SOME NEW INSIGHTS INTO SWELLING AND SWELLING PRESSURE OF LOW ACTIVE CLAY

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Abstract

This paper presents a multidimensional chemo-mechanical model for saturated clay treated as a two-phase deformable and chemically reactive porous medium. The constitutive relation is an extension of the original chemo-mechanical model proposed by Gajo et al. (2002) and Loret et al. (2002), in which a q-p formulation was proposed with a Cam-Clay-like elastic response. A novel hyper-elastic law is proposed in which shear stiffness and bulk stiffness change with stress state and ion concentration in pore solution. The proposed constitutive model and the associated coupled finite element formulation are implemented in a 2D, commercial, finite element code (ABAQUS) in the form of user-defined external subroutines. The proposed framework is used to simulate the oedometer tests performed on a low activity clay extracted from Costa della Gaveta slope. The computed chemo-mechanical behaviour of the material prepared with distilled water is compared with the experimental results obtained from reconstituted specimens. Moreover, swelling and swelling pressure are computed for the overconsolidated material reconstituted with 1 M NaCl solution and then exposed to distilled water. The comparison of simulations and experiments shows a good agreement.

Keywords: low active clay, experimental test, model simulation, FEM, swelling, swelling pressure

1. Introduction

The chemical composition of pore water has a significant effect on the mechanical behaviour of clays and clayey soils (Di Maio 1996, Di Maio et al. 2004, Musso et al. 2017). In particular, the increase of salinity of pore water leads to an increase in shear strength and to changes in volume (decrease or increase) which depend on the type of soil, its activity, fabric, void ratio and stress level (Di Maio and Fenelli, 1997; Di Maio et al., 2004). The volume change of soils causes many problems to engineering structures and infrastructures, and can also influence deformations and displacements in landslides (Ghalamzan et al. 2021). When swelling is restrained, the consequent swelling pressure causes damages to engineering structures such as foundations, retaining structures, tunnels. The effects of chemical interactions on the mechanical behaviour of soil have been analysed in several experimental and numerical works (Di Maio 1996, Gajo and Loret 2003, Witteveen et al. 2013). In these studies, chemical effects have been considered mainly on the volume change of soil. Di Maio (2001) analysed the effect - on both swelling and swelling pressure - of the composition of the pore fluid and of the fluid with which the soil comes in contact. Recently, Ghalamzan et al. (2021) proposed an improvement of the constitutive model originally proposed by Loret et al. (2002) and Gajo et al. (2003) which consists of a new hyperelastic formulation taking into account the applied stress state and pore solution concentration on both shear and bulk stiffness. Moreover, a two dimensional rectangular FEM element is formulated and implemented in a user-defined subroutine of ABAQUS. In this FEM element, diffusion of ions and transfer of water between solid and fluid phases have been considered in addition to solid deformation and water flow. The proposed framework can simulate the chemo-mechanical effects within a coupled formulation.

The validation of the model has been obtained through the comparison with the results of oedometer tests on a low activity clay soil from a landslide in tectonized clay shale of *Costa della Gaveta* slope (Potenza, Southern Italy). In the first set of tests, the compression-swelling behaviour has been evaluated by mechanical loading/unloading applied to specimens reconstituted with, and immersed in, distilled water. The second set of tests was carried out on specimens reconstituted with 1 M NaCl loaded and then unloaded to given axial stresses while in contact with the same solution. At equilibrium, the specimens were exposed to distilled water. The exposure caused a tendency to volume increase: swelling was permitted in some tests and it was prevented in others. The tests were simulated with the proposed model. The comparison of the model simulations with experimental results shows a good agreement, thus proving model reliability.

2. Methodology

Saturated clay is treated as a two-phase deformable porous medium, namely the solid phase and fluid phase. The solid phase consists of clay particles, absorbed/adsorbed water and adsorbed salt, whereas the fluid phase consists of pore water and dissolved salt. It is assumed that the clay clusters are surrounded by a semipermeable membrane that is impermeable to clay particles, while water and ion may transfer between the solid and fluid phases. In this study, in particular, due to the assumption of electroneutrality and of a single ion, only water may transfer between the solid and fluid phases. Thus the mass of clay particles and absorbed ions remains constant. The balance equations that have been considered are 1) the momentum balance equation of the whole porous medium; 2) the mass balance equation of the pore fluid; 3) the mass balance equation of the salt dissolved in the pore fluid. Besides, we have considered the mass transfer equation ruling the adsorption/desorption of adsorbed water (i.e. the water exchanged across the fictitious membrane surrounding the clay particles). In this way, most of the microscopic phenomena acting at the clay particle level are mimed at the macroscopic level. For the flux of ions in pore water, both advective and diffusive fluxes have been considered. In addition, the osmotic flows of water and salt have been considered. The fluxes of species are obtained from Clausius-Duhem inequalities introducing a generalized diffusion matrix depending on the hydraulic conductivity, on the osmotic efficiency and the effective diffusion of the salt which have been explained in detail by Gajo et al. (2003).

