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Swelling and swelling pressure of a low activity clay soil: model simulations and experimental results

Gonflement et pression de gonflement d'un sol argileux de faible activité : simulations sur modèle et résultats expérimentaux

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ABSTRACT: Chemo-mechanical effects in soils and rocks are known to be important in a number of engineering applications ranging from slope stability analysis to soil improvement. The chemical interactions in active clays affect both the plastic and the elastic response thus an extended elasticity law is needed in constitutive modelling. This work is based on 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 fully multiaxial formulation is proposed, based on a novel hyper-elastic law, in which shear stiffness and bulk stiffness depend on the applied stress state and ion concentration in pore solution. Both bulk stiffness and shear stiffness increase linearly with the increase of mean effective pressure and are affected by ion concentration. The proposed constitutive model and the associated coupled finite elements are implemented in a 2D, commercial, finite element code (ABAQUS) in the form of user-defined external subroutines. The model is used to simulate the results of oedometer tests in which a low active clay, reconstituted with a 1 molar NaCl solution, was exposed to distilled water, thus causing tendency to swell; in a series of tests, swelling was permitted and, in another series, it was prevented, inducing the development of swelling pressure.

RÉSUMÉ: Les effets chimio-mécaniques dans les sols et les roches sont connus pour être importants dans un certain nombre d'applications d'ingénierie allant de l'évaluation de la stabilité des pentes à l'amélioration des sols. Les interactions chimiques dans les argiles actives affectent à la fois la réponse plastique et élastique, donc une loi d'élasticité étendue est nécessaire. Ce travail est basé sur le modèle chimio-mécanique original proposé par Gajo et al. (2002) et Loret et al. (2002), dans laquelle une formulation q-p a été proposée avec une réponse élastique de type Cam-Clay. Dans ce travail, une formulation entièrement multiaxiale est proposée, basée sur une nouvelle loi hyper-élastique, dans laquelle la rigidité au cisaillement et la rigidité apparente dépendent de l'état de contrainte appliqué et de la concentration en sel dans l'eau interstitielle. Ainsi, à la fois la rigidité apparente et la rigidité au cisaillement augmentent linéairement avec l'augmentation de la pression moyenne et sont affectées par la concentration en sel. Le modèle constitutif proposé et les éléments finis couplés associés sont implémentés dans un code 2D, commercial, d'éléments finis (ABAQUS) sous la forme de sous-programmes externes définis par l'utilisateur. Les simulations de modèles sont comparées aux résultats d'essais oedomètres dans lesquels une argile active a été exposée à de l'eau distillée à une contrainte verticale constante (pour mesurer le gonflement) et à une contrainte de volume constant (pour mesurer la pression de gonflement).

KEYWORDS: low activity clay, chemo-mechanical interaction, experiment, FEM, simulation

1 INTRODUCTION

Particular characteristics of clays, such as low permeability, make their use appropriate for engineering applications such as barrier for water flow and contaminant transport for waste disposal. On the other hand, soil with high clay contents may cause damage to engineering structures because of the volume variations induced by changes in the applied mechanical loads or changes in the pore fluid composition. The effects of the latter changes on the mechanical behaviour of clay soils have been investigated in several experimental works (e.g., Di Maio 1996, Di Maio et al. 2004, Witteveen et al. 2013, Manca et al. 2016, Dutta and Mishra 2016, Musso et al. 2017). In particular, it has been shown that the increase in ion concentration of the pore water in a clay system with a high fraction of montmorillonite, leads to a large volume decrease and strength increase. The volume decrease is known as chemical consolidation, and the increase in ion concentration is considered a chemical loading. On contrary, when the ion concentration of pore water decreases - for instance as an effect of exposure to distilled water - the soil volume increases. This phenomenon is denoted as chemical swelling, and it can be considered as a chemical unloading. In order to prevent swelling, a pressure must be applied; this latter, defined as swelling pressure (Di Maio 2001), plays an important role in many engineering problems such as, for instance, in the

design and construction of tunnels. Several models have been proposed to consider the effect of pore solution composition on the mechanical behaviour of clay soils (Kaczmarek and Hueckel 1998, Loret et al. 2002, Gajo and Loret 2003). In these studies, chemical effects have been considered mainly on the volumetric response and an isotropic soil behaviour has been assumed. Moreover, FEM analyses were limited to 1D problems.

