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ENGINEERING GEOLOGICAL INVESTIGATION OF THE FONTANE LANDSLIDE (EASTERN LIGURIA, ITALY)

GIACOMO PEPE(*), GIOVANNI RIZZI(**), BARBARA MUSANTE(**),
GRETA VIOLA(**) & ANDREA CEVASCO(*)

(*)University of Genova - Department of Earth, Environment and Life Sciences - Corso Europa, 26 - 16132 Genova (Italy)
(**)ResGeo consultant - Via Fico Eraldo, 32/1 - 16039 Sestri Levante (Genova, Italy)
Corresponding author: giacomo.pepe@unige.it

EXTENDED ABSTRACT

La frana di Fontane è situata nel settore orientale della Liguria (Italia nord-occidentale), a pochi chilometri di distanza dal centro costiero di Sestri Levante (GE). Si tratta di un movimento franoso a cinematica lenta impostato lungo un versante collinare ubicato all'interno del piccolo bacino del Torrente Staffora, affluente di destra del Torrente Gromolo. Al di sopra del corpo di frana sorge la piccola frazione di "Fontane", dove le problematiche di instabilità connesse al movimento franoso sono note già a partire dalla fine degli anni '50. Il meccanismo di movimento della frana è da considerarsi di tipo complesso, ma con una componente prevalente di scivolamento rotazionale. L'evoluzione geomorfologica recente dell'accumulo di frana ha ripetutamente condizionato la stabilità del piccolo insediamento di "Fontane". Nel febbraio 2014, in seguito ad un periodo particolarmente piovoso, l'innesco di una brusca riattivazione dei movimenti ha causato gravi danni alla strada comunale e ad alcuni edifici, comportandone l'evacuazione.

In questo studio vengono presentati i risultati delle indagini effettuate per la caratterizzazione geologica e geotecnica del corpo di frana e per l'analisi delle caratteristiche cinematiche del movimento franoso. L'analisi dei dati provenienti da sondaggi a carotaggio continuo, indagini geotecniche di laboratorio e di sito, e da prospezioni di tomografia sismica a rifrazione, ha consentito di definire la composizione e la geometria del corpo franoso.

Dai risultati ottenuti è emerso che i materiali che costituiscono l'accumulo di frana risultano marcatamente eterogenei, sia per composizione sia per tessitura. Il deposito di frana è infatti caratterizzato dall'irregolare alternanza di terreni sabbioso-ghiaiosi, talvolta localmente caratterizzati da assetti caotici. Lungo la direzione assiale del versante, la geometria del deposito è caratterizzata da spessori medi di circa 9-10 m, osservati in corrispondenza della testata di frana, e di circa 12-14 m nelle zone intermedie dell'accumulo. Lo spessore medio del materiale instabile aumenta notevolmente verso il piede di frana, dove il substrato roccioso è stato rinvenuto alla profondità massima di circa 27 m. Inoltre, l'analisi combinata delle indagini dirette e indirette di sottosuolo ha evidenziato come lo spessore laterale del deposito franoso sia estremamente variabile. Tale osservazione rivela una morfologia particolarmente complessa della superficie del substrato roccioso sottostante, caratterizzato da depressioni probabilmente imputabili alla presenza di antichi impluvi, attualmente sepolti dai depositi di frana. Tali morfologie sepolte potrebbero rappresentare vie preferenziali di circolazione delle acque sotterranee, che a loro volta potrebbero avere un ruolo significativo nell'influenzare la cinematica della frana di Fontane.

