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Effect of fines on the compression behaviour of poorly graded silica sand

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Abstract. A series of high-pressure isotropic compression tests were performed on four types of poorly graded silica sand that were artificially prepared based on representative grading curves and similar mineralogy composition of seabed sediment containing different fines contents existing in the Nankai Trough. The addition of fines steepens the initial compression path and increases the decrement of the void ratio after loading. The transitional behaviour of the poorly graded sand with a larger amount of fines content was identified. The slope of the normal compression line shows a slight decreasing tendency with the level of fines content. The bulk modulus of silica sand with fines was lower when compared with the published results of silica sand without fines. A small amount of particle crushing of the four types of poorly graded sand with variable fines content levels was noticed, and the results indicated that the degree of particle crushing tended to decrease as the fines content increased.

Keywords: sand; compressibility; fines; particle crushing

1. Introduction

Natural gas hydrates in marine continental margins are expected to be a promising future energy source. Several laboratory experiments regarding the shear strength and deformation of methane hydrate bearing sediment by using clean sand as the host material have been conducted (Hyodo *et al*. 2005, 2013, Miyazaki *et al*. 2011). The Ministry of Economy, Trade and Industry (METI) conducted the Japan Nankai Trough Exploratory Test Wells program (Tokai-oki to kumano-nada) in 2004. The test well program indicated that methane hydrate was mainly concentrated in the sand and mud stratified layers with variable poor graded distribution and fines called turbidite (Fujii *et al*. 2005, Minagawa *et al*. 2008, Suzuki *et al*. 2009).

Previous studies revealed that compression curves of pure sand at all initial densities converged to a single normal compression line (NCL) at high pressures when particle crushing dominated the compression behaviour (Miura *et al*. 1984, Coop 1990, Consoli *et al*. 2005, Lade and Bopp 2005). A new mode of compression behaviour represented by compression curves that do not converge to a single line was recognized for gap-graded and well-graded soil with a large amount of fines and was identified as transitional behaviour (Martins *et al*. 2001, Ferreira and Bica 2006, Nocilla *et al*. 2006, Altuhafi *et al*. 2010). The occurrence of the transitional behaviour of soil with variable fines

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content requires further examination if the grain size distribution changes from well to poor. It has to be noted that the compression behaviour of the soil was complex and is greatly dependent on many factors such as relative density, fabric, grading distribution, grain size and angularity, mineralogy and structure (Pestana and Whittle 1995). Shipton and Coop (2012, 2015) reported that these factors might affect the onset of transitional behaviour.

Altuhafi and Coop (2011) studied the effect of the grading of three types of sand varying from uniform gradation to fractal gradation on transitional and breakage behaviour. Shipton and Coop (2012) performed a series of odometer tests on reconstituted soil mixed with different combinations of poorly graded sand and fines. They reported that carbonate sand and silica sand, mixed with similar proportion of fines, exhibited different compression and breakage behaviour. However, the number of investigations into the effects of fines on the compressibility and crushability of poorly graded sand, such as the seabed sediment in Nankai Trough, is quite limited. Meanwhile, few data exist that allow a better understanding of the compression characteristics of sand and silt seabed sediment mixture.

This paper presents the isotropic compression test data of four types of poorly graded specimens for investigating the influence of fines content on their compression characteristics. The specimens were artificially prepared using the representative grading curves and similar mineral composition of the methane hydrate concentration layers from the Nankai Trough. The variation in grain size distribution was measured, and the degree of particle crushing was quantified. The test results are expected to provide the necessary parameters for the mechanical behaviour modelling of methane hydrate bearing sediment.

2. Test description and tested sand

Suzuki *et al*. (2009) analyzed the sediment features such as grain size, porosity, and methane hydrate saturation of the pressure temperature core samples (PTCS) in ~~a~~ methane hydrate concentrated zone obtained from the METI exploratory test wells. Four representative grading curves of the marine sediment in the Nankai Trough with variable fines content were selected and named from Ta to Td. Ta and Tb represent the sand graded layer while Tc and Td represent the mud layer. The main mineralogy composition was measured by the X-Ray diffraction method are listed in Table 1. The core sample was composed mainly of feldspar, silica sand, mica, kaolinite, and pyrite. The specimens were artificially prepared with representative grading and minerology composition similar to the core sample from the Nankai Trough (METI 2005, MH21 Research Consortium 2008).

