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ORIGINAL PAPER

Long-term desalination leaching effect on compression/swelling behaviour of Lianyungang marine soft clays

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Abstract

In this study, Lianyungang (LYG) soft marine clays were long-term leached by the distilled water and synthetic NaCl solutions, respectively, and then oedometer tests with cycle loading/unloading were conducted to investigate the desalination leaching effect on its compression/swelling behaviour. Test results reveal that the stress-induced creep generates a void ratio change (Δe_c), whilst the long-term desalination leaching accompanying colloidal erosion further results in the aging of clays' structure, and hence, additional void ratio change (Δe_l) is identified. After long-term desalination leaching process, the compression/swelling behaviour of LYG clays in the elastic loading and unloading stage is changed slightly. However, in the elastoplastic loading stage, the desalination leaching leads to the significant compression at low stress level (less than 200 kPa), followed by the slight difference at high stress level (exceeding 200 kPa). Finally, the compression/swelling behaviour induced by clay's aging for the long-term desalination leaching process was summarized.

Keywords Lianyungang soft marine clay · Compression · Swelling behaviour · Long-term salinity leaching · Salinity chemistry · Colloidal erosion

Introduction

For the soft clays deposited in the coastal environment, the pore water in clays initially has the high salinity, usually equal to that of seawater (about 35 g/L). Because of the rainwater infiltration, groundwater migration or human activities, these soft clays are inevitably subjected to the desalination leaching process, which has been widely identified in some countries, for instance, Norway (Bjerrum 1954, 1955, 1967; Bjerrum and Rosenqvist 1956; Moum et al. 1971), Canada (Torrance 1975), Japan (Ohtsubo et al. 1982), Columbia (Geertsema and Torrance 2005) and China (Wu et al. 2020). The long-term desalination leaching can induce a series of engineering disasters, for instance, the instability of natural slopes and the uncontrollable settlement behaviour of infrastructures (Bjerrum 1954, 1955, 1967; Bjerrum and Rosenqvist 1956; Moum et al. 1971; Torrance 1975; Geertsema and Torrance 2005; Wu et al. 2020). Therefore, the investigations of long-term desalination leaching process on the hydro-mechanical behaviour of soft clays should be concerned.

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For the “quick clay” in Norwegian and Champlain clays in Canada, Rosenqvist (1953) and Torrance (1974, 1975) carried out field geological surveys to study the pore water salinity on the change of Atterberg limit and shear strength. Field test results show that the liquid limit (*LL*) and plasticity index (*PI*) of clays decrease gradually with the pore water salinity, whereas the natural water content (w_n) and plastic limit (*PL*) are almost not changed, which finally leads to increase of liquidity index (*LI*, defined as (w_n-*PL*)/(*LL*-*PL*)). On the other side, the shear strength of undisturbed clays (S_u) decreases slightly or does not change with the pore water salinity. However, the shear strength of remoulding clays (S_r) reduces significantly and therefore the sensitivity (S_t, defined as S_u/S_r) increases significantly. About the desalination leaching effect on the compression behaviour of soft clays, Torrance (1974) carried out laboratory tests, indicating that the compression lines of clays with lower pore water salinity is lower than that with higher pore water salinity, suggesting the higher compressibility of clays. Deng et al. (2011a, b) conducted several loading/unloading oedometer tests on stiff Boom clays with or without saline fluid percolation, aiming to investigate the pore water salinity effect on its hydro-mechanical behaviour. Test results reveal that the pore water salinity can change the hydro-mechanical behaviour of Boom clays with high smectite content, which is further confirmed by Nguyen et al. (2013) through laboratory tests. Despite that, the pore water salinity effect is still not significant for its high strength and stiffness properties.

In recent years, the insufficient knowledge of long-term desalination leaching on clay’s hydro-mechanical behaviour in the regional geology usually misleads engineering practices. To overcome this problem, the long-term desalination leaching process (in the geological scale) effect on Atterberg limits and shear strength of marine clays were paid attention, where Song et al. (2017), Song (2018) and Wu et al. (2020) carried out laboratory and field tests in Lianyungang (LYG) region and achieved the similar conclusions by Rosenqvist (1953) and Torrance (1974, 1975). To investigate the long-term desalination leaching process effect on the compression/swelling behaviour of LYG marine soft clays, the clays with high salinity were first “flushed” by distilled water to simulate the geological process, and then, the oedometer test was first conducted by Deng et al. (2014), revealing that this process totally increases the deformation and decreases the permeability, but it did not explain the action of this geological process on soil’s aging and hydro-mechanical evolution.

In this study, the natural soft clays with pore water salinity of 3.93 % were first drilled in LYG region, Jiangsu Province, China. Thereafter, the specimens were placed into special percolation devices, and then, the pore water was long-term leached by distilled water and synthetic NaCl solutions, respectively. Hereinafter, oedometer tests with cycled loading/unloading procedure were conducted. Hereinafter, the long-term desalination leaching process effect on the compression/swelling behaviour of LYG clays was discussed.