This paper proposes an improvement of the constitutive model by Loret et al. (2002) and Gajo et al. (2002) which consists in 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 mass transfer between solid and fluid phase have been considered in addition to solid strains and water flow. The proposed framework can simulate the chemo-mechanical effects within a coupled formulation.

The model has been validated by experimental data obtained with oedometer tests carried out on a low activity clay soil of a landslide in a tectonized clay shale of the southern Italian Apennines (Ghalamzan et al. 2021) reconstituted with a concentrated salt solution, and then exposed to distilled water. Several specimens were tested; chemically induced swelling was allowed in some specimens and prevented in others, thus

inducing the onset of swelling pressure. The comparison of experimental results with the model simulations shows a good agreement and thus demonstrates the accuracy and reliability of the proposed model.

2 MODEL DESCRIPTION

Saturated clay is a deformable porous medium consisting of two phases, namely the solid phase (S) and fluid phase (W). Each phase is a mixture of different substances. The solid phase consists of clay particles (c), absorbed/adsorbed water (w) and salt (s) and the fluid phase has pore water (w) and dissolved salt (s). A semipermeable membrane is assumed to surround the clay clusters. This membrane is impermeable to clay particles, while it is permeable to water and adsorbed ions (imperfect membrane). Under isothermal condition and assuming that membrane is permeable to water only, the differential of free energy per unit initial volume of the porous medium is (Haase 1990):

$$\delta\Psi = \sigma_{ij}\delta\varepsilon_{ij} + \mu_{wS}\delta m_{wS} + \sum_{k \in W} \mu_{kW}\delta m_{kW} \quad (1)$$

where σ_{ij} denotes the total stress, $\delta\varepsilon_{ij}$ is the strain increment, μ_{kS} and μ_{kW} are the chemical potential of species k in the solid phase and fluid phase, respectively which are mass-based. δm_{kS} and δm_{kW} are the variations of the mass of the species k in the solid phase and fluid phase respectively. The free energy is equivalent to the strain energy and it is needed to formulate the constitutive equations.

3 CONSTITUTIVE EQUATION

Since the chemistry of water does not have a direct effect on the mechanical behaviour of the solid skeleton, the elastic energy of the solid skeleton shall be considered equal to the difference between the total energy ($\delta\Psi - \delta\Psi_W = \delta U$) and the energy of the fluid phase. Thus, the elastic energy of the solid phase is (Loret et al. 2002):

$$\delta U = \sigma_{ij}\delta\varepsilon_{ij} + \mu_{wS}\delta m_{wS} + p_W\delta v_W \quad (2)$$

The species are assumed incompressible; thus, a relation has been defined between the volume change of the fluid phase (δv_W) the volume strain increment of the solid phase ($\delta tr\varepsilon$) and the mass change of adsorbed water ($\frac{\delta m_{wS}}{\rho_{wS}}$):

$$\delta v_W = \delta tr\varepsilon - \frac{\delta m_{wS}}{\rho_{wS}} \quad (3)$$

Inserting this definition in Eq. 2 leads to the following:

$$\delta U = \sigma'\delta\varepsilon + \mu'_{wS}\delta m_{wS} \quad (4)$$

where $\sigma' = \sigma + p_W I$ is Terzaghi's effective stress and $\mu'_{wS} = \mu_{wS} - p_W/\rho_{wS}$ is defined as effective chemical potential. The effective chemical potentials of species in the solid phase, that can transfer across the semipermeable membrane must be equal to the chemical potentials of the same species in the fluid phase ($\mu'_{wS} = \mu'_{wW}$). The density of water is assumed to remain unchanged ($\rho_{wW} = \rho_{wS}$).

