Monitoring and analysis of an earthflow in tectonized clay shales and study of a remedial intervention by KCl wells

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Summary

This paper describes the behaviour of an earthflow in a marine origin clay shale of the Southern Italian Apennines, and analyses the first results of an experimental remedial measure of soil improvement based on KCl wells. The main features of the structure and kinematics of the earthflow have been evaluated on the basis of geomorphologic analyses, geotechnical laboratory and field investigations, monitoring of deep/superficial displacements and pore water pressures, and modelling by phenomenological and physically-based approaches. The results of the study show that the landslide movement corresponds to a very slow sliding on a deep shear surface, along a fault line, in the residual shear strength conditions. Internal viscous strains also occur locally, above all in the weathered and softened soil, and contribute to the constancy of soil discharge along the channel. The average yearly rate of displacement, over the past ten years, has been in the order of few cm/year in the head zone and one/two orders of magnitude lower in the accumulation. The seasonal rate variations are apparently influenced by rain which can influence, besides pore pressures, pore fluid composition. The pore fluid is a composite saline-sodic solution, the concentration of which decreases dramatically from the stable soil to the landslide body and to the uppermost soil horizon. Laboratory results show that with sodium concentration decreasing, the shear strength decreases and the shear displacement rate under constant effective stresses increases. On the other side, the laboratory results show that exposure to potassium chloride solutions makes the soil shear strength increase greatly and permanently. First results of a chemical treatment by KCl wells in the head zone of the earthflow show that, locally, the ion transport in the surrounding soil is rather fast.

1. Introduction

Slow earthflows in structurally complex clay formations of the Italian Apennines are widespread and very often responsible of severe damage to structures and infrastructures such as tunnels, bridges, railways, highways and pipelines that are built on or across them. Their extension and the mechanical behaviour of the involved materials – generally prone to deterioration – make the stabilization of this type of landslides very difficult [Picarelli and Russo, 2004]. Investigation, monitoring and analysis are indeed tools of the utmost importance for the design of effective and sustainable risk mitigation measures.

Geological structure and geomorphologic features, seasonal rain/evaporation effects and weathering are generally recognized as features or natural processes which influence these earthflows' behaviour [Baum *et al.*, 1998; Leroueil, 2001; Picarelli *et al.*, 2005; Picarelli *et al.*, 2006; Comegna *et al.*, 2007; Picarelli and Di Maio, 2010; Picarelli *et al.*, 2013; Guerriero *et al.*, 2014; Hungr *et al.*, 2014; Cotecchia *et al.*, 2015; Urciuoli *et al.*, 2016]. Experimental results show that the decrease in pore solution concentration due to the interaction with rain and/or with the fresh water of confining aquifers can cause dramatic mechanical deterioration of the considered clay shales [Picarelli and Di Maio, 2010; Di Maio *et al.*, 2015]. On the other hand, similar effects capable of influencing soil behaviour and stability have been recognized in several other formations all over the world since the '50s by Bjerrum [1954] and Rosenqvist [1955], and then also by Moore and Brunsden [1996]; Geertsema and Torrance [2005]; Zhang *et al.* [2009]; Zhang *et al.* [2013]; Tiwari and Ajmera [2015].

With the aim to formulate an effective and sustainable intervention of landslide risk mitigation based on both mechanical and chemical characterization, the behaviour of the Costa della Gaveta earthflow has been long monitored and analysed. This paper summarizes the results obtained in the research "Landslide risk mitigation through sustainable countermeasures" funded by the Italian Ministry of Education, University and Research (PRIN project: https://prinrischiodafrana.wordpress.com/).

The earthflow occurs in a structurally complex clay formation outcropping east of Potenza (Fig. 1). Among others, Di Maio *et al.* [2010; 2011]; Cal-

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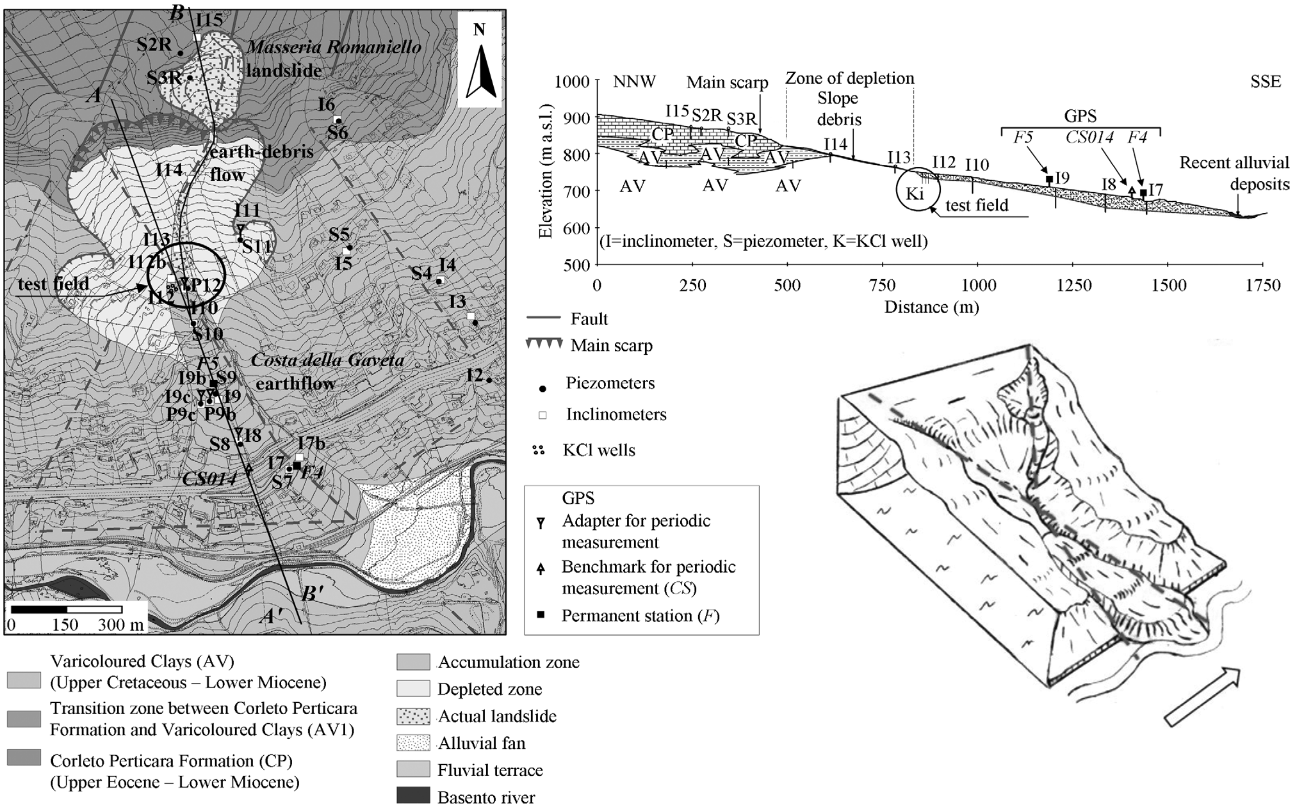

Fig. 1 – Geological map and section AA' with location of boreholes and GPS stations, and morpho-structural model of Costa della Gaveta landslide (redrawn from VASSALLO *et al.,* 2016b).

Fig. 1 – Mappa geologica e sezione geologica AA' con ubicazione dei sondaggi e delle stazioni GPS e modello morfo-strutturale della colata di Costa della Gaveta (ridisegnato da VASSALLO et al.*, 2016b).*

CATERRA *et al.* [2012]; VASSALLO *et al.* [2013], DI MAIO *et al.* [2013], VASSALLO *et al.* [2015] described the 3D geometry of the landslide and its main kinematic features. The influence of rain on pore water pressures and displacements was analyzed both by phenomenological and physically-based 3D approaches [VASSALLO *et al.*, 2015; VASSALLO *et al.*, 2016a]. The composition of the pore fluid and the effects of its natural variations on the soil mechanical deterioration have also been evaluated [DI MAIO *et al.*, 2015; DI MAIO and SCARINGI, 2016; DI MAIO *et al.*, 2016]. The possibility of improving the soil mechanical behaviour by inverting the natural process, i.e. by increasing the pore solution concentration, has been first verified by laboratory tests. Then, to find the most suitable procedures for achieving the mechanical improvement on the slip surface in reasonable time, a field experimentation has been initiated in 2015 and is still being performed in the head zone of the earthflow.

2. Geological and geomorphologic outline of the Costa della Gaveta slope

The geological structure of the hill and the geomorphology of the landslide system (Fig. 1) were investigated by DI MAIO *et al.* [2010] and VASSALLO *et al.* [2016b]. The results of the analysis are briefly summarized in this section.

The lithological succession of the slope consists of two main systems: the clay - marl system referring to the formation of Varicoloured Clays and the overlying limestone - marl system of the Corleto Perticara formation. The Varicoloured Clays are constituted by clays, marly shales, cherty marls and marly clays. The Corleto Perticara formation, first described by SELLI [1962], consists of alternating layers and benches of marly limestone and massive calcilutites.

Two fault systems, with orientation NW-SE and NE-SW respectively, probably controlled – and still control – the morphodynamic evolution of the entire slope.