Material and methods

Material

The natural deposited marine soft clay designated as 8#-5 was carefully drilled in LYG region, Jiangsu Province, China. Thereafter, this sample was sealed in steel tubes with ends closed to avoid the water loss and transported to the laboratory for testing. Table 1 presents the physical parameters, pore water salinity and the mineral compositions. Note that the specific gravity (G_s) was determined according to pycnometer method (ASTM D4318 2014). The *LL* and *PI* were obtained following ASTM standard (ASTM D4318 2010). The clay fraction (CF) was measured by sieving and hydrometer method obeying ASTM D422 (ASTM D422 2007). The natural density (ρ_n), saturation degree (S_r) and initial void ratio (e_0) were calculated, respectively. For the mineral compositions, the methods suggested by Whittig and Allardice (1986), Mitchell and Soga (2005) and Sridharan et al (2002) were adopted in this study.

To determine the pore water salinity, the clay samples were put into small-scaled centrifuge device, followed by the high-speed centrifugal dewater test. Hereinafter, the salinity in pore water (mass percentage; %) was measured through oven-drying method suggested by Deng et al. (2014), Song et al. (2017) and Song (2018), as shown in Table 1.

Table 1 Physical parameter, pore water salinity and mineralogy

Label	Depth (m)	w_n (%)	ρ_n (g/cm^3)	G_s	S_r (%)	e_0	*LL* (%)	*PI*	CF (%)	Salinity (%)
8#-5	9.0	54.5	1.69	2.67	99.05	1.40	69.16	47.45	46	3.93
Label	K-Feldspar (%)	Quartz (%)	Plagioclase (%)	Calcite (%)	Dolomite (%)	Pyrite (%)	Illite/smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)
8#-5	3.1	27.3	8.3	15.2	1.7	1.0	16.49	16.49	4.34	6.08

Table 2 Testing program in this study

Labels	Applied vertical stress before leaching (kPa)	Leaching solutions	Initial pore water salinity (%)	Final pore water salinity (%)	Applied vertical stress after leaching (kPa)
8#-5–1	12.5–50	Distilled water	3.93	0.05	50–12.5; 12.5–200; 200–12.5 12.5–800; 800–12.5; 12.5–1600
8#-5–2	12.5–50	3.93% NaCl	3.93	3.92	

Methods

Two natural soil specimens (shown in Table 2) were needed for two kinds of leachate percolation. To prepare these specimens, the steel rings with dimensions of 61.8 mm in diameter and 20 mm in height were first slightly pushed into the natural soils accompanying with the carefully hand-trimming. Note that the inner wall of rings was lubricated in advance with grease to minimize the skin friction. Thereafter, these prepared specimens were put into the special percolation devices shown in Fig. 1, and then integrally installed in the oedometer instruments.

Prior to the leaching, the vertical effective stress ranging from 12.5 to 50 kPa was applied orderly on the soil specimens to eliminate the gaps between specimens and the steel rings. This step can effectively avoid the subsequent leaching infiltration through these gaps. On the other side, the applied maximum vertical stress of 50 kPa is lower than the pre-determined pre-yielding stress of natural soils (55 kPa), to avoid destroying the soil's structure. Note that for each experimental procedure, the vertical displacement was monitored with the time (shown in Fig. 2), and the equilibrium state was reached when the vertical displacement rate was lower than 0.01 mm every 8 h (Deng et al. 2011a, b; Deng et al. 2012; Nguyen et al. 2013; Wu et al. 2019).

After the loading, the special procreation devices shown in Fig. 1 were closely connected to the controller of pressure and volume (CPV), and then, the solutions in CPV were injected into the specimens under the constant pressure (P_w) of 20 kPa. In the study, the specimen labelled as 8#-5–1 was leached by the distilled water for desalination, whereas the specimen labelled as 8#-5–2 was leached by the synthetic NaCl solutions with concentration of 3.93%, equal to the soil's total pore water salinity as a benchmark.

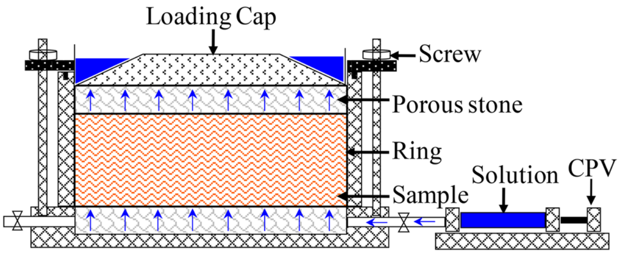


Fig. 1 Diagram of leaching oedometer device

During the long-term desalination leaching process, the change of vertical displacement (D_{isp}) was monitored with the time. Meanwhile, the solutions leached out from the specimens were also collected and the electric conductivity (EC) of them was measured following ASTM standard (ASTM D1125 1999). In this study, the leaching process lasted for 211 days shown in Fig. 2. After this long-term leaching, the EC of solutions leached out from 8#-5–1 approaches to about zero. The solution's EC in the case of 8#-5–2 first slightly increased with time, followed by the stable tendency. This suggests that the salinity in the specimen had been completely substituted by the synthetic NaCl solutions. In fact, after the test the pore water in the specimens was extracted by the centrifugation method, and their salinity was measured in the laboratory, as shown in Table 2. It obviously reveals that the pore water salinity of 8#-5–1 is close to 0% and that of 8#-5–2 equal to 3.92%.

