Sand Fraction Effect on Hydro-mechanical Behavior of Sand-Clay Mixture

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Abstract

The sand-clay mixture was prepared to simulate special soils with discontinuous gradations, *e.g.* the residual soils, clinosols or hydraulic filling soils. Incremental loading oedometer tests were conducted to investigate their hydro-mechanical behaviors. The results were first analyzed based on the plots in the semi-logarithmic planes (*i.e.* normalized void ratio by that at liquid limit *v.s.* vertical effective stress, and *v.s.* hydraulic conductivity). It appears that the normalized void ratio by that at liquid limit allows valuable and reliable normalization of the compressibility and permeability curves. To investigate the influence of sand fraction, a four-phase model of sand-clay mixture was introduced, enabling the void ratios of clay and sand to be determined. Further analysis showed that the sand void ratio and the normalized clay void ratio by that at liquid limit are also suitable parameters to describe the sand skeleton formation. Moreover, the normalized clay void ratio by that at liquid limit is an appropriate parameter to describe the hydraulic behavior of soils with or without sand fraction. When the sand skeleton was partly formed, the vertical stress was partly supported by the skeleton resulting in a different compression behavior from that of common clays. The partial formation of skeleton was found to depend on the relative dimension of coarse to fine grains as well as the stress state. This implies that during compression the interaction between sand and clay evolves, from non-, partial- to complete sand skeleton, reaching at the end of the maximum void ratio of sand.

Keywords: Sand-clay mixture; Sand fraction; Hydro-mechanical behavior; Four-phase model; Sand skeleton formation.

1. Introduction

The compression and percolation behaviors of soils are essential when analyzing the foundation deformation, dam seepage, *etc.* Many investigations were conducted in this field, but mostly focusing on cohesive soils with relatively continuous gradations (Mesri and Olson, 1971; Tavenas *et al.*, 1983; Burland, 1990; Babu *et al.*, 1993; Sridharan and Nagaraj, 2005; Yukselen-Aksoy *et al.*, 2008; Dolinar, 2009; Hong *et al.*, 2010; Hong *et al.*, 2012; Chapuis, 2012). However, for most naturally formed soils, including residual soils, clinosols and deposit clays, their fractions are composed of clay, silt, sand or gravel. On the other hand, special soils with multi fractions can also be produced by human activities. For instance, during the land reclamation of Ganyu port in Lianyungang, China, the hydraulic filling method was performed by dredging the original sand and clay interbedded layers, leading to the formation of sand-clay mixtures. Note that in this case, the sand content and the ratio of bentonite and kaolinite in clay minerals randomly deposited from 0% to 80%, and 5/5 to 9/1 respectively after site re-investigation (Wu *et al.* 2015, 2016). For this kind of soils, the hydro-mechanical behavior can strongly depend on the sand fraction, and it is thereby essential to investigate the effect of sand fraction on the compression and percolation behaviors of soils.

The sand-clay mixture is usually adopted to investigate the effect of large grain fraction and the interaction among different fractions (Cabalar and Hasan, 2013). Watabe *et al.* (2011) reported that the compressibility of compacted sand-clay mixtures was governed by the sand fraction when the sand fraction reaches a

threshold to form a sand skeleton. This observation is consistent with the previous results obtained by Fukue *et al.* (1986) and Boutin *et al.* (2011). Cabalar and Hasan (2013) further pointed out that the sand size/shape, percentage of sand or clay and stress states are also important factors affecting soil compressibility. For the percolation behavior, Watabe *et al.* (2011) found that the increase of sand fraction leads to a slight increase of hydraulic conductivity below a threshold, followed by a sharp increase beyond the threshold. Tripathi and Viswanadham (2012) further found that the percolation behavior of sand-bentonite mixtures was both controlled by the initial saturation process, testing method and bentonite content.