The main Costa della Gaveta earthflow moves in a channel along a fault line within the Varicoloured Clays. It is approximately 850 m long with an average ground inclination in the channel of about 10°, and from 100 m (in the channel) to 600 m (in the accumulation) wide. The maximum depth of the slip surface detected by inclinometer measurements is about 40 m. The main scarp, in the Corleto Perticara formation, is locally affected by instability phenomena such as the Masseria Romaniello landslide

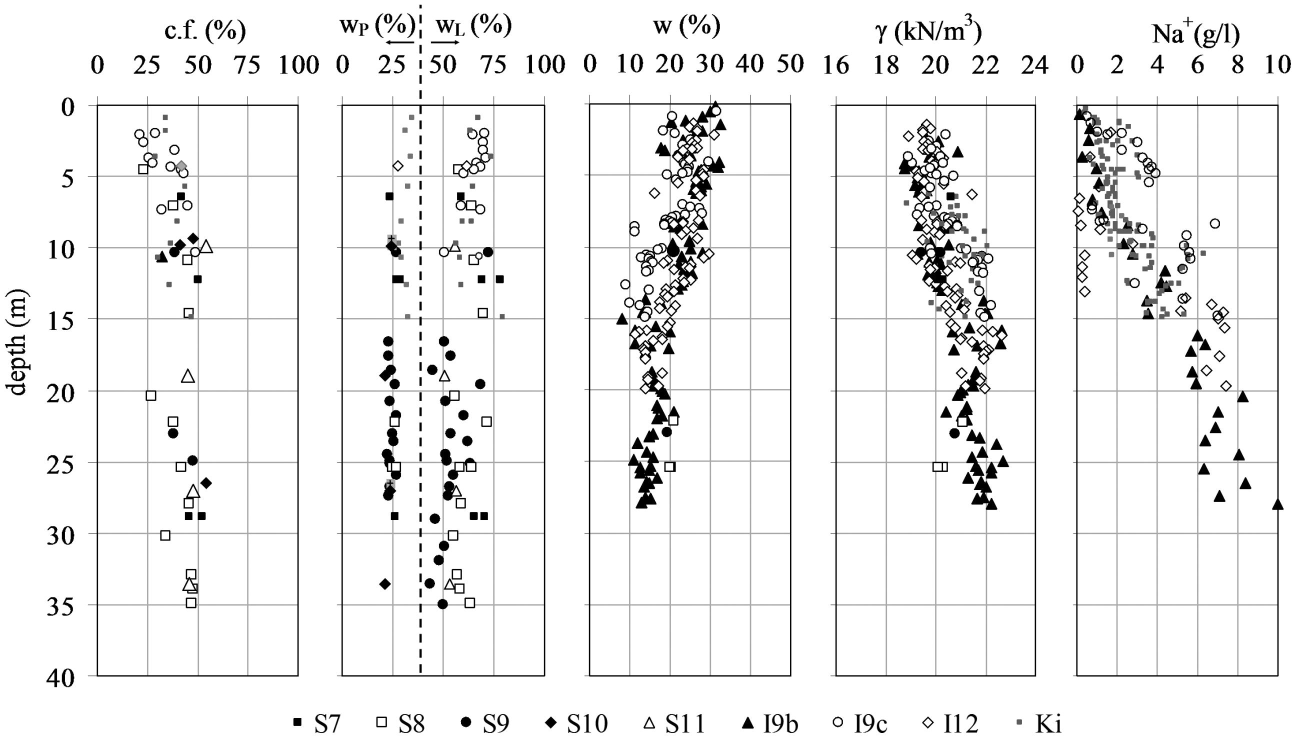

Fig. 2 – Clay fraction c.f., liquid limit w_L, plastic limit w_P, water content w, bulk unit weight γ and Na^+ concentration in the pore fluid against depth from the ground surface [DI MAIO *et al.*, 2013; DE ROSA *et al.*, 2016]. The location of the boreholes is reported in Fig. 1.

Fig. 2 – Frazione argillosa c.f., limite di liquidità w_L, limite di plasticità w_P, contenuto d'acqua w, peso dell'unità di volume γ e concentrazione di Na^+ nel fluido interstiziale in funzione della profondità dal piano campagna [DI MAIO et al.*, 2013; DE ROSA* et al.*, 2016]. La posizione dei fori è riportata in Fig. 1.*

(Fig. 1). This latter feeds a shallow earth/debris flow which runs along a fault line towards the main Costa della Gaveta earthflow.

3. Soil physical characteristics and mechanical properties

The landslide is constituted by a fine clayey matrix including rock fragments or blocks or even strata of marly limestone, calcareous marl and calcarenite. Lithorelicts of the original very hard clay formation are also widespread. The fine matrix is characterized by high values of the clay fraction (Fig. 2) which is mainly constituted by illite-muscovite and kaolinite. Locally, chlorite and smectite reach percentages of about 20% [SUMMA, 2006]. The degree of saturation of the upper soil horizon (1 m - 2 m below the ground surface) undergoes seasonal variations different from place to place in the slope. The average water content in the saturated zone beneath decreases with depth from about 25% to 15% [DI MAIO *et al.*, 2015], as shown by figure 2. The figure also shows data on the sodium concentration of the pore solution which will be commented and discussed in section 6.

The peak shear strength was determined by means of CiU triaxial tests on the few samples that could be extracted undisturbed from the landslide body (Fig. 3). By using the peak strength parameters thus evaluated (c′=50 kPa and ϕ'=14°), the 2D limit equilibrium methods of slices provide a safety factor SF = 1.8 in the most severe pore pressure conditions [DI MAIO *et al.*, 2010]. An average friction angle between 11° and 12° on the slip surface is required to obtain a 2D safety factor SF=1 [VASSALLO *et al.*, 2012]. As a matter of fact, the large displacements of the landslide, the hypothesized regularity of the slip surface, and the limit equilibrium stability analyses suggest that the shear strength available on the slip surface is close to the residual one [DI MAIO *et al.*, 2010].

The residual strength parameters were evaluated on some undisturbed samples and on a great number of remoulded samples or samples reconstituted with, and initially submerged in, distilled water. Thus, the resulting initial pore fluid depends on the void ratio and on the natural ion content of the soil which, in turn, can vary in a wide range. The Casagrande direct shear, a reversal shear box, the Bromhead and the Bishop ring shear devices were used. All the tests were carried out at a rate of dis-

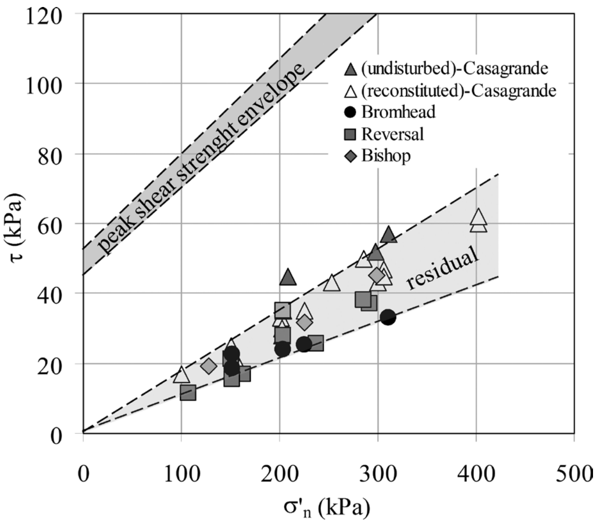

Fig. 3 – Peak and residual strength of the Costa della Gaveta soil [DI MAIO *et al.*, 2010; DI MAIO *et al.*, 2013, DI MAIO *et al.*, 2015].

Fig. 3 – Resistenza a taglio di picco e residua dei terreni di Costa della Gaveta [DI MAIO et al.*, 2010; DI MAIO* et al.*, 2013, DI MAIO* et al.*, 2015].*

placement v = 5 μm/min, with the exception of those carried out by the Bromhead apparatus for which a rate v = 18 μm/min was adopted (the minimum possible for the device). The rate difference ought not to influence the results, as shown by SCARINGI and DI MAIO [2016] who investigated the rate effects on the shear strength of the Costa della Gaveta soil in the range $10^{-3} < v < 10^{2}$ μm/min.

Figure 3 shows that the residual friction angle ϕ'_r ranges between 6° and 10°. This significant variability can be attributed to the natural heterogeneity in c.f., mineral composition and pore fluid composition. The clay fraction varies in the range 25%-50% (Fig. 2) which is the range of the most significant gradients in the relation ϕ'_r – c.f. [LUPINI *et al.*, 1981]. For c.f. close to 50%, ϕ'_r depends on the composition of both the solid skeleton and pore fluid. If this latter is distilled water, ϕ'_r varies between 5°- 6° of expansive clay minerals and 10°-11° of kaolin. The percentage of expansive minerals in the Costa della Gaveta soil varies between 5% and 25% [SUMMA, 2006], this is the range of the highest gradients in the relation ϕ'_r – *expansive mineral content* [DI MAIO and FENELLI, 1994]. Finally, the influence of the pore fluid composition can be much significant; this aspect is discussed in section 6.

Figure 3 also shows a noticeable drop in strength from peak to residual, and thus a large domain of possible shear creep [TER STEPANIAN, 1963; SUKLJE, 1969; YEN,1969]. As a matter of fact, the landslide body exhibits a creep behaviour that can be interpreted by a simple model based on the Bingham equation (Sect. 4).

