ORIGINAL PAPER

Effect of plastic fine and non-plastic fine on the compressibility behavior of granular material

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Abstract

The interaction between fine and sand grains has been studied by several researchers to evaluate the liquefaction phenomenon. However, the fine fraction effect on the compressibility behavior is less studied and requires more attention. A laboratory program was conducted to evaluate the effect of both non-plastic fines (silt) and plastic fine (clay) on the compressibility behavior of Chlef sand. The results show that the global void ratio (e) decreases with the increase of the fine content from 0 to 30% and then increases from 30 to 40% of the fine fraction for both mixtures (sand–silt and sand–clay). Inversely, the intergranular void ratio (e_s) increases with the increase in the fine fraction. Moreover, increasing the fine percentage in the sand leads to an increase in the compressibility index (C_C) and the granular compressibility index ($C_{c\text{-}s}$). Our results indicate that the transition fine content depends on the stress level, the maximum void ratio (e_{max}) calculated on the basis of some hypoplastic parameters model (granular hardness hs and exponent n), and the nature of the fine content (clay or silt). Finally, the gradation parameters (D_{10}, D_{50}, and C_u) have a significant effect on compressibility behavior.

Keywords Sand · Hypoplastic · Fine · Oedometer · Compressibility

List of symbols

G_s	Specific gravity of sand
G_f	Specific gravity of fines
G	Specific gravity of sand–silt mixture
D_{10}	Effective diameter
D_{50}	Average diameter
C_c	Compressibility coefficient
$C_{c\text{-}s}$	Intergranular compressibility coefficient
F_c	Fines content
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
e	Initial void ratio
e_s	Intergranular void ratio
RD	Relative density
R^2	Coefficient of determination
σ'	Oedometer pressure
e_{i0}	Maximum void ratios
e_{c0}	Critical void ratios
e_{d0}	Minimum void ratios
hs	Granular hardness
n	Exponent
ps	Mean pressure
IP	Plasticity index

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Introduction

Several recent researches have shown that soil liquefaction causes compaction and degradation of various structures, such as the case of Chlef earthquake in 1980 which caused soil liquefaction and subsidence.

Settlement is one of the key phenomena in the design of shallow foundations. The various factors and their effects

leading to building settlement and shallow foundations have not been well understood to date. There are two types of settlement, total settlement and differential settlement. The latter causes degradation of reinforced concrete structures due to the difference in the amount and type of fine fraction in the granular material. In this paper, effects of fine silt and clay fraction on the consolidation behavior of Chlef sand will be described.

Most of the laboratory tests concerning the mechanical behavior of granular soils have studied the response of clean sands. However, literature research indicates that soils containing clay and/or silt behave differently from soils containing clean sands. Over the last decade, studies related to fines fraction influence on liquefaction potential and shear strength have significantly accelerated (Covert and Yamamuro, 1997; Lade and Yamamuro, 1997; Thevanayagam 1998; Lade and Yamamuro 1997; Covert and Yamamuro 1997; Thevanayagam and Martin 2002; Arab 2009; Belkhatir et al. 2010; Benghalia et al. 2015; Bouri et al. 2019; Belhassena et al. 2021; Nougar et al. 2021).

Xenaki and Athanasopoulos (2003) have shown that for a fines fraction that varies from 0 to 44%, the deviator stress of the sand at a constant density decreases compared to that of clean sand. However, for a fine content that is greater than 44%, this behavior is reversed.

These fines can affect the compressibility characteristics of coarse-grained soils. Monkul and Ozden (2007) carried out a series of oedometric tests on kaolinite–sand mixtures. They concluded that the transition fines content depends on the maximum void ratio (when $e_{max} = e_s$) and that the percentage of kaolinite and the stress conditions influence the compressibility characteristics (C_c and C_{c-s}). Cabalar (2010) and Cabalar and Haasan (2013) studied the compressibility behavior of sand–clay mixtures using the concept of the intergranular void ratio to demonstrate the nature of the interaction between sand and clay. They used two different fluids, water and oil, and different shapes of the sand grains to demonstrate that the interstitial fluid with higher viscosity in a sample can cause lower compressibility and, consequently, the value of transition fine content changes. In addition, higher roundness (R) and sphericity (S) of sand grains resulted in higher values of (F_{ct}) and C_c, the value of C_c also increased with smaller diameter of sand grains.

Bouri et al. (2021) carried out oedometric tests on sand–silt mixtures; for a fine content varying from 0 to 40%, they showed that the global void ratio decreases from 0 to 30% of fines then increases again at 40% of fines. Therefore, it cannot be used to describe the behavior of sand–silt mixtures. On the other hand, the intergranular void ratio increases from 0 to 40% of fines with the addition of silt. Their results indicate that the maximum void ratio is not constant but depends on the oedometric

pressure applied using some hypoplastic parameters according to Gudehus (1996).

Research published in the literature (Bouri et al. 2021; Cabalar and Haasan 2013; Monkul and Ozden 2007) has mentioned that the intergranular void ratio is the ideal parameter to evaluate the behavior of a soil that is composed of two different soils such as our case (sand–silt and sand–clay).

Kuerbis et al. (1988) used the concept of intergranular void ratio to study the undrained shear strength, they proposed the following equation:

$$e_s = \frac{V_T.G_s.\rho_w - (M - M_{silt})}{(M - M_{silt})} \tag{1}$$

where (G_s) is the specific gravity of sand, (V_T) volume of the mixtures, (M) and (M_{silt}) are the mass of the mixtures and the silt, respectively, and ρ_w is the water unit weight.

Thevanayagam (1998), Thevanayagam et al. (2002) proposed an equation for the calculation of the intergranular void ratio:

$$e_s = \frac{e + F_c/100}{1 - F_c/100} \tag{2}$$

$$e_s = \frac{e + (1 - b)F_c/100}{1 - (1 - b)F_c/100} \tag{3}$$

where (e_s) is the index of intergranular voids, (F_c) the fines fraction, (e) the ratio of voids, and (b) the amount of fines active.

This article aims to study the effect of non-plastic fines content (silt) and plastic fines content (clay) on the compression behavior, and determine the difference between transition fine content (F_{ct}) of silt and clay on the basis of the concept of the intergranular void ratio (when $e_s = e_{max-c}$) corresponding to Monkul and Ozden (2007) and Cabalar and Haasan (2013), where they kept the maximum void ratio constant. However, Bouri et al. (2021) as well as Bauer (1999) and Gudehus (1996) indicated that the maximum void ratio depends on the oedometric stress applied based on some hypoplastic parameters model (e_{i0}, hs, ps, n) (Eq. 4), so if the maximum void ratio changes with the applied pressure, the value of the transition fine content F_{ct} changes (Fig. 1).