Dal monitoraggio inclinometrico è emerso che, negli ultimi 15 anni circa, la cinematica della frana ha alternato fasi di quiescenza a fasi di attività, intervallate ad occasionali riattivazioni. Durante le fasi attive, sono stati misurati movimenti ciclici fortemente correlati al regime pluviometrico locale. In concomitanza dei periodi piovosi autunnali e invernali sono state osservate importanti accelerazioni dei movimenti. Al contrario, movimenti estremamente lenti sono stati registrati nei periodi secchi tardo primaverili ed estivi.Tuttavia, i dati di spostamento profondo, misurati in continuo per mezzo di una sonda inclinometrica fissa, indicano che i movimenti lungo la superficie di scivolamento non coincidono con i livelli massimi di pioggia. Nello specifico, i picchi di spostamento sono stati rilevati diversi giorni dopo i massimi quantitativi di precipitazione e sono stati innescati dall'incremento della pressione interstiziale in corrispondenza della superficie di scorrimento.

Questi risultati suggeriscono una risposta "ritardata" dei meccanismi di movimento della frana a eventi meteorici intensi. Tuttavia, poiché agli episodi piovosi più intensi si sono succedute giornate di precipitazioni leggere e moderate, studi futuri dovranno approfondire il ruolo dei periodi di pioggia prolungati sulla mobilità della frana.

I risultati di questo studio possono costituire un'importante fonte di informazioni utili alla pianificazione delle strategie di mitigazione del rischio connesso all'evoluzione cinematica del fenomeno franoso; in particolare, possono rappresentare un valido riferimento a supporto della definizione di un sistema di allertamento per scopi di protezione civile e della progettazione di efficaci misure strutturali di messa in sicurezza dell'abitato.

ABSTRACT

This study deals with both the engineering-geological and kinematic characterization of the Fontane landslide based on geological and geophysical field investigations and on geotechnical monitoring campaigns. The coupled analysis of stratigraphic boreholes and of seismic refraction tomography profiles allowed to constrain the geometry of the landslide body. The outcomes showed that the thickness of the landslide deposit is extremely variable laterally. This observation suggested a complex morphology of the landslide bedrock surface, outlined by infilled V-shaped depressions. Such morphological concavities have been interpreted as hollows/channels carving the substratum. The investigation of the landslide motion revealed that, over the last fifteen years, the landslide kinematic was characterized by the alternation of dormant and active phases together with occasional reactivations. During the active periods, seasonal cyclic movements correlated to the local hydrological regime were found. However, through the analysis of displacement data measured by one fixed inclinometer probe, it was observed that the movements along the slip surface are not synchronous with severe rainfall events. Specifically, it was found that the displacements peaks are attained several days after the highest rainfall levels and are controlled by the increase in pore-water pressure on the slip surface. These findings suggest a delayed response of the landslide kinematic to severe rainstorms.

***Keywords**: flysch rock mass, Fontane landslide, geotechnical monitoring, slow-moving landslide*

INTRODUCTION

Slow-moving landslides represent a serious threat for a wide range of facilities such as buildings, roads, highways, railways, dams, bridges and pipelines (Mansour *et alii*, 2011; Del Soldato *et alii*, 2017). Based on the magnitude of cumulative displacements produced by this family of slope instabilities, the extent of damage can lead to a complete or partial loss of facility serviceability (Mansour *et alii*, 2011). These landslide-induced damage can cause severe social and economic impacts, especially in economically advanced countries. Frequently, slow-moving landslides develop along one or several existing failure surfaces, also exhibiting various stages of movements (e.g., occasional reactivations, acceleration and deceleration phases) (Massey *et alii*, 2013; Lacroix *et alii*, 2020). However, the kinematic behaviour of these phenomena is usually complex since influenced by several hydrological, geological, hydrogeological and geotechnical causal factors (Lacroix *et alii*, 2020 and references therein). Therefore, to accurately understand slow-moving landslide processes, the availability of information from engineering-geological investigations and slope monitoring techniques is essential (Turner & Schuster, 1996). The wide spectrum of available methods and techniques (e.g., in-situ measurements, laboratory tests, monitoring networks) represents a fundamental source of data for the definition of hazard caused by the slope movements (Lu *et alii*, 2014) along with enabling the design of effective remedial measures (Eberhardt *et alii*, 2007; Corsini *et alii*, 2006).

