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Variations of Na^+ and K^+ concentrations in the pore fluid of a clayey soil affected by landslides: effects on shear strength and creep behaviour

Variations des concentrations de Na^+ et K^+ dans le fluide interstitiel d'un sol argileux affecté par des glissements de terrain: effets sur la résistance au cisaillement et le comportement au fluage

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ABSTRACT: Natural or anthropic variations of pore fluid composition can influence the mechanical behaviour of clayey soils. Samples from the *Costa della Gaveta* slope (Southern Apennines, Italy), affected by complex, slow-moving landslide systems, were reconstituted with distilled water, NaCl, and KCl solutions. Several specimens of soil (mainly non expansive illite-muscovite and kaolinite) were tested in direct shear apparatuses by controlling either the rate of displacement or the driving shear stress (creep tests). During some of the tests, the specimens were exposed to a fluid different from their pore fluid. This triggered water/ion diffusion processes that altered the pore fluid composition. A progressive decrease of shear strength (or an increase of shear displacement rates in creep tests) was observed with Na^+ concentration decreasing in the pore fluid. Conversely, with K^+ concentration increasing, a rapid increase of shear strength was observed, up to values higher than those obtained in Na^+-rich solutions. The performance of KCl-filled wells in producing a shear strength increase and limit landslide displacements is currently under investigation in a portion of an active landslide body.

RÉSUMÉ: Les variations naturelles ou anthropiques de la composition du fluide interstitiel peuvent influer sur le comportement mécanique des sols argileux. Des échantillons de sol de la pente de *Costa della Gaveta* (Apennins du sud, Italie), affecté par des systèmes complexes de glissements de terrain lents, ont été reconstitués avec des solutions d'eau distillée, de NaCl et de KCl à différentes concentrations. Plusieurs échantillons, principalement constitués de kaolinite et d'illite-muscovite non expansif, ont été analysés dans des appareils de cisaillement direct en contrôlant soit la vitesse de déplacement, soit la contrainte de cisaillement (essais de fluage). Au cours de certains tests, les échantillons ont été exposés à un fluide différent de celui de leurs pores. Cette opération a initié un procès de diffusion d'eau et d'ions, qui a modifié la composition du fluide interstitiel. Une diminution progressive de la résistance au cisaillement (ou un incrément des vitesses de déplacement dans les essais de fluage) a été observée avec une diminution de la concentration de Na^+ dans le fluide interstitiel. Inversement, lorsque la concentration de K^+ augmente, un incrément rapide de la résistance au cisaillement a été observée, jusqu'à des valeurs supérieures à celles obtenues avec des solutions riches en Na^+. La capacité des puits remplis de KCl de produire un incrément de la résistance au cisaillement et de limiter la vitesse des déplacements est actuellement à l'étude dans une partie d'un glissement de terrain.

Keywords: pore fluid composition; landslide stabilisation; creep; residual shear strength; salt wells

1 INTRODUCTION

The pore fluid of marine clay formations is generally an aqueous solution in which Na^+ is the most abundant cation. Variations of pore fluid composition can greatly affect the mechanical behaviour of clay soils. Exposure of smectitic soils to fluids different from their pore fluid can cause important volume changes or the onset of swelling pressures (Di Maio, 2004), which can severely damage man-made structures (Di Maio et al., 2015b). Salt leaching in non-expansive soils of marine origin, such as the *Quick Clays*, can increase the propensity of the soil to collapse and liquefy upon disturbance (e.g., Bjerrum, 1954). In two landslides in clayey soils in England, Moore and Brunsden (1996) and Anson and Hawkins (2002) related reactivations or increased displacement rates to decreased salt concentrations in the pore fluid. Tiwari and Ajmera (2015) correlated NaCl leaching and reduction of fully softened shear strength in some landslides in mudstone in Japan. Wen and He (2012) reported an influence of irrigation-induced desalinisation on the reactivation of a landslide in mudstone in China. Marc et al. (2017) also discussed possible effects of pore fluid composition variations on the behaviour of two landslides in black marls in the French Alps. Di Maio et al. (2015a) and Scaringi (2016) analysed the pore fluid at various locations in the *Costa della Gaveta* slope (Southern Apennines, Italy), which is affected by complex slow-moving landslide systems. They found that the concentration of several cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) decreases remarkably from the deeper stable soil to the overlying landslide bod, and attains very low values in proximity to the ground surface. In the laboratory, shear strength reduction and creep displacements caused by exposure to distilled water were observed. To understand the underlying processes, Di Maio and Scaringi (2016) and Scaringi (2016) analysed the behaviour of an almost pure Na-montmorillonite, reconstituted with a concentrated NaCl solution, pre-sheared to the residual condition, and subjected to shear-controlled shearing. A progressive decrease of Na^+ concentration in the pore fluid was found to induce shear displacements with tertiary creep pattern.