3.1 Elasticity law

Cam-Clay model is the first proposed and most widely used elastic-plastic constitutive model to simulate the mechanical behaviour of clays. This model assumes that bulk stiffness changes with mean stress and there is a logarithmic relation between mean stress and volume change. On the other hand, experimental results have shown that the volume of clay changes with the salinity of pore water (Bolt 1956, Di Maio 1996). Under

constant mean stress, the volume of clay decreases with increasing the salt concentration while it increases with decreasing the salt concentration. It has been observed that the slope of the compression line and swelling line in the e-log(p) plot decreases when the clay is exposed to the salt solution. 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 here a new elasticity law in the form of a polynomial expression as follows

$$\psi = \sum_i A_i \left[(trC + \varepsilon_s)^i + \xi_i \left(trC_D^2 + \frac{(trC + \varepsilon_s)^2}{3} \right)^{\frac{i}{2}} \right] + F \quad (5)$$

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_{wS}^e , whereas ξ_i are functions of Poisson's ratio. F is the chemical part of the elastic energy depending on m_{wS}^e (Loret et al. 2002).

The elastic constitutive relation can be obtained through derivation of the elastic energy in Eq. (6) concerning the strain-like variables, namely the strain of the solid skeleton and the adsorbed mass of water. Thus:

$$\sigma' = \frac{\partial U}{\partial \varepsilon} \quad \text{and} \quad \mu'_{wS} = \frac{\partial U}{\partial m_{wS}} \quad (6)$$

3.2 The irreversible behaviour

The elastoplastic response is derived from Cam Clay yield function through a simple modification proposed by Madaschi (2019), as follows

$$F(p', q, \bar{\mu}_{wS}, tr\varepsilon^{pl}) = M^2 g^2(\tilde{p}^2 - \tilde{p}p_c) + q^2 \quad (7)$$

Where $q = (3J_2)^{1/2}$ and J_2 is the second invariant of the deviatoric effective stress tensor, $M = M(\bar{\mu}_{wS})$ is the slope of the critical state line (depending on the mass of adsorbed water), $p_c = p_c(\bar{\mu}_{wS}, tr\varepsilon^{pl})$ is the preconsolidation pressure (Loret et al. 2002) and $g = g(\theta)$ is a function of the Lode angle of the effective stress tensor defining the deviatoric section of the yield function (Argyris et al. 1974) and

$$\tilde{p} = \begin{cases} p' & p' \geq p_c/2 \\ \frac{p_c}{e^{\alpha-1}} \left(\exp \left[\frac{2p'}{p_c} \log \left[\frac{e^{\alpha}+1}{2} \right] \right] - 1 \right) & p' \leq p_c/2 \end{cases} \quad (8)$$

An associated flow rule is considered, thus G=F. Where $p' = -\frac{tr\sigma'}{3}$ is the mean effective pressure.

4 BALANCE EQUATIONS

The balance of momentum is written for the porous medium with gravity as body force:

$$\nabla\sigma + \rho g = 0 \quad (9)$$

where ρ is the density of the porous medium. Mass balance is written for each species in the solid and fluid phase. It is assumed that the mass of clay and adsorbed salt in the solid phase remain constant. Thus, the mass balance equation is needed for water

and salt in the fluid phase and absorbed water in the solid phase. For incompressible species, the change of volume of the solid skeleton (i.e. the porous medium) must be equal and opposite to the volume change of fluid, namely

$$\text{tr}\left(\frac{\delta \varepsilon}{\delta t}\right) + \nabla J_W = 0 \quad (10)$$

where $\frac{\delta \varepsilon}{\delta t}$ is the time derivative of the strain tensor and J_W is the volume flux of the fluid phase through the porous skeleton.