These equations are discretized in space through the standard approaches of the FEM method, selecting as primary unknowns the solid displacements u, the fluid pressure p_w, the salt concentration c_{sW} in pore water and the mass of adsorbed water m_{wS}. Time integration is performed using a generalized midpoint algorithm and a Newton-Rapson scheme is used for the solution of the resulting set of non-linear algebraic equations. SUPG stabilization scheme has been employed for the advective terms. A 2-dimensional plane strain rectangular element has been implemented in a user-defined, external subroutine UEL of ABAQUS (Hibbitt et al. 2009). This element has 8 nodes. The degrees of freedom at the corner nodes are the displacements of the solid skeleton along x and y directions, the pore pressure, the salt concentration in pore fluid and the mass of absorbed water. The degrees of freedom of the nodes at the middle of the element sides are the displacements of the solid skeleton along x and y directions.

Several constitutive relations have been proposed to take into account the change of mechanical behaviour with the chemical composition of pore water (Kaczmarek and Hueckel 1998, Dominijanni et al. 2013). Loret et al. (2002) have considered the results of the oedometer test of an active clay (Na-Montmorillonite) with no cation exchange by Di Maio (1996) and proposed a chemo-mechanical elasticity law derived from the Cam-Clay model. Starting from this model and taking inspiration from the elastic energy proposed by Gajo and Bigoni (2008) and Gajo (2010), we propose a new elasticity law in the form of a polynomial expression as:

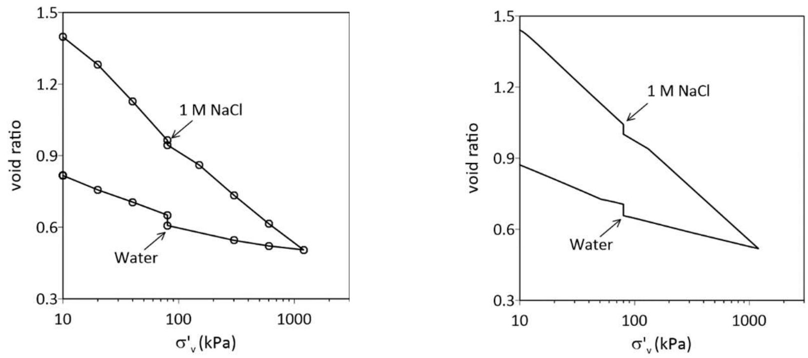
$$\psi = \sum_i A_i \left[(trC + \varepsilon_s)^i + \xi_i \left(trC_D^2 + \frac{(trC+\varepsilon_s)^2}{3} \right)^{\frac{i}{2}} \right] + F \qquad (1)$$

Where $C = B\varepsilon^e$, C_D is the deviatoric part of C, B is a fabric tensor (with $trB^2 = 3$) that introduces an anisotropic elastic response, whereas for B=I the elastic response is nearly isotropic. Finally, A_i, ε_s are suitable functions of ε^e and m^e_{wS}, whereas ξ_i are functions of Poisson's ratio. F is the chemical part of the elastic energy depending on m^e_{wS} (Loret et al. 2002). In this expression, both bulk and shear modulus change with salt concentration and stress state. Moreover, the elastic anisotropy has been accounted for through the fabric tensor B.

3. Results of the simulation

In the oedometer tests, the mechanical loading/unloading are induced by an increase or a decrease of vertical stresses while the chemical loading and unloading are applied by exposing the specimens to fluids different from the pore fluid. The proposed 2D element has been used to simulate the experimental oedometer test with chemo-mechanical loading/unloading.