Fig. 1 shows the grading curve of the seabed sediment in the Nankai Trough. The grey shade represents the grading distribution of the sand and mud stratified layer where the methane hydrate is extensively concentrated. The artificial specimens were made of silica sand R55, No. 6, No. 7, No. 8, No. 9, non-plastic fines mica MK 300, and plastic fines kaolinite, as shown in Table 2. Fig. 2 presents the grain size distribution curves of the constituted material of the four types of sand. The fines are defined as small particles with a diameter less than 0.074 mm. The fines were composed of mica, kaolinite, and silica silt with the contents quantified by proportions based on their respective dry weight. The fines content Fc was smallest for Tb (8.9%) and largest for Td (36.6%), while Tc (22.9%) had ~~a~~ larger fines content than Ta (10.6%). Table 3 presents the relative distribution factors of the four types of sand and their uniformity coefficient Cu are similar but less than 5. All four types of sand can be categorized as poorly graded soil (Mitchell and Soga 2005).

Table 1 The mineralogy composition of the core samples from Nankai Trough (METI 2005)

Silty contained sample in mud layer				Sand rich sample in sand layer			
Group	Percent	Name	Percent	Group	Percent	Name	Percent
Sheet silicates (clay)	25.67%	Montmorillonite	2.49%	Sheet silicates (clay)	15.91%	Montmorillonite	1.63%
		Biotite (Mica)	9.75%			Biotite (Mica)	4.57%
		Kaolinite	9.30%			Kaolinite	6.61%
		Illite	1.37%			Illite	1.12%
		Clorite	2.76%			Clorite	1.98%
Amphibol	4.80%	Hornblende	1.41%	Amphibol	3.88%	Hornblende	1.41%
		Amesite	3.39%			Amesite	2.47%
Quartz	48.4%	Quartz	48.4%	Quartz	54.2%	Quartz	54.2%
Feldspar	18.54%	Orthoclase	1.68%	Feldspar	23.63%	Orthoclase	1.73%
		Anorthite	8.06%			Anorthite	10.4%
		Albite	8.80%			Albite	11.5%
Others	2.59%	Calcite	1.98%	Others	2.38%	Calcite	1.85%
		Pyrite	0.61%			Pyrite	0.53%

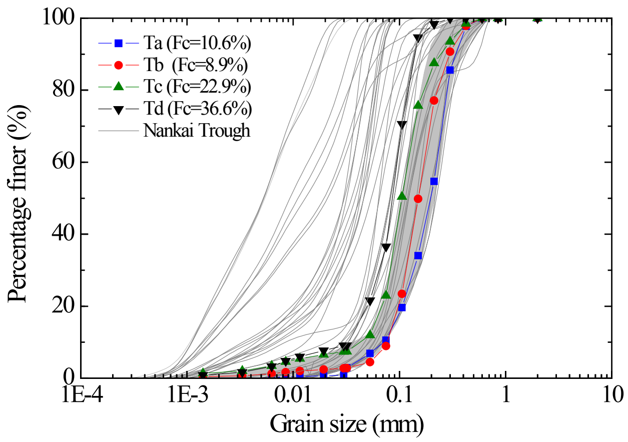

Fig. 1 Grain size distribution curves of the stratified layers in Nankai Trough and four types of sand with representative grading curves

Table 2 The mineralogy compositions of four types of sand with representative grading curves

Name of sands		(Small)			Median diameter			(Large)
		Kaolinite	Mica MK 300	Silica No.9	Silica No.8	Silica No.7	Silica No.6	Silica R55
Percent by weight (%)	Ta	0	1	9	10	10	70	0
	Tb	1	2	0	17	70	0	10
	Tc	3	5	0	55	30	0	7
	Td	2	8	12	70	8	0	0
Range of grain size (mm)		Under 0.053	0.0014-0.106	Under 0.15	0.0299-0.212	0.032 -0.3	0.053-0.425	0.15-0.85

