Evaluation of shear moduli of premature age of ultra-fine particle cement modified sand with various water-cement ratio

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ABSTRACT

Damage caused by liquefaction has been confirmed in various parts of Japan due to the recent large earthquake. The permeable grouting method is mentioned as the effective liquefaction countermeasure technical method in a limited space. Chemical grouting materials and cement-based solidifying materials are often used in the permeable grouting method. Although permeable grouting used chemical grouting material has high permeability, the long-term durability is not sufficiently secured and there are many constructor would not introduce it. On the other hand, in regard to cement-based solidifying materials, although sufficient long-term strength is exerted, permeability is low, and injection into sand having fine particles is insufficient. In recent years, ultra-fine particle cement has been developed to solve these problems of cement-based solidifying materials. Ultra-fine particle cement is a material in which cement particles are very finely divided. The cement-based solidifying materials using ultra-fine particle cement has been confirmed to have the same permeability as chemical grouting materials. The authors used the ultra-fine particle cement to change the water-cement ratio and investigate the dynamic deformation coefficient using a bender element test device. From the results, the influence of water-cement ratio on the improved sand was investigated.

Keywords: Liquefaction, shear modulus, improved sand, microfine cement, equivalent granular void ratio

1 INTRODUCTION

In The 2011 off the Pacific coast of Tohoku Earthquake that occurred on March 11, 2011, damage from liquefaction was confirmed over a wide area in East Japan (Wakamatsu et al. (2011)). In particular, harbor facilities, roads, and detached houses in landfills in the old ages that did not take sufficient liquefaction countermeasures were severely damaged, and the lives and economic activities of people were severely damaged immediately after the earthquake. In addition, liquefaction was confirmed even in sand ground containing fine particles, which was originally thought to be unlikely to liquefy. When such a ground disaster occurs, recovery requires a lot of time and cost. Therefore, how to reinforce the ground directly under the existing structure is a problem. Then, the development of ground improvement technology that can be constructed even on extremely complex ground and narrow land is expected.

Among ground improvement technologies, the injection method using cement-based injection material is applicable to the above-mentioned construction conditions, and has been used in dam and tunnel construction. However, since cement-based injectants are particles, the permeability to the ground is determined by the particle size. Even the ultrafine particle cement with a particle size of 4mm, which has the most excellent permeability among commercially available cement-based injectable materials, has a limited permeability of 10⁻³m / s or more (Mori et al. (1991)). Therefore, an injection method using ultra-fine particle cement with a particle size of 1 to 2 mm was proposed (Hashimoto (2017)). As a result, it was possible to expand the applicable ground compared with the conventional injection method using cement-based injection material. In addition, the authors conducted field injection tests and laboratory model experiments on ultra-fine particle cement, and showed that this improved material is effective for sand ground containing fine particles (e.g. Weihong et al. (2016) and Hashimoto et al. (2019)). However, it have not studied much about the dynamic behavior during earthquakes. And it is an urgent task to accumulate these data in Japan, where many large earthquakes occur. In this paper, a blending test was first conducted, and a vendor element test was conducted using a
triaxial compression tester. In this paper, we report the results of tests conducted at young ages.

2 MATERIALS

In this study, the authors used ultra microfine cement as grouting materials. In order to improve the permeability of cement-based injection material, it is indispensable to reduce the particle diameter. However, if the particle diameter is simply made smaller than the particle of ultrafine cement (average particle diameter is about 4μm), the permeability of the cement is not improved. Therefore, development of extremely fine permeable ultra microfine cement (average particle size 1 to 2 μm) which reduced particle size and increased dispersibility of particles was advanced. Figure 1 shows the particle size of ultra microfine cement and microfine cement. Iwaki silica sand No.7 was used as ground material. Table 1 shows the physical property values of Iwaki silica sand No.7 and Figure 2 shows the particle size the silica sand has a comparatively large particle size, but it can be seen that it is a material containing a small amount of fine grains.