2 COSTA DELLA GAVETA SLOPE

Costa della Gaveta (Fig. 1) is located east of the city of Potenza in the southern Italian Apennines. The lithological succession of the hill features two systems (Di Maio et al., 2013): the clay-marl

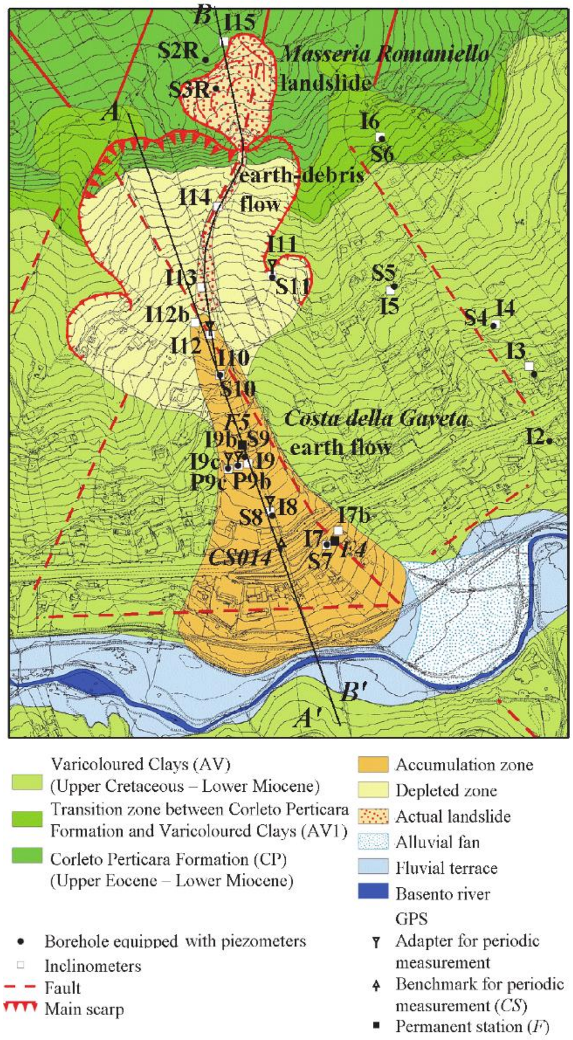

Figure 1. The Costa della Gaveta slope: geological features and monitoring network (mod. from Di Maio et al., 2017).

system of the *Varicoloured Clays* (Upper Cretaceous - Lower Miocene), and the superposed limestone marl system of the *Corleto Perticara* (Upper Eocene - Lower Miocene). The *Varicoloured Clays*, 180-200 m thick, are tectonised scaly clays, marly shales, cherty marls and marly clays with interbedded calcareous layers. The *Corleto Perticara*, 90-100 m thick, has alternating layers and benches of marly limestone and massive calcilutites. Downward from a wide and almost depleted source area, the *Costa della Gaveta* earthflow (several millions of m^3, up to 30 m thick) moves very slowly along the gently-sloping hill (about 10°), with seasonally-fluctuating rates of 2-3 cm/yr at the head, and less than 1 mm/yr in the fan-shaped toe (Di Maio et al., 2013, 2017).

