to a depth of about 10 m from the ground surface as also shown in Figure 3. The piles had a diameter of 700 mm and the interval between piles was 2 m.

## 3 IN-SITU P-WAVE VELOCITY AND DEGREE OF SATURATION BEFORE AND AFTER SAND COMPACTION

In order to precisely determine the degree of saturation and the liquefaction strength of in-situ soils, continuous undisturbed samples with a diameter of 150 mm were recovered to a depth of 3 to 12 meters from the ground surface using the in-situ freezing method. The sample at point A was taken before sand

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compaction (Figures1 and 3), the sample at point B, after (Figures2 and 3). P-S wave logging tests using the suspension-type method were also performed in the field to measure the Vp before (No.1 and 3) and after (No.2 and 6) sand compaction. It is clear that Vp was greatly reduced to about 300 to 700 m/s at depths of 5 to 10 m after sand compaction, within which the soil was improved by the SCP method (Figures2 and 3). The dramatic decrease in Vp after sand compaction was caused by the decrease in Sr due to the injection of air bubbles into the ground during performing SCP.The degree of saturation of in-situ sandy soils was adjusted by 9% increase to account for the volume expansion due to the phase change of water to ice caused by ground freezing. The effects of temperature on the solubility of air in water and on the volume change of air during ground freezing were disregarded in this study. The distribution of the degree of saturation with depth before and after sand compaction was also shown in Figures 1 and 2, respectively. As shown in Figure 1, at 4 m to 5 m depth the sand fill was not fully saturated even before compaction. This result corresponds with the lower Vp at that depth. At greater depth, the in-situ soils were almost saturated. After sand compaction, the degree of saturation of the in-situ soils decreased to between 84% and 95% due to the air injection used in the SCP method. The effect of partial saturation on the liquefaction strength is shown below.

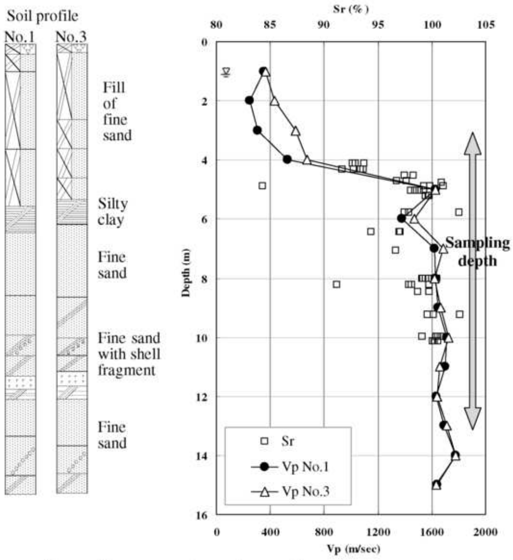

Figure 1. Soil profile, Vp and Sr of sampling site (Before compaction)

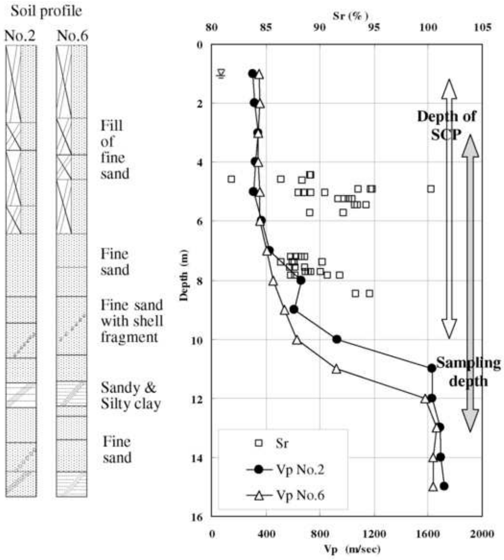

Figure 2. Soil profile, Vp and Sr of sampling site (After compaction)