![Microfine cement](image1)

![Ultra microfine cement](image2)

Fig. 1. Photomicrograph of grouting materials.

![Grain size accumulation curve](image3)

Fig. 2. Grain size accumulation curve of Iwaki silica sand No.7.

| Parameters | Value |
|------------|-------|
| Fc (%)     | 15    |
| ρg (g/cm³) | 2.65  |
| eₘₙₓ     | 1.26  |
| eₘ₁₃     | 0.713 |

Table 1. Physical characters of Iwaki silica sand No.7.

3 TESTING EQUIPMENT

3.1 Sample preparation

In order to investigate the influence of the water cement ratio of the ultra fine cement injection material on cement solidification, blending tests were carried out with injection materials of different concentrations. Specimens with a diameter of 50 mm and a height of 100 mm was produced by a falling-in-water method using a plastic mold containing cement milk of a predetermined concentration in advance. The manufacturing procedure will be described below.

1) Prepare ultra fine cement and stir at high speed with 1500 rpm of water to prepare injection material.
2) Transfer the prepared injection to a stirrer and stir to maintain dispersibility.
3) A predetermined amount of injection material is taken out by applying positive pressure according to manufacturing conditions.
4) Calculate the amount of sand beforehand so that the relative density becomes 60%, and put the sand into the underwater falling method.
5) Tap the plastic mold. Confirm that the cement injection material penetrates the surface of the sand and stop tapping.
6) Cure with 7 or 28 days.
3.2 Bender Element Test

As auxiliary experiments, the Authors performed also as series of bender element tests. The bender elements were arranged such that the transmitter was in the base pedestal and receiver in the top cap of the triaxial sample. The bender elements were located in the same plane and the transmitter was wired in parallel while the receiver was in series. (Lee and Santamarina 2005). The receiver was 4.4mm high, 12mm wide and 1.4mm thick, while the transmitter was 4.1 mm high 12mm wide and 1.2 mm thick. These dimensions include the thickness of the coating. The height of the element represented the length intruded into the sample. The bender element system was self monitoring and the voltage generated by a sensor on the transmitter was recorded as the transmitter signal. Specimens 50mm diameter and 100mm were prepared by adding sand to a mold containing cement milk beforehand in the manner of a falling underwater method so as to have a predetermined density. And in this study, the water cement ratio w / c was changed to 8, 10, 12, 14, 16, 20 and tested. In all tests, the specimen was carried out with an effective constraint pressure $\sigma'_c = 50$ kPa.

4 TEST RESULTS

Figure 3. shows relationship between Unconfined compression pressure $q_u$ and water content of cement hardened sand improved with cement milk of 6 types of water cement in 7, 28 days curing by unconfined compression test. Here, the red line indicates the design strength for application to the actual ground. From the figure, it can be seen that the strength decreases as the water-cement ratio increases at any curing time. In addition, at the same water-cement ratio, it can be seen that those with longer curing days develop more strength. On the 7 day of curing, it was below the design strength only when the water-cement ratio was 20.

Figure 4 shows the relationship between the shear modulus G and the water cement ratio of modified soil curing for 7 days and 28 days in the bender element test. Incidentally, G of the bender element test corresponds to $G_0$ of the dynamic share test. Larger stiffness was confirmed when the curing period was longer than the figure. In each curing day, the higher the water cement ratio was, the lower the rigidity was obtained.

5 EVALUATION FORMULA FOR SHEAR MODULUS OF CEMENT-IMPROVED SOIL ON GRANULAR STRUCTURE

Many studies have been conducted so far on the dynamic deformation characteristics of ground materials, and for sandy soil, equations for evaluating the dynamic deformation coefficient based on the sand particle shape, pore ratio, restraint pressure, etc. have been presented (i.e. Seed (1976), Ishihara et al. (1978) Hardin (1968) and Iwasaki et al.(1978)). However, these estimation formulas are based on experimental results using relatively clean clay soil that does not contain much sand. It is difficult to apply to plastic clay
with relatively low fine particle content such as so-called intermediate soil, which is a region where both clay soil and sandy soil are difficult to distinguish. Therefore, it is not possible to systematically evaluate the dynamic deformation coefficient of cohesive soil with various properties. From such a background, little research has been conducted on the evaluation of cement-modified soil.