The hydraulic conductivity k was evaluated by both field and laboratory tests. The field, falling head, piezometer tests provide k values in the range 10^{-9} m/s - 10^{-8} m/s within the landslide body and in the order of 10^{-10} m/s in the deeper stable soil. These results are consistent with those evaluated on similar materials by COTECCHIA *et al.* [2014], who highlighted the influence on permeability of the subsoil structure. Also the permeability of the Costa della Gaveta subsoil is influenced by several types of discontinuities, such as the contact between fine-grained soils and rock fragments, blocks, strata, fissures at various scales, and slip surfaces. In particular, the permeability around the slip surface has been evaluated by hydraulic tests carried out in boreholes crossing the surface, in the head of the landslide (boreholes Ki in figure 1, example of result in Fig.14). The interpretation of the transient following the pumping-induced water level drawdown provides values of k varying from 10^{-6} m/s to 10^{-8} m/s, different from place to place as a probable result of a marked heterogeneity in the soil structure.

4. Landslide displacements

Five inclinometer casings were installed in the Costa della Gaveta earthflow at the end of 2004. Since then, many other inclinometer tubes have been installed, some of which instrumented with fixed-in-place probes. Between 2006 and 2007, a GPS network of permanent and no-permanent stations was installed in collaboration with the National Geological Survey (nowadays ISPRA). Figure 1 indicates the location of all the instruments.

The inclinometer cumulative profiles clearly indicate the existence of a narrow zone in which the displacements are localized (Fig. 4). Three components can be identified: sliding AB on the slip surface, the resultant BC of internal subsoil deformation and the resultant CD of internal deformation of the upper soil horizons.

DI MAIO *et al.* [2013] showed that the internal deformations that give the resultant BC and CD are well interpreted by the Bingham rheological model:

$$\tau = \tau_0 + \eta \cdot (du/dy) \quad (1)$$

where: τ = shear stress, τ_0 = creep threshold shear stress, η = dynamic viscosity, u = displacement rate, y = normal to the ground surface.

Based on the simple method proposed by VAN ASCH and VAN GENUCHTEN [1990] for an infinite slope, and considering a flow factor $\lambda = \sigma'/\eta$, where σ' is the normal effective stress, the viscous displacement rate gradient can be evaluated as:

$$du/dy = \lambda \cdot (\tau - \tau_0) / \sigma' \quad (2)$$

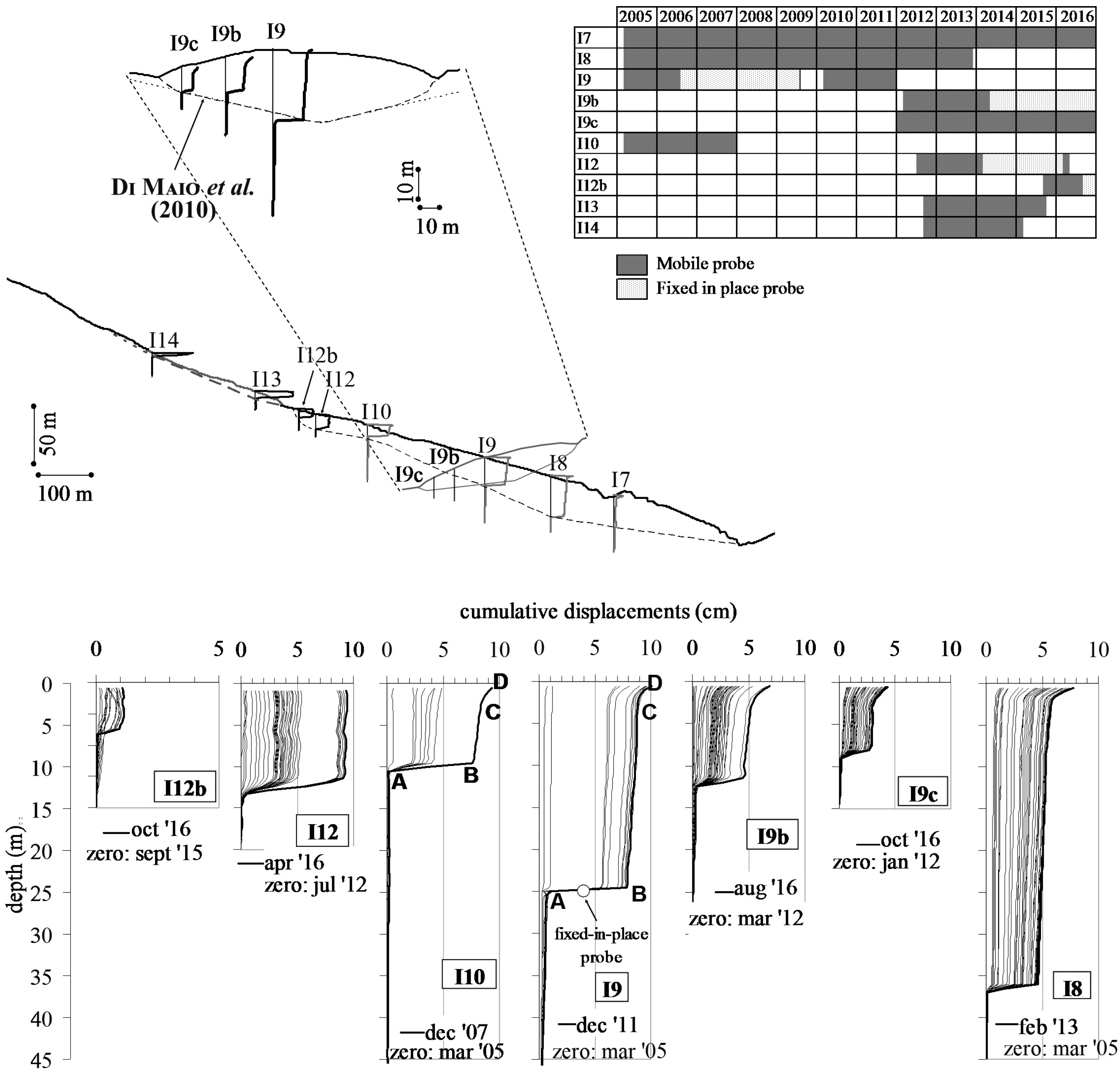

Fig. 4 – Longitudinal and transversal sections of the earthflow with inclinometer profiles, and time table of inclinometer monitoring.

Fig. 4 – Sezione longitudinale e trasversale della colata con profili inclinometrici, e tabella con l'indicazione dei periodi di funzionamento degli inclinometri.

By assuming $\tau_0 = \tau_r$ = residual shear strength, the model results [DI MAIO *et al.*, 2013] show that the creep profile at different times in the considered instrumented verticals (Fig. 5) can be simulated by using always the same values of flow factors in the upper weathered soil ($\lambda = 6 \cdot 10^{-10}\ s^{-1}$), in the underlying 6 m thick horizon ($\lambda = 6 \cdot 10^{-11}\ s^{-1}$) and in the soil underneath ($\lambda = 2.5 \cdot 10^{-11}\ s^{-1}$).

The time trend of the cumulated displacements AD is mostly influenced by the deep sliding component AB [DI MAIO *et al.*, 2013]. In fact, AB represents the prevailing component of displacements, and also its rate variations are reflected in AD rate variations. Figure 6 plots the displacements AD against time. It can be seen that: a) in each vertical the annual displacement rate has been practically constant in the monitoring period, as shown by the constancy of the average yearly slope of the historical displacement series; b) the average displacement rates decrease from I12 to I7, *i.e.* in the downslope direction; c) GPS displacements are consistent with the cumulative inclinometer displacements AD [CALCATERRA *et al.*, 2012]. In particular the station F5 for continuous GPS measurements gives results in very good agreement with those inferred from the nearby inclinometer I9. GPS periodical measurements at benchmarks