The Liguria Region (northwestern Italy) is characterized by a predominantly mountainous-hilly territory where landslides represent a frequent morphological element of the landscape (Carobene & Cevasco, 2011). Because of a large variety of weak and structurally complex rock formations (De Vita *et alii*, 2012; Pepe *et alii*, 2015) along with a complex tectonic evolution (Carobene & Cevasco, 2011), deep-seated and slow-moving landslides are widespread across the region. Moreover, due to the paucity of gentle and flat areas, several ancient landslide bodies have represented suitable zones for developing urban settlements and agricultural activities in historical times (Tofani *et alii*, 2014; Cevasco *et alii*, 2018). However, these landslides are often source of damage on the built environment because of their still active kinematic or as a consequence of recurrent reactivations.

This paper deals with the engineering-geological characterization of the Fontane landslide, a slow-moving rotational slide located in eastern Liguria. In recent years, the landslide motion produced important damage to several buildings and roads settled over the landslide body. Based on geological, geotechnical and geophysical data, collected from field surveys and sub-surface investigations, the engineering geological model of the landslide accumulation was investigated. Furthermore, through the analysis of geotechnical monitoring data, the relationships between the landslide kinematic and its causes were examined.

GENERAL SETTING OF THE STUDY AREA

The study area is situated in the eastern sector of Liguria, within the territory belonging to the coastal municipality of Sestri Levante, approximately 50 km east from the city of Genoa (Fig. 1a, b). The Fontane landslide is located just a few kilometres inland, on the left side of the small hilly catchment of the Staffora stream (1.6 km^2), a right tributary of the Gromolo stream.

From the geological point of view, this sector of the catchment pertains to the Northern Apennine and it is characterized by the tectonic units belonging to the Internal Ligurids Domain (Bortolotti *et alii*, 2014). Specifically, the landslide area shows the superposition of two turbiditic successions (bottom to top): the Forcella Banded Shales Fm. (FBS, Upper Campanian) and the Gottero Sandstones Fm. (GS, Upper Campanian – Paleocene) (Fig. 1c). The former consists of an alternation of thinly bedded argillaceous and silty- arenaceous shales. The