Equivalent granular void ratio \( e_{ge} \) may be used when evaluating soil composed of coarse and fine grains. The equivalent granular void ratio \( e_{ge} \) is an extension of the granular void ratio \( e_g \) and is a concept that contributes to the coarse-grained granular at a certain rate rather than completely ignoring the volume of fine particles, and this concept was proposed by Thevanyagam et al. (2002). Thevanyagam et al. (2002) show that by using this equivalent granular void ratio \( e_{ge} \), the pore ratio-effective stress relation in the steady state of silt and sand mixed soil is unambiguous regardless of the fine content \( F_c \).

Assuming that the soil particle density \( \rho_s \) of coarse and fine soils is equivalent, the fines content \( F_c \) is expressed by equation (1).

\[
F_c = \frac{V_g}{V_S}
\]

(1)

Here, \( V_{ge} \) is the volume of fine grains and \( V_S \) is the volume of coarse-grained soil and fine grains.

The equivalent granular void ratio age is expressed by equation (2) using the global void ratio \( e \), fines content \( F_c \), and contribution \( b \).

\[
e_{ge} = \frac{e + (1-b)F_c}{1-(1-b)F_c}
\]

(2)

In this study, an attempt was made to propose an evaluation formula by substituting Formula (2) with cement-modified soil. And in this study, cement concentration (water cement ratio) was used as an alternative to fines content \( F_c \). Equivalent granular void ratio \( e_{ge} \) in cement improved soil proposed in this study is expressed by equation (3).

\[
e_{ge}^{'} = \frac{e + (1-b)\alpha}{1-(1-b)\alpha}
\]

(3)

Where \( \alpha \) is the volume ratio of water and cement.

Figure 5 (a) and 5 (b) show the relationship between the shear modulus \( G \) of the cement-modified soil and the equivalent granular void ratio \( e_{ge} \) in the 7-day curing obtained from the vendor element test. The figure also shows the curve obtained from the following equation obtained by Hardin and Richart (1963) for clean Ottawa sand with a grain size.

\[
G = 6930 \left( \frac{2.17 - e}{1 + e} \right)^2 \left( \sigma_n^{0.5} \right)
\]

(4)

The equivalent granular void ratio \( e_{ge} \) in Figure 5 (a) is when \( b = 1 \), i.e. \( e_{ge} = e \). From the figure, even when compared with the Hardin and Richart equations, the same stiffness ratio shows a high standard stiffness at any water cement ratio. The contribution rate is shown as \( 0 \leq b \leq 1 \) as described above, but this is the case when the granular structure dominates the stiffness. In this study, the application of \( b \geq 1 \) was also considered because the injection material was cement.

Figure 5 (b) shows the relationship between the shear elastic modulus and the equivalent skeletal gap ratio obtained by substituting 3 for \( b \) in equation (3). From the figure, it can be seen that there is good correlation with the Hardin and Richart equations except for one plot. In other words, in the concept of Equation (3), it can be said that the cement improvement material contributes to three times the rigidity of sand (coarse particles). Therefore, the shear modulus of cement-modified soil with a curing period of 7 days can be expressed by equations (5) and (6).

\[
G_{ge} = 6930 \left( \frac{2.17 - e_{ge}^{'}}{1 + e_{ge}^{'}} \right)^2 \left( \sigma_n^{0.5} \right)
\]

(5)

\[
e_{ge}^{'} = \frac{e - 2e_{se}}{1 + 2e_{se}}
\]

(6)

However, the above formula is a fairly limited condition with a curing period of 7 days and \( w/c \geq 10 \). Therefore, it is necessary to collate with more data and propose a more accurate evaluation formula.
6 CONCLUSIONS

In this paper, a vendor element test was performed using a triaxial compression tester, and the shear elastic modulus of consolidated sand improved with a fine cement injection material (ultra-microfine cement) was investigated.