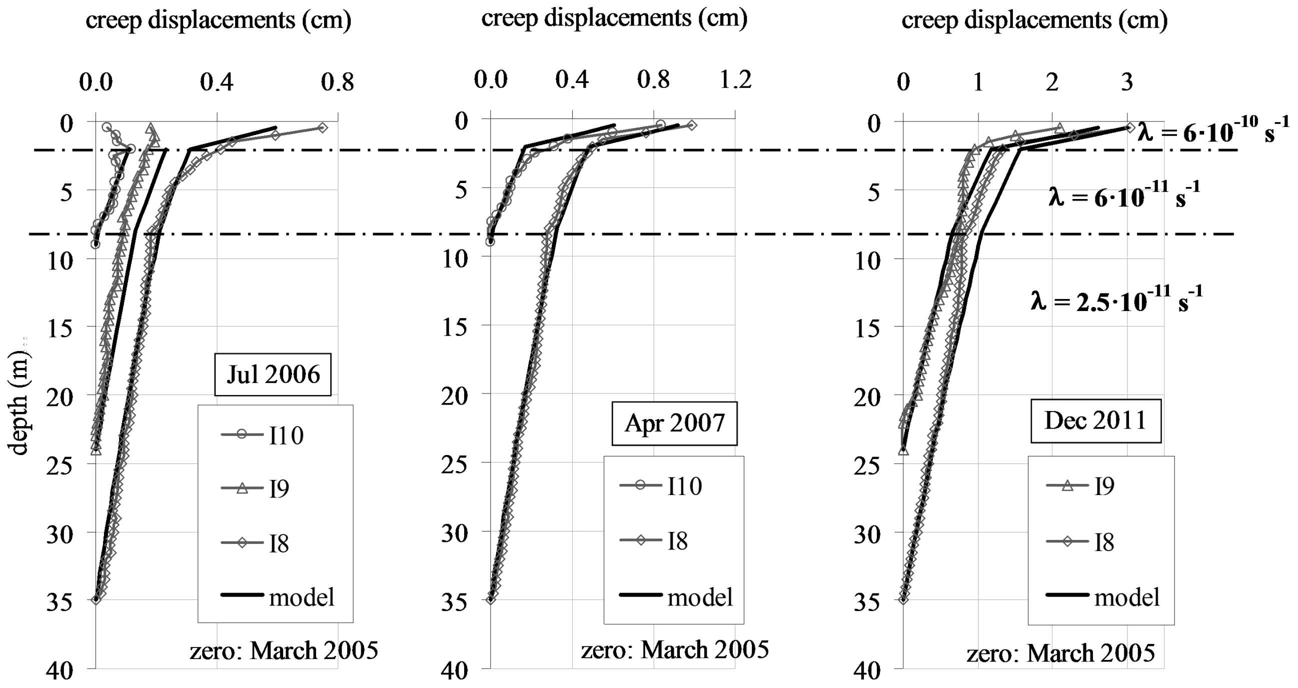

Fig. 5 – Inclinometers I8, I9 and I10: internal deformation profiles at three different dates compared with theoretical creep profiles.

Fig. 5 – Inclinometri I8, I9 and I10: profili di deformazione interna sperimentali e di creep teorico in tre diverse date.

S008 and S010, placed on the top of inclinometer tubes, also gave results consistent with those of the corresponding inclinometers I8 and I10.

The displacements of the different inclinometers are correlated to one another by the same relationship over the whole monitoring period, as shown by VASSALLO *et al.* [2016a]. The authors used the data-driven evolutionary modelling technique EPRMOGA [GIUSTOLISI and SAVIC, 2009] that works with polynomial relationships linking series of data, with the polynomial coefficients optimized by a minimum square method. Figure 7 shows, as an example of the results, the comparison between the experimental trend of the displacement rates in inclinometer I9b and the trends given by the polynomials - with the simplest structures and the highest coefficients of determination CoD - which link the series of I9b to the displacement rates in I12 and I9c respectively. The whole 3 years series of I12 and I9c have been used as input. The analysis shows that the displacements are well correlated and their rate variations are simultaneous under the considered time resolution of 10 days [VAS-

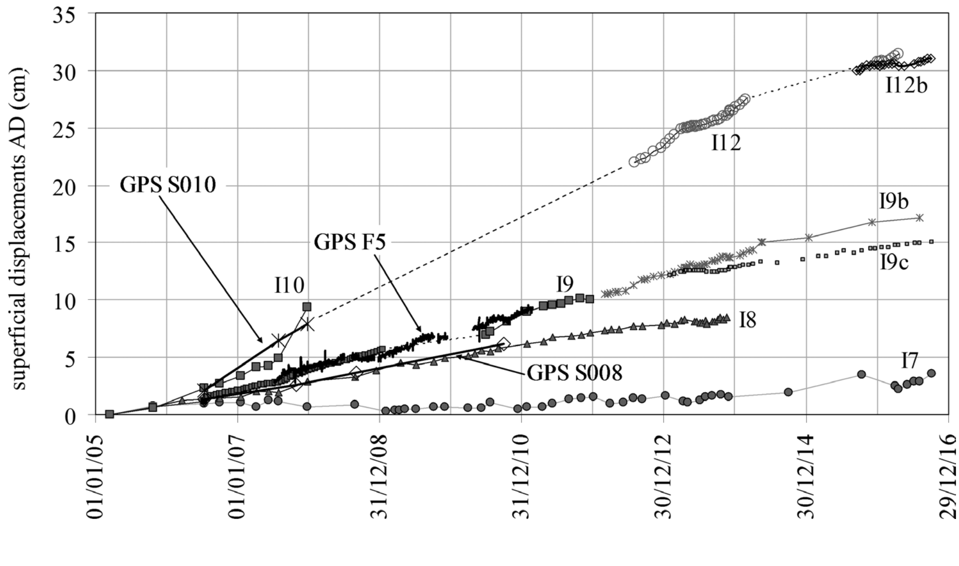

Fig. 6 – Cumulative displacements AD at the ground against time and GPS data.

Fig. 6 – Andamento temporale degli spostamenti cumulati in superficie, AD, e misure GPS.

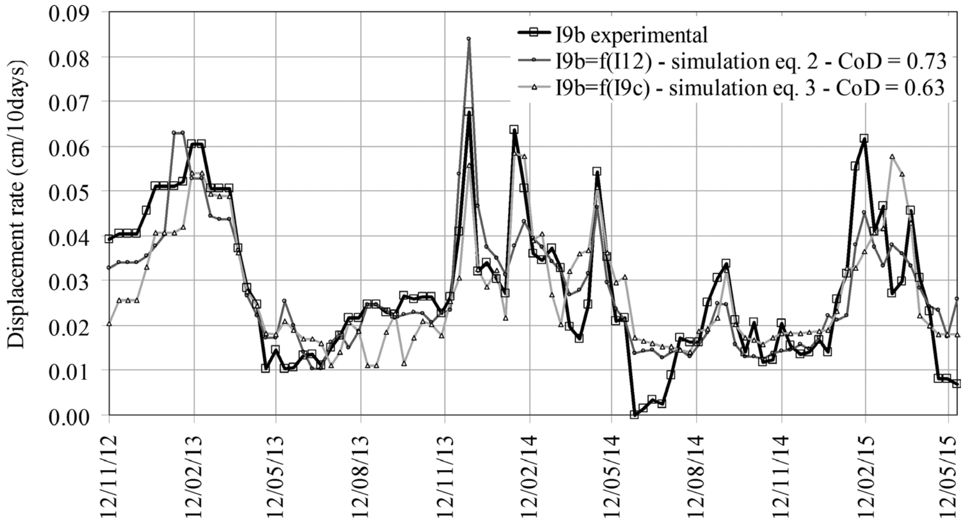

Fig. 7 – Time plot of the deep displacement rates in I9b evaluated by inclinometer measurements and calculated by the EPRMOGA equations as functions of displacement rates in I12 and I9c [re-drawn from Vassallo *et al.*, 2016a].
Fig. 7 – Velocità di spostamento lungo la superficie di scorrimento in I9b: confronto fra le serie storiche misurate e quelle calcolate con EPRMOGA in funzione delle velocità in I12 e in I9c [ridisegnato da Vassallo et al.*, 2016a].*

sallo *et al.*, 2016a]. The physical cause of the correlation has been hypothesised to be the mechanism of movement of the landslide, which corresponds to the kinematics of constant soil discharge in the channel [Di Maio *et al.*, 2010; Di Maio *et al.*, 2013].

The code EPRMOGA was also used to find a possible relationship between displacement rates and rainfall. The whole set of results reported by Vassallo *et al.* [2016a] shows that, in the monitoring period, the dependence of the displacement rate series on rainfall (cumulated in several different time intervals) is characterized, at the best, by a CoD of about 0.6. As a matter of fact, the link between pore pressures and rain and between displacements and pore pressures in the Costa della Gaveta earthflow is much complex, as shown by the next section.

5. Pore water pressures

Pore water pressures are monitored since 2005 by a number of Casagrande piezometers and electric piezometers, installed at different depths, whose location is shown in figure 1. Given the low values of permeability, pore water pressure variations measured in most of the Casagrande piezometers exhibit a significant time-lag. So, for the analyses, data of electric piezometers were considered.

The analyses carried out by using EPRMOGA show that it is not possible to find a correlation between pore pressures measured in a single piezometer and the inclinometer displacements on the slip surface [Vassallo *et al.*, 2015; Vassallo *et al.*, 2016a].

The response of pore water pressures to hydrological conditions was analysed by Vassallo *et al.* [2015] by means of the finite difference code MODFLOW3D, applying as boundary condition the long historical rainfall series of the site. The transient analysis, carried out with a daily resolution, was verified to reproduce successfully the time trend of electric piezometer data. Figure 8c shows, as an example, the comparison between the experimental data obtained by an electric piezometer and the MODFLOW3D results. The results of the analyses show that, due to the soil hydraulic conductivity and compressibility, the response of pore water pressures on the slip surface to the hydrological input strongly depends on depth from the ground surface, in terms of amplitude as well as of time-lag. In particular, calculated pore water pressure variations induced by rainfall are significant only within 10-15 m depth. It is worth noting that the area of the slip surface within this depth interval represents almost the half of the total area of the hypothesized slip surface (Fig. 8a). So, pore pressure variations occur in a large portion of the slip surface and can, in theory, influence the earthflow movements.