Gudehus (1996) and Bauer (1999) indicated that the maximum void ratio depends on the stress level using parameters of hypoplastic model, so e_{max} is not constant (Eq. 4).

$$e_i = e_{i0}\exp[-\left(\frac{3ps}{hs}\right)^n] \tag{4}$$

e_i maximum void ratio depends on the stress level

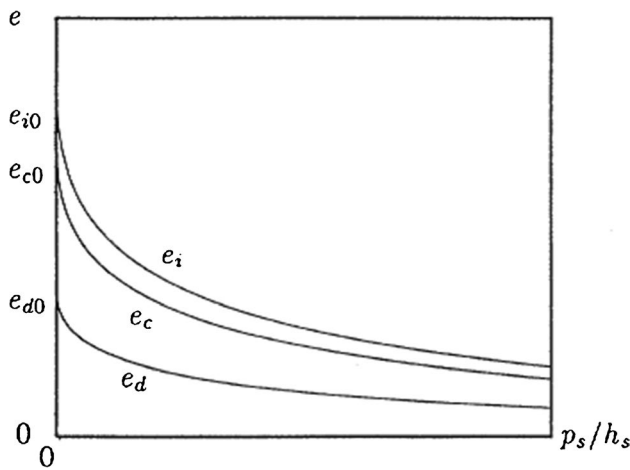e_{i0} maximum void ratio at 0 stress level

Fig. 1 Pressure dependence of void ratio according to Gudehus (1996)

hs   granular hardness

n   exponent

ps   mean pressure

Used materials

Three kinds of soil were used in this study: Chlef sand (Belkhatir et al. 2011; Belkhatir et al. 2012; Arab et al. 2014; Brahim et al. 2016, Krim et al. 2021), Chlef silt, and M'zila clay. Results of Atterberg limit tests indicated that the M'zila

clay had a liquid limit of 121, a plasticity index of 42, the plasticity is $IP = 79\%$, specific gravity is $G_s = 2.67$ for clean sand, $G_s = 2.69$ for Chlef silt, and $G_s = 2.55$ for M'zila clay (Nougar et al. 2021). The maximum and minimum void ratios were determined according to ASTM D 4253 (2002) and ASTM D 4254 (2002). The physical properties of the different mixtures are shown in Tables 1 and 2, and the particle size distribution curve is presented in Figs. 2 and 3.

Used apparatus and experimental procedure

The mixtures of sand–clay and sand–silt were placed and prepared in oedometer cells of 70 mm diameter and 20 mm height according to the standard [ASTM D 2435/D 2435 M] (1997) (Fig. 3). During the mixing step, the dry fine grains were added progressively into the sand, by 5 g per step and then mixing for 2 min. After adding all fine grains, the samples were mixed for 10 min until visual homogenization. The loads were applied by incremental loading steps, starting with a 25 kPa load which was doubled every 24 h up to an 800 kPa load. Ten oedometric tests were carried out: 5 tests on sand–silt mixtures 0, 10, 20, 30, and 40% of silt and 5 tests on sand–clay mixtures 0, 10, 20, 30, and 40% of clay. All samples were prepared using the same initial conditions (relative dry densities RD = 55% and dry pluviation method with initial water content $w = 0\%$), and this method was conducted on air-dry sand–fine mixtures. The samples were prepared in 4 equal layers by free drop height of 5 mm, and each layer was compacted using a small tamper approximately to achieve the desired density RD = 55%. After the sample mixing step, the soil is placed directly into the oedometer ring and

Table 1 Physical parameters of sand–silt mixtures

Materials	F_c (%)	G_s	D_{10} (mm)	D_{50} (mm)	C_u	e_{min}	e_{max}
Clean sand	0	2.670	0.194	0.500	2.955	0.480	0.780
	10	2.663	0.075	0.451	7.025	0.376	0.713
Sand–silt mixtures	20	2.676	0.032	0.422	15.959	0.310	0.657
	30	2.679	0.014	0.340	31.020	0.319	0.706
	40	2.682	0.004	0.261	86.790	0.362	0.775
Silt	100	2.700	-	0.030	-	1.010	1.558

Table 2 Physical parameters of sand–clay mixtures

Materials	F_c (%)	G_s	D_{10} (mm)	D_{50} (mm)	C_u	e_{min}	e_{max}
Clean sand	0	2.670	0.194	0.500	2.955	0.480	0.780
	10	2.658	0.088	0.464	6.161	0.363	0.801
Sand–clay mixtures	20	2.646	0.002	0.437	221	0.340	0.907
	30	2.634	-	0.353	-	0.397	1.040
	40	2.622	-	0.275	-	0.476	1.233
Clay	100	2.550	-	0.002	-	1.452	1.753

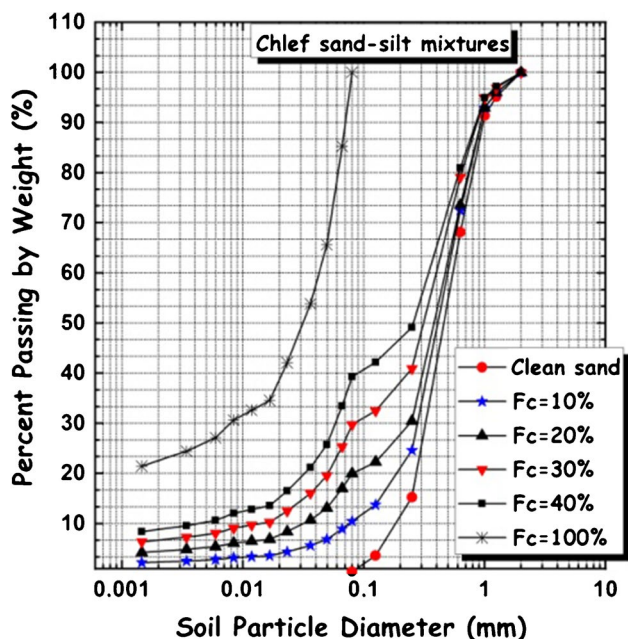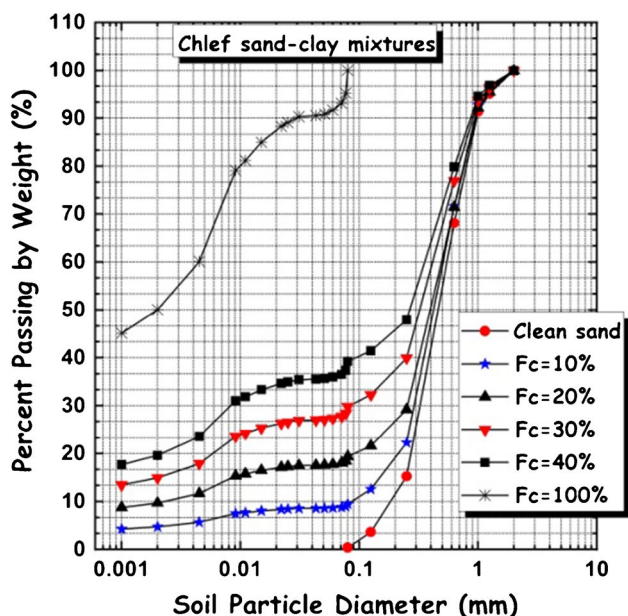**Fig. 2** Particle size distribution curves for the different sand–silt mixtures

