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A practical method for estimating maximum shear modulus of cemented sands using unconfined compressive strength

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ABSTRACT

The composition of naturally cemented deposits is very complicated; thus, estimating the maximum shear modulus (G_{max}, or shear modulus at very small strains) of cemented sands using the previous empirical formulas is very difficult. The purpose of this experimental investigation is to evaluate the effects of particle size and cement type on the G_{max} and unconfined compressive strength (q_{ucs}) of cemented sands, with the ultimate goal of estimating G_{max} of cemented sands using q_{ucs}. Two sands were artificially cemented using Portland cement or gypsum under varying cement contents (2%–9%) and relative densities (30%–80%). Unconfined compression tests and bender element tests were performed, and the results from previous studies of two cemented sands were incorporated in this study. The results of this study demonstrate that the effect of particle size on the q_{ucs} and G_{max} of four cemented sands is insignificant, and the variation of q_{ucs} and G_{max} can be captured by the ratio between volume of void and volume of cement. q_{ucs} and G_{max} of sand cemented with Portland cement are greater than those of sand cemented with gypsum. However, the relationship between q_{ucs} and G_{max} of the cemented sand is not affected by the void ratio, cement type and cement content, revealing that G_{max} of the complex naturally cemented soils with unknown in-situ void ratio, cement type and cement content can be estimated using q_{ucs}.

1. Introduction

Most natural soil deposits experiences some degree of cementation resulting from the deposition of cementing agent through interparticle contacts (Lee et al., 2009; Yun and Santamarina, 2005). In addition, soil improvement through the addition of cementing materials can produce cementation bonds between soil particles and consequent significant structural changes that dominate the behavior of soils (Schnaid et al., 2001). Therefore, it is obvious that the cementation effect, which induces a cohesion component in granular soils, should be adequately characterized. The maximum shear modulus (G_{max}, or shear modulus at very small strains) is an essential property of soils determining deformation characteristics and dynamic response of soils (Ku and Mayne, 2013); thus, the estimation of *in-situ* shear wave velocity or maximum shear modulus is very important.

Many empirical formulas have been developed to express the G_{max} of cemented sands as a function of cement content and void ratio (Acar and Eltahir, 1986; Lee et al., 2011; Mohsin and Airey, 2005; Saxena et al., 1988). However, as reflected in the different G_{max} formulas according to different studies, it is inappropriate to estimate G_{max} of cemented sand based on the function of cement (or gypsum) content and void ratio because the composition of naturally cemented deposits is very complicated, implying the determination of cement type and cement content of natural soils is almost impossible (Lee et al., 2010; Yang and Woods, 2015). In addition, the measure of *in-situ* void ratio (or porosity) of natural sediments is very difficult (Lee and Yoon, 2014). Furthermore, the behavior of cemented sand is affected by a number of factors, including the cement content, cement type, soil type, soil density (void ratio), particle shape, particle gradation and others. Therefore, estimating the G_{max} of cemented sand with unconfined compressive strength (q_{ucs}) is promising because q_{ucs} can be used as the measure of the degree of cementation of cemented deposits: in previous studies, cemented sands were categorized based on their q_{ucs} values (Rad and Clough, 1982; Schnaid et al., 2001). Additionally, the unconfined compression test is a simple, fast, repeatable, and economically viable test, while the direct measurement of *in-situ* shear wave velocity is still not very common in some countries, including South Korea, except for projects with very high risk. Thus, attempts have been made in several studies to correlate the q_{ucs} and G_{max} of cemented sands (Acar and Eltahir, 1986; Consoli et al., 2009; Porcino et al., 2016).

The aim of this experimental investigation is to determine the effects of particle size and cement type on the maximum shear modulus (G_{max}) and unconfined compressive strength (q_{ucs}) of cemented sands, with the ultimate goal of estimating the G_{max} of cemented sands using q_{ucs}.

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The background for the relation between G_{max} and q_{ucs} of cemented sand was reviewed. A series of measurements of shear wave velocity and unconfined compressive strength were then conducted for two poorly graded silica sands cemented with Portland cement and gypsum as a function of cement content and void ratio. Additionally, the results from previous studies (Consoli et al., 2007; Park and Hwang, 2014) of two poorly graded silica sands cemented with Portland cement were incorporated in this study for data analysis.

2. Background

Based on the simplified phase diagram of the cemented soil with assuming the weight of soil = 1 and the defining cement content (CC) = weight of cement/weight of soil (Fig. 1), the volume of cement (V_{ce}) and the volume of the void (V_v) can be expressed as follows:

$$V_{ce} = \frac{CC}{G_{s,ce} \cdot \gamma_w} \tag{1}$$

$$V_v = (V_s + V_{ce}) \cdot e = \left(\frac{1}{G_{s,s} \cdot \gamma_w} + \frac{CC}{G_{s,ce} \cdot \gamma_w} \right) \cdot e \tag{2}$$

where $G_{s,ce}$ and $G_{s,s}$ = specific gravities of cement and sand, respectively; γ_w = unit weight of water; and e = void ratio. Thus, the ratio between V_v and V_{ce} is:

$$\frac{V_v}{V_{ce}} = \left(\frac{1}{CC} \cdot \frac{G_{s,ce}}{G_{s,s}} + 1 \right) \cdot e \tag{3}$$

