Effect of saturation on compression wave velocity of silty sand

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ABSTRACT: Of great interest for a partially saturated sand is that it can cause greater amplification of vertical ground motion than a fully saturated sand and it becomes less vulnerable to liquefaction compared with a fully saturated sand during earthquakes. Evaluating the saturation state of sand is therefore a matter of concern at both academic and practical levels. This paper presents an experimental study on the characteristics of compression wave in silty sand, with the aim to examine whether the compression wave velocity (V_p) can be a good indicator of saturation. By using the extender element, compression wave velocity was measured on clean and silty sand specimens at various saturation states. A stepwise increase of back pressure was used to achieve different degrees of saturation, and the B-value was determined at each saturation stage accordingly. The study shows that for both clean and silty sand specimens, V_p increases with B-value, which is in general agreement with the theoretical prediction based on poroelasticity, yet departures from the prediction are observable for higher B-values. Under a similar state in terms of void ratio and confining pressure, a silty sand specimen tends to exhibit a smaller V_p than a clean sand specimen at a given B-value. Nevertheless, for both clean and silty sand specimens a dramatic increase in V_p occurs as the degree of saturation (S_r) approaches full saturation and the influence of fines on V_p is not appreciable for a given S_r.

1 INTRODUCTION

Partially saturated sand comprises three different phases, including air, water and solid grains. Often the degree of saturation (S_r) is used to characterize partially saturated sand, which describes explicitly the amount of voids replaced by water. Over the past few decades, extensive studies have been carried out on the partially saturated sand, recognizing distinct engineering behaviors as compared with the fully saturated one. For instance, it has been frequently found that the partially saturated sand shows higher liquefaction resistance than the fully saturated one under cyclic loadings (e.g., Sherif et al. 1977; Yoshimi et al. 1989; Hatanaka 2008). On the other hand, much greater amplification of vertical ground motion was recorded in the Kobe earthquake, and it was attributed to the partial saturation of the fill near the ground surface (Yang and Sato 2000; 2001). The conventional method to evaluate the degree of saturation (S_r) of sand uses the pore pressure parameter, also known as B-value in laboratory experiments, and the correlation against S_r is presented in equation 1.

$$B = \frac{\Delta u}{\Delta \sigma} = \frac{1}{1 + n\left(K_s / K_w\right) + n\left(K_s / P_a\right)(1 - S_r)} \tag{1}$$

where n is the porosity; P_a is the absolute fluid pressure; K_s and K_w are the bulk modulus of soil skeleton and pure water, respectively. By applying a small increment of confining pressure ($\Delta\sigma$) on a sand specimen, the B-value is determined as the ratio between $\Delta\sigma$ and the corresponding change in pore pressure (Δu). It is clear that a sand specimen becomes fully saturated as B-value approaches to a unit. To derive the above relationship, the sand grains are assumed incompressible and the Boyle's law is valid. A detailed investigation on the effects of grain's compressibility can be found in Yang (2005).

While the above method is simple to use in the laboratory, it is often not applicable in the field conditions. In the above context, an alternative method has been proposed to evaluate the degree of saturation of sand using compression wave velocity (Yang 2002; Tsukamoto et al. 2002). The great advantage of using the wave method is that it can be applied both in the field and in the laboratory. In this connection, it readily correlates field observations and various types of soil properties that are easily determined from laboratory. A clear evidence was given by Yang (2002), who derived the correlation between compression wave velocity (V_p) and B-value as follows.

$$V_p = \left[\frac{4G/3 + K_{sk}/(1-B)}{\rho} \right]^{1/2} \quad (2)$$

where G is the shear modulus of the soil skeleton; ρ is the bulk density of soil. Since then, a considerable amount of efforts has been placed on application of the wave method in clean granular materials over worldwide laboratories, arousing continuing research interests (e.g., Tamura et al. 2002; Lee et al. 2007; Naesgaard et al. 2007; Gu and Yang 2013).

Often natural sands are not clean but contain some amount of fines in the silt or clay size, yielding more complex particle inter-voids distribution as compared with a clean one. Whether it is fulfilled for a silty sand to evaluate the degree of saturation using the wave method is a fundamental question, yet it remains open due to the lack of solid experimental evidence. This paper presents results from an experimental study on partially saturated silty sand, with the aim to evaluate the effect of fines content on the characteristics of compression wave. In what follows, discussions are made by comparing the compression wave velocity (V_p) of partially saturated sand at various fines contents and at various saturation stages. In addition, comparisons on the received compression wave signals between the clean sand and the silty sand are also made along with a detail interpretation.