3 SOIL PHYSICAL PROPERTIES

The landslide material has a fine clayey matrix with abundant lithorelicts of the original clay fabric. Fragments (locally blocks or strata) of calcarenite, calcareous marl or marly limestone are also present. The matrix has high clay fraction (>50%) and is rich in clay minerals, mostly illite-muscovite and kaolinite, with locally abundant (up to 20%) chlorite and smectite (Di Maio et al., 2017). The soil remains saturated throughout the year, except for the topmost 1-2 m close to the surface, which experiences seasonal variations of the saturation degree with variable spatial pattern. The gravimetric water content in the saturated zone generally decreases with depth from about 25% to about 15% (Di Maio et al., 2015a). The hydraulic conductivity, evaluated in the field and in the laboratory, varies between 10^{-8}-10^{-9} m/s in the landslide body, and approaches 10^{-10} m/s in the stable soil underneath. Discontinuities (e.g., slip surfaces) increase the macroscopic conductivity in the field by up to 2 orders of magnitude (De Rosa et al., 2018). The composition of the natural pore fluid at *Costa della Gaveta* was evaluated on soil samples extracted from drilled cores at various depths and locations. Suspensions of powdered soils in distilled water were prepared and left to settle. Then, the supernatant solutions were analysed through mass spectrometry or using ion-selective electrodes. Natural gravimetric water contents also were determined (on samples from the same locations and depths) so that the

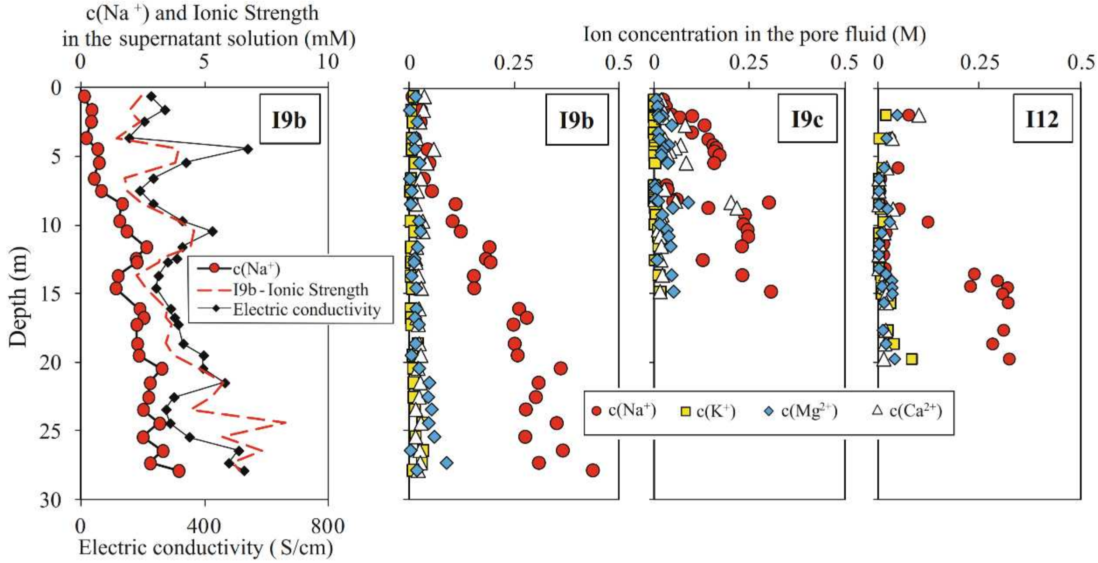

Figure 2. Vertical profiles of ionic strength and electric conductivity of the supernatant solutions (left); concentrations of some ions in the pore fluid (right) (mod. from Di Maio et al., 2015a; Scaringi, 2016).

concentrations of the main ions in the pore fluid could be estimated. Fig. 2 shows Na^+ concentrations, evaluated at some locations, against depth. In the stable soil, these concentrations reach those typical of sea water (salinity up to 35-40 g/l). In the landslide body (I9b and I9c, cf. Fig. 1), Na^+ concentration decreases gradually towards the surface, probably because of water adsorption due to strain-induced volume increase, remoulding and exposure to rainwater, ion diffusion and other transport processes. In the head (borehole I12), the ion concentration is almost uniform in the landslide material and much lower than that in the stable soil underneath. This might be location-specific as the head of the earthflow is located in the impluvium of the source area, where run-off and shallow groundwater, colluvial material and shallow earth-debris flows converge.