To analyse this possibility, the calculated transient pore water pressure distributions were used to evaluate the time evolution of a global limit equilibrium 3D safety factor SF. The stability analysis was carried out by the freeware code STAB3D developed by Chen *et al.* [2003]. Based on the method of vertical columns, the code assumes parallel inter-column forces, similarly to Spencer's 2D method. The slip surface of the 3D geometrical model of the landslide body had been reconstructed on the basis of inclinometer and geomorphological data by Di Maio *et al.* [2010]. Transient pore pressures induced by the historical rain series, evaluated by MODFLOW 3D,

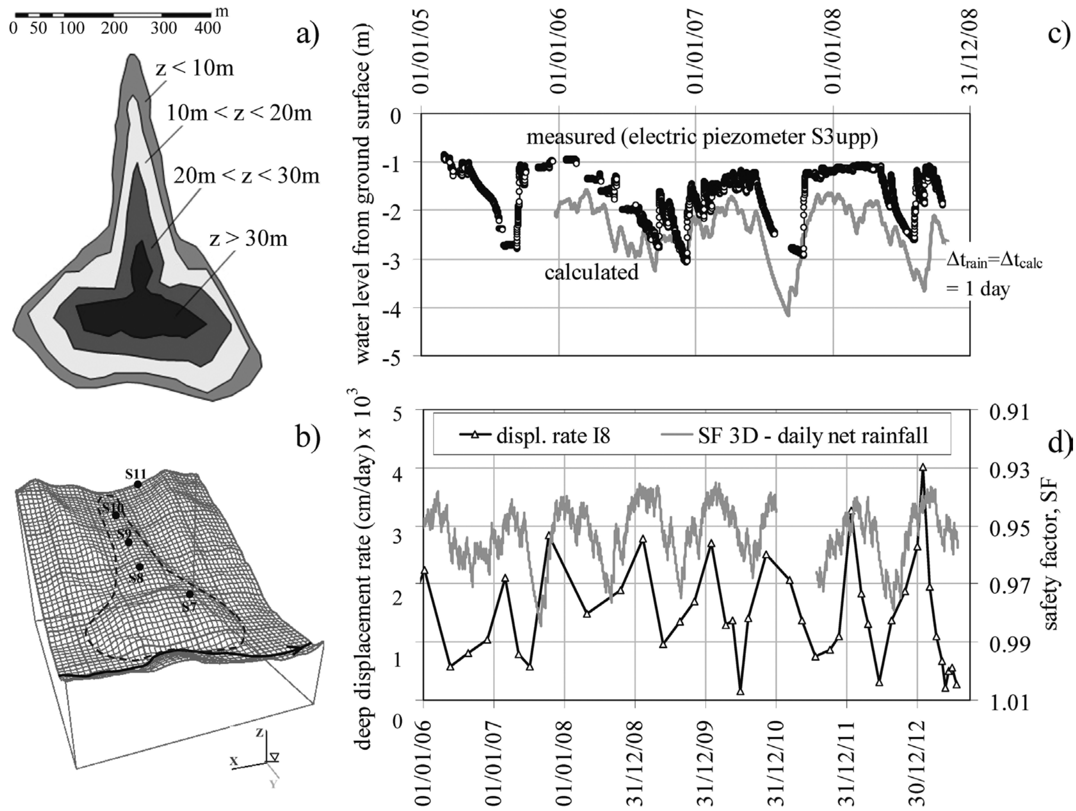

Fig. 8 – Slip surface with indication of areas at different depths a); MODFLOW 3D domain and mesh b); experimental data of the electric piezometer S3 and numerical results obtained by MODFLOW3D c); 3D safety factor SF and deep displacement rates in borehole I8 d).

Fig. 8 – Rappresentazione della superficie di scorrimento, suddivisa in zone caratterizzate da diversa profondità dal piano campagna a); dominio di calcolo in MODFLOW3D b); dati sperimentali della cella piezometrica S3 e risultati numerici ottenuti con MODFLOW3D c); fattore di sicurezza 3D e spostamenti profondi nel foro I8 d).

were assigned as input to the analysis [Vassallo *et al.*, 2015]. As a matter of fact, figure 8d shows that the time trend of displacement rates of inclinometer I8 – and thus of all the other inclinometers, given the landslide kinematics – is similar to that of SF. This latter linearly depends on the average pore water pressure u_{avg} along the slip surface, which varies with pore water pressures in the shallowest parts of the slip surface (within 10-15 m depth). It can thus be inferred that the landslide movements are influenced by the response to rainfall of the shallowest parts of the slip surface.

The model, although carefully constructed, represents an over-simplification of the complex conditions of earthflows which involve fissured, not homogeneous, tectonized clay shale formations, and thus it can be used only to a first approximation. The chemical composition itself of the clay pore fluid can give rise to osmotic potentials capable of modifying pore pressure distribution. The analysis of this aspect is currently under study. Furthermore, it is worth noting that, in large parts of the landslide, the upper soil undergoes seasonal variations of the saturation degree which can influence the soil shear strength not only through pore pressures but also through the variations induced in pore solution concentration.

6. Pore fluid composition and its influence on shear strength and displacements

The content and composition of the natural pore fluid of the Costa della Gaveta subsoil was determined on a number of samples extracted at different depths from several boreholes (Fig. 2). The chemical analysis was carried out on suspensions of the powdered material in distilled water. At the end of sedimentation, the supernatant liquid was analyzed by means of an inductively coupled plasma (ICP) spectrometer and by ion-selective electrodes. Then, the soil water content w having been determined, the concentrations of the main ions in the pore solution could be evaluated. The results show that the pore fluid is a composite solution in which Na^+ is the prevailing cation [Di Maio *et al.*, 2015; Di Maio *et al.*, 2016]. Figure 2, which plots Na^+ concentration against depth, shows that at about 28 m, Na^+ concen-

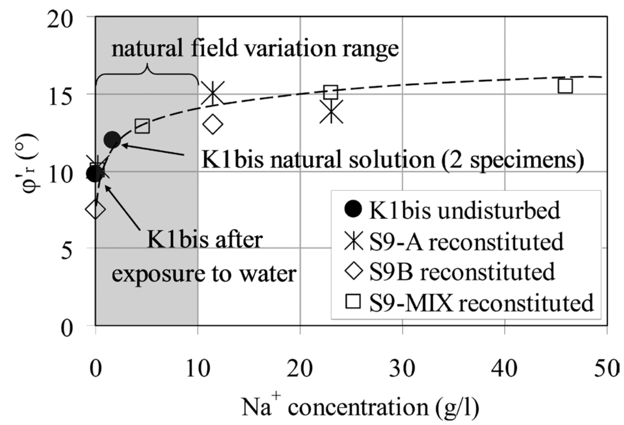

Fig. 9 – Residual friction angle φ'$_r$ against Na^+ concentration in the pore fluid of the Costa della Gaveta soil with indication of the range of the field natural variation inferred by Fig. 2 [DI MAIO *et al.*, 2016].
Fig. 9 – Angolo d'attrito residuo al variare della concentrazione di Na^+ nel fluido di porosità per il terreno di Costa della Gaveta, con indicazione del campo di variazione naturale in sito desunto dalla Fig.2 [DI MAIO et al.*, 2016].*

tration is close to that of the ion in a seawater with salinity of 35 g/l. In the main landslide body (boreholes I9b and I9c), the ion concentration gradually decreases towards the ground surface. Water adsorption due to exposure to rain and to the fresh water of confining aquifers, strain softening, ion diffusion and other transport phenomena are the most probable processes responsible of such a decrease. In the head zone (I12 and Ki), the ion concentration is almost uniform in the landslide material and much lower than that in the stable soil underneath. A reasonable explanation of this is given by the location of the head of the earthflow in the impluvium of the source area, where the ground/superficial fresh water and the material which strongly interacts with it, i.e. the colluvial material and shallow earth-debris flows, converge.

The reduction in pore solution concentration is known to cause a decrease in the shear strength of clay soils. The influence of pore fluid composition on the residual strength parameters of the Costa della Gaveta earthflow, to which the parameters available on the slip surface are reasonably close, was evaluated by several shear tests carried out on the material reconstituted with, and submerged in, NaCl solutions at different concentrations. Figure 9 shows that φ'$_r$ varies greatly with the solution concentration in the range of natural variation of Na^+ (which can be inferred by figure 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 (≈14°), and higher than the value the material can achieve for further contact with fresh water. This is suggested by the same figure 9 which shows that exposure to distilled water of the undisturbed specimens caused a reduction of φ'$_r$ from 12° to 10°.