2 TEST MATERIALS AND PRODUCURES

In this experiment, Toyoura sand was used as the base sand and crushed silica fines were used as the additive. By using artificially created mixtures, it allows good control of grain characteristics so that any more complex effects or uncertainties are eliminated. It is worth noting that all specimens in this study were prepared using dry tamping method and no particle segregation was found between the coarse and the fine grains. To produce a sequence of sand-fines mixtures, the quantity of silica fines varies from 0 to 10% by mass and the particle size distribution curves are presented in Figure 1. To measure the compression wave velocity, the state-of-the-art resonant column (RC) apparatus that also incorporates the extender element function was used. The extender elements are used to generate compression waves that propagate vertically with the same polarization. More detailed information about the apparatus can be found in Yang and Liu (2016).

After sample preparation, an isotropic confining pressure of 30 kPa was applied on the sand specimen. The tap-water was used to circulate through the sand specimen with enough time to fill the void space. Upon the end of water flushing, no air bubbles at the drainage outlet can be observed, indicating a continuous water phase inside of the sand specimen, and the leftover air is assumed only in bubble-like forms. To further increase the degree of saturation, a stepwise increment of back pressure (i.e. 100 kPa) was applied on sand specimens, whilst the effective stress remains constant (σ'=30 kPa). Following the above procedures, an equilibrium of inflow was established at each saturation stage, and it thus allows to evaluate the compression wave velocity and the associated B-values with reliable measures.

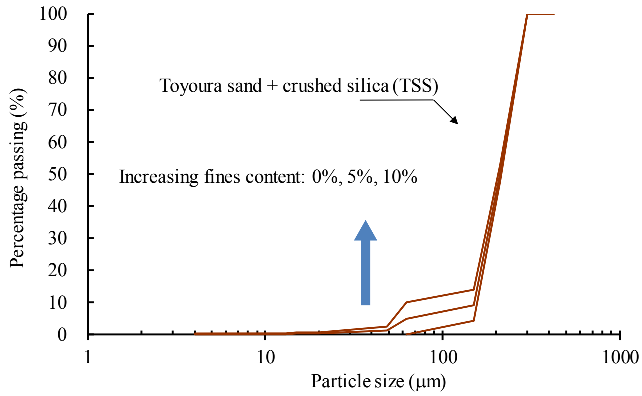


Figure 1. Particle size distribution curves of test materials.

3 TEST RESULTS AND DISCUSSION

3.1 *Signal interpretations*

In each test, a set of sinusoid signals at 10 kHz was used as the excitation, and the received signals at various saturation stages were examined in a whole view to better identify the arrival time of compression waves. Figure 2 shows the received signals in clean sand specimen under a succession of saturation stages. Bearing in mind that V_p is state dependent, it is therefore important to keep the effective stress constant (σ'=30 kPa) during the test, whilst the back pressure increases at each saturation stage. Accordingly, B-value increases with back pressure, indicating an enhanced degree of saturation of sand specimens. Given that the compression wave component travels in phase with the excitation signals, and it also travels at greater speed than any other received component, as shown in Figure 2, the arrival time of compression wave is therefore identified at the first bump in the received signals, denoting as a downward triangle. It is clear from this figure that the travel time of compression wave at dry state is longer than that at higher B-values, saying $B = 0.903$ for instance. As back pressure (or B-value) increases, the travel time becomes shorter. Besides, a clear distinction is found in the arrival time between the compression and shear wave components when the B-value is approaching to 0.513 and the back pressure is about 300 kPa.

In Figure 3 and 4, comparisons of received signals are made for sand specimens with different fines content. To facilitate comparisons, arrival time of compression wave from the clean sand specimen is also included. As an example, a downward triangle and an upward arrow are used to represent the travel time of clean sand and silty sand specimens, respectively.