Considering the incompressibility assumption, the mass balance for the salt in the fluid phase can be expressed in terms of volumes and takes account of the deformation of the solid skeleton and the volume of water exchanged across the fictitious membrane as:

$$n_W \frac{\delta c_{sW}}{\delta t} + c_{sW} \text{tr}\left(\frac{\delta \varepsilon}{\delta t}\right) + \nabla J_{sW} - \frac{c_{sW}}{\rho_w} \frac{\delta m_{ws}}{\delta t} = 0 \quad (11)$$

Where c_{sW} is the salt concentration expressed in terms of volume of salt per unit volume of solution, ρ_w is the density of adsorbed water (assumed equal to 1000 kg/m³, for the sake of simplicity) and J_{sW} is the sum of the diffusive flux and advective flux.

The adsorption/desorption equation of water across the semipermeable membrane depends on the difference in the chemical potentials of adsorbed water and free water and is postulated in the following format:

$$\frac{\delta m_{ws}}{\delta t} = k^t (\mu_{wW} - \mu_{wS}) \quad (12)$$

where k^t is a suitable transfer coefficient that can be related to a transfer time and μ_{wW} is the chemical potential of pore water. In this way, most of the microscopic phenomena acting at the clay particle level are taken into account at the macroscopic level. The fluxes of species are obtained by 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).

The finite element formulation is obtained from the balance equations written in weak forms by selecting as primary unknowns the solid displacement u , the fluid pressure p_W , the salt concentration in pore water c_{sW} and the mass of adsorbed water m_{ws} . SUPG stabilization scheme has been employed for the advective terms. A two-dimensional rectangular element with 8 nodes for solid displacements and 4 nodes for the other unknowns was implemented in the user-defined subroutine UEL of ABAQUS (Hibbitt et al. 2009). In particular, pore pressure, salt concentration and mass of adsorbed water have been considered only at the corner nodes.

5 EXPERIMENTAL RESULTS AND MODEL SIMULATIONS

Consolidation and swelling of clays occur as a result of a change in mechanical load or a change in pore fluid composition. Mechanical and chemical behaviors were analyzed in the course of oedometer tests carried out on a low activity clay soil characterized by $c.f. = 35\%$ and $w_L = 49\%$. In oedometric conditions, the specimen is constrained in the horizontal direction while it is free to deform in the vertical direction. Figure 1 shows the compression and swelling curves obtained for three specimens reconstituted with distilled water and submerged in distilled water during the loading phase up to 1200 kPa and the subsequent unloading to 10 kPa. The comparison between the experimental data and the model simulation shows a good agreement.

Figures 2-4 report the results obtained for the material reconstituted with 1M NaCl solution, compressed to 1200 kPa and then unloaded to 300 kPa while submerged in the same

solution. Once the mechanical swelling had terminated, the specimens were exposed to distilled water, simply by replacing the cell solution. The cell water was continuously renewed in order to remove the ions diffusing from the clay pores.

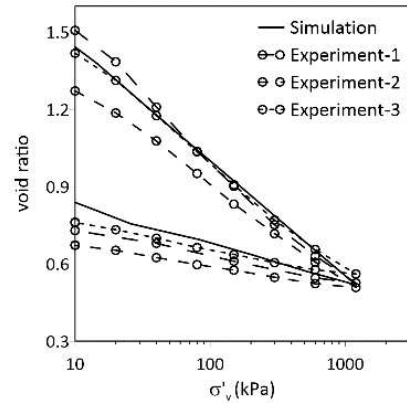
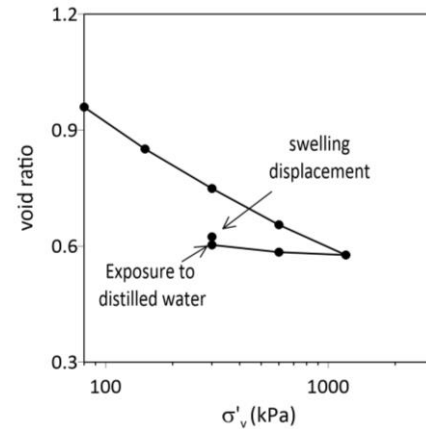
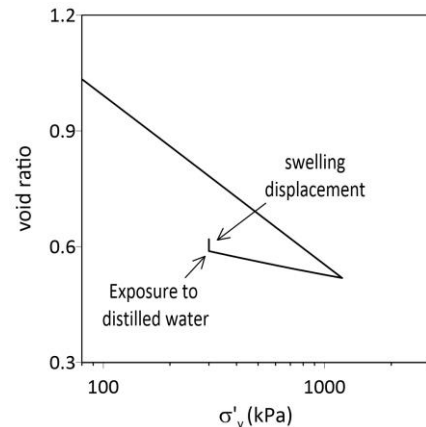