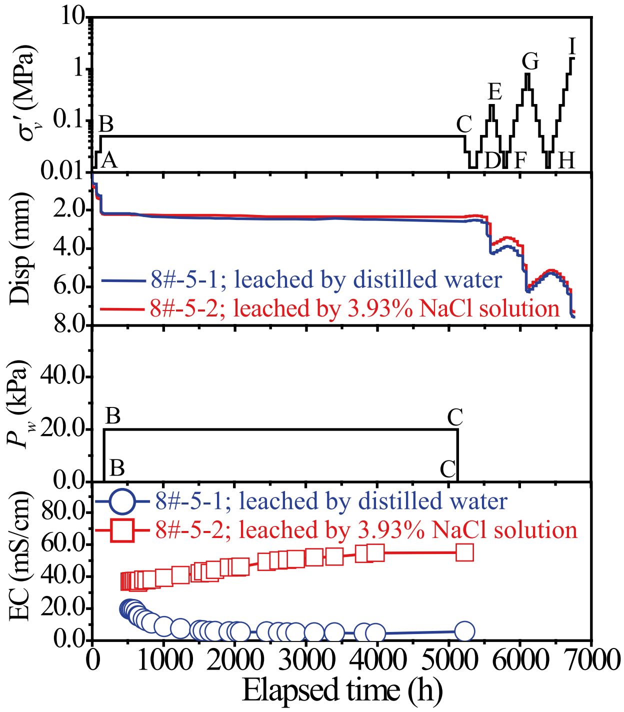


Fig. 2 Leaching procedure and loading/unloading path

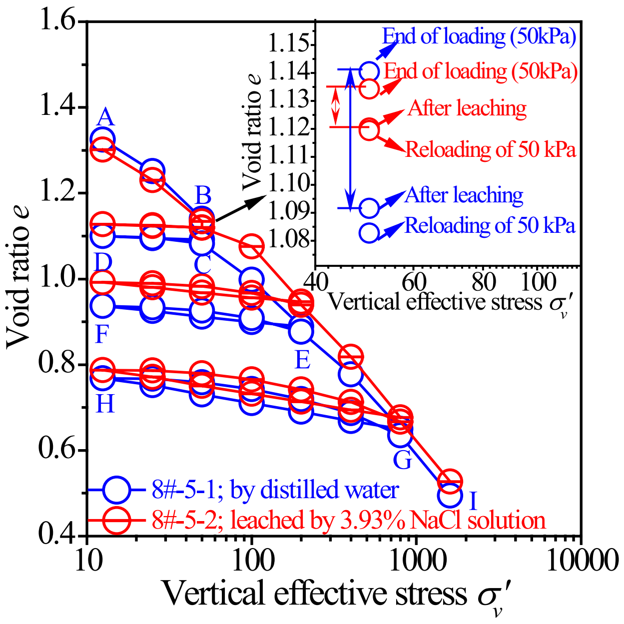


Fig. 3 Void ratio e versus vertical effective stress $\sigma_v{}'$

After leaching, the pressure of CPV was set as 0 kPa. Then, three cycled loading/unloading paths shown in Fig. 2 were orderly applied on these specimens: unloading from 50 to 12.5 kPa (C-D); reloading from 12.5 to 200 kPa (D-E); unloading from 200 to 12.5 kPa (E–F); reloading from 12.5 to 800 kPa (F-G); unloading from 800 to 12.5 kPa (G-H); and finally reloading from 12.5 to 1600 kPa (H–I). For each loading/unloading stage, the vertical displacement rate less than 0.01 mm every 8 h was also regarded as the criterion of complete consolidation.

Results and analysis

Compression curves and parameter definitions

Figure 3 shows the change of void ratio (e) with the vertical effective stress (σ_v') in the semi-logarithmic coordinates. It can be observed that the compression of samples (8#-5–1 and 8#-5–2) are almost the same before leaching (A-B), as these two specimens have the same initial state and subsequent experience the same loading procedure.

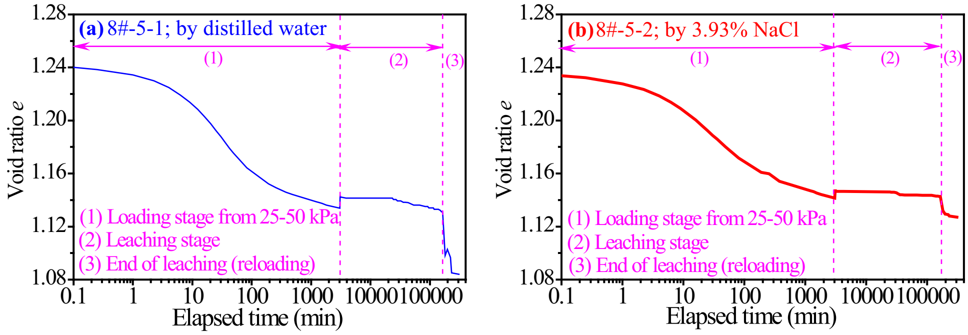
During the stage from B to C, the leaching by NaCl solutions induces a small change of void ratio in the case of 8#-5–2, whereas the obvious change is identified in the specimen labelled as 8#-5–1. To further analyse these results, the changes of void ratio in the last loading step (25–50 kPa) before and during leaching (B-C) are detailed in Fig. 4. It can be observed that the void ratio changes with the leaching period. This appearance is attributed for the below possibilities (Nguyen et al. 2013): (1) unloading due to the application of injection pressure (20 kPa); (2) reloading due to the removal of injection pressure; (3) the creep of the soils; and (4) the desalination leaching process. As the injection pressure (20 kPa) is lower than the pre-yielding stress (55 kPa), the deformation induced by the application and removal of injection pressure is within the elastic zone where the volume change can be assumed to be recoverable. Therefore, the change of total void ratio during this period is generated by the coupled effects of stress-induced creep and desalination leaching process. The elements of void ratio can be expressed as below:

$$\Delta e_T = \Delta e_c + \Delta e_l \tag{1}$$

where Δe_T is the change of total void ratio; Δe_c refers to the change of void ratio by the stress-induced creep, that is, defined as $C_a \times log\Delta t$ shown in Fig. 5. Based on the differentiation, the change of void ratio induced by the long-term leaching process (Δe_l) can be determined.

After the leaching completion, three cycled unloading/reloading paths were orderly conducted. The reloading (D-E, F-G and H-I) induces the compression, and the unloading (C-D, E–F and G-H) results in the swelling. In the first reloading stage (D-E), the maximum vertical effective stress is 50 kPa, lower than the pre-yielding stress (55 kPa) of soils, and hence, the pre-yielding stress in this stage (D-E) is considered still as 55 kPa. In the second and third reloading stages (F-G and H-I), the maximum vertical effective

Fig. 4 Void ratio evolution during leaching process



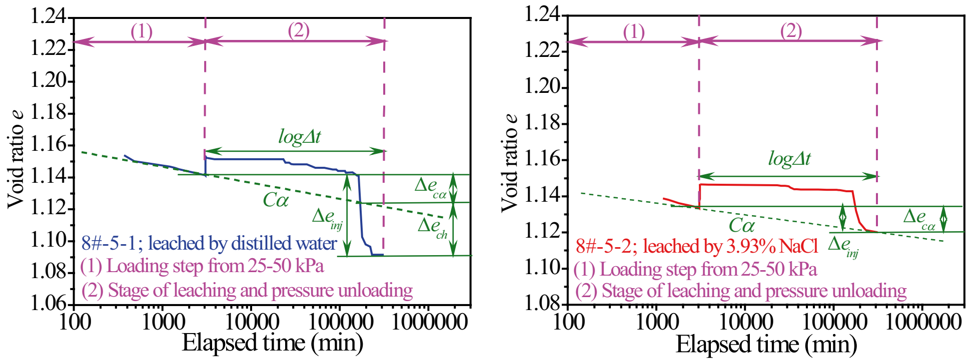


Fig. 5 Void ratio identification induced by creep and leaching process

stress is preset as 200 kPa and 800 kPa, respectively. As LYG marine soft clay is a kind of typically elastoplastic materials, the pre-yielding stress is considered as 200 kPa after experienced the second loading path (F-G), and that is 800 kPa after subjected the third path (H-I). Note that prior to reaching the pre-yielding stress, the deformation of clays locates in the elastic zone, followed by the elastoplastic zone after yielding, as shown in Fig. 6a. In the unloading stages (C-D, E–F and G-H), the applied vertical stress is always less than the pre-yielding stress, and hence the swelling stage is within the elastic zone, as shown in Fig. 6b. To analyse the compression/swelling behaviour at different zones (elastic or elastoplastic), the compression index (C_c) and swelling index (C_s) are calculated, respectively, by the methods illustrated in Fig. 7.

Void ratio change during leaching process

Figure 8 shows the calculated Δe_c and Δe_l values. It is observed that the Δe_c is almost not changed with the leaching solution types (distilled water or 3.93% NaCl solutions), as this Δe_c is solely controlled by the clay's stress-induced creep (clay mineral, particle size distribution and density). It also reveals that the Δe_l of 8#-5–2 (salinity is almost substituted by 3.93% NaCl) is close to 0, suggesting that the synthetic NaCl solutions can represent the salinity component of in-situ pore water. However, the large Δe_l value (0.032) is observed in the case of 8#-5–1 (leached by distilled water). This finding is consistent to the engineering practice in LYG region, that is, the clays far from the coastal line (less pore water salinity, namely subjected the longer leaching process) appears larger creep.