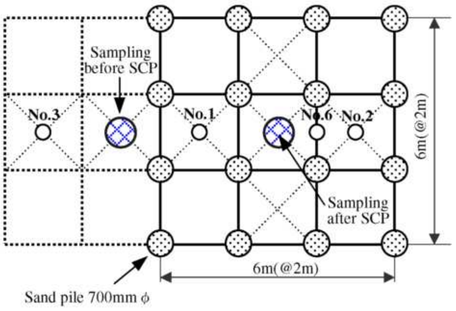

Figure 3. Locations of freezing sampling, field test and SCP

## 4 LIQUEFACTION STRENGTH OF UNDISTURBED SAND SAMPLES

The liquefaction strength of two kinds of undisturbed samples (in the sand fill at -5.0 m and the alluvial soil at -7.8 m) before and after soil improvement was determined by performing a series of consolidated undrained cyclic triaxial compression tests. Each test sample had a diameter of 50 mm and was about 120 mm long. Two kinds of undrained cyclic triaxial tests were performed, Method A and Method B.

The procedure for Method A involved performing the tests on fully saturated samples. After the sample was completely thawed, it was fully saturated irrespective of its in-situ degree of saturation. The sample was saturated with the aid of $CO_2$ gas, de-aired water and a back pressure of about 196 kN/m$^2$ until the pore pressure coefficient B-value reached 0.95 or greater. After saturation, the sample was isotropically consolidated at the effective vertical stress of the sampling depth. After consolidation, the primary wave velocity for undisturbed samples were measured using a bender element, and then the samples were cyclically sheared in an undrained condition in a sinusoidal form with a frequency of 0.1 Hz.

The procedure of test Method B was basically the same as that of Method A, except that the sample was not fully saturated with the aid of $CO_2$ gas and de-aired water; the only treatment was to apply the same hydraulic pressure as existed at the sampling depth. The pore pressure coefficient B-values of the samples tested by Method B were much lower than 0.95, as shown in Table 1.

Figure 4 (sand fill) and Figure 5 (alluvial sand) show the effect of full saturation and partial saturation on the liquefaction strength of undisturbed samples (at GL-5.0 m for the fill and GL-7.8 m for the alluvial sand). As shown in Figure 4, the liquefaction strength of the partially saturated samples before sand compaction was about 70% higher than that of the fully saturated samples. For the partial saturation tests, the partial saturation conditions were reproduced in the laboratory by applying a pore water pressure equal to the hydraulic pressure at the sampling depth (40–70 kN/m$^2$).

Due to the limitations of the cyclic triaxial test, it is impossible to apply a cyclic stress ratio higher than 0.5 for the lower back pressure in partial saturation liquefaction test. As shown in Figure 4, even for the fully saturated samples after sand compaction, the liquefaction strength was estimated to be more than five times of that before the sand compaction, and much larger than 0.5. It is impossible to apply a stress ratio lower than 0.5 to cause a 5% double amplitude axial strain with the appropriate number of cycles. But it is obvious that the liquefaction strength of the partially saturated samples is much larger than that of the fully saturated samples. Similar results can be seen for the samples of the alluvial sand at 7.8 m depth. These test results imply that the method of injecting air bubbles into the ground may be a useful method of increasing the liquefaction strength of in-situ soils as long as the inserted air bubbles can persist in-situ for a long time. There is reason to believe that air bubbles can persist for a long period in sandy soils as shown in Figure1 (Vp at GL:1~3m ever before sand compaction is only about 300 m/s) as also reported by Okamura, et al. (2003).

Table 1. Cyclic undrained triaxial test results

| In-situ soil condition | | | | Test condition | | | |
|---|---|---|---|---|---|---|---|
| **Soil improvement** | **Depth (m)** | **Relative density Dr (%)** | **Degree of saturation Sr(%)** | **Full/partial saturation** | **P-wave velocity (m/s)** | **B-value** | **Cyclic stress ratio at 15 cycles and DA=5%** |
| Before SCP | 5.0 m | 37 | 96 | Full Saturation | 1522 | 0.99 | 0.15 |
| | 7.8 m | 70 | 100 | | 1501 | 0.99 | 0.42 |
| | 5.0 m | 35 | 96 | Partial Saturation | 471 | 0.33 | 0.25 |
| | 7.8 m | 68 | 97 | | 554 | 0.39 | 0.51 |
| After SCP | 5.0 m | 68 | 96 | Full Saturation | 1532 | 0.99 | >0.80 |
| | 7.8 m | 79 | 89 | | 1458 | 0.97 | >0.80 |
| | 5.0 m | 66 | 89 | Partial Saturation | 408 | 0.16 | — |
| | 7.8 m | 80 | 89 | | 565 | 0.20 | — |

