



## Research paper

# Effect of pore water chemistry on the hydro-mechanical behaviour of Lianyungang soft marine clay

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## ABSTRACT

The effect of pore water chemistry on the hydro-mechanical behaviour of soft marine clay of Lianyungang was investigated. Field investigation and piezo-cone penetration tests at two sites with 0.56% and 4.91% salinity respectively were first performed, and a significant difference was observed in terms of Atterberg's limits (*LL* and *PL*), density, net tip resistance, sleeve friction and pore water pressure parameter, suggesting a significant effect of pore water chemistry. To confirm this observation, identification tests were extended to an artificial soil corresponding to a mixture of kaolinite/bentonite with different salinities. The results obtained confirm the significant effect of pore water chemistry. To further clarify this effect, oedometer tests were performed with both site water and deionised water. The results indicated that the compression index, swelling index, and secondary consolidation coefficient are higher in the case of deionised water, whereas the oedometer modulus, consolidation coefficient and hydraulic conductivity are larger in the case of site water. However, the ratio between secondary consolidation coefficient and compression (or swelling) index indicates no significant effect of pore water salinity. After completion of the oedometer tests, the microstructure features were studied by the mercury intrusion porosimetry. The results showed that deionised water led to an increase of porosity, whereas the site water led to a decrease of porosity.

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## 1. Introduction

In the east and the south of China, quaternary sediments, such as marine soft clays, are widely deposited. These sediments are quite common in the area around Lianyungang city (LYG), Jiangsu Province, in relation to the soft marine clay deposited in the north of the Yellow sea (see Fig. 1). Note that the clays in LYG area were deposited in the sea regression environment from about 4800 to 6000 years ago. Roughly 1000 years ago, the ancient Yellow River (or Huanghe) changed its runway and entered the Yellow Sea in the south of the LYG region, bringing large amount of sediment from the loess plateau in the northwest of China. These works were confirmed by geologists and geographers (see for instance Xue et al., 2003).

Recently, many new structures, such as highway, railways and buildings, have been constructed in this region, explaining the particular interest of many researchers for this clay – the mechanical behaviour of the LYG marine clay was intensively studied in the last decades. Liu et al. (2008) conducted a number of *in-situ* piezo-cone penetration

(CPTu) tests and verified the existing methods of determining soil parameters by CPTu. Deng (2005) performed *in-situ* vane tests and compared the values of shear strength before and after remoulding. They concluded that the sensitivity value of the LYG marine clay is approximately 6–8. Hong et al. (2010) analysed the compression behaviour of the reconstituted LYG marine clay in the plane of  $\log(1 + e)$  and  $\log \sigma'_v$  and concluded that the intrinsic remoulding pressure is a function of the ratio of initial water content to liquid limit (*LL*).

Although a number of studies on the LYG marine clay have been conducted, the effect of pore water salinity has not been investigated, even though the pore water composition can be quite different for different coastal lines and can change significantly by land desalination. Indeed, the soil close to the seas or the salterns has been inevitably eroded over time by fresh water, leading to desalination, and in turn changing the soil behaviour and causing hazards to infrastructure such as highways and embankments.

Several authors have reported the significant effect of pore-water chemistry on the hydro-mechanical behaviour of soils. Chen and Anadarajah (1998), Sridharan and Prakash (1999) and Kaya et al. (2006) studied the pore water effect on the sedimentation of dispersions and slurries with NaCl, CaCl<sub>2</sub>, AlCl<sub>3</sub> and some organic fluids, and observed that the sedimentation behaviour and the final volume depend on the ion valence, concentration, pH value and dielectric

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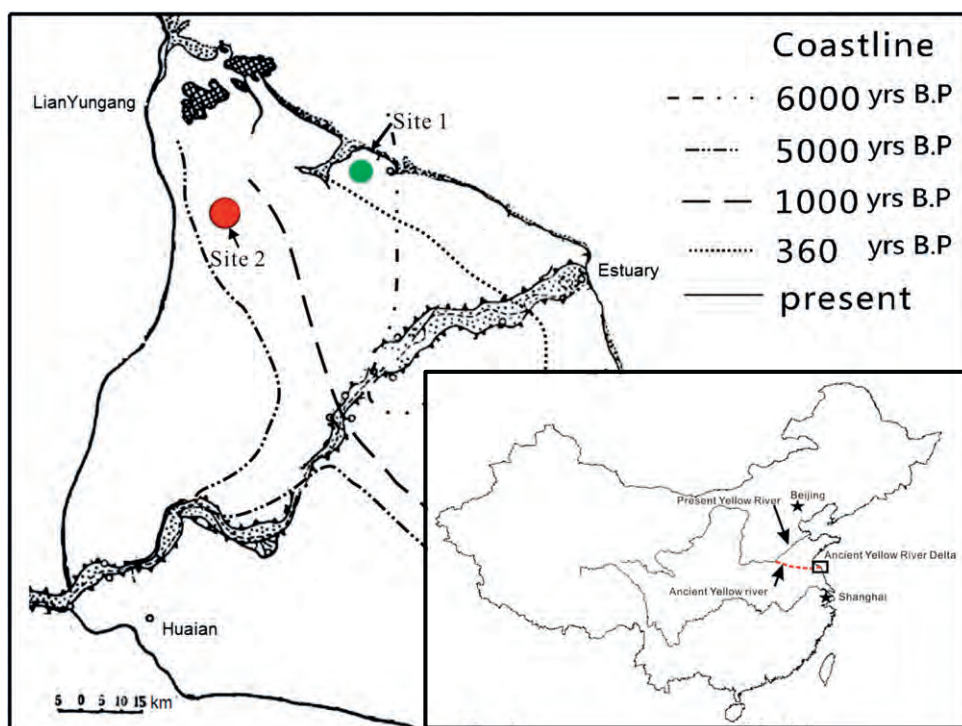


Fig. 1. Estuary of the Ancient Yellow River and site locations.