Figure 1. Mechanical loading and unloading of three specimens reconstituted with distilled water and submerged in distilled water for the whole duration of the oedometer test (Ghalamzan et al. 2021).



(a)



(b)

Figure 2. Oedometric curves of a specimen reconstituted with 1M NaCl solution, loaded to 1200 kPa, unloaded to 300 kPa, and swelling caused by exposure to distilled water: a) experimental result, b) model simulation (Ghalamzan et al. 2021).

5.1 Swelling

Figure 2 shows the change of void ratio with vertical stress for a specimen of soil reconstituted with 1 M NaCl solution and

initially submerged in the same solution. After the compression by steps to 1200 kPa and the subsequent unloading to 300 kPa the specimen was exposed to distilled water, under constant total axial stresses. The exposure caused ion diffusion from the pore fluid to the cell water. As a consequence, the pore solution concentration decreased and the void ratio increased. In the considered case of low activity clay, the chemically induced swelling is noticeable, although much lower than that can be observed in more active soils (Di Maio 1996). The consistency of model simulations with experimental results shown in the figure is very good.

5.2 Swelling pressure

Figure 3 shows the results of a test in which, after exposure to distilled water, swelling was prevented by applying successive load increments and thus evaluating the swelling pressure.

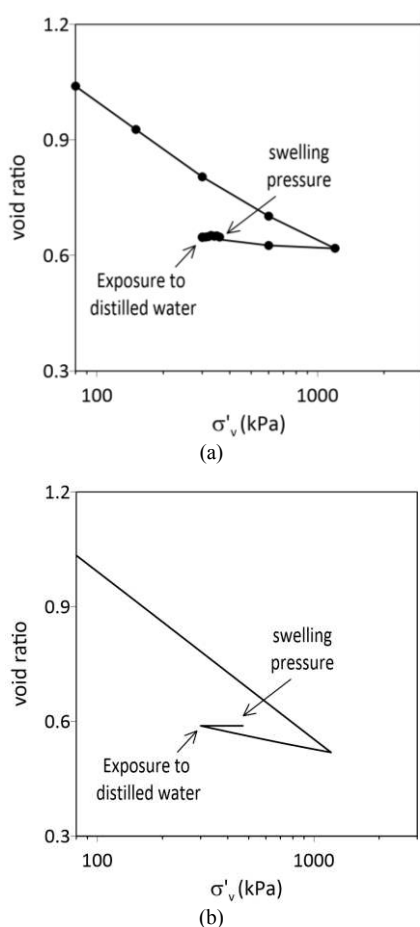


Figure 3. Compression and swelling of a specimen prepared with 1M NaCl solution followed by swelling pressure evaluation after exposure to distilled water at an axial stress of 300 kPa: a) experimental result, b) model simulation (Ghalmazan et al. 2021).

Similarly to the procedure followed in the previous section, after reconstituting the soil with 1 M NaCl solution, the specimen was submerged in the same NaCl solution, and the vertical stresses were increased by step up to 1200 kPa, by successive mechanical consolidations. Then, the vertical stresses were reduced to 300 kPa. When mechanical swelling had finished, the cell solution was substituted by distilled water and vertical swelling was prevented by applying increasing vertical stress increments until the specimen did no more exhibit tendency to swell. The final value of the applied axial stress is the swelling pressure of the specimen. Figure 3 shows the comparison between experimental results and model simulations. The general behaviour of the soil, including both compression and

swelling, is well simulated by the proposed model. However, the model swelling pressure is almost 30% larger (467 kPa) of the experimental value, which is equal to 360 kPa (Figures 3 and 5).