Previous studies (Consoli et al., 2009; Consoli et al., 2007) showed that V_v/V_{ce} effectively captures the behaviors of cemented sand, including the unconfined compressive strength (q_{ucs}) and maximum shear modulus (G_{max}). The following q_{ucs} and G_{max} formulas can be therefore be given as a function of V_v/V_{ce}:

$$q_{ucs} = a_1 \cdot \left({}^{V_v}\!/_{V_{ce}} \right)^{b_1} \tag{4}$$

$$G_{\max} = a_2 \cdot \left({}^{V_v}\!/_{V_{ce}} \right)^{b_2} \tag{5}$$

where a_1 and a_2 = q_{ucs} and G_{max} at $V_v/V_{ce} = 1$, respectively and b_1 and b_2 = fitting parameters capturing the dependency of q_{ucs} and G_{max} on V_v/V_{ce}, respectively. Eqs. (4) and (5) demonstrate that V_v/V_{ce} may act as a medium connecting the relation between q_{ucs} and G_{max}; therefore, the substitution of Eq. (4) into Eq. (5) yields the following relationship between q_{ucs} and G_{max}:

$$G_{\max} = \frac{a_2}{{a_1}^{b_2/b_1}} \cdot {q_{ucs}}^{b_2/b_1} \tag{6}$$

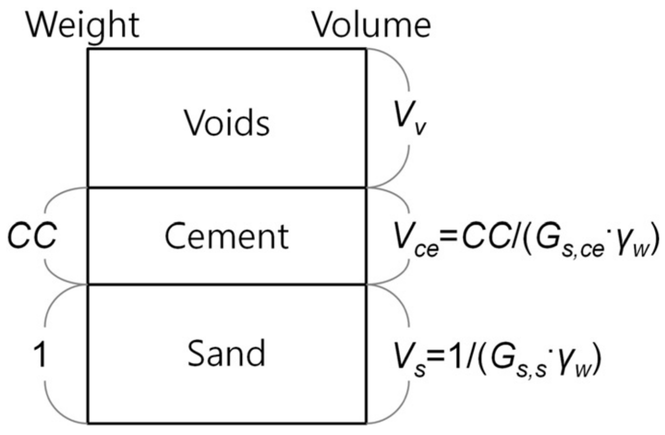

Fig. 1. Simplified phase diagram of cemented sand: CC = cement content by weight (weight of cement/weight of sand); V_v = volume of void; V_{ce} = volume of cement; V_s = volume of sand; G_s = specific gravity; γ_w = unit weight of water.

Among the several factors affecting the mechanical properties of cemented sands, cement content, cement type, packing density (void ratio), and sand particle size were selected as the testing variables in this study for the evaluation of q_{ucs} and G_{max}, and the consequent relation between q_{ucs} and G_{max} of the tested cemented sands. Because the cement content and void ratio determine the ratio between V_v and V_{ce}, the following experimental program were designed to evaluate the effects of cement type and sand particle size on the variations of the a and b values in Eqs. (4), (5), and (6).

3. Experimental program

3.1. Materials

Two artificially crushed sands with different particle sizes were derived from the same parent rock in Kangwon Province, South Korea, and were used to measure both unconfined compressive strength and shear wave velocity. Each tested material is classified as SP (poorly graded sand) according to the USCS (Unified Soil Classification System) and is mainly composed of silicon dioxide (>98%) with other trace materials such as aluminum oxide and iron oxide. The basic properties of the tested materials are given in Table 1. Additionally, the results of two poorly graded silica sands from previous studies (Consoli et al., 2007; Park and Hwang, 2014) are incorporated in this study for the data analysis (Table 1). Consequently, the results of four poorly graded silica sands with median particle sizes (D_{50}) ranging from 0.16 to 1.01 were used in this study.

Portland cement and gypsum were used as the cement agent in this study. Because the unconfined compressive strength of type III (high early strength) Portland cement cured for 7 days is comparable to that of type I (ordinary) Portland cement cured for 28 days, type III Portland cement (Ssangyong Cement Industrial Company, Korea) was used. The curing of the selected gypsum (Mungyo Plaster, Korea) initiates approximately 16 min after mixing with water and the curing continues for around 40 min. A previous study (Lee et al., 2011) noted that the unconfined compressive strength (q_{ucs}) of the tested gypsum cured at a water content of 40% is approximately 20 MPa.

3.2. Sample preparation and testing program

K-4 and K-6 sands were mixed with the cement (or gypsum) in the dry state to obtain a varying cement content (CC = weight of cement (or gypsum)/weight of sand), ranging from 2% to 9% (Table 2). Water with the amount of 10% water content (weight of water/weight of cement and sand) was then added to each solid mixture to obtain a homogeneous paste. To prepare artificially cemented specimens with various relative densities, ranging from 30% to 80% (Table 2), the wet mixture

Table 1
Material properties.

Type	D_{50}	C_u	G_s	e_{max}	e_{min}	Particle shape
Crushed K-4	1.01	1.19	2.65	1.08	0.71	Angular
Crushed K-6	0.47	1.52	2.65	1.04	0.66	Angular
Park and Hwang (2014)	0.24	1.32	2.64	1.18	0.85	Sub-angular
Consoli et al. (2007)	0.16	1.90	2.65	0.90	0.60	Rounded

Note: D_{50} = median particle size (50% passing); C_u = uniformity coefficient; G_s = specific gravity; e_{max} = maximum void ratio; e_{min} = minimum void ratio.