4 LABORATORY TESTS

The decrease of concentration of some ions in the pore fluid is known to alter various mechanical properties in many clay soils. To evaluate the effects of such a decrease on the residual shear strength, which probably is the available resistance on the slip surface of the *Costa della Gaveta* earthflow, several direct shear tests were carried out. These were performed in the Casagrande shear box or in the Bishop ring shear apparatus, on the soil reconstituted with NaCl or KCl solutions at different concentrations. The specimens were submerged in the same fluid as the pore one (Fig. 3). Some tests were performed with a solution similar to the natural pore solution at the location at which the tested soil was extracted; some other tests were done on undisturbed specimens that preserved their natural (*in situ*) pore fluid. Fig. 3 demonstrates that the residual friction angle φ'_r varies greatly with concentration in the range of natural variation of Na^+ (cf. Fig. 2). The points relative to specimens of the undisturbed material extracted across the slip surface lie on the same curve as that interpolating the results of reconstituted specimens. The residual friction angle φ'_r=12° of the undisturbed soil is probably lower than the original value of the material before the natural reduction of pore solution concentration (about 14°), and higher than the value that the material can achieve after further contact with freshwater. This also is suggested by Fig. 3 which shows that exposure to distilled water of the undisturbed specimens caused a decrease of φ'_r from 12° to 10°.

Under constant Terzaghi's effective stresses, a decrease of pore solution concentration can cause

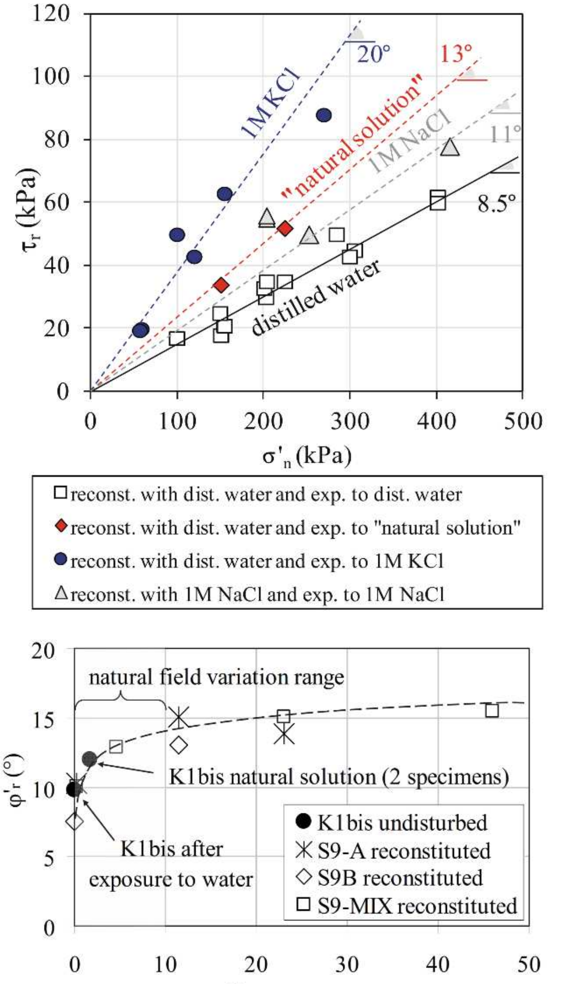

Figure 3. Residual shear strength (top) or residual friction angle (bottom) of several soil specimens from Costa della Gaveta, with various pore fluid composition (mod. from Di Maio et al., 2015a, 2017).

an increase of shear strain/displacement rates. This effect was observed in controlled shear stress tests performed both on intact specimens and on specimens pre-sheared to the residual. Fig. 4 shows some results obtained on soil specimens from *Costa della Gaveta*, reconstituted with 1 M NaCl solution and initially submerged in the same solution. They were first sheared until the residual strength was attained under controlled shear displacement rate. Then, the apparatuses were turned in stress-controlled mode, and shear stresses lower than the current residual shear strength were applied. As expected, only negligible shear displacements occurred, the rates of which decayed rapidly with a primary creep pattern. The subsequent and continued exposure to distilled water induced displacements with rates increasing to values typical of failure (tertiary creep pattern).