Figure 1 shows the comparison of the measured and simulated chemo-mechanical compression and swelling behaviour of a sample prepared with distilled water. In this test, the specimen is normally consolidated by steps to 80 kPa. Then the specimen is put in contact with a 1 mol NaCl solution, thus causing the chemical consolidation of the sample which can be seen as a drop of void ratio at constant Terzaghi's effective stresses. Then the mechanical loading is resumed by increasing the vertical stress up to 1200 kPa and then unloading to 80 kPa. When mechanical swelling has been completed, the specimen is exposed to distilled water, thus inducing chemical swelling. As shown in Fig. 1, the agreement between simulation and experiment is good.



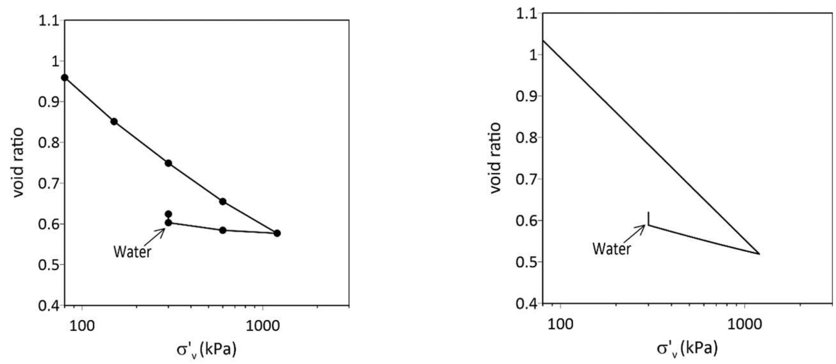
(a) *(b)*

Fig 1. Chemo-mechanical compression and swelling behaviour of a specimen reconstituted with distilled water: a) experiment, b) simulation (Ghalamzan et al. 2021).

In the considered oedometer tests, the deformation of the sample is free in the vertical direction and is constrained laterally. Swelling pressure during exposure to distilled water has thus been evaluated by preventing the vertical displacement of the specimen.

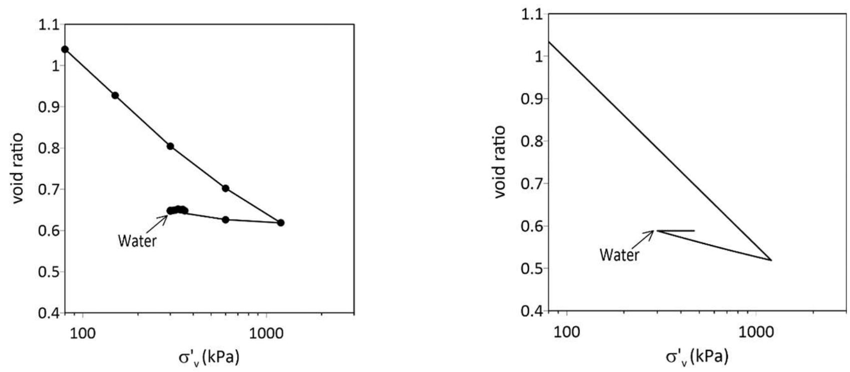
Figure 2 shows the comparison of the numerical and experimental results of swelling displacement of an overconsolidated sample reconstituted with 1 molar NaCl solution. In this test, the sample was prepared with 1 molar NaCl solution, the vertical stress was increased to 1200 kPa and then decreased to 300 kPa. Then the sample was exposed to distilled water which causes the chemical swelling of the sample under constant vertical stress. It can be observed that the computed swelling displacement is very similar to the measured one.

Figure 3 shows the computed and measured swelling pressure of an overconsolidated sample with vertical stress equal to 300 kPa. In this test, the sample prepared with 1 molar solution was loaded to 1200 kPa and unloaded to 300 kPa. After mechanical swelling was finished, the pore solution has been substituted with distilled water while the vertical swelling of the sample has been constrained in order to evaluate the swelling pressure.



(a) *(b)*

Fig 2. Swelling of an overconsolidated specimen reconstituted with 1 M NaCl solution, loaded, unloaded, and then exposed to distilled water at 300 kPa; a) experiment, b) simulation (Ghalamzan et al. 2021).



(a) *(b)*

Fig 3. Swelling pressure of an overconsolidated specimen prepared with 1 M NaCl solution and exposed to distilled water under vertical stress equal to 300 kPa: a) experiment, b) simulation (Ghalamzan et al. 2021).

3.1 Time evolution of vertical swelling and swelling pressure

The swelling and swelling pressure have been monitored during the time of exposure to distilled water. Figure 4 shows the comparison between measured and simulated swelling displacements due to exposure to distilled water vs. time, under a constant vertical stress of 300 kPa. It can be observed that the overall process of swelling is correctly simulated.