Table 3 The grain size at specific diameter, specific gravity and relative distribution factors of the uniformity coefficient Cu and coefficient of curvature Ccu of four types of sand

Name of sands	d_{50} (mm)	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	C_u	C_{cu}	G_s (kN/m^3)	F_c (%)
Ta	0.195	0.077	0.141	0.226	2.935	1.126	2.6559	10.6
Tb	0.147	0.072	0.119	0.171	2.372	1.149	2.6613	8.9
Tc	0.114	0.043	0.085	0.120	2.797	2.797	2.6668	22.9
Td	0.087	0.034	0.065	0.094	2.795	2.795	2.6722	36.6

$C_u = d_{60}/d_{10}$; $C_{cu} = (d_{30})^2/d_{10}/d_{60}$

Table 4 Summary of the isotropic compression tests on poorly-graded sand

Test No.	Sand	F_c (%)	Initial void ratio e_i	Void ratio e_f at p_{max}	Maximum stress p_{max} (MPa)
T01	Ta	10.6	0.834	0.423	36
T02	Ta	10.6	0.667	0.433	36
T03	Tb	8.9	0.842	0.486	36
T04	Tb	8.9	0.676	0.443	36
T05	Tc	22.9	0.822	0.445	36
T06	Tc	22.9	0.664	0.384	36
T07	Td	36.6	0.837	0.391	36
T08	Td	36.6	0.667	0.391	36

The isotropic compression test was performed using a high-pressure, hydraulic servo-controlled triaxial apparatus with a maximum cell pressure of 50 MPa. Table 4 presents the details of the isotropic consolidation tests. The moist-tamped method was adopted, and the granular materials were compacted into ten layers for preparation of the two target porosities n of 45% and 40% in accordance with the data from the test wells (MH21 Research Consortium 2008). The specimen was 10 cm in height and 5 cm in diameter. The initial cell pressure of 120 kPa and the back-pressure of 100 kPa were simultaneously applied to saturate the specimens. The specimens were saturated until the B-value attained a value of 0.95 or more. The cell pressure increased in an orderly fashion from 120 kPa to 10 MPa in increments of 1 MPa and from 10 MPa to 36 MPa in increments of 3 MPa. At each target cell pressure, the consolidation process was continued for 1 hour to ensure that the change in volume was within 0.005% per minute. Finally, the specimens were unloaded to 0.1 MPa. The sieving analysis test was performed on all specimens before and after loading to understand the evolution of grain size distribution. The variation in the fines content was measured using the sedimentation analysis method.

The accuracy estimation of the initial void ratio e_i was the prerequisites used to identify the possible transitional behaviour of soil. Shipton and Coop (2012, 2015) used four different equations to compute the initial void ratio and then compared with the results from different methods. e_i is calculated from the initial water content before test ω_i, final water content after test ω_f, the initial dry unit weight γ_{di}, and the initial bulk unit weight γ_i. This method was also employed in this study to assess the accuracy estimation of the initial void ratio e_i. Table 5 shows a typical example of the initial void ratio determination for Tb with porosity n of 45% and the specific expression of four equations. The specific gravity G_s of the four types of poorly graded

Table 5 Example of initial void ratio estimation

Test No.	Equations for void ratio e determination				Chosen e_i	Estimated accuracy
	(1)	(2)	(3)	(4)		
Tb (F_c = 8.9%), n = 45%	0.845	0.840	0.847	0.834	0.842	± 0.008

Calculation equations:

$$e_i = w_i G_s / S_{ri} \qquad (1)$$

$$e_i = (G_s \gamma_w / \gamma_{di} - 1) \qquad (2)$$

$$e_i = (G_s - S_{ri})/(\gamma_i/\gamma_w - S_{ri}) - 1 \qquad (3)$$

$$e_i = \left(w_f G_s + 1\right)/(1 - \varepsilon_v) - 1 \qquad (4)$$

w_i and w_f are initial and final water contents, γ_{di} and γ_i are initial dry and bulk unit weight, S_{ri} is initial degree of saturation, γ_w is water unit weight, ε_v is overall volumetric strain