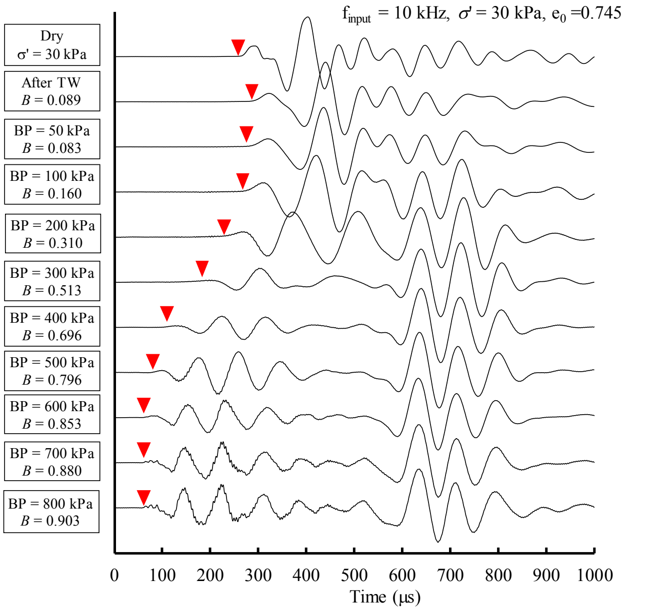


Figure 2. Received compression wave signals of clean sand specimen.

Like the clean sand specimen, a clear shear wave component also appears in the received signals of silty sand specimens, when the *B*-value is approaching to a range between 0.5 and 0.6. At dry state, in Figure 3, the compression wave of sand specimen with 5% fines content exhibits slightly greater arrival time than the clean sand specimen, suggesting a detrimental impact of fines content on the soil stiffness. Similar observations have also been found for the mixture having 10% fines content. Of more interest, as shown in these two figures, the arrival time of clean sand is always shorter than that of silty sand specimens under similar conditions. For instance, under the back pressure of 400 kPa the arrival time of compression wave is about 108μs for the clean sand specimen, while it increases to 210μs and 248μs for the silty sand specimens that have 5% and 10% fines content, respectively. As *B*-value increases, the difference in arrival time becomes more evident. Bearing in mind that compression wave travels much faster in water than in solid grains, the above observations strongly suggest that the silty sand is a lot more difficult to saturate than the clean sand under similar conditions.

3.2 *Compression wave velocity (V_p)*

To have a better understanding, Figure 5 shows the measured relationship between V_p and *B*-value for sand specimens at various fines content. In the same figure, predictions of V_p using equation 2 are also plotted as a function of *B*-values. Note that the predicted value is based on the stiffness of sand (K_{sk}) that is determined during consolidation at an effective stress of 30 kPa. Likewise, in Figure 6, V_p is plotted in a similar manner yet against the degree of saturation (S_r). Note that S_r is determined by using equation 1. Several features that characterize the changes of V_p under a succession of saturation stages are found from these two figures. Firstly, for both clean and silty sand specimens V_p increases with *B*-value that agrees with the prediction based on poroelasticity. Yet, departures from the prediction are observable for the specimens at higher *B*-values (i.e., *B*-value = 0.6). Given that the theory used in the prediction assume overall homogenous pore fluid with no consideration on the distribution of air bubbles, the discrepancy is likely due to the impacts from varying distribution of air bubbles. Of course, more experimental evidence towards a complete explanation on this aspect is worthwhile.

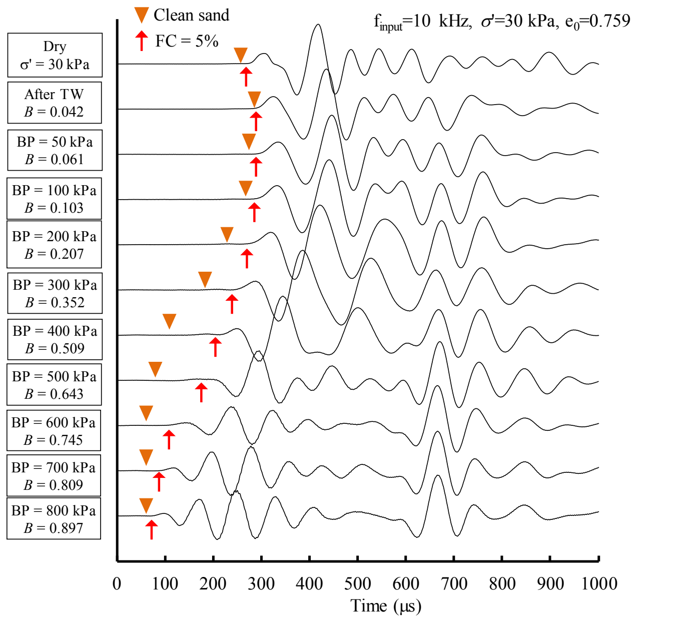


Figure 3. Received compression wave signals of sand specimen with 5% fines.