5.3 Time evolution of chemical swelling

Time evolution of swelling and swelling pressure was simulated with a 2D finite element model. The model considers: initial sample thickness equal to 2 cm, hydraulic conductivity and diffusion coefficient equal to $K_h=10^{-10}$ m/s and $D_s=2 \times 10^{-10}$ m²/s, respectively. The sample is confined between two porous stones with the thickness equal to 1.2 cm and 0.8 cm on the top and bottom, respectively. The porosity, the hydraulic conductivity and the effective diffusion coefficient of the porous stones are assumed equal to $n = 0.32$, $K_h=10^{-4}$ m/s, $D_s=1.5 \times 10^{-9}$ m²/s, respectively. In the simulations, the reservoir (namely, the cell fluid) has been simulated as two fictitious porous stones with high hydraulic conductivity and diffusion coefficient (assumed equal to 1 m/s and 10^{-6} m²/s, respectively) to prevent salt concentrating gradient at the beginning of the renewal process. In the experiment, the cell fluid was substituted once per day with distilled water until the end of osmotic swelling. We have considered the same renewal process in the simulation.

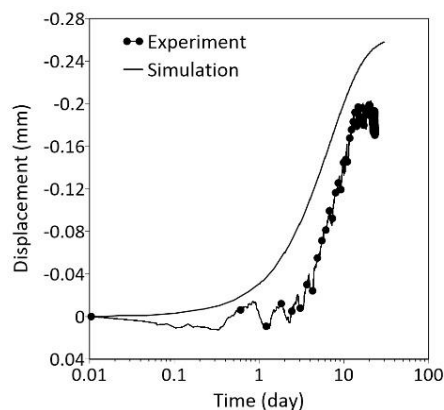


Figure 4. Time evolution of swelling induced by exposure to distilled water of an overconsolidated specimen under a vertical stress equal to 300 kPa (Ghalmazan et al. 2021).

Since the proposed 2D FEM element is plane strain, the dimension of the reservoir has been computed so that the ratio between real volume of each part of the experiment and simulation is retained.

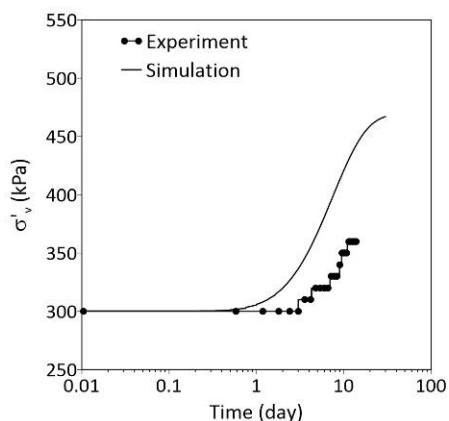


Figure 5. Time evolution of swelling pressure induced by exposure to distilled water of an overconsolidated sample at a vertical stress equal to 300 kPa (Ghalmazan et al. 2021).

Figure 4 shows the time trend of swelling of the overconsolidated specimen during exposure to distilled water. The comparison of experimental data and model shows that time

evolution of displacements has been correctly simulated; however, the final amount of swelling from the simulation is almost 30% larger than the experiment.

Figure 5 shows the swelling pressure evolution of the overconsolidated specimen of Figure 3 after exposure to distilled water, under a vertical stress equal to 300 kPa, with constrained vertical displacement. The beginning of the increase of swelling pressure occurs in the simulation earlier than in the experiments. In fact, the experimental swelling pressure begins to increase three days after exposure to distilled water, whereas it increases from the real beginning of the exposure to distilled water in the simulation. Also, the final value of swelling pressure in the simulation is almost 30% larger than in the experimentation.