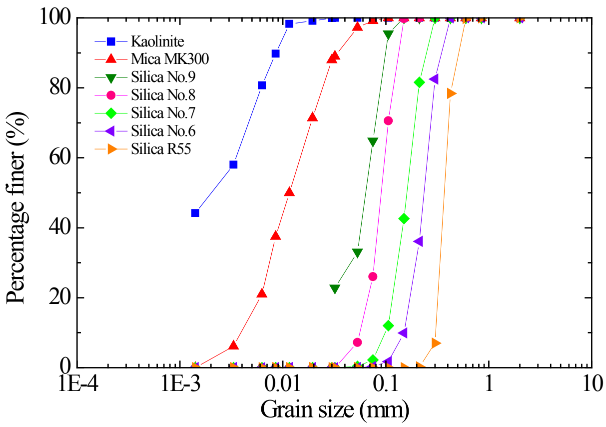

Fig. 2 Grain size distribution curves of the constituent material of four types of sand

sand is given in Table 3. For the example considered in this study, the estimated error is ± 0.008, which is within the acceptable estimated error range ± 0.02 for the triaxial tests. The average value from the results of the four types of sand was chosen.

3. Test results

3.1 Effect of fines content on compression characteristics

Fig. 3 shows the void ratio e plotted against the logarithm of the isotropic consolidation stress p' for the four types of sand at the two initial porosities. The addition of fines steepens the initial compression path and reduces the curvature of the compression curves. The decrement of the void ratio after maximum stress is also dependent on the fines content. The compression curve of the four types of sand are separately expressed in the specific volume ($v = 1+e$), and the logarithmic isotropic consolidation stress space is shown in Figs. 4(a), (b), (c) and (d). The compression behaviour of the sand at low stress is controlled by the combined influences of density and pressure. The deformation originates from the compression of the soil skeleton and subsequent