In case of 8#-5–1, the pore water salinity decreases gradually with the long-term leaching. In this case, the salinity constraint on the hydrophilicity of clay minerals is weakened, resulting in the aging of soil's structure and hence increasing the void ratio change (Δe_l). For the traditionally cognition, with the desalination leaching, the *LL* should be increased according to the diffuse double layer (DDL) theory. However, based on the testing data (Wu et al. 2020) and those from previous literatures (Rosenqvist 1953; Bjerrum 1954, 1955; Geertsema and Torrance 2005; Song et al. 2017; Song 2018), the *LL* also decreases with the desalination leaching, conflicting to the DDL theory. For these interesting results, the colloids with diameter less than 1000 nm are thought to be eroded out during leaching process, and this suppose

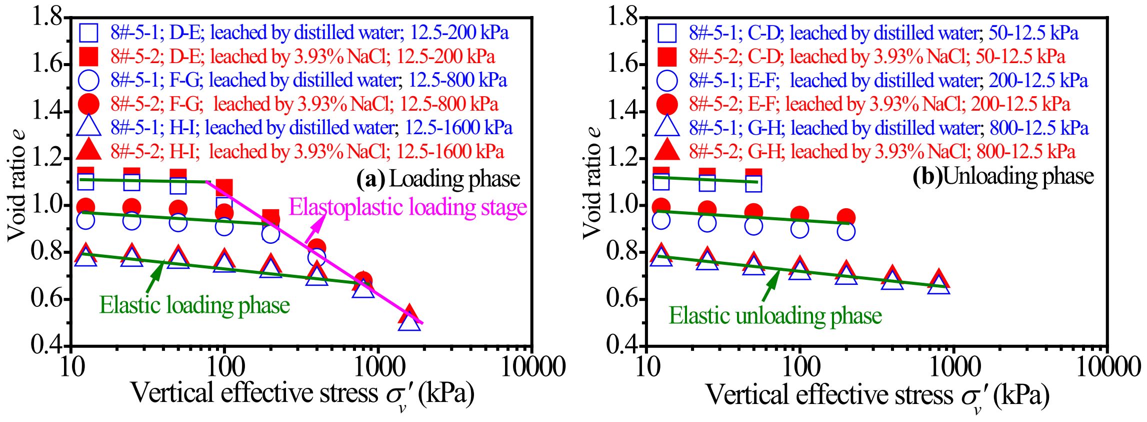


Fig. 6 Divisions of elastic and elastoplastic stages

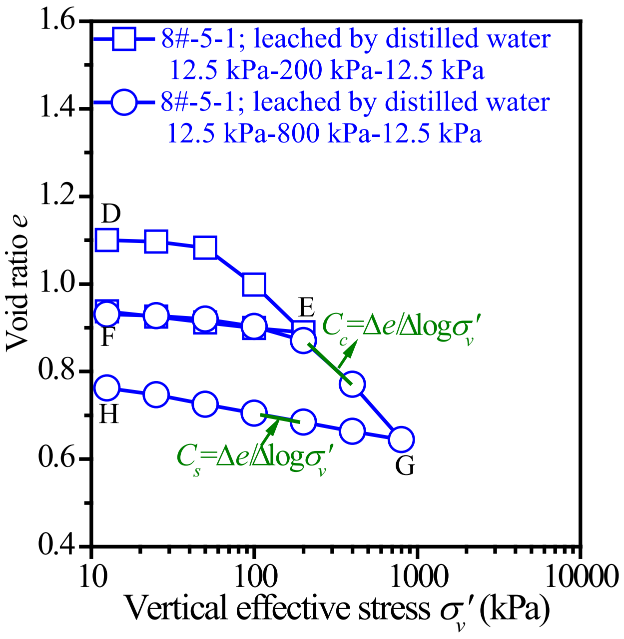


Fig. 7 Determinations of C_c and C_s

has been verified by authors through laboratory tests. In fact, after the long-term leaching (211 days) in this study, the EC of solutions leached out from 8#-5–1 should be zero in theory, whereas the EC slightly exceeds zero. Considering that the colloids are negatively charged (Deng et al. 2019) and the solutions containing colloids have the conductivity, and therefore the EC exceeding zero also verifies the existing of colloid's erosion. Note that the colloids' erosion during leaching process enlarges the soils' inner channels and destroys the inner structure's integrity, leading to the aging of soil's structure and finally increasing the void ratio change (Δe_l). Therefore, the change of Δe_l during leaching process is induced by pore-water salinity and the clay colloidal erosion.