Although there have been some investigations on the compressibility and percolation behaviors of sand-clay mixtures, the sand fraction effect on the hydro-mechanical behavior of this kind of soils has not been fully understood yet. In this study, a series of oedometer tests on sand-clay mixtures with various sand/clay fraction ratios were carried out. The compressibility and the hydraulic conductivity obtained by back analysis (Sivapullaiah *et al.* 2000, Watabe *et al.* 2011) were adopted to evidence the effect of sand fraction.

2. Materials and methods

2.1 Materials

The basic materials studied were composed of standard quartz sand, commercial kaolin and bentonite. The standard sand was provided by Fujian Sand Product Company, with the maximum void ratio (e_{max}) of 0.83 and the minimum void ratio (e_{min}) of 0.485 respectively. The particle size distribution curve was shown in **Fig. 1**.

Note that the size distribution of sand in this study was obvious different from that in other literatures, aiming to simulate the sand composition of soils from Ganyu Port, and to investigate the effect of particle size distribution on the hydro-mechanical behaviors.

The commercial kaolin and bentonite were provided by Zhenjiang and Xuzhou Clay Manufacturing Company in China respectively. Their grain size distributions measured by the Marlvern laser particle size analyzer were shown in **Fig. 1**. It can be observed that the kaolin and bentonite have the similar grain size distributions. The mineralogical compositions of kaolin and bentonite materials were semi-quantitatively determined by X-ray diffractometry method and presented in **Table 1**. It shows that the minerals of kaolin are composed of quart (4.0%), K-felspar (5.1%), plagioclase (17.1%), calcite (3.5%) and dolomite (2.1%) respectively, and the clay mineral is just kaolinite with a content of 68.2%. On the other hand, the minerals of bentonite are of quart (1.3%), K-felspar (0.3%), calcite (0.1%), and the clay minerals are mostly composed of smectite (90.5%).

The basic physicochemical properties of studied kaolin and bentonite were listed in **Table 2**, which shows that the bentonite has the higher values of liquid limit (w_L), plastic limit (w_P), plasticity index (I_p), exchangeable cations, specific surface area (SSA) and pH, owing to the high smectite content. According to the Unified Soil Classification System (ASTM, 2010a), the kaolin and bentonite are low-plasticity clay (CL) and high-plasticity clay (CH), respectively.

2.2 Methods

Sand-clay mixtures were prepared by mixing the pure clays and sand. To consider the mineralogy influence in the clays, three dry mass ratios of bentonite to kaolin were considered: 9/1, 7/3 and 5/5. The sand fractions (w_s) were preset as 0%, 30%, 40% and 50%, defined by Eq. (1):

$$w_s = \frac{m_s}{m_s + m_c} \quad (1)$$

where m_s and m_c are the dry mass of sand and clay, respectively.

During the sample preparation, a predetermined mass of sand and air-dried clays were thoroughly mixed using a paddle mixer. The basic properties of the mixtures are presented in **Table 3**, where the liquid limit (w_L) was determined following ASTM D4318 (2010b), the specific gravity (d_{sc}) of clay and that (d_{ss}) of sand were determined following ASTM D854 (2010c), and the specific gravity (d_{sm}) of mixtures was calculated by the weighted average method.

After mixing, distilled water was added until the water content reached the liquid limit (w_L). Then, stirring process was applied to further homogenize the mixtures. Afterwards, the wetting sand-clay pastes were poured into the consolidation rings (61.8 mm in diameter and 20 mm in height) with tapping to minimize entrapped air bubbles in the specimens. The prepared samples were vacuumed in distilled water for 24 h to achieve full saturation. Note that the inside of ring was previously lubricated with silicon grease to minimize skin friction.

The one-dimensional oedometer tests were conducted on the prepared samples following ASTM (2011). The first load applied was 12.5 kPa and the subsequent load

was doubled each time until a maximum load of 1600 kPa. Note that before loading each time, the steady state should be reached, and the criterion shown in **Fig. 2** is adopted regarding the deformation stabilization for all odometer tests: the displacement rate lower than 0.01 mm/h. Despite that the steady state was usually realized in the first 24 h of each loading step in this study, the duration of each step was still preset as 24 h considering the test convenience and the standard of the oedometer tests.