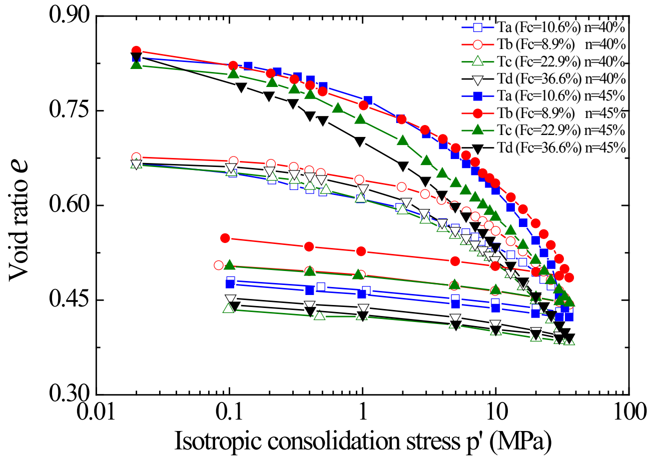

Fig. 3 The void ratio plotted against isotropic consolidation stress

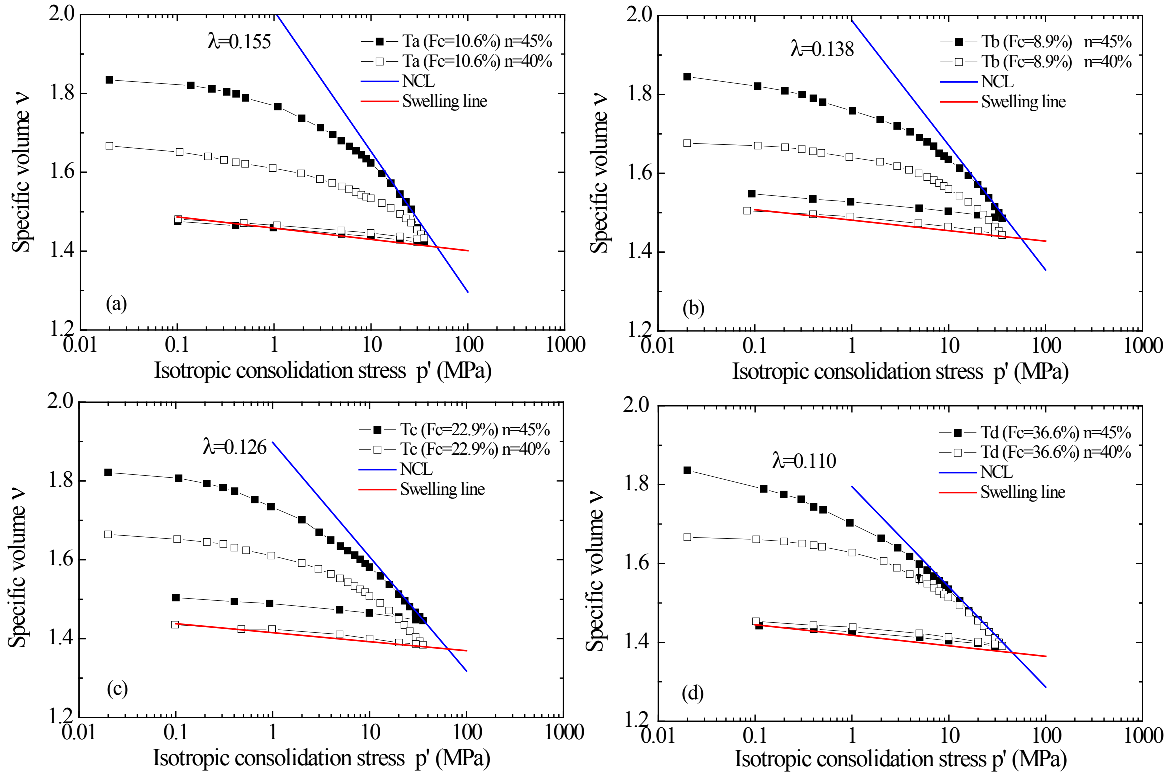

Fig. 4 The isotropic consolidation curves and NCL and swelling line of four types of sand: (a) Ta; (b) Tb; (c) Tc; (d) Td

rearrangement. The stress at the yield point of the one-dimension and isotropic compression curves for the maximum curvature is recognized as an influential parameter associated with the yield characteristics and the initiation of substantial particle crushing (De Souza 1958, Hagerty *et al*.

1993, Mesri and Vardhanabhuti 2009, Wu and Yamamoto 2015). However, the distinctive yield point is difficult to identify on the compression curves of the four types of poorly graded sand. Therefore, particle crushing is regarded as a minor factor governing the compression behaviour of sand with variable fines content. The NCL and the swelling lines are drawn on each figure, respectively. The NCL is expressed by Eq. (1) in the specific volume and isotropic consolidation stress space.

$$v = N + \lambda \ln p' \tag{1}$$

where N is the projected specific volume when the isotropic consolidation stress is 1 kPa and λ is the slope of NCL.

It is observed that the compression curves of Tb and Tc at the two porosities did not converge at the maximum stress level applied in this study as shown in Figs. 4(b) and (c). The non-convergent compression behaviour of soil with fines were reported by Martins *et al*. (2001), Nocilla *et al*. (2006), Altuhafi *et al*. (2010), Zhang and Baudet (2013) and called transitional behaviour. Because of the difficulty in performing the high-pressure isotropic compression tests, the compression tests at only two initial densities were performed in this study. Although there were a limited number of tests performed, the transitional behaviour was assessed for Tb and Tc. However, no transitional behaviour would seem to occur for Td or Ta. Shipton and Coop (2012) pointed out that the factors governing the convergent and non-convergent behaviour was complex, and each soil should be assessed individually. Fig. 5 presents the slope of the NCL and swelling line of the four types of sand with variable fines content. The slope of NCL λ tends to decrease as the fines content increases. It was noted that the slope of the swelling line κ was minimally influenced by the fines content. Table 6 shows the parameters λ and κ of the four types of sand.

