



Shear displacements induced by decrease in pore solution concentration on a pre-existing slip surface



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ABSTRACT

This paper reports on experimental results that show how variations in pore fluid composition can induce time dependent shear displacements in clay soils under constant effective stresses. The experimentation has been carried out on a bentonite, mainly composed of Na-montmorillonite. The clay, reconstituted with distilled water and with NaCl solutions at various concentrations, was first sheared to the residual state under constant displacement rate. The residual friction angle was found to increase greatly with the pore solution concentration. Then, the solution-saturated specimens were submitted to shear tests under constant driving shear stresses lower than the residual strength obtained with the salt solutions and higher than the residual strength obtained with distilled water. As a consequence, shear displacements with decreasing rate occurred. On the subsequent exposure to distilled water, the displacement rate increased progressively and the specimens re-experimented failure. The observed behaviour has been attributed to the loss of strength caused by the decrease in pore solution concentration following exposure to water. During this transient phase, shear strength and average pore ion concentration on the slip surface seemed to be related by the same relation as that evaluated in the absence of chemical gradients.

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1. Introduction

Chemical changes, such as the decrease in pore solution concentration, can cause loss of strength in clay soils, as shown by many authors, among whom: Bjerrum and Rosenqvist (1956), Kenney (1967), Mesri and Olson (1970), Sridharan (1991), Moore (1991), Di Maio (1996a), Anson and Hawkins (1998). The decrease in pore solution concentration can occur because of several different processes in different types of soils. The leaching of Quick Clays is a well known process, deeply investigated since the mid-1950s (e.g. Bjerrum, 1954; Rosenqvist, 1955). Noticeable variation with depth of pore solution concentration in these clays and its effects on remoulded strength are reported among others by Geertsema and Torrance (2005). In Cretaceous marls of the Southern coast of England, Moore and Brunnsden (1996) recorded fluctuations in groundwater salinity at a mudslide toe due to the seasonal deposition of sea-spray and salts, and observed low pore solution concentrations before seasonal reactivation or periods of high activity of the landslide. In several Tertiary Mudstone landslides of coastal areas in Japan, Tiwari and Ajmera (2015) also verified the reduction in fully softened shear strength due to NaCl leaching. Zhang et al. (2009) and Zhang et al. (2013) reported evidences that the desalinization caused by irrigation influenced the

initiation and movements of a number of landslides in the Chinese Loess Plateau. Di Maio et al. (2015), studying deep earthflows in Cretaceous–Miocene clayey–marly soils of marine origin, in Southern Italy, found that the concentration of the natural pore solution decreases gradually from the depth to the ground surface (Fig. 1). The authors discussed the possibility that such a decrease could be a “hidden” cause of the landslide viscous displacements. In order to verify the hypothesis, a study was undertaken of which the work here presented is a part.

This paper analyses the effect of a decrease in the pore solution concentration on the shear displacements of a clay element submitted to constant external normal and shear forces.

A bentonite, mainly constituted of Na-montmorillonite, was chosen as test soil because, among the different types of clays, it exhibits the largest sensitivity to pore fluid composition. NaCl solutions were used as pore fluids because NaCl is the main dissolved salt in sea water, and thus its effects are of practical and direct interest for the marine origin soils. Furthermore, it allows to minimise ion exchange processes when used with Na-clays (Di Maio, 1998). The shear test under constant shear forces were performed on specimens pre-sheared to the residual condition, in order to have a deeper insight in the viscous behaviour of active landslides which have undergone large displacements on a regular slip surface (Di Maio et al., 2013). On the other hand, the residual state is the ideal condition to evaluate the role of chemical changes on clay behaviour. It can be in fact considered a “steady state” in which the soil is supposed to slip continuously, at constant volume and structure, under constant average normal and tangential interparticle forces.

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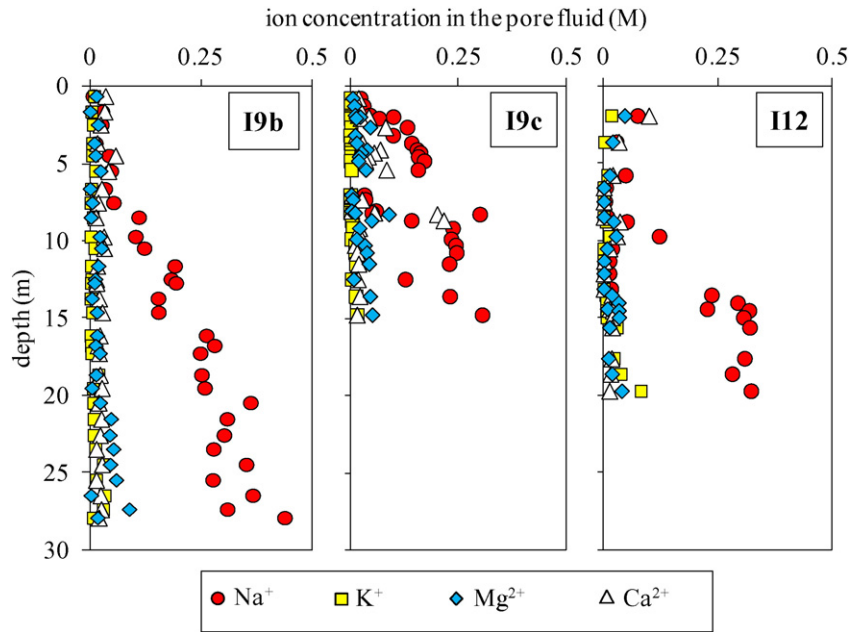