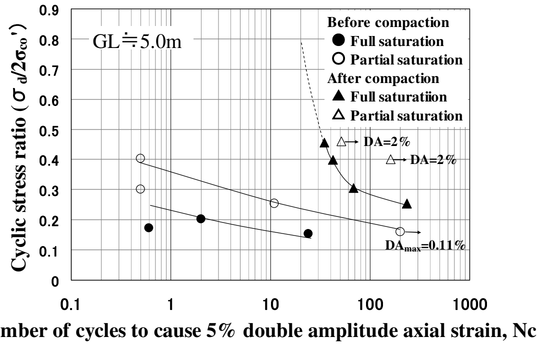

Figure 4. Comparison of liquefaction strength for a sand fill under full and partial saturation condition (at-5.0m)

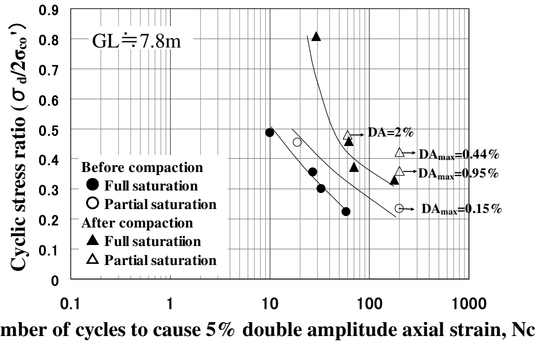

Figure5. Comparison of liquefaction strength for alluvial sand under full and partial saturation condition (at-7.8m)

## 5 EFFECTS OF PHYSICAL PROPERTIES OF SOIL PARTICLES, RELATIVE DENSITY, PORE WATER AND EFFECTIVE CONFINING STRESS ON THE $V_P$-$S_R$ RELATIONSHIP

Test samples of 100 mm in height and 50 mm in diameter were prepared using an air pluviation method to ensure a specified relative density. Test samples were then isotropically consolidated at a cell pressure of 50 kN/m$^2$. Thereafter, specified pore water was poured into the test samples through a burette, and Vp was measured for each degree of saturation. The degree of saturation of test samples was controlled by the difference of the water head between the test sample and the burette, and also by back pressure.

Four kinds of sand (Toyoura sand, Futtsu sand, Keisa-sand No. 2, and Keisa-sand No. 3), three relative densities (Dr=45 %, 55 % and 70 %), three kinds of pore water (tap water, de-aired water, and groundwater) and three levels of effective confining stress (49kN/m$^2$, 98kN/m$^2$ and 196kN/m$^2$), were used in tests. Table 2 lists the test parameters.

Table 2. Reconstituted samples test parameters

<table>
<tr><th>Sample name</th><th colspan="3">Toyoura sand</th><th colspan="2">Futtsu sand</th><th>Keisa-sand No .2</th><th colspan="2">Keisa-sand No. 3</th></tr>
<tr><td>Relative density (%)</td><td>70</td><td>70</td><td>70</td><td>45</td><td>70</td><td>70</td><td>55</td><td>70</td></tr>
<tr><td>Pore water</td><td>Tap water</td><td>De-aired water</td><td>Ground water</td><td>Tap water</td><td>Tap water</td><td>Tap water</td><td>Tap water</td><td>Tap water</td></tr>
<tr><td>Back pressure (kN/m<sup>2</sup>)</td><td>800</td><td>850</td><td>800</td><td>850</td><td>850</td><td>500</td><td>600</td><td>700</td></tr>
<tr><td rowspan="4">Effective confining stress (kN/m<sup>2</sup>)</td><td>49</td><td colspan="7" rowspan="4">50</td></tr>
<tr><td>50</td></tr>
<tr><td>98</td></tr>
<tr><td>196</td></tr>
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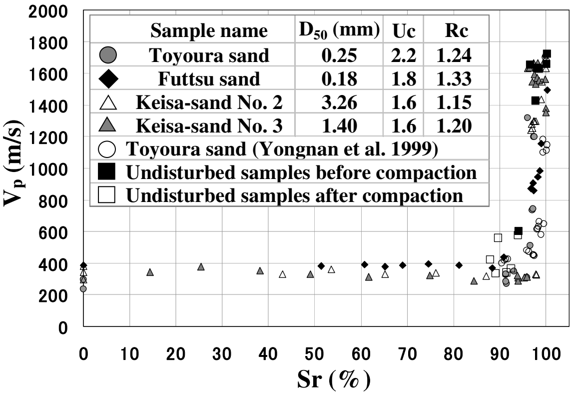