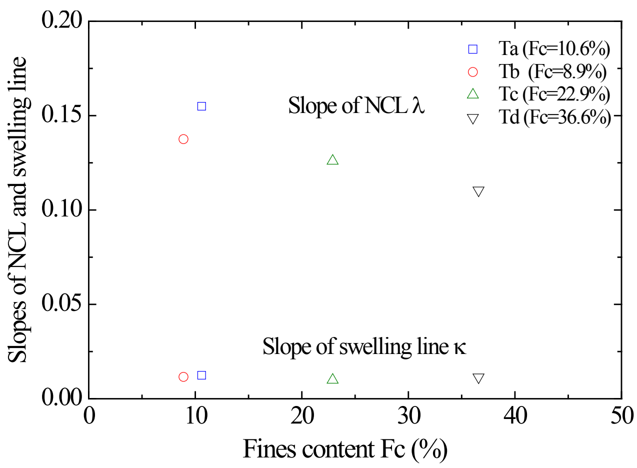

Fig. 5 Effect of fines content on the slopes of NCL and swelling line of four types of sand

Table 6 The slopes of NCL and swelling line of four types of sand

Name of sands	Ta	Tb	Tc	Td
Slope of NCL λ	0.155	0.138	0.126	0.110
Slope of swelling line κ	0.0124	0.0115	0.0099	0.0114

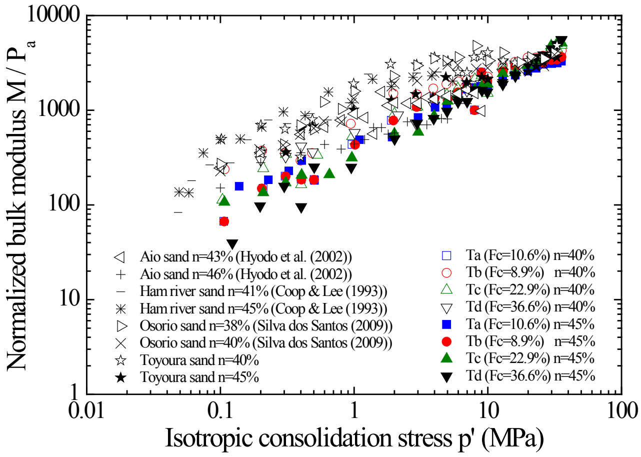

Fig. 6 The bulk modulus *M* plotted against isotropic consolidation stress of four types of sand and silica sand without fines

Fig. 6 presents the plot of the normalized bulk modulus M/Pa of the four types of sand as well as other types of sand without fines versus the isotropic consolidation stress p' for a double logarithmic plane. The vertical axis adopts the normalization value of bulk modulus M to the atmosphere pressures p_a to become a dimensionless form. The bulk modulus M in Eq. (2) is employed to describe the variation in the stiffness of the sand with the level of isotropic consolidation stress.

$$M = \frac{dp'}{d\varepsilon_v} \tag{2}$$

where dp' is the isotropic consolidation stress increment, and $d\varepsilon_v$ is the volumetric strain increment. The normalized bulk modulus of the four types of sand was compared with the published data of the silica sand without fines as discussed in the literature (Coop and Atkinson 1993, Hyodo *et al*. 2002, 2017, Silva dos Santos *et al*. 2009). It is noted that the results of the sand with fines are located below those of silica sand without fines. The results indicate that the behaviour of pure silica sand was stiffer than silica sand containing fines. As can be seen, the divergence in bulk modulus between those of the pure sand and those containing fines is more apparent for sand containing fines content within and in excess of the threshold range, such as Tc and Td.