Fig. 1. Molarity of the main cations in the pore solution of the material extracted from three boreholes of the Costa della Gaveta landslide (Di Maio et al., 2015).

2. Material

The experiments were carried out on specimens of a commercial bentonite (provided by Laviosa Srl) reconstituted with distilled water and salt solutions at various concentrations. Some properties of the material are reported in Table 1. The clay fraction is mainly composed of Na-montmorillonite, as shown by X-ray powder diffraction analysis, using $\text{CuK}\alpha$ radiation. The liquid limit was evaluated with distilled water and also by mixing the powdered clay with solutions at various concentrations of NaCl, KCl, CaCl_2 and MgCl_2 . Fig. 2a shows that w_L decreases dramatically with increasing pore solution concentration. For any of the used solutions, most variations occur in the range 0–1 M, in which noticeable variations in residual strength and osmotic deformation of smectitic soils can occur (Di Maio, 1996a, 1996b). Fig. 2a also shows that the plastic limit evaluated with NaCl solutions is only slightly influenced by the salt concentration.

3. Methods and results

Shear tests were carried out under constant displacement rate to evaluate the residual shear strength, and under constant shear stresses to observe the creep behaviour and the displacement evolution chemically induced. The Casagrande direct shear, the Bishop and the Bromhead ring shear apparatuses were used. For the creep tests, the first two devices were modified by inserting pulleys to convert vertical forces, applied by means of dead loads, into horizontal forces acting on the upper box or ring respectively (Di Maio et al., 2015). In the ring shear apparatus the shearing area does not change during the test, thus constant forces correspond to constant average shear stresses. On the contrary, small variations of the shearing area, which have been accounted for in the test interpretation, occur in the Casagrande direct shear apparatus.

The tests were performed on specimens prepared by mixing the powdered clay with distilled water or with NaCl solutions, mostly at a concentration of 1 M, but also with other different concentrations. All the specimens were reconstituted at about the liquid limit corresponding to the used fluid, consolidated in oedometric conditions to given normal stresses while immersed in a fluid equal to the pore one, and then submitted to shear tests. Their initial conditions in terms of void ratio e against normal effective stress σ'_n are shown in Fig. 2b. The figure reports the results of oedometer tests, which were carried out on the same material to determine the hydraulic conductivity. Values of k in the order of 10^{-10} m/s were evaluated for the material in the solution.

Each shear test consisted of three phases: 1) shearing under constant displacement rate until the residual conditions; 2) shearing under constant shear stresses or forces without chemical gradient for about two weeks, and then with exposure of solution-saturated specimens to distilled water; and 3) shearing under constant displacement rate again, with continued exposure to distilled water. The exposure was performed by simply substituting distilled water to the cell solution and by renewing it twice a day to remove the ions which could have diffused from the specimen. Electrical conductivity and temperature of the cell fluid were monitored and its chemical composition was also analysed.

3.1. First phase: controlled displacement rate

In the first phase, the specimens were sheared under a constant displacement rate, $v = 5 \mu\text{m}/\text{min}$, until the residual strength was obtained. The tests were often interrupted and the specimens were cut manually in order to ensure the flatness of the shear surface. To avoid chemical gradients in this phase, the cell fluid in which the specimens were submerged was maintained equal to the pore fluid.

The results are not influenced by the type of apparatus (Figs 3 and 4) but are strongly influenced by pore solution concentration. In a plot

Table 1

Specific weight G_s , liquid limit w_L and plastic limit w_P determined in distilled water and in 1 M NaCl solution, clay fraction c.f. and specific surface A_s of the tested bentonite.

G_s	w_L (%) in distilled water	w_L (%) in 1 M NaCl solution	w_P (%) in distilled water	w_P (%) in 1 M NaCl solution	c.f. (%)	A_s (m^2/g)
2.75	324	116	45	37	80	500

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