Figure 6. Effects of the size and roundness of soil particles on the Sr–V$_p$ relationship

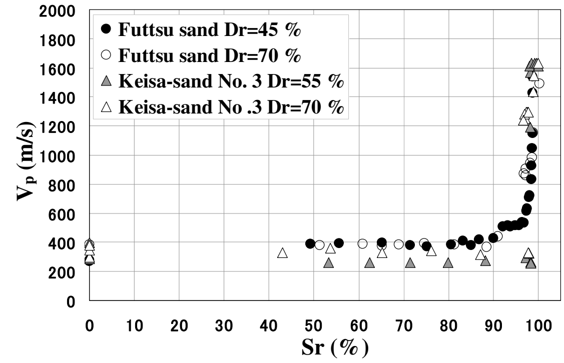


Figure 7. Effect of relative density on the Sr–V$_p$ relationship

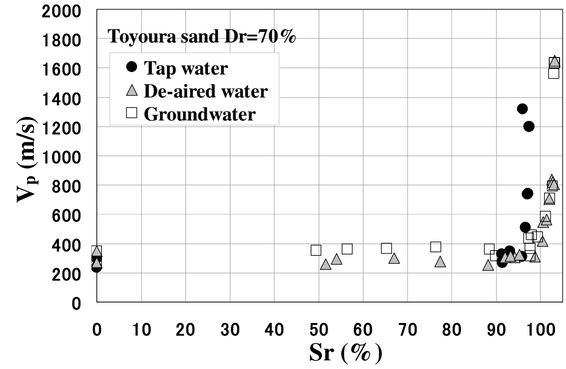


Figure 8. Effect of pore water characteristics on the Sr–V$_p$ relationship

Figure 6 shows the Sr–Vp relationships determined for each sample, along with the test results presented by Yongnan et al. (1999). All of the samples show similar quantitative relationships between Sr and Vp, indicating negligible effects of the size and roundness of soil particles on the Sr–Vp relationship. All of the samples show the same tendency in that the Vp increases rapidly from 90 % saturation.

Figure 7 shows similar quantitative relationships for both Futtsu sand (Dr=45% and 70%) and Keisa-sand No.3 (Dr=55% and 70%). The test results suggest that the effect of relative density on the Sr–Vp relationships are minor.