Figure 5 shows the swelling pressure induced by exposure of the sample to distilled water while the vertical displacement of the sample has been constrained. The experimental results are compared with model simulation. Although the overall time evolution has been simulated correctly, the simulated amount of swelling pressure is larger than the measured one. Ghalamzan et al. (2021) have shown that the simulations can be improved by employing the elastic anisotropy through the fabric tensor B.

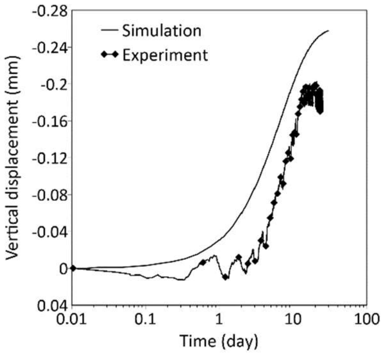


Fig 4. Time evolution of swelling of an overconsolidated sample with vertical stress equal to 300 kPa during exposure to distilled water (Ghalamzan et al. 2021).

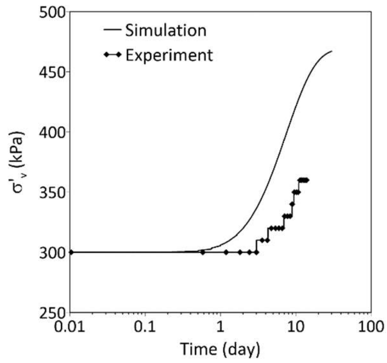


Fig 5. Time evolution of swelling pressure of an overconsolidated specimen with vertical stress equal to 300 kPa during exposure to distilled water (Ghalamzan et al. 2021).

3.2 Time evolution of ion removal

Time evolution of ion removal from the whole sample has been measured and computed during exposure of the sample to distilled water. The amount of removed ion has been measured and computed based on the pore volume of the sample and porous stone at the beginning of the exposure to distilled water. Figures 6 and 7 show the comparison of the amount of removed ion during the swelling and swelling pressure test, respectively, for two overconsolidated specimens starting from vertical stress equal to 300 kPa. It can be observed that the simulated ion removal is faster at the beginning of the exposure and it slows down over the time of swelling. In both tests, the measured ion removal is faster than the simulated one. Anyway the total computed amount of ion at the end of exposure to distilled water is similar to the measured one.

4. Conclusion

A 2D chemo-mechanical model and a new hyper-elastic law have been proposed to simulate the swelling and swelling pressure due to exposure to distilled water of a low activity clay reconstituted with 1M NaCl solution. The elasticity law is an improvement of the chemo-mechanical model proposed by Gajo et al. (2003) and Loret et al. (2002). The simulation of oedometer tests has been performed for the low activity component of the clayey soil of Costa della Gaveta slope and were compared with the experimental results. The comparison shows that model simulations agree well with the experiments for both swelling and swelling pressure.

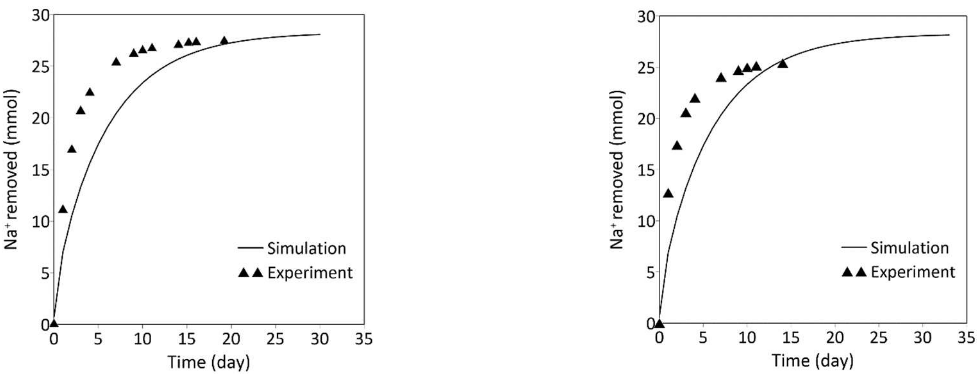


Fig 6. Time evolution of removed Na^+ during exposure to distilled water, at 300 kPa initial vertical stress, of overconsolidated specimens reconstituted with 1 M NaCl solution: a) swelling test, b) swelling pressure test (Ghalamzan et al. 2021).

Acknowledgments

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