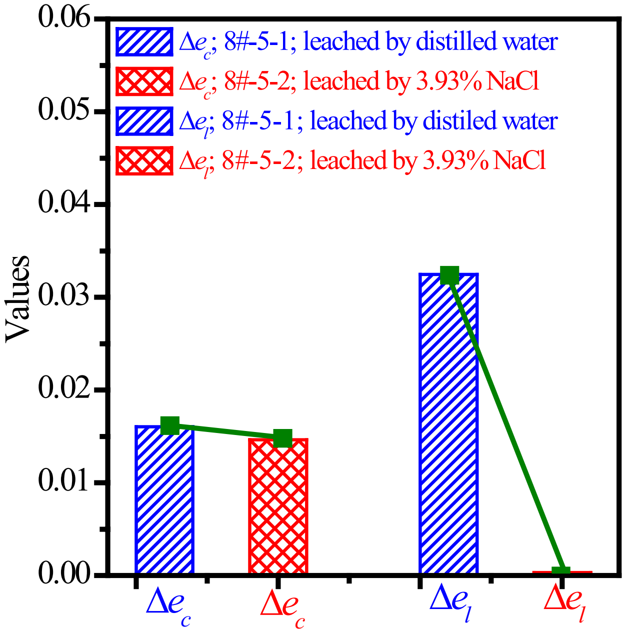


Fig. 8 Values of Δe_c and Δe_l

Compression/swelling behaviour after leaching

As two existing zones (before and after pre-yielding or elastic and elastoplastic) in the reloading stages, the change of compression index (C_c) is calculated and separated for further analysis. Figure 9a shows the relationship between C_c before pre-yielding and σ_v' in the semi-logarithmic coordinates. It can be found that at a vertical effective stress, the C_c of soil leached by the distilled water is almost equal to that leached by 3.93% NaCl solution. This finding suggests that despite the long-term leaching process would result in the constraint release on clay minerals and colloid's erosion, it would still not change the compressibility of clays before pre-yielding. Note that this finding is consistent to the in-situ vane shear strength of LYG soft marine clays from geological investigations, as shown in Fig. 10. It indicates that the shear strength of LYG clays is almost not changed with the salinity leaching (Wu et al. 2020).

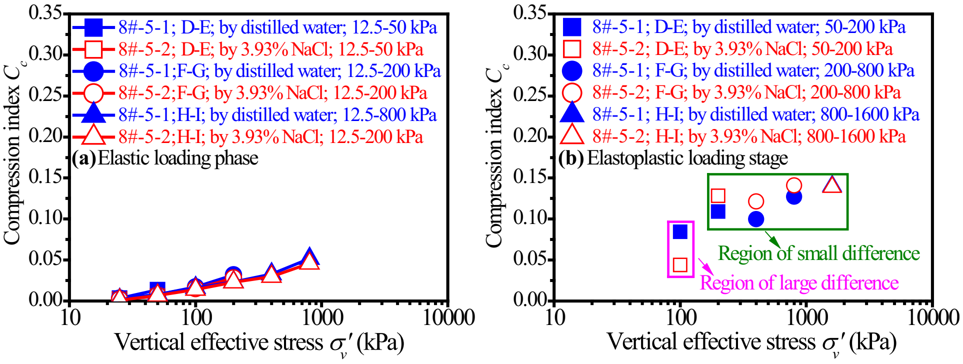
Figure 9b presents the C_c change after pre-yielding. It is observed that the index leached by distilled water is significantly higher than that leached by 3.93% NaCl at low stress level (less than 200 kPa), with the value equal to 0.08 and 0.04, respectively. Additionally, Fig. 9b also reveals that with the increase of stress level (exceed 200 kPa), the C_c's difference leached by the distilled water or 3.93% NaCl is very slight, especially at the stress of 1600 kPa. In other words, the desalination leaching effect on the compression behaviour would be concealed at high stress level.

Figure 11 shows the relationship between C_s and σ_v' in the semi-logarithmic coordinates. It is observed that despite that the C_s increases with the loading/unloading cycles, the long-term salinity leaching effect on the C_s can be ignored. This appearance is similar as the C_c evolution before pre-yielding.

Discussion on clay's aging considering desalination leaching process

For traditional oedometer test, just vertical load was applied to observe the consolidation and creep behaviour. In this investigation, to simulate the desalination leaching process to reflect the post-depositional process of soft marine clay, the percolation procedure was introduced. The different compression/swelling behaviour was obtained as below:

Fig. 9 Compression index versus vertical effective stress



(1) During long-term desalination leaching process, the void ratio change (Δe_l) induced by the coupled pore water desalination and colloidal erosion is also identified.

(2) In the elastic loading and unloading stages, the long-term desalination leaching effect on the compression/swelling behaviour can be neglected.

(3) In the elastoplastic loading stage, this process increases the compression at low stress level (less than 200 kPa), whereas this effect can be concealed at high stress level (yielding 200 kPa).

The compression/swelling behaviour of aged clays undergoing the long-term desalination leaching process is sketched in Fig. 12. For the soil percolated with synthetic NaCl solution, the aged compression line by creep (just stress creep) obeyed the law proposed by Bjerrum (1967), where the stress creep would improve the soil structure heightening the pre-yielding stress, and then the soil follows the aged normal compression line at the high stress level. However, for the soil percolated with the distilled water, the deformation composed of both creep by stress and by desalination leaching process. It indicates that the creep by desalination leaching would lead to the limited structure damage whilst keeping the constant pre-yielding stress and resulting the large compression index. At the high stress level, this structure damage would be overcome, leading to the almost same compression index as that percolated by synthetic solution.

It is well known that for the soil encountering creep by the stress, its microstructure would be rearranged to keep soil skeleton adapting the effective stress and increasing the pre-yielding stress. Hence, what would happen for long-term desalination leaching process on the soil's structure?