Fig. 3 Particle size distribution curves for the different sand–clay mixtures

compacted by dynamic blows until the desired void ratio is reached, then the top cap was installed and the sample was flooded to saturate, the loading step started after 24 h of saturation.

Results and discussion

Effect of fines content on the void ratios

Global void ratio

Figures 4a and b present the global void ratio variation versus the oedometric pressure. The obtained results show an exponential relationship between the void ratio and the oedometric pressure; it is observed from our results that the global void ratio decreases with the increase in fine fraction up to 30% and decreases with further increase in fines up to 40% for both mixtures (sand–silt and sand–clay). The sand–silt samples give larger void ratio than the sand–clay samples. The difference in the global void ratio values is attributed to the difference in grain size between clay and silt; clay fills well the voids between the sand grains. Example for the sand containing 30% of clay content, the void ratio decreases from 0.50 for an oedometric pressure of 25 kPa to 0.26 for an oedometric pressure of 800 kPa, while for the sand containing 30% of clay, the void ratio decreases from 0.47 for an oedometric pressure of 25 kPa to 0.33 for an oedometric pressure of 800 kPa.

Intergranular void ratio

Belkhatir et al. (2010) and Bouri et al. (2021) showed that the global void ratio cannot represent the amount of grain contacts in the mixed sand–fine soil. When granular soil contains fines, the overall soil void ratio (e) can no longer be used to represent soil behavior. Indeed, up to a certain fines content, F_c (ratio between the weight of fine and the total weight of the sand–fine mixture), fines occupy only the void spaces and do not significantly affect the mechanical behavior of the mixture. For this reason, the use of the intergranular void ratio has been suggested.

Belkhatir et al. (2010) indicated that the concept of the intergranular void ratio (e_s) assumes that the finer grains do not actively participate in the maintenance of internal forces; for a low fines content, the coarse grains are in contact with each other (Fig. 5a), this phase is called underfilled according to Shire et al. (2016).

If the fines content significantly increases, the mechanical behavior of the soil is governed by the fine contacts, and the coarse grains float in the fines (Fig. 5b), this phase is called overfilled according to Shire et al. (2016).

Figures 6a and b show the variation of the intergranular void ratio (e_s) versus the oedometric pressure (σ') for the two mixtures (sand–silt and sand–clay). The intergranular void ratio (e_s) was calculated according to the equation of Monkul and Onal (2006):
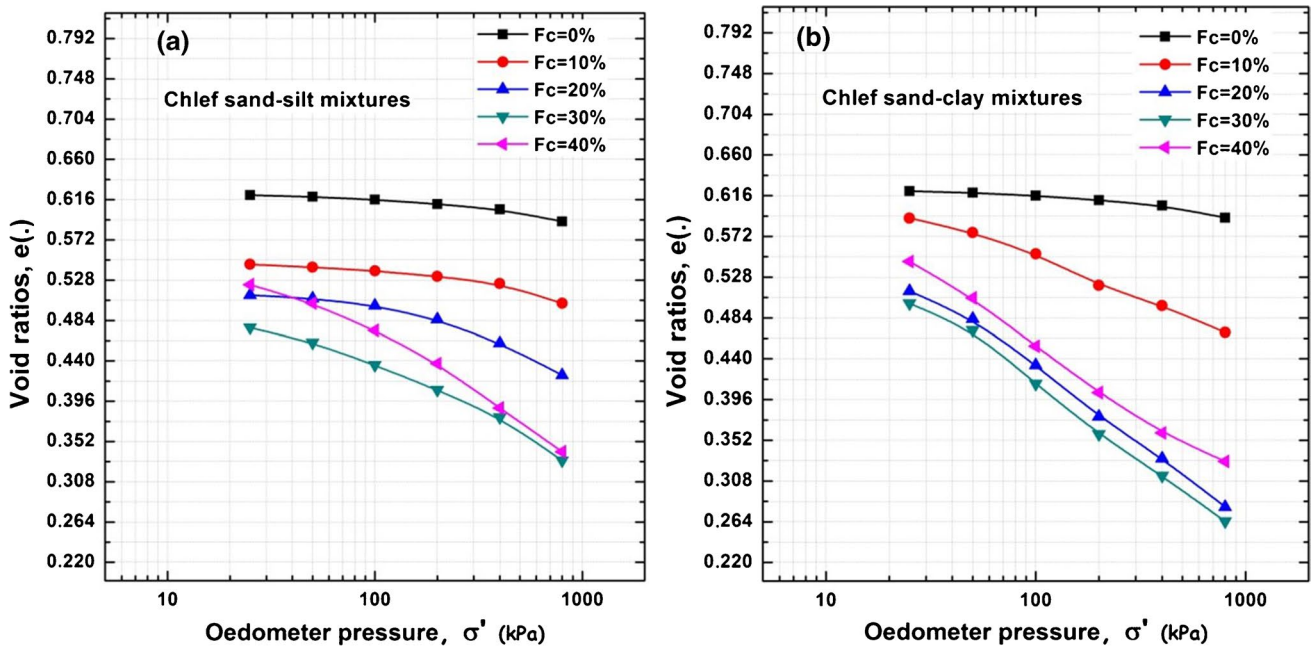
Fig. 4 The change in the global void index (*e*) as a function of the oedometer pressure (*F_c*). **a** Sand–silt mixtures, **b** sand–clay mixtures
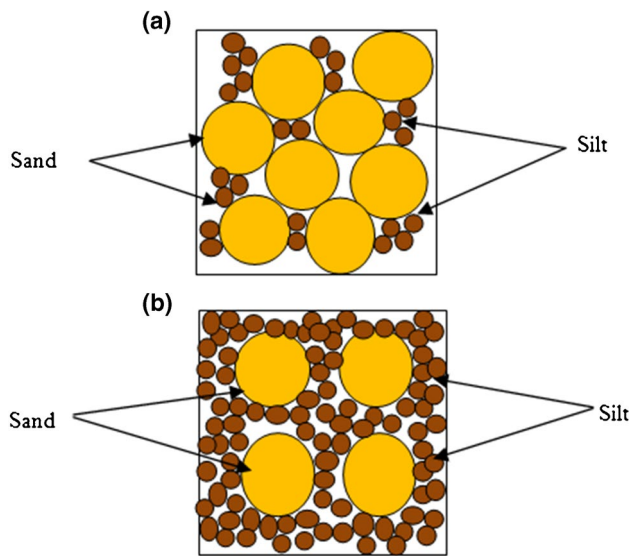