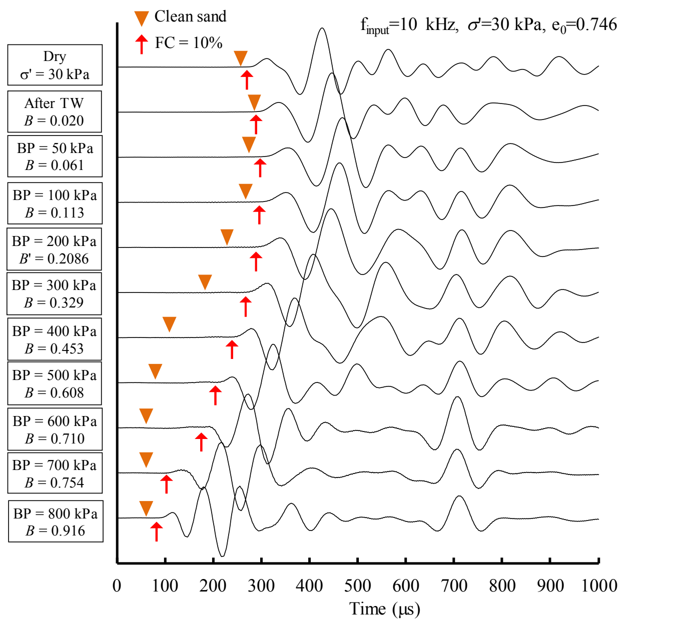


Figure 4. Received compression wave signals of sand specimen with 10% fines.

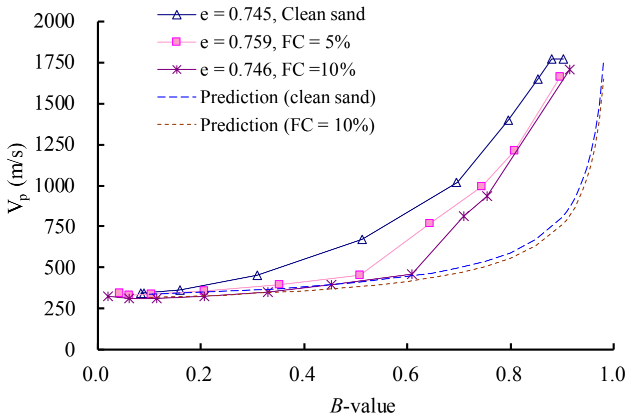
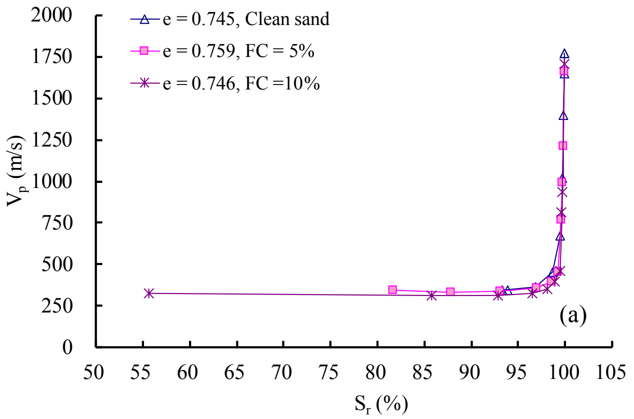


Figure 5. Variation of compression wave velocity with *B*-value.



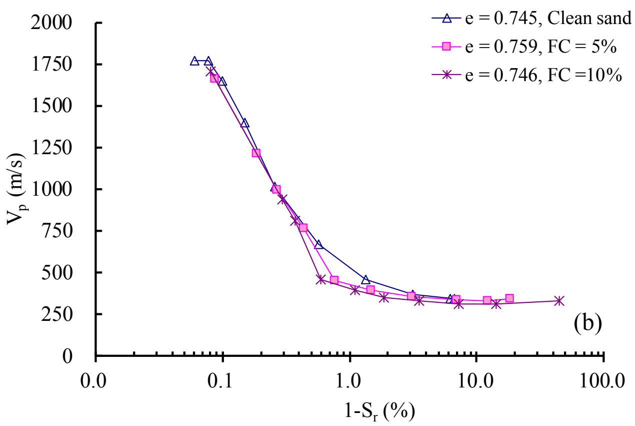


Figure 6. Variation of compression wave velocity with degree of saturation: (a) normal scale; (b) logarithm scale.