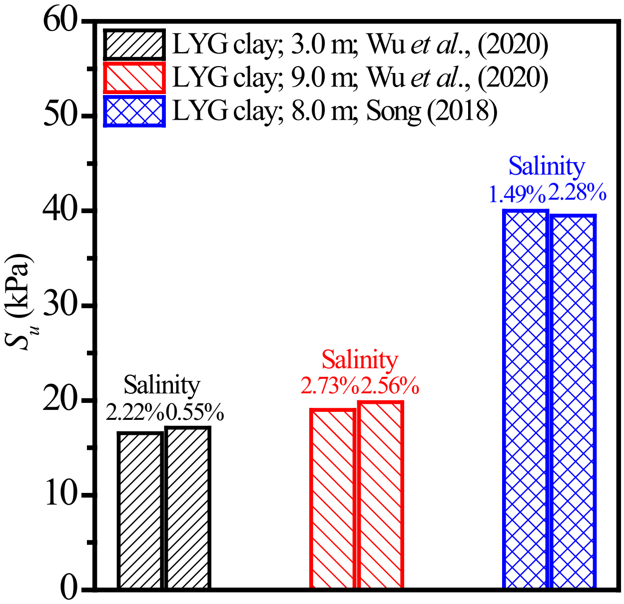


Fig. 10 S_u change with pore water salinity leaching

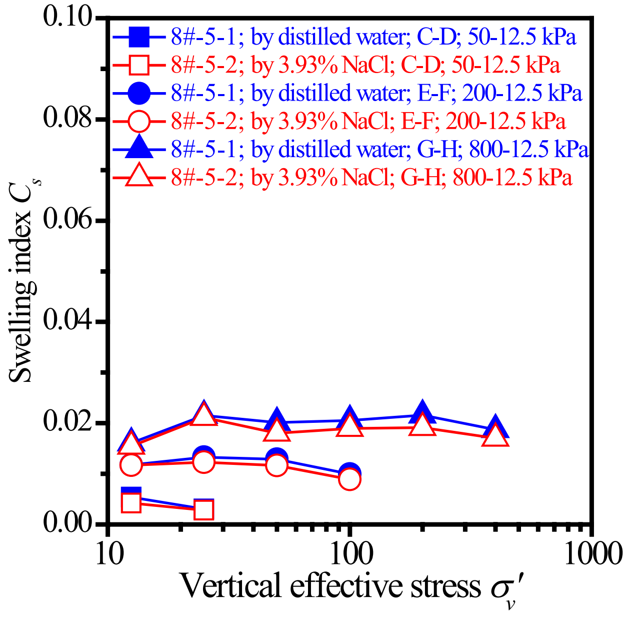


Fig. 11 Comparison on swelling index

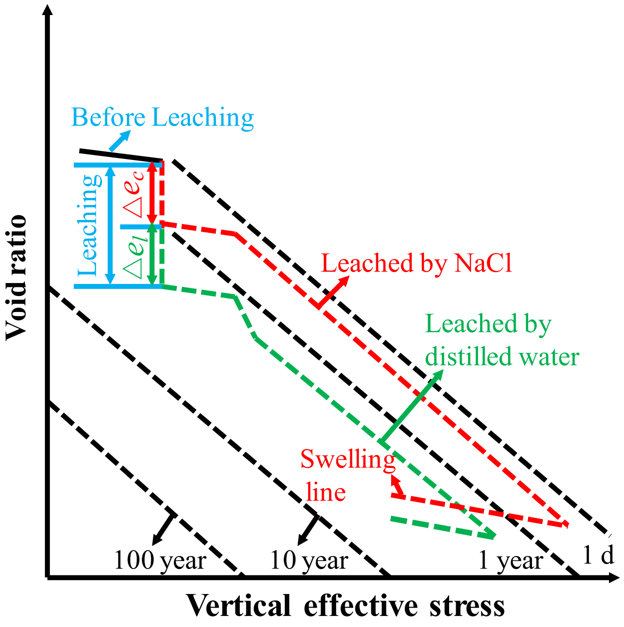


Fig. 12 Schematic of compression behaviour considering leaching process

In this investigation, the leachate was just measured by EC to evaluate the salinity evolution. After 211 days' percolation, the EC is still not equal to zero, suggesting the existence of electric conductivity. Deng et al. (2014) analysed the salinity component within pore water of two sites in LYG region and found the unbalanced total electric charge valence; i.e. the total cation charge valence is significantly lower than the total anion charge valence. Deng et al. (2019) analysed the substance of the tailing water from the muddy by vacuum loading and found that the clay colloidal fraction (negatively charged) dissolved in the pore water. The native charge can balance the unbalanced total electric charge valence. Hence, it can be imagined that the charge balanced system existed in the pore water should compose of cation/anion and clay's colloidal fraction. In the hydro-geochemistry and hydrodynamics disciplines, the underground water movement in aquifer always accompanies the mass transportation, including the clay's colloidal fraction (Zhou 2010). In view of geotechnical engineering and clay mineralogy, the clay's colloidal fraction is of large surface area and potential energy, and its loss would decrease the soil's hydrophilic property (reflected by the liquid limit) leading to internal erosion and then the micro-structure damage.