constant of the fluid. They tried to describe the mechanism using parameters such as the dielectric constant and Zeta potential, based on the diffuse double layer theory. Kaya and Fang (2000), Sridharan et al. (2002), Di Maio et al. (2004), Gajo and Maines (2007) and Yukselen-Aksoy et al. (2008) analysed the effects of cation valence, ion concentration, pH of pore water and clay minerals on the Atterberg's limits ( $LL$  and plastic limit:  $PL$ ) based on the diffuse double layer theory. They noted that when the  $LL$  of clays is lower than 110%, the salinity effect on the Atterberg's limits is not significant. Gajo and Maines (2007) observed that the  $LL$  of a Na-bentonite from Italy firstly increases slightly from 436% to about 500% with the increase of ion concentration, then decreases sharply to approximately 100% with further increase of ion concentration, the threshold ion concentration being 0.1 mol/dm<sup>3</sup>. Abdullah et al. (1997), Sridharan and Prakash (1999), Ören and Kaya (2003), Di Maio et al. (2004), Abdullah et al. (1997), and Gajo and Maines (2007) studied the pore water salinity effect on the compressibility behaviour of clays and compacted soils. Ören and Kaya (2003) observed that the compressibility of homoionised clays treated with Na<sup>+</sup>, Ca<sup>2+</sup> and Al<sup>3+</sup> solutions differs from each other, and the compression index order is: Al-clay > Ca-clay > Na-clay. Abdullah et al. (1997) observed that highly plastic Jordan clays with the major clay minerals as illite and a mixed layer of illite-smectite, treated without or with Ca<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> solutions have different maximum dry densities. In all cases, drastic decreases in swelling potential and ratio of the secondary consolidation coefficient to the compression index were identified. Gajo and Maines (2007) studied the pore water chemistry effects on the shear strength of remoulded and compacted soils and observed that with deionised water, the residual friction angle is the smallest; it increases with the concentration of HCl or NaOH. Smiles (2008) analysed the pore water effect on hydraulic conductivity and proposed a relationship between hydraulic conductivity and water chemical potential.

The studies mentioned above dealt with either remoulded soils or compacted soils or slurries. Some authors investigated natural stiff soils. Wakim (2005) placed natural clay samples in a controlled salinity environment to study the salinity effect. Deng et al. (2011a) performed oedometer tests on natural Boom Clay with deionised and site waters. In

their tests, the completion of the pore water replacement was not verified and was thus uncertain.

To the authors' knowledge, the pore water chemistry effect has not been studied for soft marine clays. In this study, the *in situ* CPTu and borehole investigation were performed at two sites, i.e. Site 1 and Site 2 (see Fig. 1). Site 1 is located in a saltern 50 m far from the coastline of the Yellow Sea and involves clay at 4.91% pore water salinity. Site 2 is 30 km far from the coastline of the Yellow Sea and involves clay at 0.56% pore water salinity. In the laboratory, a special oedometer was used to study the effect of salinity on the volume change behaviour of the clay from Site 1. The mercury intrusion porosimetry (MIP) was applied for the microstructure observation. Moreover, the effects of pore water chemistry on the Atterberg's limits were examined for further verification.

## 2. Materials and methods

The results of CPTu for Site 1 and Site 2 were presented respectively in Figs. 2 and 3. For both sites, the investigated 20 m depth can be divided into three layers, i.e., crust, soft clay and substratum. The thicknesses of the crust and soft clay are approximately 0.5 m and 16.0 m, respectively, at Site 1, and approximately 1.5 m and 10.5 m, respectively, at Site 2.

The ranges of water content ( $w$ ),  $LL$ ,  $PL$ , density ( $\gamma$ ) and initial void ratio ( $e_0$ ) at these two sites are presented in Table 1. Note that the  $LL$  and  $PL$  were measured with deionised water using Cassagrande's method and the rolling method, respectively. The  $w$  value at Site 1 ranges from 54.7 to 65.4%,  $LL$  from 51.4 to 73.9%,  $PL$  from 25.3 to 29.3% and  $\gamma$  from 16.2 to 16.9 kN/m<sup>3</sup>, whereas the ranges for Site 2 are 67.5 to 79.6% for  $w$ , 64.2 to 79.6% for  $LL$ , 29.4 to 33.8% for  $PL$  and 14.8 to 15.9 kN/m<sup>3</sup> for  $\gamma$ . With a value of 2.70 for the specific gravity,  $e_0$  at Site 1 varies from 1.51 to 1.84, whereas that at Site 2 varies from 1.79 to 2.11. An obvious difference is observed for the two sites, and the water chemistry was suspected to be the origin. To verify this point, specific identification tests were conducted in the laboratory. The LYG marine clay from Site 1 was mixed with tap water to reach low pore water salinity, where the electric conductivity ( $EC$ ) of the supernatant

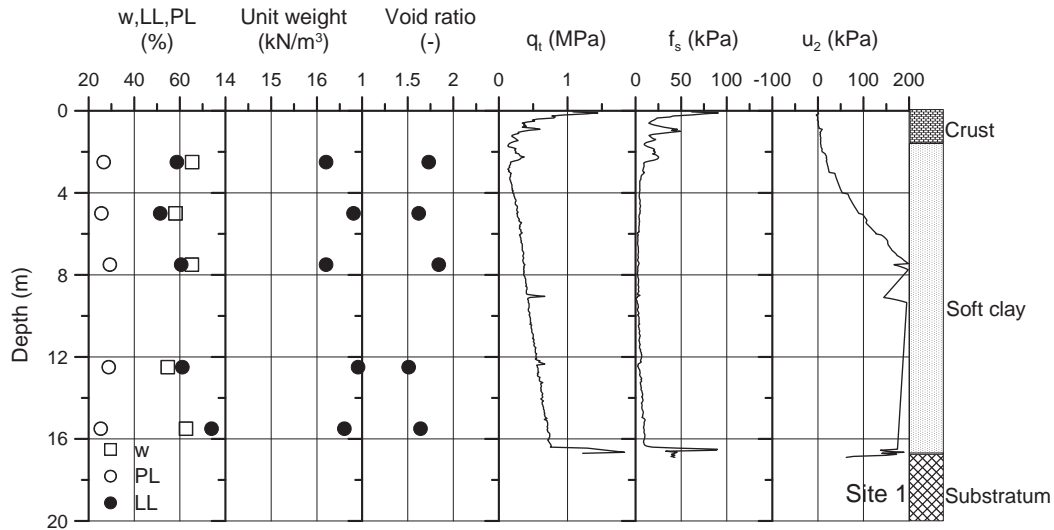


Fig. 2. Profiles at Site 1.

was monitored. When the measured  $EC$  was  $0.3 \text{ mS/cm}$  (corresponding to a salinity of approximately  $0.03\%$  for the solution), close to that of tap water, the supernatant was removed, and the clay was naturally dried and smashed for identification tests with water of different salinities. The results show that the  $LL$  and  $PL$  with deionised water are  $54.1\%$  and  $27.2\%$ , respectively, whereas those with a salinity of  $4.91\%$  (the same as at Site 2) are  $50.9\%$  and  $29.4\%$ , respectively. This confirms the significant effect of water chemistry.