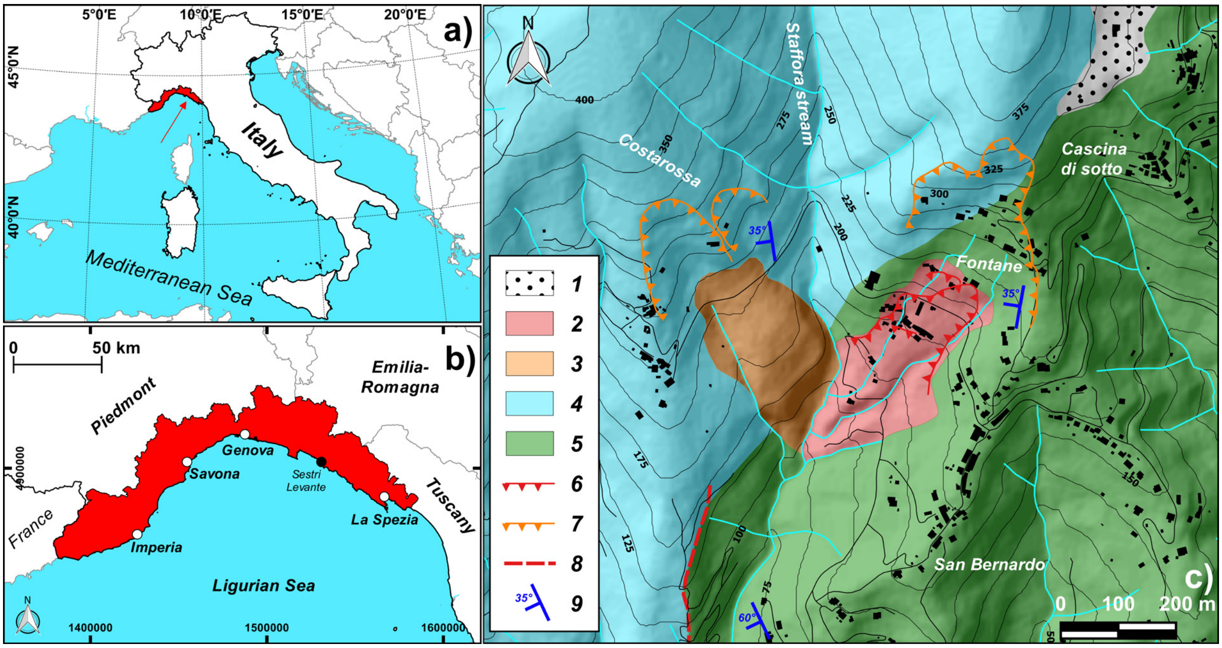

Fig. 1 - a, b) Location of the study area; c) Geological and geomorphological map of the study area (after Bortolotti *et alii, 2014, redrawn and modified). LEGEND: 1) slope debris; 2) active landslide deposit; 3) dormant landslide deposit; 4) Gottero Sandstones Fm.; 5) Forcella Banded Shales Fm.; 6) tension crack; 7) dormant landslide crown; 8) presumed fault; 9) bedding attitude*

latter is typically made up of thickly bedded quartz-feldspatic sandstones with subordinated intercalations of thinly bedded argillaceous shales and siltstones. During the tectonic phases of the Northern Apennine orogenesis, both rock formations were involved in large recumbent folds (Bortolotti *et alii*, 2014). Simultaneously, rock masses undergone intense deformation and tectonic disturbance. Indeed, the FBS formation, which largely crops out in the eastern zone of the study area, is affected by a pervasive schistosity and is intensively folded. Overall, bedding surfaces show a primary attitude prevalently west-southwards oriented with dips usually in the range 35-60°. However, the orientation of bedding surfaces can locally change due to secondary geo-structural patterns. The Fontane landslide affects a SW-facing slope located just westwards of the small village of "San Bernardo". The landslide extends between 350 and 125 m a.s.l. and it consists of a complex movement showing a dominant rotational sliding component (Federici *et alii*, 2004). The main landslide crown is visible in the upper part of the slope, at approximately 350 m a.s.l., and it develops downslope up to the average elevation of 250 m a.s.l. (Fig. 1c). Currently, the main crown is covered by a dense vegetation and it can be considered as dormant since no active geomorphological signs of movement are discernible (Federici *et alii*, 2004). The main landslide body is enclosed between two slope ridges approximately NE-SW oriented, while the landslide foot directly reaches the path of the Staffora stream. The zone of accumulation shows a smooth and hummocky topography (average steepness of 20°) which is carved by two short and linear channels. The displaced material has a length of approximately 450 m and a maximum width of approximately 200 m. The landslide deposit is occupied by the small hamlet of "Fontane", which is characterized by scattered buildings, while in its upper part is crossed by a municipal road.

In the zone of accumulation, some secondary active tension cracks can be identified (Fig. 1c). These cracks were produced by an important reactivation of the movement that took place in early 2014, after a rainy period of about three months. According to witness statements of local inhabitants, the movements in this portion of the landslide are known from the late 1950s.

MATERIALS AND METHODS

Three main borehole drilling campaigns (i.e., 2006, 2014 and 2016) were executed in the different part of the landslide body (Fig. 2). During continuous coring boreholes, 11 partially remoulded soil samples were withdrawn, whereas Standard Penetration Tests (SPT) were executed at different depths. The following geotechnical laboratory tests were carried out on collected soil samples: grain size analyses (9 through sieve method and 2 through both sieve and sedimentation analysis), water content and bulk unit weight measurements, consistency limits determinations. In 2014, borehole data were integrated with seismic refraction tomography surveys (Fig. 2). Seismic alignments were oriented roughly perpendicular to the local dip direction of the slope.