This behaviour was observed in tests carried out by direct shear box (specimens P1 and S9A in Fig. 4) as well as in those performed by ring shear apparatus (specimen B2). The same behaviour was observed also on specimens of an almost pure Na-montmorillonite (Di Maio and Scaringi, 2016; Scaringi, 2016), actually with more regular patterns of displacement due to the much higher material homogeneity and activity. Chemical analyses of the submerging fluid during the tests, and of the pore fluid after the tests, demonstrated the progressive decrease of ion concentrations in the pore fluid, which diffused into the submerging fluid causing a decrease of the available shear strength (Di Maio et al., 2015a; Pontolillo et al., 2016, 2018; Scaringi, 2016). If and how the observed natural reduction of ion concentrations in the soil pores (c.f. Fig. 2) can cause a similar process in the field, contributing to the slow deformation of the clayey slope, is currently under study.

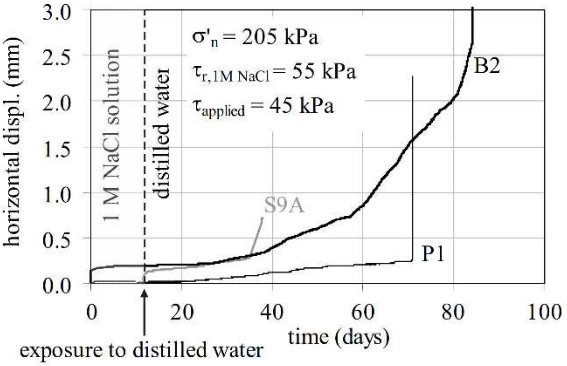

Figure 4. Horizontal shear displacement under constant driving stress of specimens reconstituted with 1 M NaCl solution and then exposed to distilled water (mod. from Di Maio et al., 2016; Pontolillo et al., 2016).

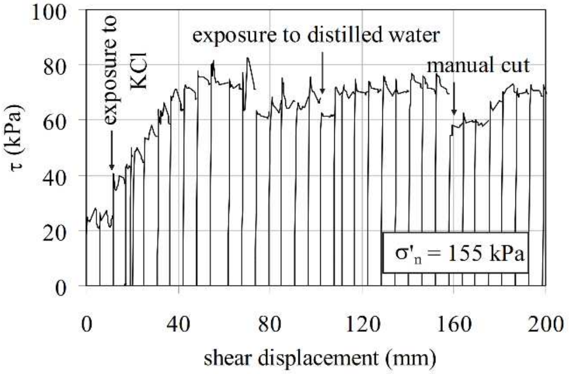

Figure 5. Shear strength of a specimen initially water-saturated, ex-posed to 1M KCl solution and then to distilled water again (mod. from Di Maio et al., 2015a).

Laboratory and field tests also are being carried out to investigate possible ways of improving the mechanical behaviour of the soil by inducing variations in the pore fluid composition. Exposure to K^+-rich aqueous solutions has been found to serve this scope well in some clay soils (such as in *Quick Clays*, cf. Helle et al., 2017). To verify this, specimens of *Costa della Gaveta* soil were exposed to concentrated KCl solutions during shear tests at different stages and in different conditions. The exposure triggered ion diffusion towards the pores, and produced a dramatic increase in shear strength (Fig. 5). The final values were much higher than those of the same material reconstituted with – and exposed to – freshwater, and even higher than those obtained by exposure to concentrated NaCl solutions (and Fig. 3). Upon subsequent exposure to distilled water, even though K^+ was removed from the pores, only a negligible decrease of shear strength occurred, possibly because ion exchange had occurred (K^+ replacing Na^+), resulting in “permanent” modification of the clay composition/structure and in the desired improvement of the mechanical behaviour.