The hydraulic conductivity was estimated following Terzaghi's one-dimensional consolidation theory, as follows:

$$k = c_v m_v \gamma_w \quad (2)$$

where k is the hydraulic conductivity, c_v is the coefficient of consolidation determined by Taylor method, m_v is the coefficient of volume change and γ_w is the unit weight of water. Note that this method was also considered by Sivapullaiah *et al.* (2000) and Watabe *et al.* (2011). Watabe *et al.* (2011) also found that when the sand content was less than 50%, the value of k obtained by this method is consistent with that by the falling head percolation test.

3. Results

3.1 Compression behavior

Fig. 3 shows changes of void ratio (e) versus vertical effective stress (p) in semi-logarithm plane. It is observed that the void ratio decreases with the increase of sand fraction at given stress and fine compositions. For instance, the void ratio (e) with a B/K ratio equal to 9/1 reduces from 6.75 to 4.75 when the sand fraction rises

from 0% to 30%. This is consistent with that the replacement of the clay fraction by the sand particle without pore voids. On the other hand, the composition of clay minerals also significantly affects the compressibility: the void ratio increases with the mass ratio of bentonite to kaolin.

Fig. 3 also reveals that the void ratio without sand almost straightens down with the vertical effective stress. However, a bi-linear compression behavior is observed with a threshold vertical stress in the case with sand; when the vertical stress is higher than the threshold, the compressibility is suppressed significantly.

Based on the analysis of the compressibility of different remolded clays, Nagaraj *et al.* (1986, 1993, 1995) found that the compression lines can be normalized by the void ratio at w_L (e_L) and the intrinsic state line (*i.e.* ISL) can be written as Eq. (3):

$$\frac{e}{e_L} = 1.23 - 0.276 \log p \quad (3)$$

This normalization index is used in this study to clarify the effect of sand fraction on the compression behavior. **Fig. 4** shows the normalized curves for the mixtures and the natural clays (Lianyungang clay and Baimahu clay) studied by Hong *et al.* (2013). It appears that all curves of soils without sand fall on a unique straight line, while the curves of soils with sand fall on a bi-linear line: for the vertical stress lower than about 200 kPa, the normalized curve is same as that without sand; when the vertical stress is higher than about 200 kPa, the normalized compression line becomes different and can be expressed by Eq. (4):

$$\frac{e}{e_L} = 0.92 - 0.13 \log p \quad (4)$$

3.2 Percolation behavior

Fig. 5 shows changes of hydraulic conductivity (k) with void ratio (e). It is observed that the sand fraction significantly affects k , which increases with the increase of sand fraction at given mass ratio of bentonite to kaolin and void ratio. Additionally, the k decreases with the increase of mass ratio of bentonite to kaolin at given sand fraction and void ratio. This suggests that the diameter of flow channels depends on the mineralogy of clay.

The index (e/e_L) is also used to quantitatively analyze the percolation behavior of these soils. **Fig. 6** reveals a linear relationship between k and e/e_L for the soils without sand, in agreement with observations by Nagaraj *et al.* (1986, 1993, 1995). By contrast, an exponential relationship is identified for the soils with sand and expressed:

$$k / 10^{-9} (cm / s) = -1.65 + 1.75 \exp^{\frac{(e/e_L - 0.34)/0.27}{e_L}} \quad (5)$$

It seems that there is a threshold e/e_L (about 0.4) that separates two regions: when e/e_L is larger than 0.4, the soils with and without sand almost follow the same curve. On the contrary, below this threshold value, the curve of soils with sand is below that of soils without sand, indicating a lower hydraulic conductivity.