Under constant effective stresses, the decrease in pore solution concentration can cause an increase in the rate of shear displacements. This effect was observed in the course of controlled shear stress tests carried out on specimens both intact and pre-sheared to the residual. Figure 10 refers to specimens reconstituted with a 1 M NaCl solution and initially immersed in the same solution. The specimens were first sheared to the residual strength under controlled shear displacement rate. Once at the residual, the tests were turned in stress controlled mode, and shear stresses lower than the residual shear strength in the solution were applied. While

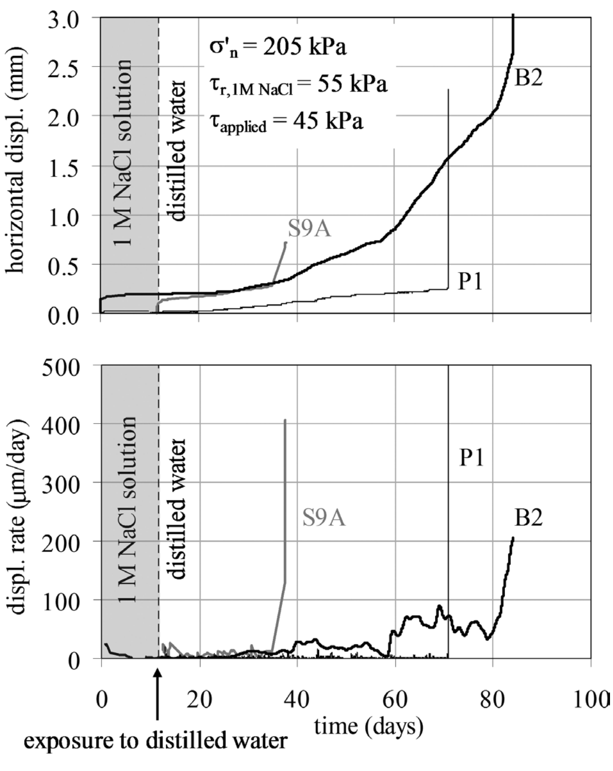

Fig. 10 – Horizontal shear displacement and displacement rate against time of Costa della Gaveta soil reconstituted with, and initially immersed in, 1 M NaCl solution, subjected to constant shear stresses ($\tau_{applied}$ = 45 kPa) and exposed to distilled water at the time indicated by the arrow [DI MAIO *et al.*, 2016; PONTOLILLO *et al.*, 2016].
Fig. 10 – Andamento nel tempo dello scorrimento e della velocità di scorrimento per provini di Costa della Gaveta ricostituiti con soluzione 1M di NaCl, sottoposti a tensioni tangenziali costanti ($\tau_{applied}$ =45 kPa) ed esposti ad acqua distillata a 14 giorni dall'inizio della prova [DI MAIO et al.*, 2016; PONTOLILLO* et al.*, 2016].*

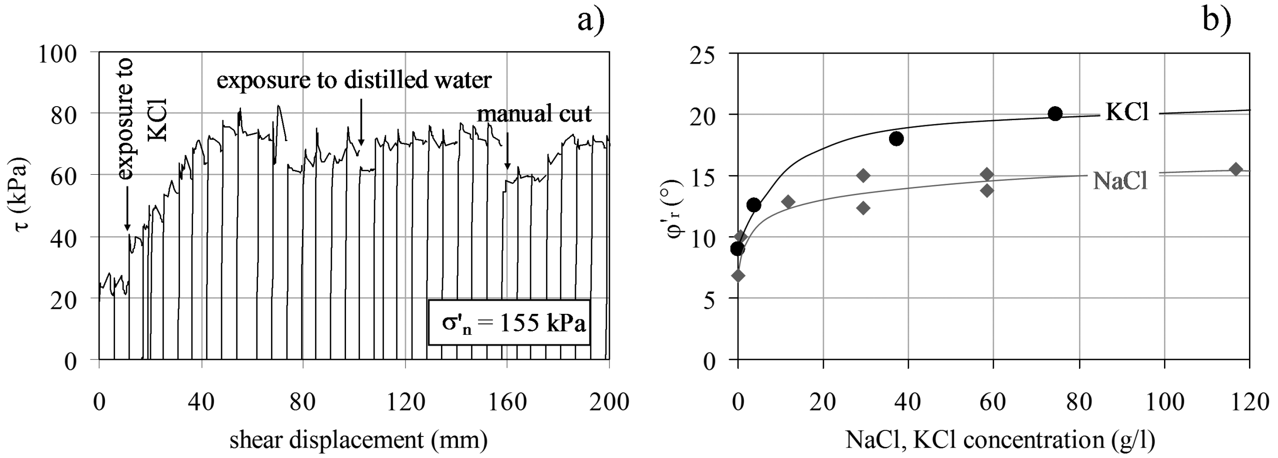

Fig. 11 – Shear strength against shear displacements of a specimen reconstituted with, and initially submerged in, distilled water, then exposed to 1M KCl solution and subsequently to distilled water again a), residual friction angle φ'_r against pore salt solution b) [DI MAIO *et al.*, 2015; DE ROSA *et al.*, 2016].

Fig. 11 – Resistenza al taglio in funzione dello scorrimento di un provino ricostituito con, ed inizialmente immerso in, acqua distillata, successivamente esposto a soluzione 1M di KCl e quindi ancora ad acqua a), angolo di attrito residuo φ'_r *in funzione della concentrazione della soluzione salina di porosità b) [DI MAIO* et al.*, 2015; DE ROSA* et al.*, 2016].*

submerged in the same solution, all the specimens did not undergo but negligible displacements, with rates decreasing to zero. Exposure to distilled water caused a gradual increase in the horizontal displacement rate up to values typical of failure. This type of behaviour was observed in tests carried out by the Casagrande shear box (specimens P1 and S9A in Fig. 2) as well as the Bishop ring shear (specimen B2), for the Costa della Gaveta soil as well as for pure clays. The analysis showed that the behaviour can be attributed to a drained loss of strength caused by the decrease in pore solution concentration following exposure to water [DI MAIO *et al.*, 2015; DI MAIO and SCARINGI, 2016; PONTOLILLO *et al.*, 2016].

If and how the observed natural reduction in pore solution concentration (Fig. 2) can cause an analogous process in the field conditions, contributing to the slow deformation of the clay slope, is currently under study. In the meanwhile, many laboratory and field tests are being carried out in order to verify whether it is possible to turn the chemical soil-pore fluid interaction to an improvement process.

Starting from data of the technical literature [HELLE *et al.*, 2015], which indicate KCl as one of the most adapt salts for a long-lasting improvement of clay mechanical behaviour, many specimens of the Costa della Gaveta soil were exposed to concentrated KCl solutions in the course of shear tests. The exposure produced ion diffusion towards the pores and an increase in strength to values much higher than those obtained with water (Fig. 11a), and even stronger than those obtained with NaCl (Fig. 11b). On the subsequent exposure to distilled water, the shear strength decreased negligibly, probably because ion exchange had taken place, thus making permanent the mechanical improvement. DI MAIO [1996; 1998] showed that exposure of clays containg Na-smectite to concentrated KCl solutions can cause a partially irreversible potassium fixation due to cation exchange. Furthermore, the author stressed that potassium effects are permanent under test conditions similar to those described in this paper, as well as under the conditions that normally occur in nature.

7. Soil improvement by KCl wells

7a. Data from literature

The concept of KCl wells aiming at stabilising clay deposits dates back to the 60s, when MOUM *et al.* [1968] proposed to drill low-diameter boreholes and fill them with crystalline salt and water. The salt would slowly dissolve and diffuse through the pore fluid towards the surrounding soil, resulting in an increasing concentration with time in the pore fluid at increasing distances. Based on field and laboratory K^+ diffusion tests, the authors estimated that in less than two years, the portion of Quick Clays clay up to 75 cm from the salt well axis would no longer be "quick", and that K^+ concentration would have increased at least up to 500 mg/l.

In 1972, a very high number of salt wells (2,629!) was installed in a Quick Clay deposit at Ulvensplitten, Oslo, Norway, in what was probably the largest application of the salt wells concept. The boreholes, 15 cm in diameter, were driven at a mutual distance of 1.5 m down to depths of about 15 m and filled with solid KCl. The natural pore fluid composition in the deposit was determined before the installation, resulting in: 350-470 mg/l Na^+, 31-33 mg/l K^+, 20-34 mg/l Mg^{2+} and 13-20 mg/l Ca^{2+} [EGGESTAD and SEM, 1976]. About 14 months after the intervention, the shear strength increased significantly up to a distance of 60-65 cm from the wells, thus stabilising the soil almost completely [EGGESTAD and SEM, 1974]. Approximately 21 months after the installation, the concentration of K^+ had increased 60 cm from the well to at least 50 mg/l, producing significant strength improvement [EGGESTAD and SEM, 1976]. In 2002 and in 2013, further investigations were carried out with the aim of verifying whether the effects of the KCl wells persisted 30-40 years after the intervention. The results [HELLE *et al.*, 2015] clearly showed that the soil improvement had further increased. The concentration profiles with depth showed values up to 3 g/l of K^+. Interestingly, also the concentration of Na^+, Ca^{2+} and Mg^{2+} were noticeably higher than those in the pore fluid of the non-treated soil. This was attributed by the authors to ion-exchange: K^+ adsorption would result in the release of the other counter-ions.

In Italy, KCl wells have been successfully adopted by VENIALE *et al.* [1986] in the northern Apennines. MAGGIÒ and PELLEGRINO [2002] showed some preliminary results obtained in a test field at Bisaccia (Avellino, Italy). The authors found that – probably because of the presence of discontinuities – ion transport had been faster than expected on the basis of laboratory tests.

Notwithstanding the promising results, the installation of salt wells is not yet commonly considered a reliable intervention, probably because its effectiveness in terms of actual improvement and of time necessary to achieve the improvement has not been sufficiently proved. Nevertheless, the topic is nowadays being receiving renewed attention. TORRANCE [2014] regards the salt wells as the safest method for Quick Clay stabilisation, being relatively non-intrusive but very effective. In North Europe, laboratory and field studies on the feasibility of such type of intervention are being undertaken both in Sweden [ANDERSSON-SKOLD *et al.*, 2005; SUER *et al.*, 2014] and in Norway [HELLE *et al.*, 2014].