3.2 Effect of fines content on particle crushing

The grain size distribution (GSD) curves of the four types of sand at loose and dense states before and after consolidation are displayed in Figs. 7(a), (b), (c) and (d). The slight shift of the grading curve after isotropic compression is seen for Ta and Tb. A negligible change in the grading curve can be noticed for the poorly graded sand Tc and Td. Altuhafi and Coop (2011) showed that no measurable variation in the GSD curve was seen for well-graded sand but exhibited a remarkable volume change. Experimental results demonstrate that a small amount of particle crushing occurs for all the contents of the four types of sand with variable fines. Additionally, the degree of particle crushing decreases as the porosity decreases. Recently, Shipton and Coop (2012)

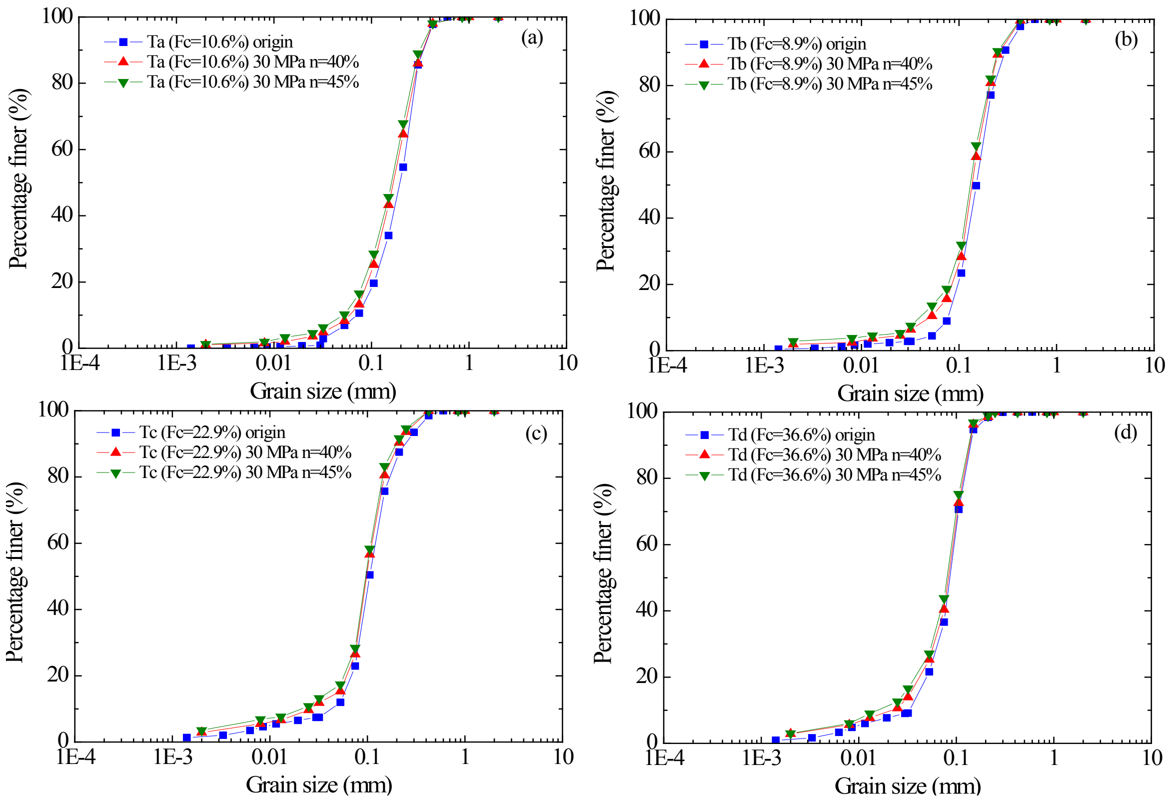

Fig. 7 GSD curves of four types of sand before and after the isotropic loading: (a) Ta; (b) Tb; (c) Tc; (d) Td

had reported that no detectable breakage was observed for poorly graded silica sand mixed with 25% plastic and non-plastic fines. However, no abrupt change point could be identified on those compression curves.