Semi-quantitative mineral analysis by X-ray diffraction was conducted on soils taken from the two sites at  $5 \text{ m}$  depth and the results were also listed in Table 1. The clay at Site 1 has clay minerals ( $45.0\%$ ), quartz ( $23.2\%$ ), plagioclase ( $15.6\%$ ), feldspar ( $4.1\%$ ) and calcite ( $12.1\%$ ). A similar mineral composition was found for Site 2:  $53.0\%$  clay,  $30.0\%$  quartz,  $13.0\%$  plagioclase,  $4.0\%$  feldspar and  $0\%$  calcite. The clay minerals fraction (less than  $2 \mu\text{m}$ ) also shows that the two sites have the same clay minerals, e.g., kaolinite, illite, chlorite and interstratified illite/smectite. The contents of the interstratified illite/smectite, kaolinite, illite and chlorite at Site 1 are  $44.0\%$ ,  $13.0\%$ ,  $29.0\%$  and  $14.0\%$ , respectively, whereas those at Site 2 are  $57.0\%$ ,  $5.0\%$ ,  $32.0\%$  and  $6.0\%$ , respectively. The mineral components at both sites were almost the same (the difference

between them is less than  $10.0\%$ ) regardless of the total minerals or the clay minerals. The soils at both sites are of high clay fraction, close to  $50.0\%$ , and the content of interstratified illite/smectite reaches  $50.0\%$ , which suggests an expansive nature.

The ion concentration of the pore water in Table 1 was the value for the water taken from a borehole at approximately  $2 \text{ m}$  in depth at Site 1, and the average value of the water from  $4.0 \text{ m}$  to  $12.0 \text{ m}$  depth at Site 2 respectively. The table shows that the total salinity of pore water at Site 1 is approximately  $8.8$  times higher than that at Site 2 ( $4.91\%$  against  $0.56\%$ ). The main ions were found to be  $\text{Na}^+$  and  $\text{Cl}^-$  by spectroscopy. It should be noted that the phenomenon of unbalanced solubilisation was observed when further comparing the ratio of mono ion and the ratio of total salinity at the above two sites. The concentrations of the monovalent cation ( $\text{Na}^+$ ) and anion ( $\text{Cl}^-$ ) at Site 1 are approximately  $5.0$  and  $11.1$  times higher than those at Site 2, and those of the bivalent cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) and anion ( $\text{SO}_4^{2-}$ ) at Site 1 are approximately  $8.3$  and  $58.5$  times higher than those at Site 2. In addition, the contents of the monovalent cation ( $\text{Na}^+$ ) and anion ( $\text{Cl}^-$ ) are approximately  $5.0$  times higher than those of the bivalent cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) and anion ( $\text{SO}_4^{2-}$ ) at both sites. The contents of the monovalent cation

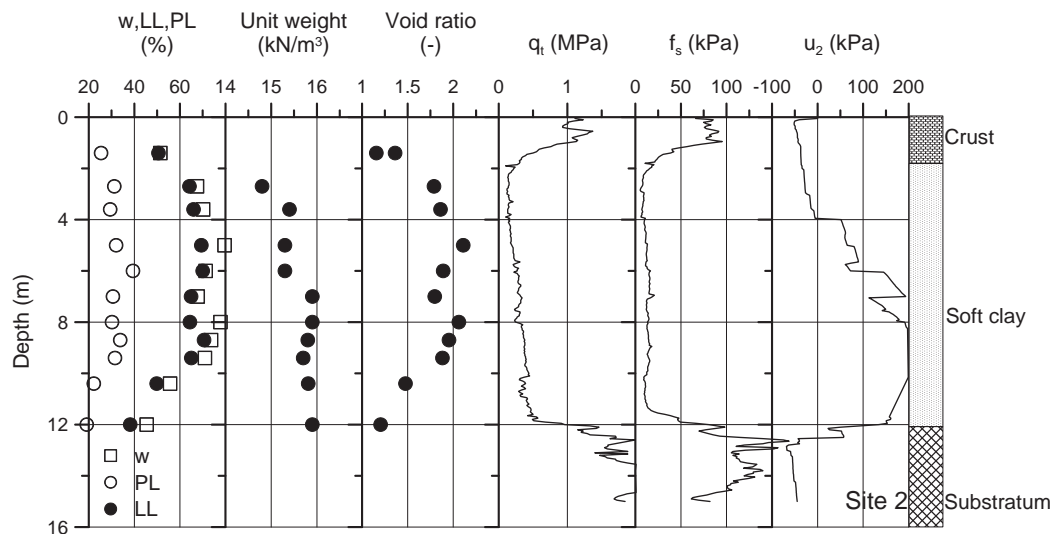


Fig. 3. Profiles at Site 2.

**Table 1**  
Characterisation comparison at the two sites.

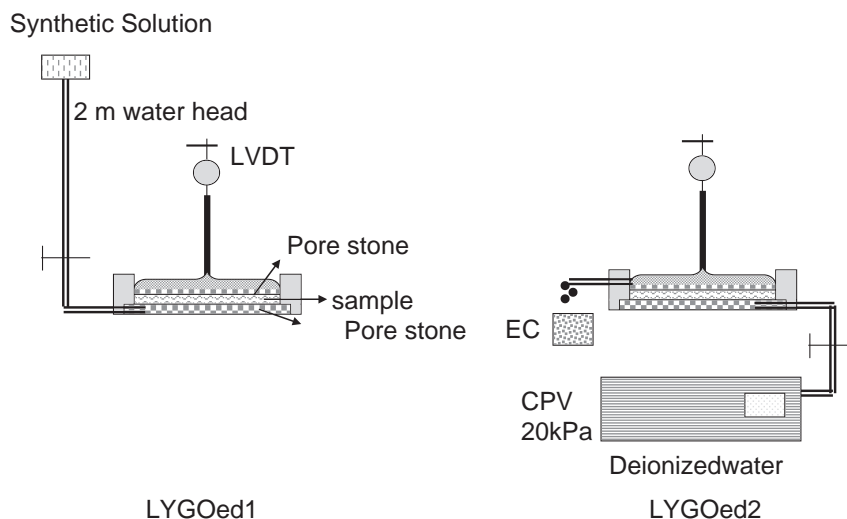
		$w$ (%)	$LL$ (%)	$PL$ (%)	$\gamma$ (kN/m <sup>3</sup> )	$e_0$ (–)	$q_t$ (MPa)	$\bar{f}_s$ (kPa)	$u_2$ (kPa)	
Geotechnical properties	Site 1	54.7–65.4	51.4–73.9	25.3–29.3	16.2–16.9	1.51–1.84	0.13–0.75	2.2–18.0	5.4–518.0	
	Site 2	67.5–79.6	64.2–79.6	29.4–33.8	14.8–15.9	1.79–2.11	0.13–0.68	9.6–49.6	– 54.2–309.0	
		Total mineral				Clay mineral				
		Quartz	Feldspar	Plagioclase	Calcite	Clay content	Illite	Kaolinite	Chlorite	Illite/smectite
Mineral	Site 1	23.2	4.1	15.6	12.1	45.0	29.0	13.0	14.0	44.0
	Site 2	30.0	4.0	13.0		53.0	32.0	5.0	6.0	57.0
		Ion concentration (g/L)					Total salinity (‰)			
		$SO_4^{2-}$		$Cl^-$	$Ca^{2+}$	$Mg^{2+}$	$Na^+$			
Ion concentrations of pore water		Site 1	3.51	25.53	0.57	2.1	14	49.1		
		Site 2	0.06	2.31	0.19	0.13	2.81	5.6		
		Site 1/Site 2	58.5	11.1	3.0	16.2	5.0	8.8		