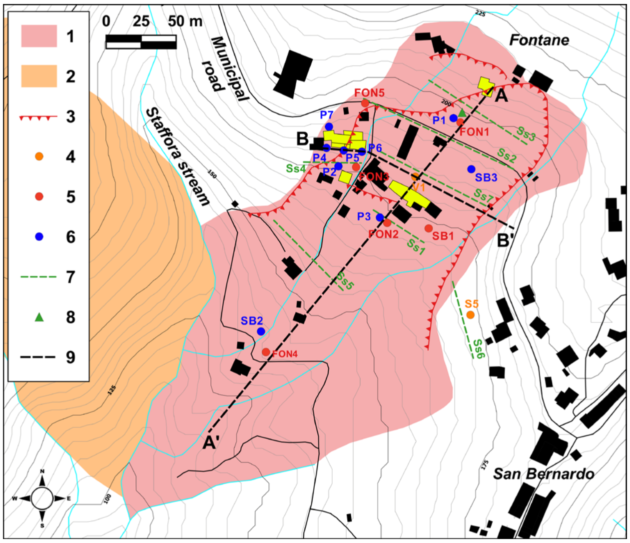

Fig. 2 - Map of geological and geophysical investigations and of geotechnical monitoring systems. LEGEND: 1) active landslide deposit; 2) dormant landslide deposit; 3) tension crack; 4) stratigraphic borehole; 5) inclinometer; 6) piezometer; 7) seismic survey; 8) rain gauge; 9) cross section profile. Buildings coloured in yellow are those that suffered from major damage due to the landslide reactivation occurred in February 2014

The first geotechnical monitoring campaign was performed in the period 2006-2008 based on one vertical equipped with inclinometer (i.e., SB1) and two with open standpipe piezometers (i.e., SB2 and SB3). The second monitoring period was set up in 2014, when both continuous coring and core destruction boreholes were exploited for the installation of flexible inclinometer casings and open standpipe piezometers for traditional and periodical measurements (Fig. 2). In June 2015, in-place automatic inclinometer probes were installed within some pre-existing inclinometer tubes (i.e., FON1, FON2, FON3, FON4). Automatic probes were positioned in correspondence to failure surfaces and/or zones of more pronounced deformations detected during the previous inclinometric traditional measurements. Moreover, a pore-water pressure transducer was installed within a borehole (i.e., P3) drilled close to the inclinometer FON2 (Fig. 2). The pore-water pressure transducer was positioned at a depth of 12 m, in correspondence to the slip surface detected within the tube FON2. Eventually, the monitoring network was completed with a rain gauge positioned at the landslide head. In 2016, geotechnical monitoring was further implemented through the installation of four open standpipe piezometers and one standard inclinometer tube (Fig. 2). This last group of monitoring devices was concentrated in the western side of the "Fontane" hamlet, in the framework of the design of remedial interventions to consolidate a damaged residential building.

In this study, on the basis of information coming from direct and indirect investigations, the engineering-geological model of the landslide body was defined. To this purpose, two representative cross-sections profiles were drawn. The first profile (AA') was taken parallel to the landslide axis whereas the second one (BB') was carried out roughly perpendicular to it, approximately along the middle portion of the unstable area and across the most densely built-up zone of the "Fontane" hamlet (Fig. 2). Subsequently, based upon geotechnical monitoring data, the landslide motion from 2006 to 2008 and from 2014 to 2016 was investigated. These monitoring periods allowed to explore the patterns of movement of the landslide and their correlations with rainfall. Up to 2015, rainfall data collected from the rain gauge located in the center of Sestri Levante (i.e., Sara rain gauge station) were used. Starting from June 2015, information on rainfall recorded by the rain gauge installed on the landslide were employed. Finally, with the aim of investigating the relationships between rainfall, pore-water pressure and displacements, a preliminary analysis of automated and continuous monitoring data measured on the slip surface detected within tube FON2 was performed.

RESULTS

Engineering-geological characterization

Stratigraphic logs and geotechnical laboratory analyses revealed that the landslide materials are markedly heterogeneous, both in terms of composition and texture. In fact, the landslide deposit is characterized by the irregular alternation of sandy-gravelly soils, often including cobbles and rock fragments, and sometimes locally showing chaotic fabrics.