Fig. 5 Schematic diagram showing sand–silt mixtures: **a** coarse grains are in contact with each other, **b** coarse grains are swimming in the matrix of fines. Adopted from Belkhatir et al. (2010) and Bouri et al. (2021)

$$e_s = \frac{e + G.F_c/G_f.100}{G/G_s.(1 - F_c/100)} \tag{5}$$

G_s and G_f are the specific gravity of sand and finer grain matrices forming the soil, respectively. G is the specific gravity of the soil itself, e is the void ratio of the mixtures, and F_c represents the fine content.

The obtained results show that the increase in the fine content from 0 to 40% and the oedometric pressure (σ') from 0 to 800 kPa decreases the intergranular void ratio (e_s), sand–silt mixtures have intergranular void ratio (e_s) greater than sand–clay mixtures. Also, results show that increasing the fines fraction from 0 to 40% increases the intergranular void ratio (e_s). For example, for a sand containing 30% of clay at an oedometric pressure of 200 kPa, the intergranular void ratio is equal to 0.94 (Fig. 6b), while for sand containing silt at the same fraction of fine (30%) and oedometer pressure (200 kPa), the intergranular void index is equal to 1 (Fig. 6b). This difference in the intergranular void ratios is due to the difference in the global void ratio.

Effect of fines content on the compressibility coefficients C_c and $C_{c\text{-}s}$

The compressibility coefficients C_c and $C_{c\text{-}s}$ versus the fine content are respectively presented in Figs. 7a and b. The compressibility coefficient C_c was calculated based on the global void index e, whereas the granular compressibility coefficient of the sand $C_{c\text{-}s}$ was calculated based on the intergranular void index e_s according to the equation of Monkul and Ozden (2007). The calculation of the granular compression index ($C_{c\text{-}s}$) is similar to the computation of the compression index (C_c):
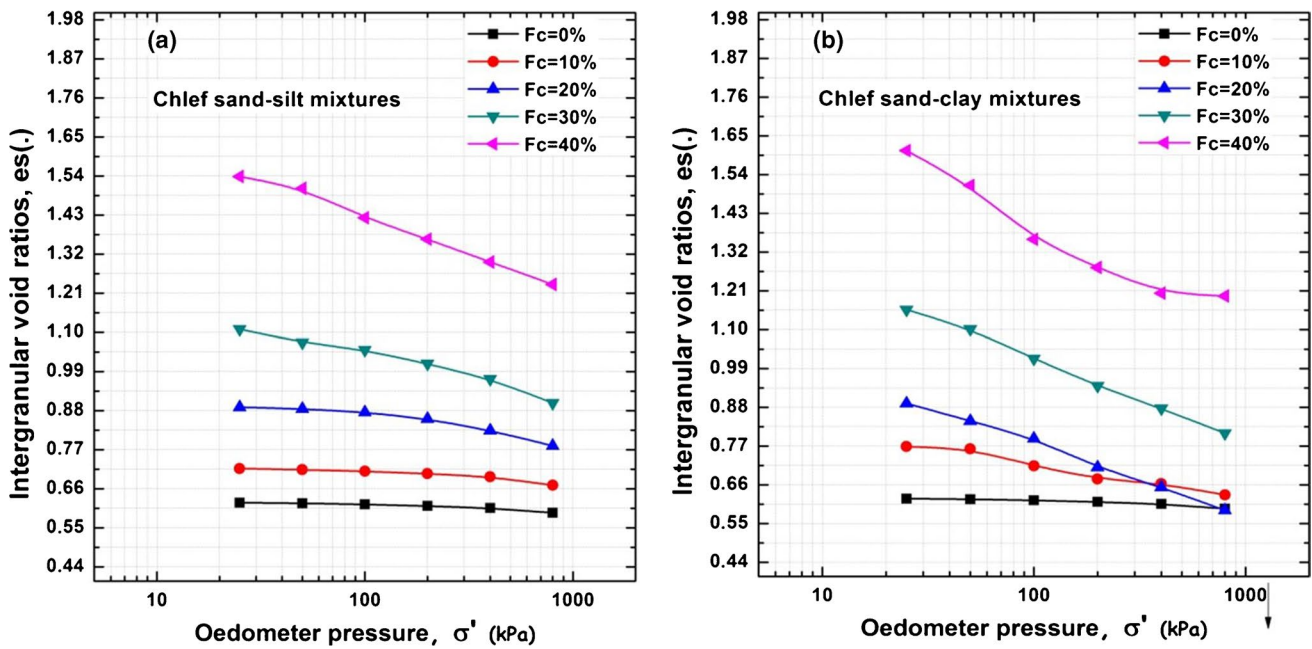
Fig. 6 The change in the intergranular void index (*e*) as a function of the oedometer pressure (σ′). **a** Sand–silt mixtures, **b** sand–clay mixtures
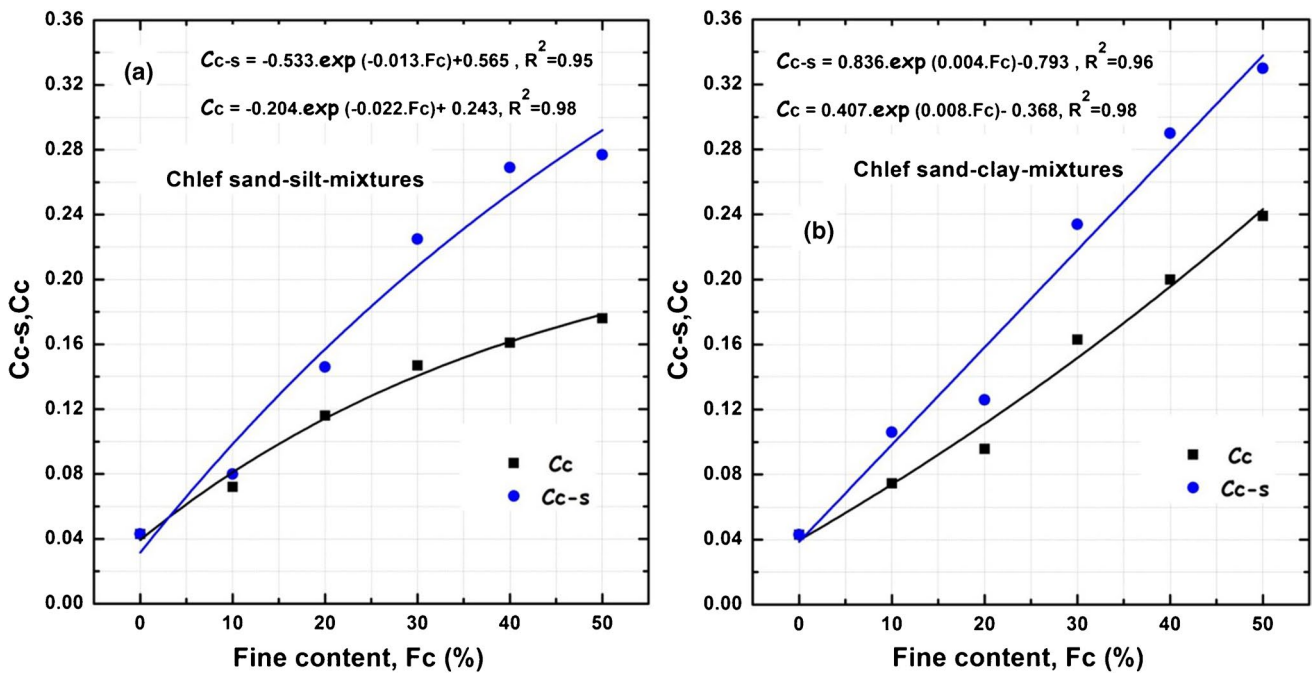