Besides, at a similar state in terms of void ratio and confining stress, the measured V_p of partially saturated sand is also influenced by the fines content. More specifically, V_p of sand specimens with higher fines content is less sensitive to the changes of *B*-values. For instance, at *B*-value = 0.7, V_p is measured as 1018m/s and 814m/s respectively for clean sand and silty sand with 10% of fines content. Furthermore, at final stage of saturation similar V_p are obtained (i.e. around 1650 m/s) that are independent on the fines content. This observation indicates that the influence of fines content on V_p is less profound for specimens that are nearly saturated. On the other hand, as shown in Figure 6, both clean sand and silty sand specimens exhibit dramatic increases in V_p as the degree of saturation approaches full saturation. Unlike the distinct trends that are observed in Figure 5, the influence of fines content on V_p is less appreciable for a given S_r.

4 CONCLUSIONS

In this paper, characteristics of received compression wave signals and associated compression wave velocity were investigated on partially saturated sand with different fines content. In particular, discussions were made on whether the compression wave velocity can be used as an indicator to evaluate the degree of saturation of sand with fines. The main findings of this study are summarized as follows.

1) At each saturation stage, the arrival time of compression wave is shorter in clean sand specimens than that with fines. The distinction becomes evident as *B*-value increases, with the implication that the silty sand is more difficult to saturate than the clean sand.

2) For both clean and silty sand specimens V_p increases with *B*-value that is in agreement with the prediction. Yet, discrepancies are found for the specimens at higher *B*-values. Under otherwise similar conditions, a silty sand specimen tends to exhibit a smaller V_p than a clean sand specimen at a given *B*-value.

3) For both clean and silty sand specimens, a dramatic increase in V_p occurs as the degree of saturation (S_r) approaches full saturation and the influence of fines on V_p is not appreciable for a given S_r.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Gu, X.Q., Yang, J. & Huang, M.S. 2013. Laboratory investigation on relationship between degree of saturation, *B*-value and P-wave velocity. *J. Cent. South Univ.* 20(7): 2001–2007.

Hatanaka, M. & Masuda, T. 2008. Experimental study on the relationship between degree of saturation and P-wave velocity in sandy soils. *Proceeding of Geotechnical Engineering for Disaster Mitigation and Rehabilitation* Part 4. Beijing: Science Press, 346–351.

Lee, S.H., Choo, Y.W., Youn J.U. & Kim, D.S. 2007. Determination of P, S-wave velocities and pore water pressure build up with *B*-value for nearly saturated sands. *J. Korean Geotech. Society* 23(2): 71–84.

Naesgaard, E., Byrne, P. M. & Wijewickreme, D. 2007. Is P-wave velocity an indicator of saturation in sand with viscous pore fluid? *Int. J. Geomech. ASCE* 7(6): 437–443.

Sherif, M.A., Ishibashi, I. & Tsuchiya, C. 1977. Saturation effect on initial soil liquefaction. *J Geotech. Engng Div., ASCE* 103(8): 914–917.

Tamura, S., Tokimatsu, K., Abe, A., & Sato, M. 2002. Effects of air bubbles on *B*-value and P-wave velocity of a partly saturated sand. *Soils Found.* 42(1): 121–129.

Tsukamoto, Y., Ishihara, K., Nakazawa, H., Kamada, K. & Huang, H. 2002. Resistance of partly saturated sand to liquefaction with reference to longitudinal and shear wave velocities. *Soils and Foundation* 42(6), 93–104.

Yang, J. & Sato, T. 2000. Interpretation of seismic vertical amplification observed at an array site. *Bull. Seism. Soc. America* 90(2): 275–285.

Yang, J. & Sato, T. 2001. Analytical study of saturation effects on seismic vertical amplification of a soil layer. *Géotechnique* 51(2): 161–165.

Yang, J. 2002. Liquefaction resistance of sand in relation to P-wave velocity. *Géotechnique* 52(4): 295–298.

Yang, J. 2005. Pore pressure coefficient for soil and rock and its relation to compressional wave velocity. *Géotechnique* 55(3): 251–256.

Yang, J. & Liu, X. 2016. Shear wave velocity and stiffness of sand: the role of non-plastic fines. *Géotechnique* 66(6): 500–514.

Yoshimi, Y., Tanaka, K. & Tokimatsu, K. 1989. Liquefaction resistance of a partially saturated sand. *Soils and Foundation* 29(3): 157–162.