( $Na^+$ ) and anion ( $Cl^-$ ) at Site 1 are approximately 7.7 times higher than at Site 2, whereas those of the bivalent cations ( $Ca^{2+}$  and  $Mg^{2+}$ ) and anion ( $SO_4^{2-}$ ) are approximately 16.3 times greater. These results show that the cation  $Mg^{2+}$  and anion  $SO_4^{2-}$  are more easily leached than the cations  $Ca^{2+}$  and  $Na^+$ .

From the analyses above, it appears that the physical properties (e.g.,  $w$ ,  $LL$ ,  $PL$  and  $e_0$ ) at Site 2 are generally higher than at Site 1. The clays at Site 1 have a higher  $\gamma$  and smaller  $e_0$  while having similar mineral contents than at Site 2. This is suspiciously contrary to that of the depositional and consolidation history. To clarify these differences and to study the pore water effect on the soil hydro-mechanical behaviour, field CPTu tests at two sites, and oedometer tests percolated by site water and deionised water with samples from Site 1, were carried out. In the CPTu tests, the cone had a bottom section area of 10 cm<sup>2</sup>, a cone angle of 60°, and a bottom diameter of 35.7 mm. During the penetration of the probes at 20 mm/s, the tip resistance  $q_c$ , pore pressure  $u_2$  behind the cone tip, and the sleeve friction  $f_s$  were measured. It is worth noting that the cone tip resistance  $q_t$  corrected by the area ratio ( $\alpha$ ) and the pore pressure, the pore pressure parameter  $B_q$  and the friction ratio  $f_s/q_t$  are popularly used for site characterisations. In this study,  $q_t$  was calculated as  $q_t = q_c + u_2(1 - \alpha)$ , where  $\alpha$  is a constant for a given probe ( $\alpha = 0.8$  in this study).  $B_q$  was calculated by  $B_q = (u_2 - u_0)/(q_t - \sigma_{v0})$ , where  $\sigma_{v0}$  is the total overburden stress using the natural density of soil (16.5 kN/m<sup>3</sup> in this study), and  $u_0$  is the initial

pore pressure (the water table is considered at the ground surface). With the calculated values, the site characterisation and the comparison between the two sites were conducted and discussed later.

To study the pore water effect on the soil behaviour, oedometer tests after percolation by site water and deionised water were performed. Fig. 4 is the sketch of the equipments for two parallel percolation and oedometer tests, where LYGOed1 is set for the percolation test with the site water (4.91‰ salinity with the same salts as at Site 1), whereas LYGOed2 is the test with the deionised water. In the LYGOed1 test, the site water was placed at 2 m height above the centre of oedometer since the controller of pressure and volume (CPV) cannot work in the saline environment. During percolation, the pre-set pressure was 20 kPa for the LYGOed2 (equal to 2 m water head as in LYGOed1). The leachate from the top of LYGOed2 was gathered and measured with an EC sensor to verify the completion of the ion exchange. After installation of the soil sample in the oedometer cell, the loading sequences (0.125 kPa, 25 kPa and 50 kPa) were applied to ensure a good contact between the sample, porous stone and cell and to eliminate the effects of possible soil disturbance due to the transport, conservation and sample preparation. Each loading stage was maintained for 24 h (BS:1377-5, 1990). The vertical stress of 50 kPa was considered as the pre-yield stress from previous oedometer tests. When the EC of the leachate came to be stable and was close to that of tap water, the sample was considered as fully saturated with the desired water. Thereafter, the



**Fig. 4.** Equipment for the percolation test.



pore water pressure at the base of oedometers was removed. To study the compressibility behaviour after the water percolation phase, the sample was unloaded from 50 kPa (I) to 12.5 MPa (II), loaded to 1600 kPa (III) and unloaded again to 12.5 kPa (IV), with each stage lasting 24 h (BS:1377-5, 1990).

### 3. Results and discussion

#### 3.1. Soil identification

Because the pore water chemistry effect on the plasticity limit was observed for the LYG marine clay, a commercial kaolinite, commercial bentonite and a mixture of the two were used to further investigate the pore water chemistry effect on the soil identification parameters. In these tests, the mixtures of the commercial kaolinite and bentonite were prepared with the kaolinite content equal to 0%, 10%, 20% and 100%. The solutions were prepared with the same salts as in Site 1 (see Table 1), and their concentrations were pre-set at 0% (deionised water), 4.9% (site water) and 9.8% (2 times the site water concentration). For the mixtures and the solutions, the  $LL$  and  $PL$  values obtained are presented in Fig. 5. In addition, the data of the LYG marine clay at Site 1 and Site 2 are also reported in the plasticity chart.

The  $LL$  and  $PL$  of bentonite with deionised water are 301.4% and 37.7%, respectively; the values with the 4.9% salinity solution are 114.7% and 36.0% respectively, and those with the 9.8% salinity solution are 99.4% and 36.6%, respectively. The values for kaolinite are 26.6% and 19.1% with deionised water, 28.6% and 20.4% with the 4.9% salinity solution and 30.6% and 21.5% with the 9.8% salinity solution, respectively. The results of the plasticity chart also show that (1) the relationships between the  $LL$  and  $PL$  for the bentonite and kaolinite mixtures are linear; (2) these relationships move toward “A” line with the increase of concentration, and when the salinity reaches 9.8%, the soils are very close to “A” line; (3) the pore water chemistry effect on the pure kaolinite and on the bentonite is opposite – the  $LL$  of bentonite significantly decreases with the increase of pore water salinity while that of pure kaolinite increases slightly with the increase of pore water chemistry; and (4)  $LL$  is more sensitive to pore water chemistry than  $PL$ .

The tendency of the clays of LYG marine clay at Site 1 is below that at Site 2 in the plasticity chart, which is consistent with the mineral compositions with more interstratified illite/smectite at Site 2.

Yukselen-Aksoy et al. (2008) proposed that the pore water chemistry effect on the Atterberg's limits can be neglected when the  $LL$  is lower than 110%. But they did not give the information about the soils' mineral compositions and whether the initial salinity of the soils was modified. This information would help better understand this threshold value ( $LL = 110\%$ ).