Fig. 7 Variation of compression parameters as a function of the fines content. **a** Sand–silt mixtures, **b** sand–clay mixtures

$$C_c = \frac{\Delta e}{\Delta \log \sigma'} \qquad (6) \qquad C_{c-s} = \frac{\Delta e_s}{\Delta \log \sigma'} \qquad (7)$$

We notice from the two figures that the increase in the fines content from 0 to 40% increases the compressibility coefficients C_c and C_{c-s}. This increase is due to the increase in the fines quantity in the sand. The granular compressibility coefficient C_{c-s} presents greater values than the compressibility coefficient C_c due to the difference values between the intergranular void ratio and the global void ratio. It is clear that the sand–clay mixture samples have larger compression coefficients than the sand–silt samples. This difference in the compressibility coefficients is due to the difference in plasticity between the two types of fines (the clay is more plastic than the silt). Both granular C_{c-s} and global compressibility C_c indices of sand–silt mixtures are smaller than the ones of sand–clay mixtures. This is due to the greater initial void ratios (e_o) of the samples of sand–clay mixtures (Monkul and ozden 2007). The results indicate that the silt is more favorable to the soil compared to clay against the compressibility phenomenon.

Effect of the maximum void ratio on the transition fine content (F$_{ct}$)

Figure 8 shows the variation of the maximum void ratio versus the applied oedometer pressure. As it can be seen from this figure, a further increase in the oedometer pressure leads to a constant decrease in the maximum void ratio causing change in transition fine content value (Tables 4 and 5). These maximum void indexes were calculated based on the hypoplastic model parameters for granular materials according to Gudehus (1996) (Eq. 4). Table 3 shows the clean sand
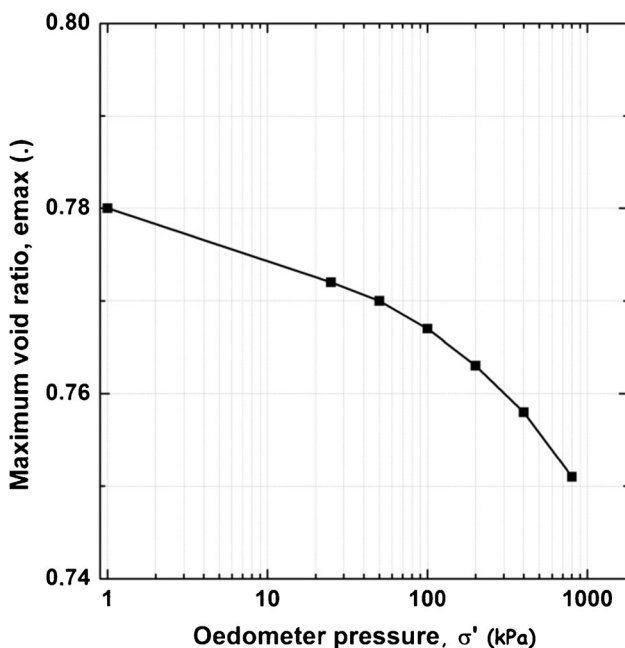
Table 3 Hypoplastic parameters for pressure equal to 400 kPa P

Hypoplastic parameters	Value
Exponent (n)	0.42
Granular hardness (hs)	5831 MPa
Mean pressure (ps)	400 kPa
Initial maximum void ratio (e_{i0})	0.758

parameters used for the maximum void index $e_{\max}$ calculation. Intergranular void ratio, oedometer pressure, and fine content relationships are respectively presented in Figs. 9a and b. The border $e_s = e_{max-C}$, according to Monkul and Onal (2006), is represented by several dashed lines in our figures, because the maximum voids index is not supposed to be constant, but it depends on the applied oedometer stress, which will have an effect on the transition fine content F_{ct} value according to Bouri et al. (2021). Figures 9a and b show the upper limit, under which the sand matrix grains form a continuous frame with grain–grain contacts. The interaction between the dotted line and the curves allows obtaining the transition fines content values (F_{ct}).