4. Interpretation based on a four-phase frame

The results obtained reveals that the hydro-mechanical behavior of soils with sand is different from that of soils without sand. This is to be explained by considering the interaction between clay particles and sand grains, in particular the sand skeleton formation. To clarify the difference between the soils with and without sands, the four-phase frame (**Fig. 7**) of sand-clay mixture is adopted (Dixon *et al.*, 1985; Lee *et al.*,

1999; Wang *et al.*, 2013), where the clay void ratio (e_c) is defined as the ratio of void volume (V_v) to clay volume (V_c), e_s as the ratio of V_l (sum of void volume and clay volume) to sand volume (V_s). They can be deduced from Eq. (6), Eq. (7) and Eq. (8).

$$\rho_{dc} = \frac{(W_c / 100) \rho_m G_{ss} \rho_w}{G_{ss} \rho_w (1 + w_m / 100) - \rho_m (1 - W_c / 100)} \quad (6)$$

$$e_c = \frac{G_{sc} \rho_w}{\rho_{dc}} - 1 \quad (7)$$

$$e_s = \frac{G_{ss} \rho_w}{(1 - W_c / 100) \rho_{dm}} - 1 \quad (8)$$

where ρ_{dc} and ρ_{dm} are the initial dry unit mass of clay and sand-clay mixture, respectively; ρ_m is the unit mass of sand-clay mixture; ρ_w is the unit mass of water; G_{ss} is the specific gravity of sand and G_{sc} is the specific gravity of clay in the mixture; w_c is the clay content (in dry mass), and w_m is the water content of mixture.

For the most clays, V_s (or m_{ss}) of sand is close to zero, the e_c is the same as the total void ratio e , and e_s approaches infinity meaning that the sand fraction can be ignored in the clays. On the contrary, when V_c (or m_c) is close to zero, the soils become pure sand and in that case e_s ranges from the maximum to minimum void ratios of soils.

4.1 Compression behavior under four-phase frame

Fig. 8 depicts the compression behavior of the mixtures in e_s - p plane. Bilinear compression curves can be clearly identified, with a stress threshold at about 400 kPa. The value of compression index C_{cs} is much larger below 400 kPa stress compared to that beyond 400 kPa stress. Sand skeleton was probably formed at this threshold. In other words, before this threshold sand grains are supposed to be relatively independent within the matrix of fine particles (**Fig. 9 a**). Thus, the soil compression

was not controlled by sand skeleton. On the contrary, after the threshold sand grains came into contact and the soil compression became being governed by the sand skeleton (**Fig. 9 b**).

To further investigate this phenomenon, the normalized curve of e_c/e_{cL} versus p is re-plotted, where e_c and e_{cL} are the void ratio excluding the influence of the sand fraction. Note that they are equal to e and e_L respectively when the sand fraction was equal to zero. **Fig. 10** shows that e_c/e_{cL} decreased linearly with p at the same rate in all cases when p is lower than about 200 kPa. Beyond 400 kPa, e_c/e_{cL} decreases slower in the case with sand. This is consistent with the bi-linearity identified in **Fig. 4** (the bifurcation zone is located at 200-400 kPa or e/e_L (e_c/e_{cL}) equal to 0.4-0.5). This observation confirms the conclusion on sand skeleton formation.

4.2 Percolation behavior under four-phase frame

The percolation behavior of the soils with sand was found different from that without sand as shown in **Fig. 6**. This could be attributed to the composite system of impenetrable sand particles and clays with permeate pores (*i.e.* e_c) in the view of the clay-based porous materials. To clarify this percolation behavior, the relationship between k and e_c/e_{cL} is established in **Fig. 11**. The same linearity is identified as that of the case without sand shown in **Fig. 6**. The empirical relation proposed by Nagaraj *et al.* (1993) for soils with negligible sand fraction is also presented in **Fig. 11**. A good agreement is observed with the experimental data. This observation confirms that the percolation behavior of soils with sand can be dealt with as common clays provided that the four-phase model and e_c/e_{cL} are adopted.

5. Discussions

The above analysis reveals the existence of the sand formation through its significant effect on the hydro-mechanical behavior of mixtures. Two aspects need to be further investigated: (1) the threshold sand fraction and (2) the mechanism related to the sand skeleton formation.