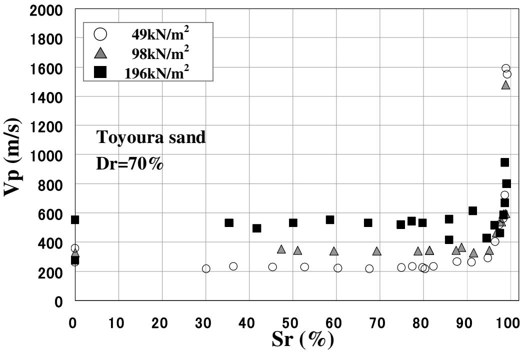


Figure 9. Effect of confining stress on Sr–$V_p$ relationship

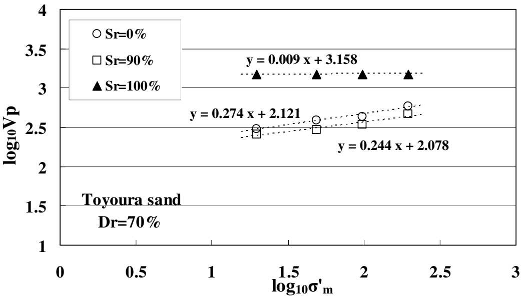
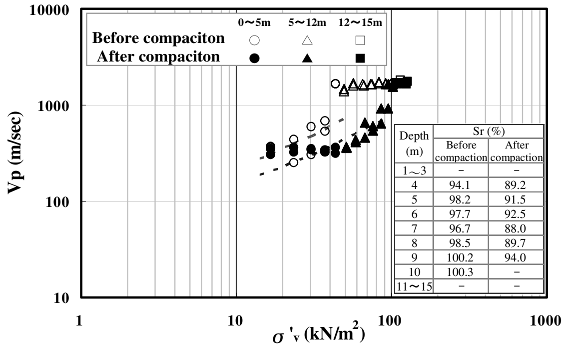


Figure 10. Effect of confining stress on P-wave velocity



| Depth (m) | Sr (%) | |
|---|---|---|
| | Before compaction | After compaction |
| 1∼3 | − | − |
| 4 | 94.1 | 89.2 |
| 5 | 98.2 | 91.5 |
| 6 | 97.7 | 92.5 |
| 7 | 96.7 | 88.0 |
| 8 | 98.5 | 89.7 |
| 9 | 100.2 | 94.0 |
| 10 | 100.3 | − |
| 11∼15 | − | − |

Figure 11. Effect of confining stress on the P-wave velocity observed at the sampling site

Figure 8 shows the Vp-Sr relationships of Toyoura sand with a relative density of 70 % for different kinds of pore water (tap water, de-aired water, and ground water). The use of de-aired water and ground water yields similar quantitative Vp –Sr relationships. The test results suggest that the ground located much deeper than the ground water level is almost fully saturated.

Figure 9 indicates the effect of the confining stress on the Vp-Sr correlation. It is obviously that in the range of degree of saturation lower than about 95 %, the Vp-Sr correlation is affected by the level of the confining stress, in the manner that the P-wave velocity increases with increasing confining stress. However, in the range of Sr higher than 95 %, P-wave velocity is almost irrelevant to the degree of confining stress. The effect of the confining stress on the Vp for partial saturated sand is also clearly shown in Figure10. There is a good linear log Vp-logσ'$_m$ correlation (hollow symbols). These results suggest that it is important to take account of the effect of the confining stress in evaluating the degree of saturation of partial saturated soils based on the Vp-Sr correlation in the range of Sr lower than 95%. On the other hand, for sand with higher degree of saturation, confining stress has little effect on P-wave velocity (solid triangle). The effect of the confinig stress on the P-wave velocity was also observed at the sampling site as indicated in Figure 11. For the fine sand of fill which is not saturated even before sand compaction as described before, the effect of the confining strees on the P-wave velocity can be seen (hollow circle). It is also clear that Vp increses with increasing confining stress at depth of 5 to 12m after sand compaction, within which the soil was improved by SCP method (solid triangle). On the other hand, the sand layers at a depth below 5m before sand compaction and at a depth below 12m after sand compaction are saturated and the P-wave velocity in those sands is not affected by the confining stress (hollow triangle and square and solid square).

## 8 CONCLUDING REMARKS

Based on a series of field and laboratory test results, following are concluded.

1. After performing the sand compaction by the SCP method, at depths of 5 to 10 m, the primary wave velocity was decreased from about 1600 m/s to about 300–700 m/s due to the injection of air bubble into the ground.
2. After sand compaction, the degree of saturation of in-situ sandy soils was decreased to 84–95% at depths of 5 to 9 m.
3. The liquefaction strength of partially saturated sand before and after sand compaction was estimated to be much higher than that of fully saturated samples.
4. The effects of the size and roundness of soil particles and relative density on the Sr–Vp relationship are minor.
5. It is important to take account of the effect of the confining stress on the Vp-Sr relationship in evaluating the degree of saturation of partial saturated soils.
6. For all tested sands, the Vp increased rapidly with increasing degree of saturation from 90 to 100 %.

The test results suggest that the injection of air bubbles into the ground has potential as a practical method of increasing the liquefaction strength of in-situ sandy soils.

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