7b. Test field at Costa della Gaveta

Structure and mechanical behaviour of Varicoloured Clays are very different from those of Quick Clays, but exposure to concentrated KCl solution also causes a strong increase in their residual shear strength, as shown by laboratory tests. In order to evaluate the field K^+ effects and rate of propagation, an experimentation has been recently initiated in the head zone of the Costa della Gaveta earthflow [DE ROSA *et al.*, 2016]. In a test field of 600 m^2, eleven boreholes, with depths between 11 m and 15 m - deeper than the slip surface which is there at about 8 m - were drilled at a mutual distance of about 5 m (Ki holes in Figs. 1 and 12) and stabilised by jacket slotted tubes (inner diameter 80 mm). Several reasons justify the choice of the location, among which: a) the earthflow head is the boundary from which water, driven by gravity, can transport ions in the whole landslide; b) pore ion concentration is uniformly very low in the head zone and thus ion transport from KCl wells can cause more significant and measurable effects; c) the depth of about 8 m of the slip surface, which reaches 40 m downslope, makes the investigation easier (possibility of drilling several boreholes, collecting soil and water samples, and so on); d) the higher displacement rate of this part of the earthflow makes the evaluation of its dynamics and of the effects of remedial interventions clearer.

Given the very limited soil volume interested by the experimental field, an influence of the wells on the landslide displacement rate is unlikely. At the moment, the experimentation is thus carried out mainly to find the most suitable procedures for increasing the rate of ion propagation in the soil surrounding the slip surface. To this aim, some of the boreholes indicated in figure 12 are filled with granular KCl while the others are used to monitor the ion transport caused by the chemical gradients. Hydraulic gradients are also applied to speed up the ion transport.

Figure 13 shows the time trend of K^+ and Na^+ concentration in the well water in the upper 6 - 7 m. The wells were initially full of perforation water with very low concentrations of several different ions. The figure shows that in the monitoring time, Na^+ concentration has increased to values within the natural range of the pore solution, towards a chemical equilibrium. K^+ concentration has reached the natural range in some boreholes (Fig. 13a) and much higher values in other boreholes (Fig. 13b), reasonably for the arrival of the ions from the salt well. The peaks of concentration have been generally recorded after prolonged rainfall or after the application of high hydraulic gradients by means of intense pumping. Figure 14a shows the transient following a rapid water table drawdown induced by pumping (about 7.5 m, i.e. beneath the slip surface) in terms of time evolution of water levels in the emptied hole (K2bis) and in a nearby KCl well (K3bis). During the transient, the dissolved salt could have been transported from the KCl well towards the emptied, attractor borehole. In order to verify this occurrence, ion concentration at about 6 m depth was measured, finding about 180 mg/l K^+ (Fig.13). Furthermore, the electrical conductivity profile of the water in the attractor was evaluated by means of a field multiparametric probe (courtesy of Dr Enzo Rizzo, CNR IMAA). Figure 14b compares the electrical conductivity profiles in the attractor before and after pumping, and

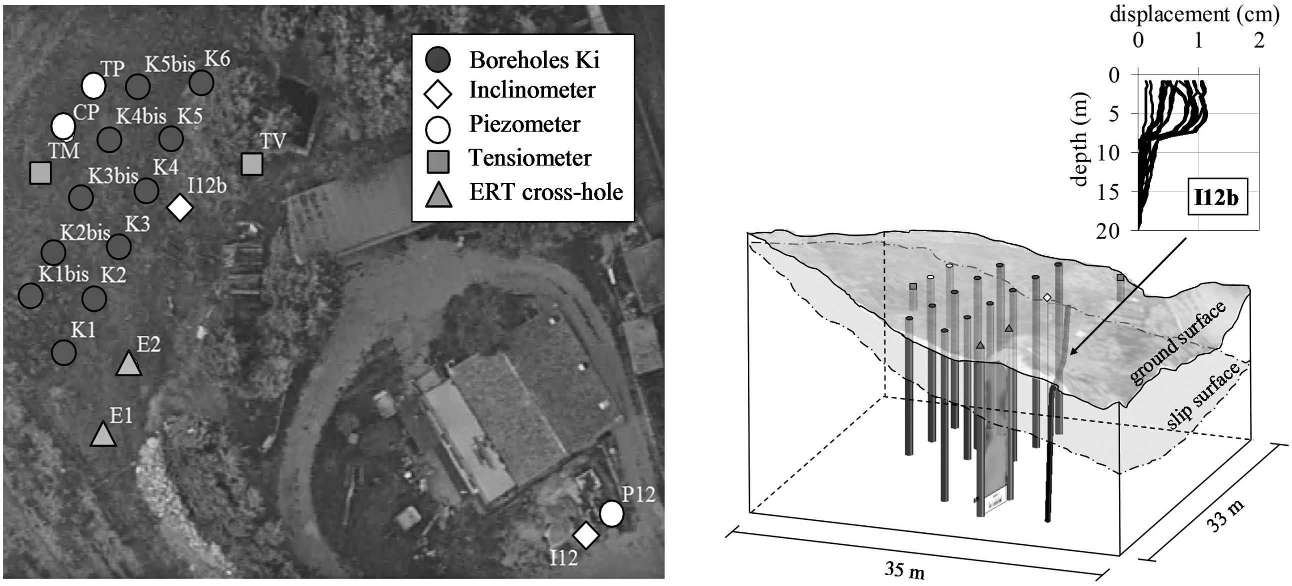

Fig. 12 – Test field in the head of the Costa della Gaveta earthflow. Schematic of the boreholes and of the installed instruments.

Fig. 12 – Campo prove realizzato in corrispondenza della testa della colata di Costa della Gaveta. Schema della distribuzione dei fori e degli strumenti di monitoraggio.

shows that one day after the beginning of the test, the electrical conductivity had increased significantly. Below the slip surface it had reached a value of about 40 mS/cm. To this value of electrical conductivity, salt concentrations higher than 20 - 30 g/l are likely to correspond, concentrations which, whatever the salt, can determine a great increase in the residual friction angle (Fig. 11b).

Thus, few months after the salt well installation, the increase in ion concentration 5 m from the well K3bis has increased from the natural range of 20 - 40 mg/l to values higher than 150 mg/l, showing a rate transport much higher than that evaluated by EGGESTAD and SEM [1976].

The coefficient of diffusion of Varicoloured Clays and Quick Clays being very similar ($2 \cdot 10^{-10}$ m^2/s and $6 \cdot 10^{-10}$ m^2/s [EGGESTAD and SEM, 1976] respectively), the higher transport rate determined at Costa della Gaveta can be reasonably related to advection induced by the applied hydraulic gradients. Consistently, first theoretical elaboration of the experimental results show that between the boreholes K2bis and K3bis the permeability coefficient k of the soil surrounding the slip surface is in the order of 10^{-6} m/s, higher than that evaluated within the landslide far from discontinuities ($k=10^{-8}$ m/s).

Between other couples of boreholes, the ion transport phenomenon is not so rapid, and the values of k of the soil around the slip surface result in the order of 10^{-8} m/s, equal to the value of the landslide material. A deeper investigation of the heterogeneity of the hydraulic characteristics of the landslide body is currently under study. Nevertheless, on

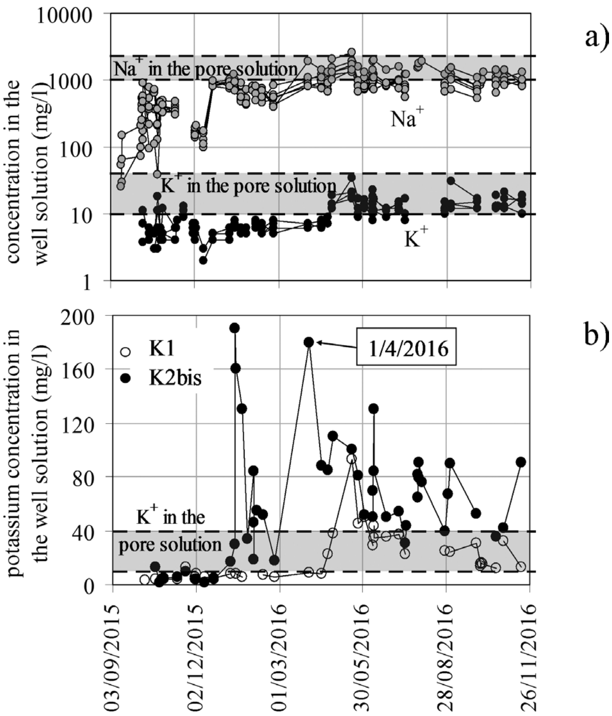

Fig. 13 – Time trend of K^+ and Na^+ concentration in the well water above the slip surface in the boreholes K1bis, K2, K3, K4 (a) and analogous K^+ concentration in the boreholes K1 and K2bis (b). The shadowed areas represent the range of the ions' concentration in the pore fluid.

Fig. 13 – Andamento nel tempo delle concentrazioni di K^+ e Na^+ nell'acqua dei fori K1bis, K2, K3, K4 al di sopra della superficie di scorrimento(a) e di K^+ nei fori K1 e K2bis (b). Le aree ombreggiate indicano il campo di concentrazione della soluzione interstiziale.