Kumar and Muir Wood (1999) performed fall cone and one-dimensional compression tests on the mixtures of kaolin and fine gravel, and found that the mechanical behavior was controlled by the clay matrix when the clay content was higher than 35%. Monkul and Ozden (2007) conducted oedometer tests on reconstituted kaolinite-sand mixtures, and pointed out that up to a fine content between 19% and 34%, the compression behavior was mainly controlled by the sand grains. Watabe *et al.* (2011) also performed oedometer tests on the mixtures of Nagoya clay with sand or bentonite, and found that the compression behavior was controlled by sand when the fine content was lower than about 35%. In this study, the sand content was just higher than 30%, while the compression behavior began to differentiate from that without sands totally after a relative higher vertical stress supplied. Above all, the notion of critical sand content is still an open question and needs further investigation. As a first attempt on the effects of particle size distribution of sand and the relative dimension of the coarse to fine grains can be explored. The particle size distribution of the four sands referred to above are presented in **Fig. 1**. It was found that there existed a tendency that threshold sand fraction (compression behavior transformation) gradually decreases when the average sand dimension grew

up. For instance, the threshold sand fraction range from 66% to 81% with the small sand particle in Monkul and Ozden (2007), while it was 65% with the large particle in Kumar and Muir Wood (1999).

On the other hand, the relationship between the compression index C_c defined as $\Delta e / \Delta \log p$ (from 100 to 200 kPa) and the sand fraction is usually used to quantitatively identify the sand skeleton formation during compression. Watabe *et al.* (2011) established the relationships between C_c and sand fraction (**Fig. 12**), and found that when the sand formation was more than about 70%, the compression behavior was almost the same as that of sand. In this study, as the sand fractions are lower than 50%, the sand fraction did not affect the compression behavior below 200 kPa (e/e_L is larger than 0.4). With higher vertical stress, the turning point in **Fig. 12** moved to the left, *i.e.*, the sand fraction of the turning points evolved from more than 50% at less than 200 kPa, to 30% at more than 800 kPa. This suggests that the formation of sand skeleton does not depend only on sand fraction but also on the stress state.

Additionally, in this study, the maximum void ratio of sand was also determined by the sand pourer method, and a value of 0.83 was obtained. Note that under a vertical stress higher than 400 kPa, e_s with 30% sand fraction ranges from 4.5 to 6.2 (**Fig. 8**), significant larger than the sand maximum void ratio. As sand is necessarily skeletonized with the pourer method, this state can be considered as a complete sand skeleton. Hence, the skeleton occurred in the sand-clay mixtures is then a partial skeleton. Above all, the formation of the sand skeleton in the mixtures under stress can be divided into three stages, *i.e.* non-, partial- and complete- skeleton (In **Fig. 9** a, b, c).

Note that in the non-skeleton stage and complete-skeleton stage the compression behavior is totally controlled by clay and sand matrix, respectively.

6. Conclusions

A series of oedometer tests were conducted on sand-clay mixtures and their hydro-mechanical behaviors were investigated. The obtained results allow the following conclusions to be drawn:

(1) The normalized compression behavior in the semi-logarithmic planes (*i.e.* normalized void ratio by that at liquid limit *v.s.* vertical effective stress, and *v.s.* hydraulic conductivity) was significant different between mixtures and natural remolded clays. When the vertical stress was larger than or equal to about 400 kPa, or the normalized void ratio by that at liquid limit was less than about 0.4, the hydro-mechanical behavior deviated from that of the natural remolded clays. Otherwise, the behavior is similar to that of natural remolded clays.

(2) A four-phase model was introduced to analyze the hydro-mechanical behavior of the mixtures and the natural clays. It was found that the sand void ratio and the normalized clay void ratio by that at liquid limit are appropriate parameters to be used in identifying the sand skeleton formation. Furthermore, the relationship between the hydraulic conductivity and the normalized clay void ratio by that at liquid limit can well depict the percolation behavior of soils with or without sand, indicating that addition of sand reduced nominal void ratio whilst the porosity of mixtures only depended on fine fraction.