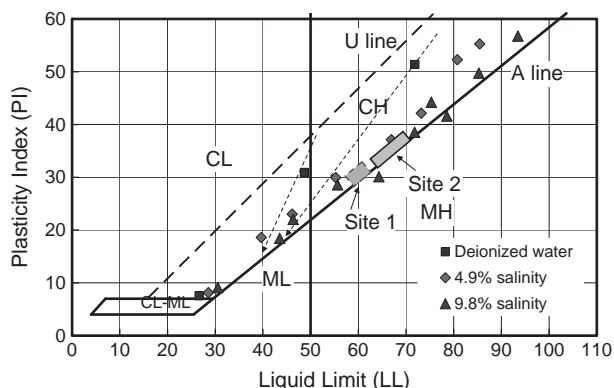


Fig. 5. Soil states in the plasticity chart (ASTM: D-2487, 2011).

#### 3.2. CPTu tests

To further analyse the differences of the soft clays between Site 1 and Site 2, the CPTu data between 3.0 m and 12.0 m were considered because the soils are more uniform in this zone – the relationship between  $q_t$  and depth is almost linear. It is observed in Fig. 6 that the  $q_t$  and  $B_q$  at Site 1 are greater than at Site 2, whereas the sleeve friction and the friction ratio are smaller at Site 1. This observation can be explained as follows: (1) Even though the clay at Site 1 was deposited more recently than that at Site 2, the value of  $q_t$  at Site 1 was higher; and (2) the soil behaviour at Site 1 is more similar to that of a silt than at Site 2, according to the soil classification chart of Robertson et al. (1986) for the clay at Site 1 has a higher  $q_t$ , a lower  $f_s$  and  $B_q$ . Furthermore, it is worth noting that the higher sleeve friction at Site 2 and the lower tip resistance may be consistent with the changes of  $LL$ ,  $PL$  and the soil categories following the Universal Soil Classification System – the tendency from CH to CL or MH: sand or silt has lower sleeve friction and higher tip resistance than clays.

#### 3.3. Oedometer tests

Fig. 7 shows the results of the two parallel percolation and oedometer tests. The tests lasted about 1470 h (i.e., 61 days); the percolation phase lasted 1000 h (i.e., 43 days). During the percolation procedure, only a small secondary consolidation was observed for LYGOed1 with the site solution, whereas an obvious swelling occurred for LYGOed2 with the deionised water, which was most likely due to the high illite/smectite content in the clay fraction. The leachate from the top of the LYGOed2 oedometer cell was gathered and its  $EC$  was measured. The results show that the  $EC$  decreased with elapsed time and almost reached stabilisation at 1.29 mS/cm (equal to  $EC$  of the solution with 0.1% concentration of the site salts) after 43 day percolation. In addition, the  $EC$  change during the last 8 days (i.e. from day 36 to day 43) was only 24  $\mu$ S/cm. The injected water volume of LYGOed2 increased over time, and the total volume of the injected deionised water is 334  $\text{cm}^3$ , 5.6 times the initial sample volume or 11.5 times the initial pore volume.

In Fig. 8, the void ratio is plotted versus the vertical effective stress for the two tests. The first loading step ( $\sigma'_v$  increased from 12.5 kPa to 50 kPa) induced a similar small change of void ratio in the two tests. During the percolation under the 50 kPa vertical pressure, the LYGOed1 (with site water) did not show obvious changes of void ratio; by contrast, the LYGOed2 (with deionised water) showed significant soil swelling. After the percolation phase, the unloading from  $\sigma'_v = 50$  kPa (I) to 12.5 kPa (II) did not induce any swelling in LYGOed1, whereas a small swelling (void ratio from 1.04 to 1.05) was identified in LYGOed2. During the loading path from  $\sigma'_v = 12.5$  kPa (II) to 1600 kPa (III), the curve of LYGOed1 showed a bi-linearity and the turning point corresponds to the pre-yield stress, i.e. 50 kPa. By contrast, a compression behaviour with a nonlinear hysteresis loop is identified for LYGOed2. At point III ( $\sigma'_v$  equal to 1600 kPa), the void ratio of LYGOed2 is smaller than that of LYGOed1 (0.548 against 0.580); at point IV ( $\sigma'_v$  equal to 12.5 kPa), the void ratio of LYGOed2 is larger than that of LYGOed1 (0.763 against 0.679). It is concluded that flushing the sample with deionised water increased the compressibility and swelling of soil.

To further analyse the soil behaviour, the compression curves obtained after the saturation phase were used to determine the compressibility parameters such as the compression index ( $C_c$ ), the swelling index ( $C_s$ ) and the oedometer modulus  $E_{Oed}$  that is defined as:  $E_{Oed} = h_i(d\sigma'_v / dh)$ , where  $h_i$  is the initial height of the soil sample and  $dh$  is the height change induced by a vertical stress increment  $d\sigma'_v$ . In this study, the compression index  $C_c$  and the swelling index  $C_s$  were defined as the values at each loading or unloading step because the compression and swelling indexes changed from one step to

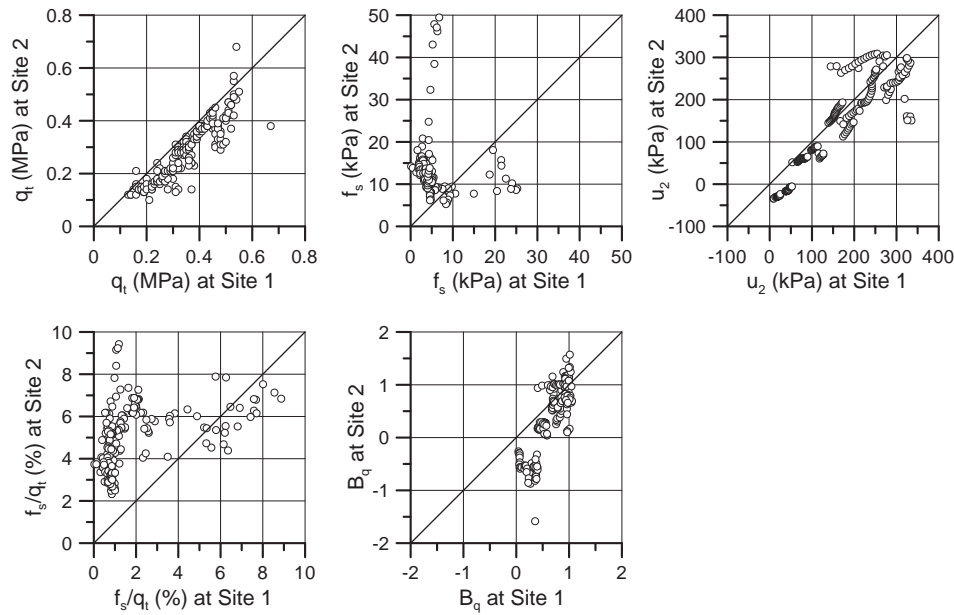


Fig. 6. Comparison of the CPTu parameters between Site 1 and Site 2.

another. This determination method of  $C_v$ ,  $C_s$  and  $E_{Oed}$  was also adopted by Deng et al. (2011a).