In the shear modulus $G$ and water cement ratio $w/c$ calculated in the bender element test, it can be seen that the stiffness decreases as the water cement ratio increases, that is, the water cement ratio decreases, in any curing period. It was also found that the longer the curing days, the higher the rigidity.

Based on the results of the bender element test, an attempt was made to propose an evaluation formula for the shear modulus using the equivalent granular void ratio used in the mixed soil. The following evaluation formula was calculated when the effective restraint pressure was 50 kPa and the curing period was 7 days.

$$G = \frac{6900 (2.17 - \varepsilon')^2}{1 + \varepsilon'} (\sigma_u')^{0.5}$$

$$\varepsilon' = \frac{\varepsilon - 2\alpha}{1 + 2\alpha}$$

However, the above formula is a fairly limited condition with a curing period of 7 days and $w/c \geq 10$. Therefore, it is necessary to collate with more data and propose a more accurate evaluation formula.

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REFERENCES

1) Wakamatsu K. and Senna S. (2011): Liquefaction and their Site Conditions in Kanto Region during the 2011 Off the Pacific Coast of Tohoku Earthquake, The Journal of JAE, vol.15, No.2.2 25-2.44(in Japanese), DOI: https://doi.org/10.5610/jaee.15.2.25
2) Mori, A., Tamura, M. and Aoki, K. (1991): Permeation Limit of GROUTS with Ultra-fine Granular Materials, The Journal of JSCE, 426, 237-240. (in Japanese), DOI: https://doi.org/10.2208/jscej.1991.426_237
3) Hashimoto, K. (2017): Development of Soil Liquefaction Mitigation Method by means of Permeation Grouting of Ultra Microfine Cement, Ph. D. thesis of Tokyo University of Science. (in Japanese)
4) Weihong, W. et al. (2016): Examining efficient assisting geotechnology for permeation grouting of ultra microfine cement for soil liquefaction countermeasure, Japanese Geotechnical Society Special Publication, 4(5), 97-100. DOI: https://doi.org/10.3208/jgssp.v04.p94
5) Hashimoto, K., Hyodo, T., Tsukamoto, Y. and Arai, Y. (2019): Proceedings of 7th International Conference on Earthquake Geotechnical Engineering, Rome.
6) Seed, H.B. (1976): Evaluation of soil liquefaction effects on level ground during earthquakes, State-of-Art Report, Preprint of ASCE Annual Convention and Exposition on Liquefaction Problems in Geotechnical Engineering, Philadelphia.
7) Ishihara, K., F. Tatsuoka and S. Yasuda. (1978): Undrained deformation and liquefaction of sand under cyclic stress, Soils and Foundations, 15(1), 29-44.
8) Hardin, B.O. and F.E. Richart Jr. (1968): Elastic wave velocities in granular soils, Jour. Of SMF Div., Proc. ASCE, Vol.89, No.SM1, 33-63.
9) Iwasaki, T., F. Tatsuoka and Y. Takagi (1978): Shear moduli of sands under cyclic torsional shear loading, Soils and Foundations, 18(1), 39-59.
10) Thevanayagam, S., Shethan, T., Mohan, S. and Liang, J. (2002): Undrained fragility of clean sands, silty sands, and sandy silts, Journal of Geotechnical and Geoenvironmental Engineering, 128(10), 849-859.
11) Hardin, B.O. and Richart Jr. F.E. (1963): Elastic wave velocities in granular soils, Proc. ASCE., 89(1), 33-65.