From Tables 4 and 5, we notice that the transition fines content values are in the interval of 20.37 to 17.10% for the sand–silt mixtures and 29.34 to 27.17% for the sand–clay mixtures under applied oedometer pressure that is equal to 25 kPa. The results indicate that the clay is more favorable to the soil compared to silt against the liquefaction phenomenon, because the sand–clay mixtures have greater values of transition fine content than those of sand–silt mixtures.

It is clear from our results that the transitional fines content decreases with the decrease in the maximum voids ratio, calculated from Gudehus (1996) equation, which is unfavorable for the soil. Therefore, the unfavorable state of the sand is at the maximum void ratio calculated under 800 kPa of applied oedometer pressure and not at 0 kPa of applied oedometer pressure.

Effect of granulometric composition on the compressibility behavior

Effect of effective diameter D_{10}

The variation of the compressibility parameters versus the effective diameter are respectively shown in Figs. 10a and b. The results indicate that the compressibility coefficient (C_c) and the granular compressibility coefficient (C_{c-s}) decrease exponentially with the increase in the effective diameter (D_{10}) for the two mixtures (sand–silt and sand–clay). These results are associated with a decreasing quantity of the silt and clay in the sand; it means that the fine contributes to greater mixture compressibility. Similar observations were
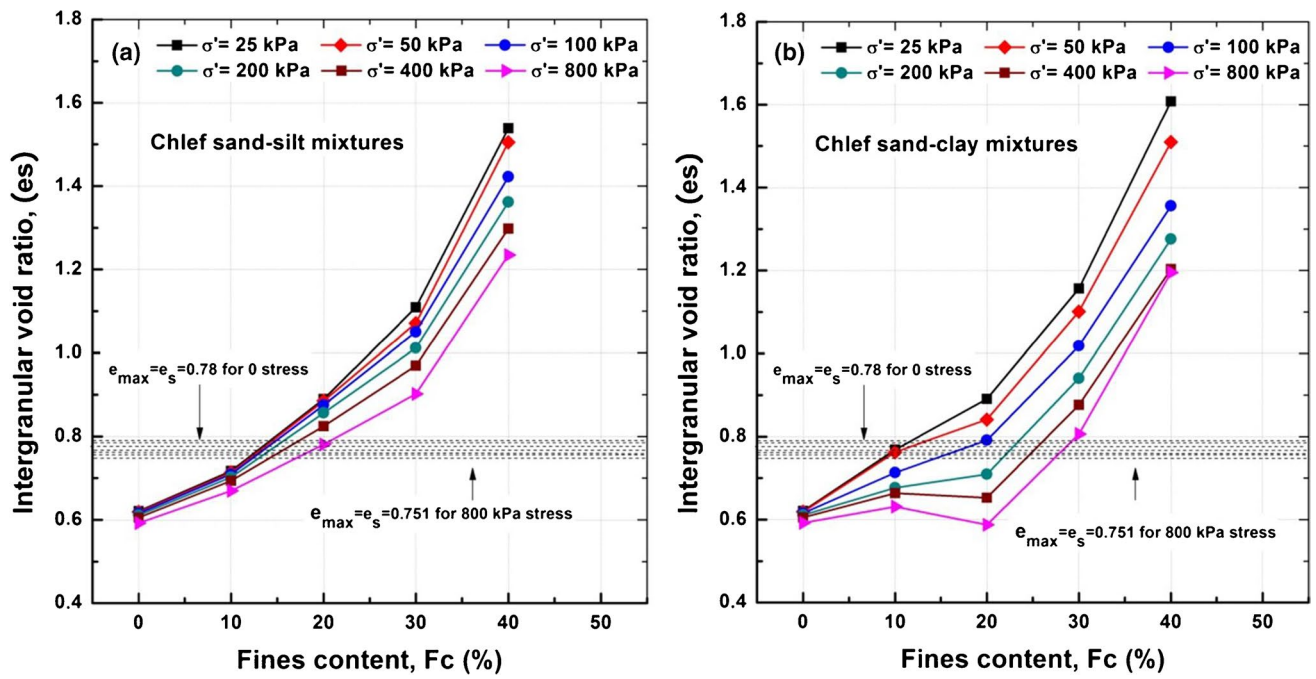

Fig. 8 Maximum void ratio versus oedometer pressure for clean sand

Fig. 9 Variation in the intergranular void ratio versus the fines fraction. ($\sigma' = 25$, 50, 100, 200, 400, 800 kPa), **a** sand–silt mixtures, **b** sand–clay mixtures

Table 4 Content transition (F_{ct}) for sand–silt samples, under different oedometric pressures for each e_{max} calculate from equation of Bauer (1999)

σ' (kPa)	F_{ct} for $e_{max}=0.78$	F_{ct} for $e_{max}=0.772$	F_{ct} for $e_{max}=0.770$	F_{ct} for $e_{max}=0.767$	F_{ct} for $e_{max}=0.763$	F_{ct} for $e_{max}=0.758$	F_{ct} for $e_{max}=0.751$
25 kPa	13.92	13.41	13.03	12.39	12.12	11.99	11.48
50 kPa	14.31	13.97	13.42	12.77	12.65	12.54	11.86
100 kPa	14.82	14.31	13.92	13.15	13.03	12.94	12.43
200 kPa	15.73	15.33	15.21	14.17	13.98	13.90	13.19
400 kPa	17.39	16.87	16.62	15.98	15.89	15.04	14.14
800 kPa	20.37	20.30	19.57	19.19	18.94	17.90	17.01

Table 5 Content transition (F_{ct}) for sand–clay samples, under different oedometric pressures for each e_{max} calculate from equation of Bauer (1999)