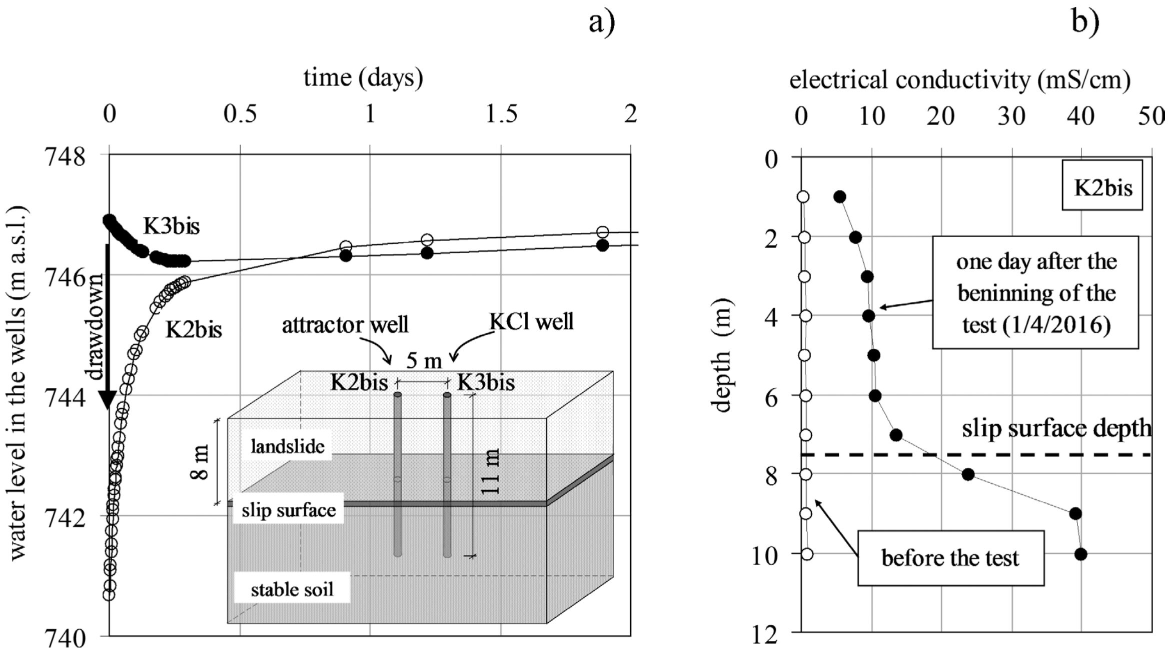

Fig. 14 – Water level in the wells K2bis and K3bis after a rapid drawdown in K2bis a), electrical conductivity evaluated by a field multi-parametric probe in the borehole K2bis before and after the drawdown of the water level b).
Fig. 14 – Livello d'acqua nei fori K2bis and K3bis dopo il pompaggio rapido in K2bis a), conducibilità elettrica valutata con una sonda multiparametrica da campo nel foro K2bis prima e dopo il pompaggio b).

basis of first results, it is possible to hypothesize that in the region of lower permeability, the ion transport is reasonably mainly due to diffusion and thus time evolution of the expected effects on pore fluid composition is not different from that described in Section 7a for the Quick Clay formation. According to HELLE *et al.*, [2014] these effects, even if achieved progressively in some years, can anyway be considered positive. In fact the use of KCl wells is safe, low cost, it would not cause but an improvement of the soil behaviour that is permanent in the conditions which occur in nature, and does not require maintenance.

8. **Summary and conclusions**

This paper summarizes the results of the study of the Costa della Gaveta landslide carried out within a research project funded by the Italian Ministry of Education, University and Research, MIUR.

In order to study an effective and sustainable intervention of landslide risk mitigation, the mechanical and chemical characterization of the earthflow has been carried out. The main results of the study can be summarized as follows. With the shape of an earthflow, the Costa della Gaveta landslide is currently characterized, fundamentally, by a very slow sliding on a thin shear zone. The internal, viscous deformations can be described by the Bingham rheological model. The mechanism of movements corresponds to a constant soil discharge in the channel. Over the monitoring period, the average yearly discharge has been practically constant. The seasonal variations can be qualitatively explained by the influence of rain on pore water pressures. The results of the first "classical" study, as a whole, allow the prevision of the future behaviour of the landslide for the next years, in the absence of exceptional events such as earthquakes or anthropogenic causes which must be analyzed case by case.

The design of an effective and sustainable intervention has been studied starting from a chemo-mechanical characterization of the landslide. The large displacements, the regularity of the slip surface, the stability analysis and the laboratory results indicate that the strength parameters available on the slip surface should be close to the residual ones. The results of laboratory tests show that the residual friction angle ϕ'_r is strongly influenced by the composition of the pore fluid which, in turn, varies greatly in the considered domain. In fact it is a composite aqueous ion solution, in which Na^+ prevails, the concentration of which decreases from high values in the bedrock to very low values in the upper soil horizons. The ion concentration distribution is not at equilibrium and can still decrease even on the slip surface. Laboratory tests show that under constant driving shear stresses, condition which is not far from the deep slip surface condition, a process of pore ion reduction can be a cause of strain or displacement acceleration.

Laboratory results also show that a treatment with KCl can effectively improve the mechanical properties of the Costa della Gaveta soil. To test procedures and to evaluate effects and applicability of such a type of treatment, an experimental test field has been installed in the earthflow head. Several wells, deeper than the slip surface, are filled with KCl grains, and ion concentration in nearby wells is monitored. Hydraulic gradients are also applied in order to speed up ion transport. The results show that the ion transport is such that a few months after the beginning of the tests, in some boreholes at 5 m distance from the KCl wells, the increase in salt concentration is noticeable and the soil surrounding the slip surface is exposed to a solution capable of influencing its shear strength.

The technical procedures to evaluate both the ion transport with spatial continuity and the consequent possible strength improvement actually obtained are currently under study.

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Monitoraggio e analisi di una colata in argilliti tettonizzate e studio di un intervento di mitigazione basato su pozzi di KCl

Sommario

Le colate in Argille Varicolori della valle del Basento, e in particolare le colate del versante di Costa della Gaveta a est della città di Potenza, costituiscono i casi di studio. Sulla base di indagini di sito e di laboratorio, monitoraggio degli spostamenti superficiali e profondi, misura e calcolo delle pressioni interstiziali, si è ricostruita la struttura geologica del colle, descritta la cinematica delle frane principali e studiata l'influenza delle piogge sulle pressioni interstiziali e sugli spostamenti.

Integrando la rete di monitoraggio installata sulla frana di Costa della Gaveta nel 2005, sono stati realizzati nuovi fori in punti "strategici", in cui sono state installate sonde inclinometriche fisse e celle piezometriche con acquisizione continua. E' stato quindi valutato l'andamento nel tempo degli scorrimenti profondi e delle deformazioni interne del corpo di frana in vari punti della sezione longitudinale e di alcune sezioni trasversali. Il meccanismo di scorrimento sembra corrispondere a un movimento a portata di terreno costante nel canale, con velocità medie annue poco variabili nei dieci anni di osservazione. Le piogge influenzano le variazioni di velocità stagionali. Il legame fra spostamenti e piogge, analizzato tramite regressione polinomiale ottimizzata con approccio data driven, è descrivibile con un buon grado di approssimazione per i dieci anni di osservazione con un polinomio semplice. Mediante modellazione 3D, sono stati valutati gli effetti della serie storica di piogge sulle pressioni interstiziali. Questi sono risultati significativi fino a profondità di circa 10-15 m e trascurabili alle profondità maggiori. Le variazioni di velocità lungo la superficie di scorrimento sembrano pertanto dipendere dalle variazioni delle pressioni interstiziali sulle fasce perimetrali, meno profonde, della superficie di scorrimento che peraltro contribuiscono con una percentuale notevole dell'area totale. Gli effetti delle piogge sui terreni superficiali possono essere anche di natura chimica. Allo scopo di caratterizzare la frana da un punto di vista chemo-meccanico, sono stati valutati la composizione del fluido interstiziale naturale in numerose verticali e gli effetti delle sue variazioni su numerosi parametri meccanici e, in particolare, sulla resistenza residua a taglio e sugli scorrimenti viscosi lungo superfici di rottura al residuo. I risultati sperimentali suggeriscono che la riduzione di concentrazione di Na^+ del fluido interstiziale, avvenuta per vari processi naturali, abbia contribuito al decadimento delle proprietà meccaniche dei terreni in esame. E' stata quindi valutata la possibilità di indurre un efficace recupero di resistenza sempre mediante processi chimici e, in particolare, mediante l'incremento della concentrazione di K^+ della soluzione di porosità. A tale scopo è stato realizzato un campo prove di "miglioramento chemo-meccanico" con vari fori, in parte usati per l'immissione di sali di potassio a profondità predefinite, in parte per l'imposizione di gradienti idraulici in grado di direzionare flussi di acqua e ioni. La propagazione ionica nel corpo di frana viene monitorata analizzando la soluzione prelevata da fori realizzati ad hoc a varie distanze dai pozzi di sale.

I primi risultati mostrano che la velocità di propagazione degli ioni K^+ risulta abbastanza alta, in alcune zone della superficie di scorrimento, e tale da rendere i tempi dell'intervento accettabili da un punto di vista applicativo.