The void ratio change over time can be plotted for only one loading step with the data shown in Fig. 7. This curve also allows the

determination of the consolidation coefficient  $C_v$  following the Casagrande's method ( $C_v = 0.197H^2/t_{50}$ , where  $H$  is the drainage length equal to the half of the sample height and  $t_{50}$  is the time required to reach 50% consolidation). Using the expression  $k = C_v \rho_w g / E_{Oed}$ , the hydraulic conductivity  $k$  can be calculated, where  $\rho_w$  is the unit mass of water and  $g$  is the gravitational acceleration. Moreover, the curve can also be used to determine the secondary consolidation coefficient  $C_\alpha$  that corresponds to the slope  $-de/d\log t$  of the line after the primary consolidation.

The compression index, swelling index and oedometer modulus (i.e.,  $C_c$ ,  $C_s$  and  $E_{Oed}$ ) between LYGOed1 and LYGOed2 are compared in Figs. 9 and 10. The points of  $C_c$  or  $C_s$  from LYGOed2 with deionised water lay above those from LYGOed1 with site water, regardless of the loading or unloading paths. On contrary,  $E_{Oed}$  shows a reversed trend, suggesting a weakening effect of deionised water. This effect is more significant during unloading or during loading when the  $\sigma'_v$  is lower than 50 kPa.

The results of  $C_v$  are shown in Fig. 11. It appears that the values of  $C_v$  from LYGOed2 with deionised water are lower than those from LYGOed1 with site water, especially during loading. Fig. 12 shows the hydraulic conductivity  $k$  versus the void ratio. It is observed that before the percolation, the hydraulic conductivity is the same as that with percolation by the site water. After the percolation, the curves of hydraulic conductivity versus void ratio in the coordinates of  $\log k$  and  $e$  for LYGOed1 and LYGOed2 were parallel while that of LYGOed2 with deionised water lay below. In other words, the hydraulic conductivity with site water and deionised water changes the intercept; the value with deionised water is smaller than that with site water, but the slope is almost the same. These results are consistent with those reported by Taylor (1948) and Tavenas et al. (1983) who suggested a slope of  $0.5e_0$ . Thereby, it can be concluded that the slope is not affected by the salinity of pore water if the two samples have the same initial void ratio  $e_0$ . On the other hand, the KC function proposed by Kozeny (1927) and Carman (1956) shows that the hydraulic conductivity at a given void ratio is determined by the samples' SSA (specific surface area), which can be well correlated with the liquid limit. Therefore, Deng et al. (2011b) tried to correlate the hydraulic conductivity, void ratio and  $LL$  of Boom Clay, and concluded that the intercept is a function of  $LL$  in the semi-logarithmic coordinates. Because  $LL$  with deionised water is higher than that with the site water ( $LL$  with deionised water and site water is 54.1% and 50.9%, respectively), it is reasonable that

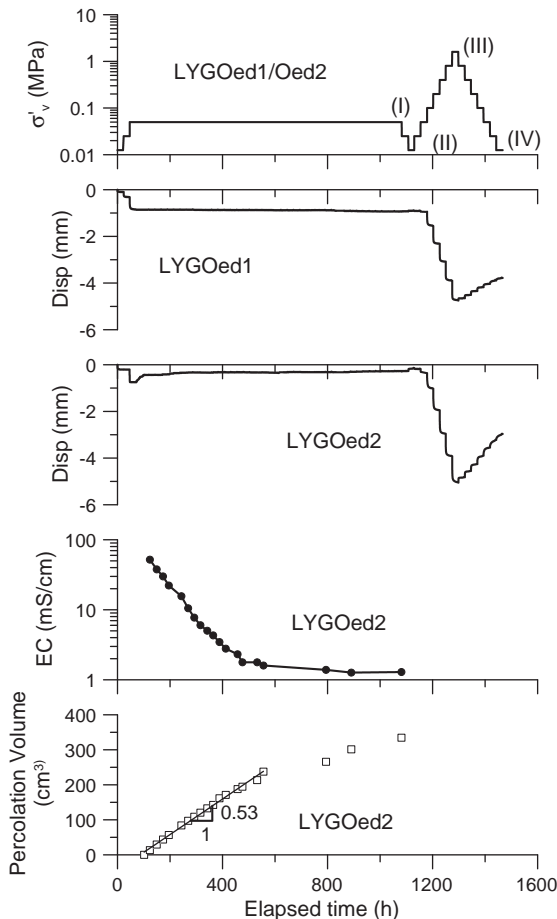


Fig. 7. Results from the percolation and oedometer tests.

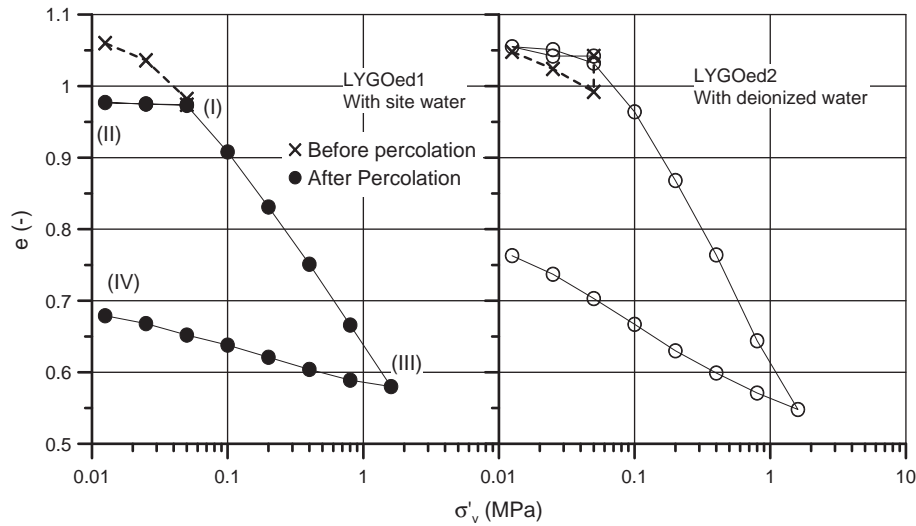


Fig. 8.  $e$ - $\log \sigma'_v$  compression curves.

the line after percolation with deionised water lies below that with the site water.