5 FIELD INTERVENTION AND PERSPECTIVES

Soil improvement *in situ* that relies solely on K^+ diffusion, for instance using KCl wells, and/or on ion transport by seepage water might be extremely slow due to the low hydraulic conductivity of the soil under investigation. However, the landslide material presents heterogeneities that enhance the transport properties, at least along some preferential paths such as the slip surfaces. An experimentation is currently ongoing in the head zone of the *Costa della Gaveta* earthflow that aims to evaluate the field rate of K^+ propagation (Di Maio et al., 2016; De Rosa et al., 2016, 2018) and compare it to that exhibited by soil specimens in the laboratory (Pontolillo et al., 2018). Additionally, the experimentation seeks to identify ways of enhancing ion propagation, monitoring the process effectively, and ultimately optimise in terms of costs and benefits a possible large-scale intervention of landslide stabilisation. Thus far, a test field of 600 m^2 was prepared, in which 11 boreholes were drilled to a depth of 11-15 m (i.e. across the slip surface which at the location is about 8 m deep) at a mutual distance of about 5 m (K_i holes in Fig. 6) and stabilised by jacket slotted tubes (inner diameter 80 mm). Given the very limited soil volume involved, an influence on the landslide displacement rate is unlikely. As a matter of fact, as said above, the experimentation is aimed to analyse ion transport processes in the landslide. In the course of the experimentation, some of the boreholes are filled with KCl solutions, while others are used to monitor the advancing salt front. Hydraulic gradients are also applied at given times to enhance ion transport. Preliminary results put in evidence that K^+ propagation occurs preferentially along the slip zone, where the hydraulic conductivity is higher than elsewhere (Di Maio et al., 2017; De Rosa et al., 2018). The fact that the highest concentration of K^+ would be available preferentially in the weakest zone of the landslide seems to be a very effective improving process of its mechanical behaviour: it is very promising and motivates the current research.

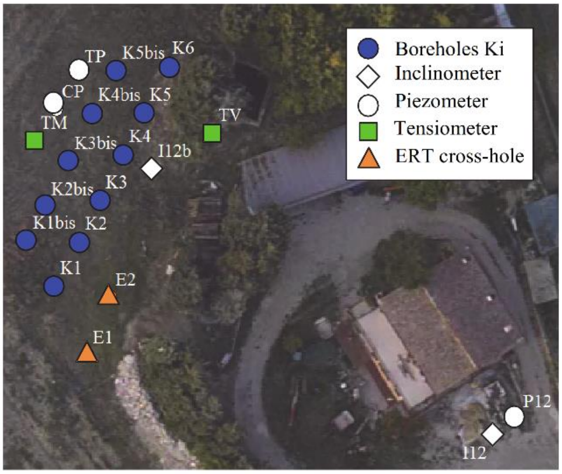

Figure 6. Test field in the Costa della Gaveta earthflow: location of boreholes and instruments.

6 REFERENCES

Anson, R., Hawkins, A. 2002. Movement of the Soper’s Wood landslide on the Jurassic Fuller’s Earth, Bath, England. *Bull. Eng. Geol. Environ.* 61, 325–345.

Bjerrum, L. 1954. Geotechnical Properties of Norwegian Marine Clays. *Géotechnique* 4, 49–69.

De Rosa, J., Pontolillo, D.M., Di Maio, C., Vassallo, R. 2016. Chemical Clay Soil Improvement: From Laboratory to Field Test. *Procedia Eng.* 158, 284–289.

De Rosa, J., Pontolillo, D.M., Grimaldi, G.M., Maio, C.D. 2018. Determinazione delle variazioni di concentrazione ionica e di resistenza indotte da pozzi di soluzione di KCl in una frana in argille varicolori. *Proc. of IARG* (Italian Meeting of Geotechnical Researchers), Genova, 2018, AGI, ISBN 9788897517016, in Italian, 6 pp.