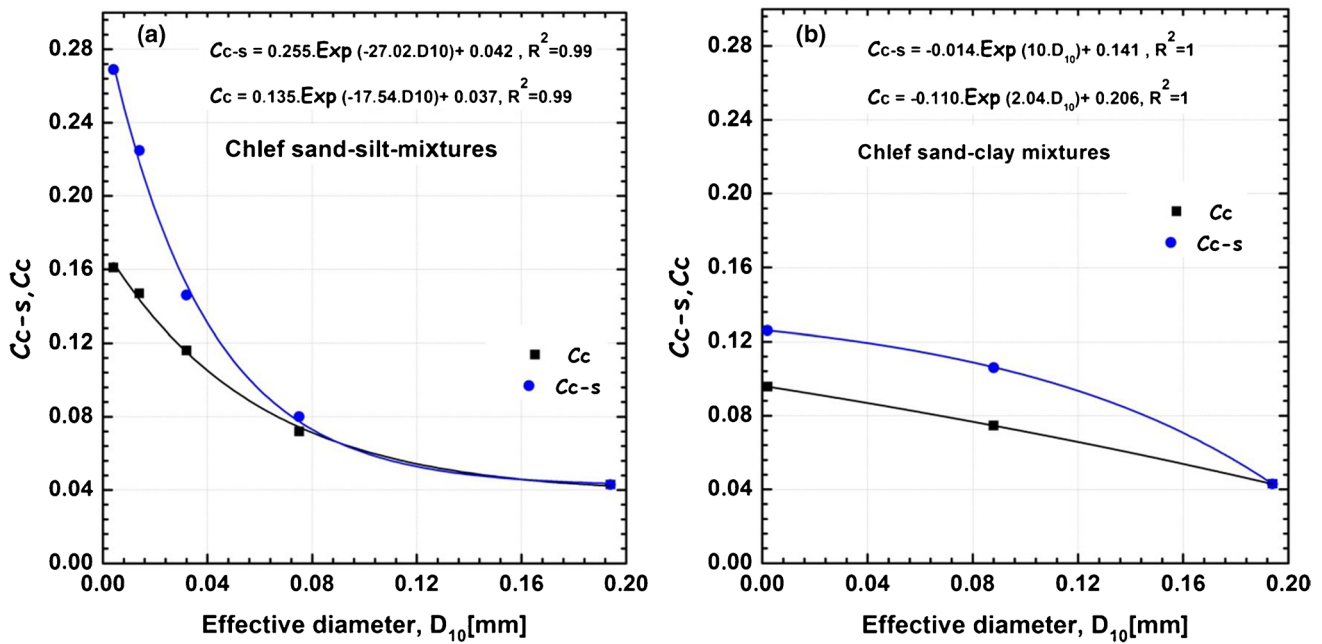| σ' (kPa)	F_{ct} for $e_{max}=0.78$	F_{ct} for $e_{max}=0.772$	F_{ct} for $e_{max}=0.770$	F_{ct} for $e_{max}=0.767$	F_{ct} for $e_{max}=0.763$	F_{ct} for $e_{max}=0.758$	F_{ct} for $e_{max}=0.751$
25 kPa	11.92	11.17	10.87	10.20	10.02	9.36	8.66
50 kPa	14.20	12.88	12.40	11.53	10.98	10.13	9.23
100 kPa	19.80	18.98	19.07	17.63	17.27	16.04	14.95
200 kPa	23.62	23.18	23.08	22.77	22.60	22.14	21.81
400 kPa	26.29	26.04	25.52	25.26	24.88	24.80	24.48
800 kPa	29.34	29.09	28.57	28.31	27.93	27.66	27.17

Fig. 10 Variation of the compression coefficients versus the effective diameter D_{10}, **a** sand–silt mixtures, **b** sand–clay mixtures

denoted by Bouri et al. (2021). The following equations are suggested to evaluate the compression coefficients (C_c) and (C_{c-s}) which is a function of the effective diameter (D_{10}):

$$C_c = a.\exp(b.D_{10}) + c \tag{8}$$

$$C_{c-s} = a.\exp(b.D_{10}) + c \tag{9}$$

It was found that the compressibility coefficient (C_c) and the granular compressibility coefficient (C_{c-s}) can be correlated to the effective diameter (D_{10}) for the sand–fine mixture.

Effect of the average diameter D_{50}

The variation of the compressibility coefficients are plotted against average diameter (D_{50}) for the both mixtures (sand–silt and sand–clay), this is illustrated by Figs. 11a and b. The obtained data indicate that the compressibility coefficient (C_c) and the granular compressibility coefficient (C_{c-s}) decrease exponentially with the increase of the average diameter (D_{50}) for sand–silt and sand–clay mixtures. This decrease results from the increase in the quantity of silt and clay in the granular material, which generates higher value of compressibility coefficient. These are in good agreement with the findings of Bouri et al. (2021). The following equations are suggested to evaluate the compression coefficients (C_c) and (C_{c-s}) which is a function of the average diameter (D_{50}):

$$C_c = a.\exp(b.D_{50}) + c \tag{10}$$

$$C_{c-s} = a.\exp(b.D_{50}) + c \tag{11}$$

The compressibility coefficient (C_c) and the granular compressibility coefficient (C_{c-s}) can be correlated to the average diameter (D_{50}) for the sand–fine mixture.

Effect of uniformity coefficient C_u

Figures 12a and b illustrate the uniformity coefficient (C_u) effect on the compressibility coefficients; the obtained data indicate that the compressions coefficient (C_c and C_{c-s}) and the uniformity coefficient (C_u) display a good exponential relationship for both the sand–silt and sand–clay mixture samples. The compressibility coefficient (C_c) and granular compressibility coefficient (C_{c-s}) increase exponentially with the increase in the uniformity coefficient (C_u). The following equations are suggested to evaluate the compression coefficients (C_c) and (C_{c-s}) which is a function of the uniformity coefficient (C_u):