Conclusions

In this study, the natural soft clays with pore water salinity of 3.93% were first drilled in LYG region and then these soils were long-term desalination leached by the distilled water and synthetic NaCl solutions, respectively. Hereinafter, oedometer tests with cycled loading/unloading were conducted, aiming to study the long-term salinity leaching effect on its compression/swelling behaviour. The main conclusions can be drawn as follows:

(1) During the long-term leaching process, the stress-induced creep generates a void ratio change (Δe_c). Meanwhile, the long-term desalination leaching process and internal colloidal erosion further lead to the aging of clays' structure, and then the additional void ratio change (Δe_l) is identified.
(2) In the elastic loading and unloading stages after desalination leaching process, this process effect on the compression/swelling behaviour of LYG clays is very slight.
(3) In the elastoplastic loading stage after long-term leaching process, the compressibility at low stress level (less than 200 kPa) will be amplified. However, with the increase of stress level (yielding 200 kPa), the desalination leaching process effect on the clays' compression would be overcome.
(4) The compression/swelling behaviour induced by clay's aging for the long-term desalination leaching process was summarized.

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References

American Society for Testing and Materials (ASTM) (1999) Standard test methods for electrical conductivity and resistivity of water. Soil and Rock, West Conshohocken, PA.D1125
American Society for Testing and Materials (ASTM) (2007) Standard test method for particle-size analysis of soils. Soil and Rock, West Conshohocken,PA. D422-63
American Society for Testing and Materials (ASTM) (2010) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. Soil and Rock, West Conshohocken,PA. D4318
American Society for Testing and Materials (ASTM) (2014) Standard test methods for specific gravity of soil solids by water pycnometer. Soil and Rock, West Conshohocken,PA. D4318
Bjerrum L (1954) Geotechnical properties of Norwegian marine clays. Géotechnique 4(2):49–69
Bjerrum L (1955) Stability of natural slopes in quick clay. Géotechnique 3(2):101–119
Bjerrum L, Rosenqvist IT (1956) Some experiments with artificially sedimented clays. Géotechnique 6(3):124–136
Bjerrum L (1967) Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. Géotechnique 17:81–118

Deng YF, Cui YJ, Tang AM, Nguyen TP, Li XL, Geet MV (2011a) Investigating the pore-water chemistry effects on the volume change behaviour of Boom clay. Phys Chem Earth 36:1905–1912

Deng YF, Tang AM, Cui YJ, Nguyen XP, Li XL, Wouters L (2011b) Laboratory hydro-mechanical characterisation of Boom Clay at Essen and Mol. Phys Chem Earth 36:1878–1890

Deng YF, Cui YJ, Tang AM, Li XL, Sillen X (2012) An experimental study on the secondary deformation of Boom clay. Appl Clay Sci 59:19–25

Deng YF, Yue XB, Cui YJ, Shao GH, Liu SY, Zhang DW (2014) Effect of pore water chemistry on the hydro-mechanical behaviour of Lianyungang soft marine clay. Appl Clay Sci 95:167–175

Deng YF, Liu L, Cui YJ, Feng Q, Chen XL, He N (2019) Colloid effect on clogging mechanism of hydraulic reclamation mud improved by vacuum preloading. Can Geotech J 56(6):611–620

Geertsema M, Torrance JK (2005) Quick clay from the mink creek landslide near Terrace, British Columbia: geotechnical properties mineralogy and geochemistry. Can Geotech J 42:907–918

Moum J, Loken T, Torrance JK (1971) A geochemical investigation of the sensitivity of normally consolidated clay from Drammen Norway. Géotechnique 21(4):329–340

Mitchell JK, Soga K (2005) Fundamentals of Soil Behaviour, 3rd edn. Wiley, New York

Nguyen XP, Cui YJ, Tang AM, Deng YF, Li XL, Wouters L (2013) Effects of pore water chemical composition on the hydro-mechanical behavior of natural stiff clays. Eng Geol 166:52–64

Ohtsubo M, Takayama M, Egashira K (1982) Marine quick clays from Ariake bay area Japan. Soils Found 22(4):71–80

Rosenqvist ITH (1953) Considering on the sensitivity of Norwegian quick clay. Géotechnique 3(5):195–200

Sridharan A, El-Shafei A, Miura N (2002) Mechanisms controlling the undrained strength behaviour of remolded Ariake marine clays. Mar Georesources Geotechnol 20(1):21–50

Song MM, Zeng LL, Hong ZS (2017) Pore fluid salinity effects on physicochemical-compressive behaviour of reconstituted marine clays. Appl Clay Sci 146:270–277

Song MM (2018) Investigation of salt leaching effects on mechanical behavior of natural marine clays. Doctor's thesis. Southeast University

Torrance JK (1974) A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. Géotechnique 24(2):155–173

Torrance JK (1975) On the role of chemistry in the development and behavior of the sensitive marine clays of Canada and Scandinavia. Can Geotech J 12:326–335

Whittig LD, Allardice WR (1986) X-ray Diffracttion Techniques Methods of Soil Analysis, 2nd edn. American Society of Agronomy Soil Science Society of America, Madison

Wu ZL, Deng YF, Cui YJ, Zhou AN, Feng Q, Xue HC (2019) Experimental study on creep behavior in oedometer tests of reconstituted soft clays. Int J Geomech 19(3):1–10

Wu ZL, Deng YF, Cui YJ, Chu CF, Feng Q (2020) Geological investigation of the settlement behaviour of two highways in Lianyungang region. Eng Geol 272:105648

Zhou J (2010) Studies of colloidal behaviour and effect in porous media. China Ocean University, Qingdao, p 114