Di Maio, C. 2004. Consolidation, Swelling and Swelling Pressure Induced by Exposure of Clay Soils to Fluids Different from the Pore Fluid. In: Loret, B., Huyghe, J.M. (Eds.), *Chemo-Mechanical Couplings in Porous Media Geomechanics and Biomechanics*. Springer Vienna, pp. 19–43.

Di Maio, C., Scaringi, G. 2016. Shear displacements induced by decrease in pore solution concentration on a pre-existing slip surface. *Eng. Geol.* 200, 1–9.

Di Maio, C., Scaringi, G., Vassallo, R. 2015a. Residual strength and creep behaviour on the slip surface of specimens of a landslide in marine origin clay shales: influence of pore fluid composition. *Landslides* 12, 657–667.

Di Maio, C., Scaringi, G., Vassallo, R., Rizzo, E., Perrone, A. 2016. Pore fluid composition in a clayey landslide of marine origin and its influence on shear strength along the slip surface. In: Aversa, S., Cascini, L., Picarelli, L., Scavia, C. (Eds.*), Landslides and Engineered Slopes. Experience, Theory and Practice.* Proc. 12th Int. Symp. on Landslides (Naples, 12-19 June 2016), Ch. 85, 8 pp.

Di Maio, C., Vassallo, R., Caputo, V. 2015b. Structural damage caused by swelling of the foundation soil: a case history. In: *Geotechnical Engineering for Infrastructure and Development, Conference Proceedings.* ICE Publishing, pp. 2263–2268.

Di Maio, C., Vassallo, R., Scaringi, G., De Rosa, J., Pontolillo, D., Grimaldi, G.M. 2017. Monitoring and analysis of an earthflow in tectonized clay shales and study of a remedial intervention by KCl wells. *Ital. Geotech. J.* 51, 48–63.

Di Maio, C., Vassallo, R., Vallario, M. 2013. Plastic and viscous shear displacements of a deep and very slow landslide in stiff clay formation. *Eng. Geol.* 162, 53–66.

Helle, T.E., Aagaard, P., Nordal, S. 2017. In Situ Improvement of Highly Sensitive Clays by Potassium Chloride Migration. *J. Geotech. Geoenvironmental Eng.* 143, 04017074.

Marc, V., Bertrand, C., Malet, J.-P., Carry, N., Simler, R., Cervi, F. 2017. Groundwater-Surface waters interactions at slope and catchment scales: implications for landsliding in clay-rich slopes: Hydrochemistry and geochemical modelling to infer groundwater flows. *Hydrol. Process.* 31, 364–381.

Moore, R., Brunsden, D. 1996. Physico-chemical effects on the behaviour of a coastal mudslide. *Géotechnique* 46, 259–278.

Pontolillo, D.M., De Rosa, J., Lauria, M., Di Maio, C. 2018. Analisi dei fenomeni di propagazione ionica nei terreni argillosi di una frana di Costa della Gaveta (PZ). *Proc. of IARG* (Italian Meeting of Geotechnical Researchers), Genova, 2018, AGI, ISBN 9788897517016, 6 pp., in Italian.

Pontolillo, D.M., De Rosa, J., Scaringi, G., Di Maio, C. 2016. Clay Creep and Displacements: Influence of Pore Fluid Composition. *Procedia Eng.* 158, 69–74.

Scaringi, G. 2016. Influence of pore fluid composition on clay behaviour and chemo-mechanical study of a clayey landslide. *PhD Thesis,* University of Basilicata, Italy.

Tiwari, B., Ajmera, B. 2015. Reduction in Fully Softened Shear Strength of Natural Clays with NaCl Leaching and Its Effect on Slope Stability. *J. Geotech. Geoenvironmental Eng.* 141, 04014086.

Wen, B.P., He, L. 2012. Influence of lixiviation by irrigation water on residual shear strength of weathered red mudstone in Northwest China: Implication for its role in landslides' reactivation. *Eng. Geol.* 151, 56–63.