5.3.1 Time evolution of ion removal

During exposure to distilled water, Na^+ concentration of the removed solution was carefully measured, and the weight of the removed cell solution was measured. Thus, it is possible to evaluate the amount of salt removed from the specimen pores and from the porous stones. The initial NaCl concentration in the sample, in the porous stones and the cell fluid was equal to 1 M. Thus, the number of moles of Na^+ inside the sample and porous stones can be evaluated from the pore volume of the specimen and porous stones at the beginning of substitution of the solution in the reservoir with distilled water. In the simulation, at the beginning of exposure to distilled water, the specimen thickness and void ratio are equal to 13.75 mm and 0.59, respectively. The pore volume of the specimen is thus equal to 12.53 cm^3 . The pore volume of the top and the bottom porous stone is 9.45 cm^3 and 6.3 cm^3 , respectively. Thus, the total number of moles of Na^+ in the porous stones and sample is equal to 28.28 mmol. This value is expected to be the amount of Na^+ that will be completely removed at the end of the diffusion process.

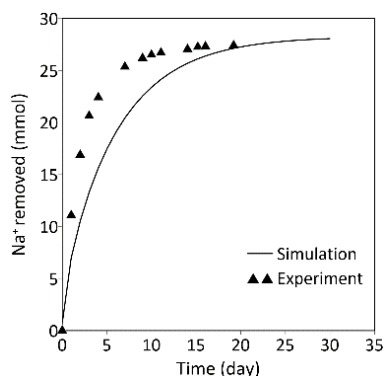


Figure 6. Time evolution of ion amount removed from specimen and from porous stones during exposure to distilled water in the swelling test (Ghalamzan et al. 2021).

Figure 6 and 7 shows the experimental data and the model simulation of the time evolution of Na^+ removed from specimens and porous stones during the swelling and swelling pressure test, respectively. It can be observed that the final amount of removed Na^+ from the simulation is close to the measured one. In the experiments, the ion removal is initially faster than the simulated one, in both swelling and swelling pressure tests.

Figures 5 and 7 show that, in the experiments, the swelling pressure begins to increase after 3 days, when the amount of removed Na^+ is almost 80% of the total removed amount. In contrast, in the simulation, the swelling pressure begins to increase from the first day of exposure to distilled water, when the Na^+ removal is much smaller than the experiment. This aspect is currently under examination

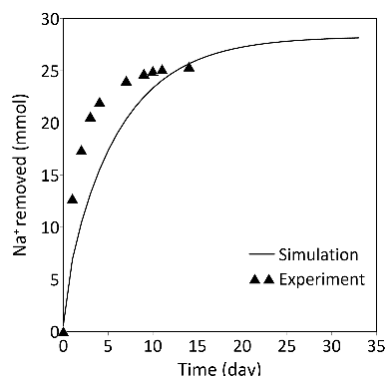


Figure 7. Time evolution of ion amount removed from specimen and from porous stones during exposure to distilled water in the swelling pressure test (Ghalamzan et al. 2021).

6 CONCLUSIONS

We have proposed a new hyper-elastic law for describing the chemo-mechanical behavior of clays, thus substantially improving the chemo-mechanical model proposed by Gajo et al. (2002) and Loret et al. (2002). The new relationship takes account of the dependence of shear stiffness and bulk stiffness on stress state and concentration of pore solution. The governing equations have been written for a two-phase deformable porous medium and include the momentum balance equation, the mass balance of pore water and salt in the fluid phase, the mass balance of absorbed water in the solid phase. A two dimensional FEM element has been implemented in a user-defined subroutine (UEL) of ABAQUS in which salt concentration and mass of absorbed water have been considered as nodal unknowns, in addition to pore pressure and displacement. In addition, the amount of removed ions has been calculated and compared with the experimental results.

The model shows satisfactory consistency with the experimental results although the simulation of the swelling pressure and swelling displacement could be improved by considering an anisotropic elasticity, as it will be considered in a forthcoming work.

The model has been calibrated and compared to the experimental oedometer test results obtained for reconstituted and overconsolidated specimens of a low active clay. So, the observed chemo-mechanical effects represent a minimum of what can occur in natural clayey soils. Notwithstanding this, Ghalamzan et al. (2021) have shown that even in this case, the effects on slope stability of a decrease in pore solution concentration can be very important.

7 ACKNOWLEDGMENTS

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