According to the Unified Soil Classification System (USCS), the coarser soil samples withdrawn from continuous coring boreholes consist of clayey-silty gravels (GM-GC) and clayey gravels (GC), whereas finer materials are made up of clayey-silty sands (SM-SC) and clayey sands (SC). Generally, the maximum gravel content can be as high as 45% while the minimum value is lower than 5% (Fig. 3a). The sand percentage ranges approximately from 25% to 55% while the fines content (i.e., silt + clay) is broadly comprised between 25% and 50% (Fig. 3a). In Fig. 3b the consistency limits of the fine matrix versus depth are depicted.

The liquid limit (w_L) ranges approximately between 23% and 35% while the plastic limit (w_P) varies between 16% and 22% (Fig. 3b). The Plasticity Index (PI) usually falls within a somewhat narrow range of values (i.e., 6-9%) (Fig. 3c). Anyway, most of PI values are abundantly less than 15%, indicating a general low plasticity of the fine matrix (Fig. 3c). Given the nature of soils under investigation along with the frequent appearance of rock fragments, only partially remoulded samples were extracted during drilling operations. Notwithstanding, some standard geotechnical laboratory tests were performed to obtain a rough estimate of fundamental physical parameters

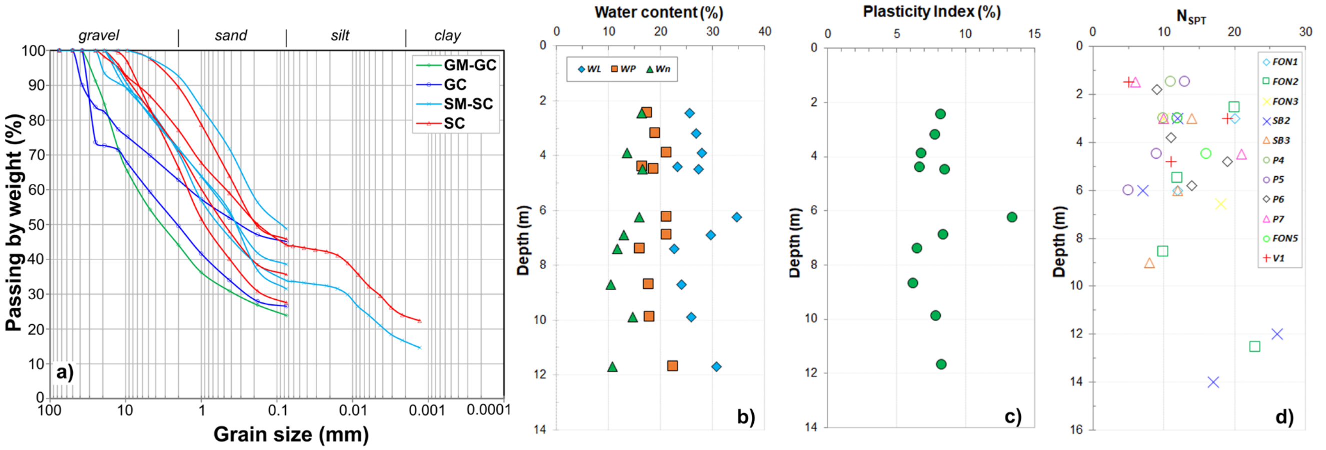

Fig. 3 - Geotechnical features of the landslide materials: a) grain size distribution; b, c) consistency limits, natural water content and plasticity index versus depth; d) SPT-N value versus depth

of soils. The outcomes indicated that the natural moisture content (w_n) assumes quite similar values with depth, spanning approximately from 10.5 to 15.5% (Fig. 3b), albeit these values can be affected by the presence of coarser soil particles. Instead, the bulk unit weight of soil samples is comprised between 19.4 and 21.5 kN/m^3.