The comparison of  $C_\alpha$  is presented in Fig. 13. It appears that the value of LYGOed2 with deionised water is greater than that of LYGOed1 with site water, the ratio between them being 1.65 for both loading and unloading paths. These results also suggest a weakening effect and obvious secondary deformation of the deionised water. It is observed that  $C_\alpha/C_c$  ranged from 0.02 to 0.04 during loading and  $C_\alpha/C_s$  ranged from 0.04 to 0.08 during unloading in Fig. 14, indicating that the variation  $C_\alpha/C_s$  is larger than  $C_\alpha/C_c$  for the LYGO marine clay. Furthermore, the  $C_\alpha/C_c$  (or  $C_\alpha/C_s$ ) shows no significant difference between LYGOed1 and LYGOed2.

### 3.4. MIP tests

In order to better understand the effect of the salinity of pore water on the soil behaviour, after the unloading and uninstalling in oedometers, small samples were taken from the two oedometer amples, and were freeze-dried to perform the MIP tests. The MIP results are shown in Fig. 15. It is observed that the pore size of LYGOed1 ranges

from 0.05 to 1.0  $\mu\text{m}$ . The pores of LYGOed2 can be divided into two parts, i.e., the small pore diameter ranging from 0.05 to 1.0  $\mu\text{m}$ , as in the case of LYGOed1, and the larger pore diameter ranging from 5.0 to 50  $\mu\text{m}$ , which is almost absent in LYGOed1. In other words, LYGOed1 has mono-modal pore size distribution, whereas LYGOed2 has bi-modal one. This shows that the percolation with deionised water changed the soil microstructure by creating a large pore family. Noted that despite the large pores existing in the sample with deionized water after releasing the stress, the hydraulic conductivity of this sample is still lower than that with site water (see Fig. 12). This suggests that the hydraulic behaviour is not only controlled by the volume of macro-pores but also by other physical parameters ( $SSA$  or  $LL$ ) according to the KC function or the expression proposed by Deng et al. (2011b) because  $LL$  and  $SSA$  have changed with the type and concentration of pore water salinity (see also Fig. 5).

## 4. Conclusions

In this work, the soft LYGO marine clay was used to study the pore water chemistry effect. Filled characterisation and piezocone tests were performed at two sites: Site 1 with a 4.91% pore water salinity

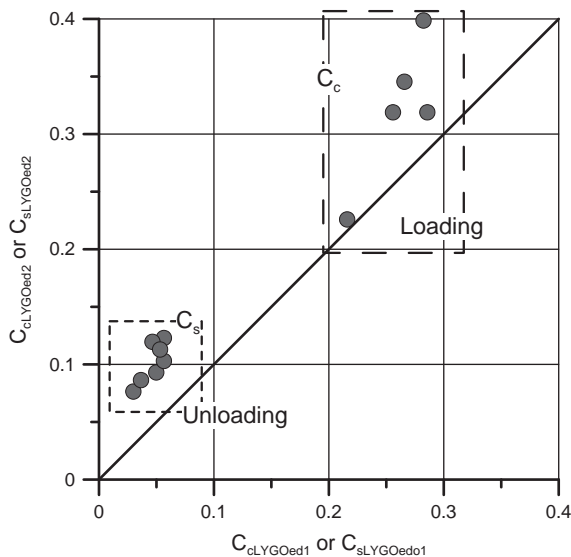


Fig. 9. Comparison of the compression and swelling indexes ( $C_c$  and  $C_s$ ) between LYGOed1 and LYGOed2.

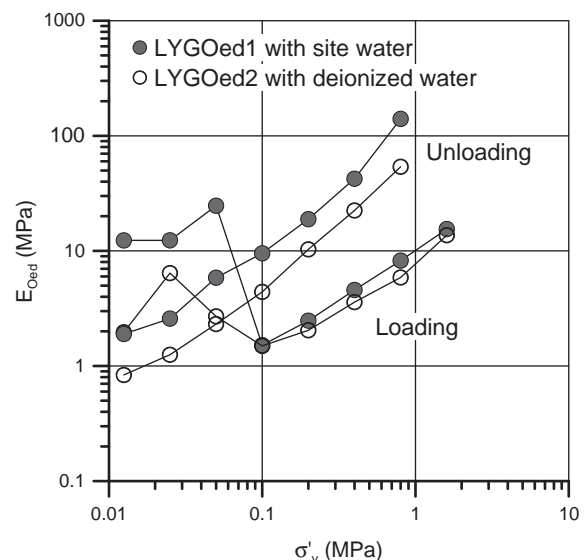


Fig. 10.  $E_{oed}$  versus  $\sigma'_v$  from LYGOed1 and LYGOed2.

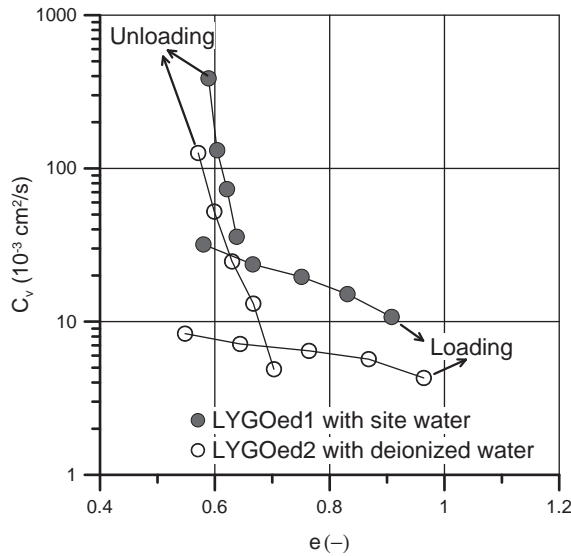


Fig. 11.  $C_v$  versus  $e$  from LYGOed1 and LYGOed2.