(3) The formation of sand skeleton upon loading can be divided into three stages,

i.e. non-, partial- and complete- skeleton stages. When the partial skeleton was formed, the vertical stress was partly supported by the skeleton and the soil showed different compression behavior compared to natural remolded clays.

(4) The formation of partial skeleton depended on the relative dimension of coarse to the fine grains as well as the stress state. The sand fraction formed the partial skeletons gradually became less when the average sand dimension grew up, and then, it evolved from more than 50% at the vertical effective stress less than 200 kPa, to 30% at more than 800 kPa.

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Table 1 Semi-quantitative analysis of the kaolin and bentonite materials

Materials	Mineral composition (%)								
	Quartz	K-feldspar	Plagioclase	Calcite	Dolomite	Siderite	Illite	Kaolinite	Smectite
Kaolin	4.0	5.1	17.1	3.5	2.1	0		68.2	
Bentonite	1.3	0.3	0	0.1	0	2.0	3.9	1.9	90.5

Table 2 Properties of bentonite and kaolin used in this study

Property	Testing method	materials	
		kaolin	Ca-bentonite
Liquid limit, w_L (%)	ASTM (2010b)	42	301
Plastic limit, w_P (%)	ASTM (2010b)	23	95
Plasticity index I_p	—	19	206
Sand (%; $> 0.075\text{mm}$)	<i>a</i>	5%	3%
Silt (%; $0.005\text{mm}-0.075\text{mm}$)		47%	42%
Clay (%; $< 0.005\text{mm}$)		48	55%
Exchangeable cations (cmol/kg)	ASTM (2010d)		
Na ⁺		4.75	53.39
K ⁺		0.34	0.53
Ca ²⁺		1.44	22.74
Mg ⁺		0.08	1.41
Sum		6.61	78.07
Specific surface area (m ² /g)	<i>b</i>	45.7	378.5
pH	ASTM (2007)	8.7	10.0
Classification	ASTM (2010a)	CL	CH

a: Measured using a laser particle analyzer Mastersizer 2000 (Malvern Instruments Ltd., UK).

b: Measured used EGME method according to Cerato and Lutenege (2002).

Table 3 Properties of sand-clay mixtures

B/K	w_c (%)*	Liquid limit w_L (%)	specific gravity d_{sm}	specific gravity d_{sc}	specific gravity d_{ss}
9/1	50	98.5	2.696	2.75	2.66
9/1	60	127.7	2.705	2.75	2.66
9/1	70	155	2.714	2.75	2.66
9/1	100	260	2.75	2.75	—
7/3	50	84.6	2.688	2.73	2.66
7/3	60	106.3	2.695	2.73	2.66
7/3	70	123.7	2.702	2.73	2.66
7/3	100	198.4	2.73	2.73	—
5/5	50	68.8	2.676	2.70	2.66
5/5	60	85.5	2.68	2.70	2.66
5/5	70	101.2	2.684	2.70	2.66
5/5	100	157.2	2.70	2.70	—

*: w_c (%) stands for the clay content in the mixtures. $w_c=100\%-w_s$

Fig. 1 Particle size distribution of sand, kaolin and bentonite

Fig. 2 Criterion for steady state

Fig. 3 Compression curves of mixtures

Fig. 4 Relationship between e/e_L and vertical stress

Fig. 5 Hydraulic conductivity versus void ratio

Fig. 6 Relationship between e/e_L and hydraulic conductivity k

Fig. 7 Four-phase frame of sand-clay mixtures

Fig. 8 Relationship between sand void ratio and vertical stress

(a) non-skeleton

(b) partial skeleton

(c) complete skeleton

Fig. 9 Sand distribution configurations

Fig. 10 Relationship between e_c/e_{cL} and vertical stress

Fig. 11 Relationships between k and e_c/e_{cL}

Fig. 12 Relationship between C_c and sand fraction