Hardin (1985) proposed a relative breakage B_r to quantify the degree of particle breakage. The relative breakage B_r is defined to be the area ratio in Eq. (3). Total breakage B_t represents the integral area between the initial grading curve and the current grading curve. Breakage potential B_p is the area between the initial grading curve and the line for the specified diameter size of 0.074 mm.

$$B_r = \frac{B_t}{B_p} \tag{3}$$

Einav (2007) revised the relative breakage index by using continuum breakage mechanics and replaced the maximum diameter of silts as 0.0074 mm with an ultimate cumulative distribution curve Fu(d) using the fractal theory expressed in Eq. (4).

$$F_u = \left(\frac{d}{d_M}\right)^{3-\alpha} \tag{4}$$

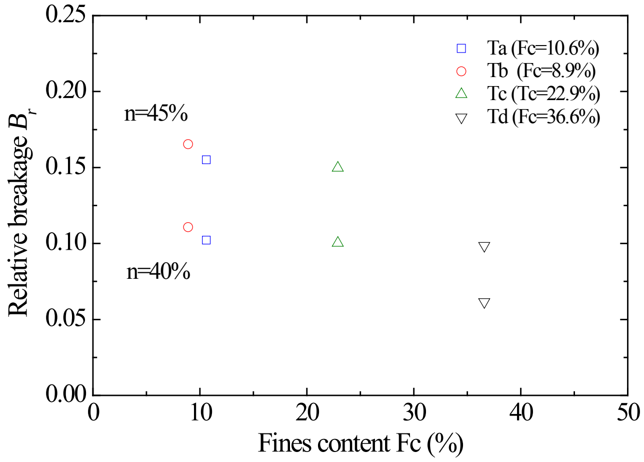

Fig. 8 The relative breakage Br plotted against fines content of four types of sand

where d is the grain size diameter, d_M is maximum grain diameter, α is the fractal dimension and takes the value of 2.6 for sand (Coop *et al*. 2004). The revised relative breakage is adopted to quantify particle crushing. The commination limit for determining the relative breakage adopts 0.001 mm which is also suggested by Einav (2007).

Fig. 8 indicates that the relative breakage of the poorly graded sand exhibited a decreasing tendency with the fines content. The possible reason for the reduction of relative breakage is that the presence of fine particles separates the contact of coaser-grain and fine particles are severed as soft mass to lubricate the coaser-grain. The increasing fines sharply reduce the contact of the sand grains and change the inter-particle stress transmission pattern. It was noted that the compression behaviour of Ta with representative grading of sand graded layer was slightly affected by particle crushing. The compression behaviour of Tc based on the representative grading of the mud layer was minimally affected by the particle crushing but dependent on the initial density.

4. Conclusions

This study presents the experimental study on the compression characteristics of four types of poorly graded silica sand based on the representative grading curve and similar mineralogy composition of seabed sediment from the Nankai Trough when subjected to isotropic loading. These four grading curves had a similar uniform coefficient but with variable fines content. A comparison study on the four types of sand was made to investigate the influence of fines content on the variation in the compression index, bulk modulus and degree of particle crushing. Several conclusions can be summarized as follow:

(1) The increasing fines content steepened the initial compression curves and increased the compressibility of the sand. The slope of the NCL decreased with an increasing fines content. The distinctive yield point of the four types of poorly graded sand was difficult to be identify on the compression curves. However, the slope of the swelling line was minimally affected by the fines content.

(2) The bulk modulus of poorly graded sand increased with a decreasing porosity and fines

content. The behaviour of pure silica sand was stiffer when compared to the four types of sand tested containing different fines content.

(3) The transitional behaviour of the two types of poorly graded sand (Tb and Tc) with a representative grading curve and variable fines was identified. No transitional behaviour would seem to occur for Td or Ta. The results suggest that the transitional behaviour is quite complex for the soil with the representative grading curve and similar mineralogy composition of marine sediment from the Nankai Trough. It should be assessed individually.

(4) A small amount of particle crushing was noticed for the poorly graded sand with variable fines content. The compression behaviour of Ta with representative grading of the sand graded layer was slightly affected by particle crushing. The compression behaviour of Tc with representative grading of mud layer was minimally affected by particle crushing but dependent on the initial density. In spite of this, the relative breakage tended to decrease as the fines content increased.

Acknowledgments

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