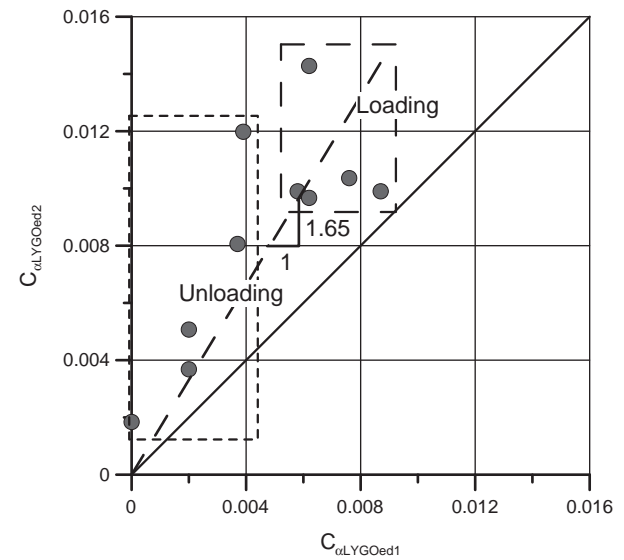


Fig. 13. Comparison of the secondary consolidation coefficient between LYGOed1 and LYGOed2.

and Site 2 with a 0.56% pore water salinity. The pore water effect on soil geotechnical properties was discussed using the plasticity chart with the data on the LYG marine clay and the commercial kaolinite and bentonite mixtures. Oedometer tests with loading and unloading were conducted on soils after percolation by site water or deionized water. The parameters such as the compression index  $C_c$ , swelling index  $C_s$ , oedometer modulus  $E_{Oed}$ , consolidation coefficient  $C_v$ , hydraulic conductivity  $k$  and secondary consolidation coefficient  $C_\alpha$  were then determined. Their values in the case of site water were compared with those in the case of distilled water to reveal the pore water chemistry effect. Microstructure observation was made using the MIP technique to investigate the pore water chemistry effect on the pore size distribution. The results obtained allow the following conclusions to be drawn:

- (1) As the LYG soft marine clay was deposited in the sea regression with the materials from the Ancient Yellow River, the part closer to the sea should be more recently consolidated with same sedimentary materials from loess plateau in the northwest of China and with pore water with a greater salinity. The site

characterisation showed that the clay closer to the sea is of lower  $w$ ,  $LL$ , and  $e_0$  but higher  $\gamma$ .

- (2) The identification test on the kaolinite and bentonite mixtures showed that the bentonite was affected by the pore water chemistry but the kaolinite was not. The  $LL$  of bentonite decreased with the concentration of salt but that of kaolinite increased slightly. In addition, the  $LL$  was more sensitive to changes in pore water chemistry than  $PL$ . On the whole, the results on the mixtures and the LYG marine clay suggest a significant pore water chemistry effect on the soil geotechnical properties.
- (3) The *in situ* CPTu results showed that the pore water salinity affected the hydro-mechanical behaviour of the soft marine clays: a higher net tip resistance  $q_t$  and pore pressure parameter  $B_q$ , and a lower sleeve friction  $f_s$  were identified in the case of higher salinity. In other words, a clay with a higher salinity behaves more as a silt.

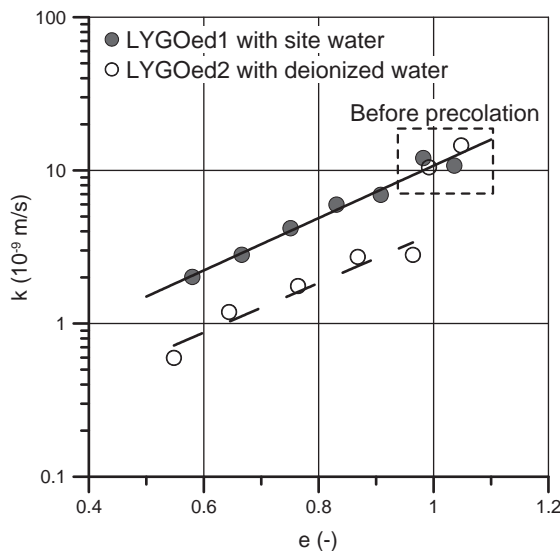


Fig. 12.  $k$  versus  $e$  from LYGOed1 and LYGOed2.

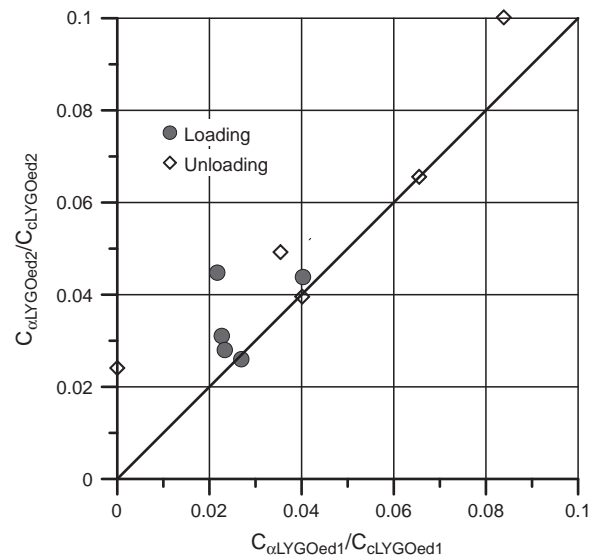


Fig. 14. Comparison of  $C_\alpha/C_c$  between LYGOed1 and LYGOed2.



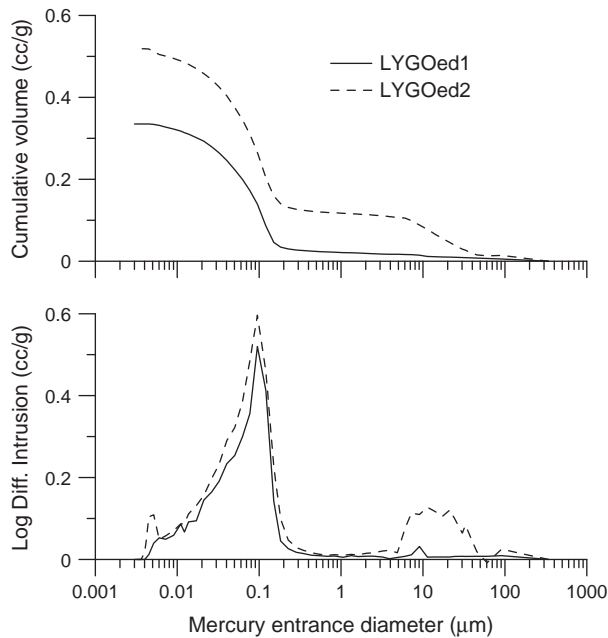


Fig. 15. MIP results on samples of LYGOed1 and LYGOed2.

- (4) With deionised water percolation, a slight swelling was identified, whereas with the site water, swelling was absent and only secondary consolidation. Parameters  $C_c$ ,  $C_s$ ,  $E_{Oed}$ ,  $C_v$  and  $k$  were greater in the case of site water as compared with deionised water, whereas parameter  $C_\alpha$  showed an opposite trend. Despite the large pores existing in the sample with deionized water, the hydraulic conductivity of this sample is still lower than that with site water, suggesting that the hydraulic behaviour is not only controlled by the pore size distribution but also by other physical parameters ( $SSA$  or  $LL$ ).

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