$$C_c = a.\exp(b.C_u) + c \tag{12}$$

$$C_{c-s} = a.\exp(b.C_u) + c \tag{13}$$

The compressibility coefficient (C_c) and the granular compressibility coefficient (C_{c-s}) can be correlated to the uniformity coefficient (C_u) for the sand–fine mixture.
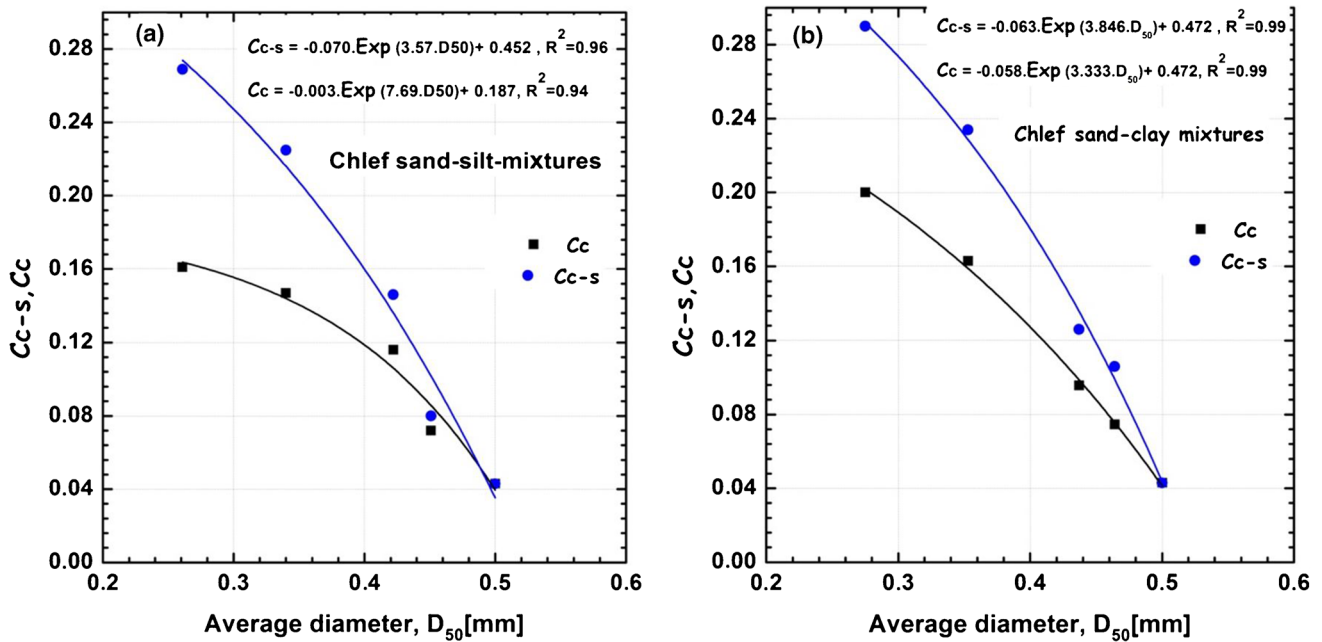
Fig. 11 Variation of the compression coefficients versus the average diameter D_{50}, **a** sand–silt mixtures, **b** sand–clay mixtures
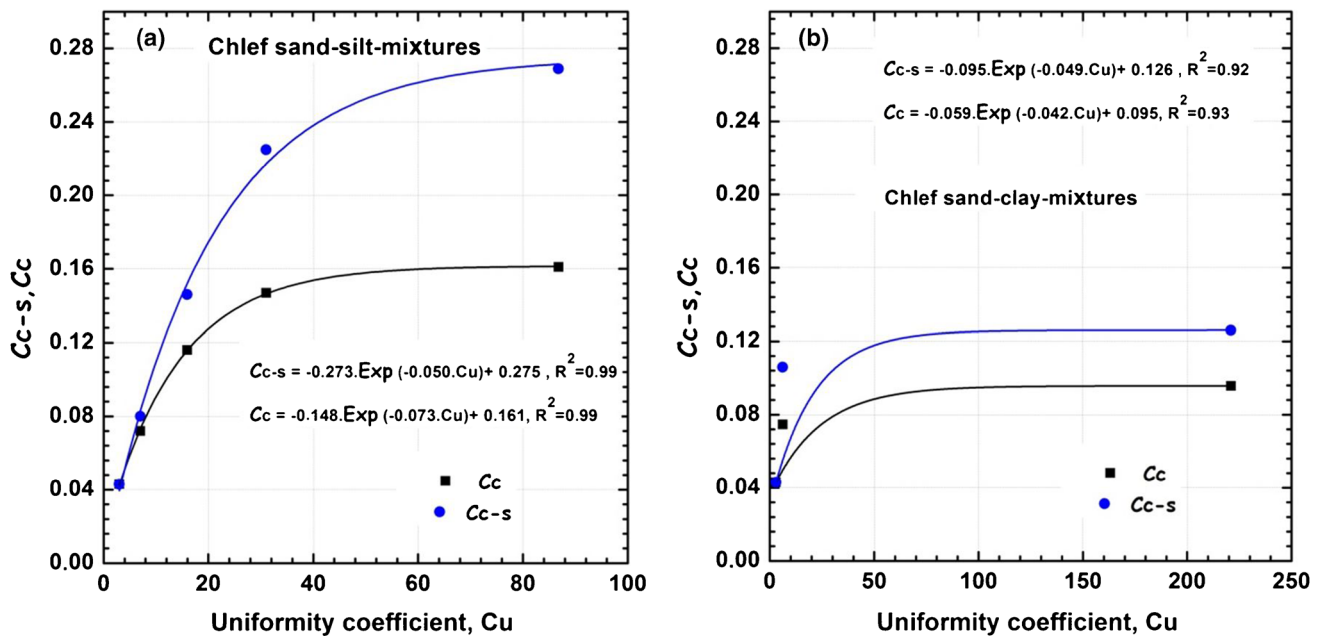

Fig. 12 Variation of the compression coefficients versus the uniformity coefficient C_u, **a** sand–silt mixtures, **b** sand–clay mixtures

Conclusion

A series of laboratory tests were conducted to evaluate the compressibility behavior of two mixtures (sand–silt and sand–clay) at medium dense state (RD = 55%). The main results from this research are the following:

(1) The compression index (C_c) is increased with the increase in the fine quantity (clay and silt). The increase in the fines percentage in the sand causes an increase in the compressibility phenomenon of granular materials and clay is more compressible compared to silt. For this reason, the compressibility

coefficient (C_c) is greater in the case of sand–clay mixtures.

(2) The compression granular index ($C_{c\text{-}s}$) is increased with the increase in the fine fraction (clay and silt). The increase in the granular compressibility index is due to the increase in the intergranular void index (e_s) (the void between the granular soils). The sand–clay mixtures' samples have larger compression coefficients than the sand–silt samples. This difference is due to the difference in plasticity and compressibility between the two types of fines (the clay is more plastic and compressible than the silt).

(3) Transition fine content depends on the oedometer pressure, the maximum void ratio (e_{max}) that is calculated on the basis of some hypoplastic parameters model (granular hardness hs and exponent n), and the fine content nature; sand–silt mixtures have greater values of transition fine content than those of sand–clay mixtures which is favorable to the soil.

(4) The results indicate that the silt is more favorable to the soil compared to clay against the compressibility phenomenon. And on the other hand, the clay is more favorable to the soil compared to silt against the liquefaction phenomenon.

(5) The gradation parameters have a significant effect on the compressibility behavior; the obtained data indicate that the compressibility parameters (C_c and $C_{c\text{-}s}$) can be correlated to the grading characteristics (D_{10}, D_{50}, and C_u).

Author contribution BN: conceptualization, methodology; DEB: methodology, conceptualization, writing—original draft, investigation; AB: writing—review and editing. FZB: review and editing. AA: conceptualization, supervision, methodology.

Declarations

Conflict of interest The authors declare no competing interests.

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