Standard Penetration Test data are considerably scattered with depth (Fig. 3d), suggesting that the resistance of subsoil to the advancement of the probe may have been influenced by the presence of levels containing cobbles and rock fragments of varied sizes. However, SPT-N values are prevalently comprised between 5 and 25, indicating that the landslide deposit can be assumed from loose to medium dense. According to seismic tomograms, S-wave velocities (V_S) are generally low within the landslide body, with values ranging from approximately 200 to 700 m/s (Fig. 4). The lowest velocities, namely lower than 250 m/s, were found in the first 2 or 3 m below ground level (b.g.l.). These shallow velocities can be associated to the organic and anthropically reworked organic soils. Subsequently, S-wave velocities gradually increase with depth, up to reaching maximum values of approximately 700 m/s within the deeper horizons of the landslide deposit (Fig. 4). Borehole investigations showed that the bedrock underlying the landslide deposit belongs to the FBS Fm.. The bedrock is from slightly to highly weathered, even though the higher weathering degrees are more frequently confined to the shallowest rock mass horizons. The geo-mechanical complexity and heterogeneity of the landslide bedrock is mirrored by the wide spectrum of RQD values, usually ranging between 10 and 55, with the scattered occurrence of RQD values equal to zero because of severely fractured and crushed horizons. According to RQD index, the geo-mechanical quality of the rock mass can be classified as from very poor to fair.

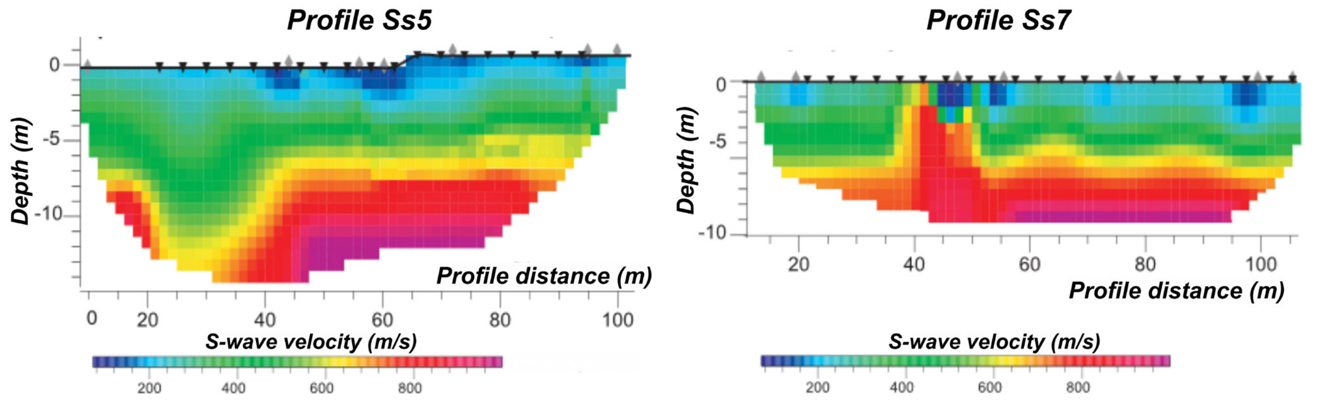

Fig. 4 - Representative S-wave seismic refraction tomography profiles (see Fig. 2 for location)

Based on information coming from stratigraphic boreholes and geophysical surveys, two representative engineering-geological cross-sections were drawn (Fig. 5).

Along the axial direction, the thickness of the landslide deposit generally increases moving from the upper to the lower sectors (Fig. 5). The smallest thicknesses (about 9-10 m) can be observed at the landslide head, while they are slightly higher (about 12-14 m) along the middle zones of the accumulation. The thickness of the unstable material increases noticeably towards the landslide foot, where the landslide bedrock was found at the maximum depth of approximately 27 m within borehole SB2 (Fig. 5). However, as can be note from the cross-section with trace BB' (Fig. 5), the outcomes of direct and indirect investigations indicated a pronounced variability of the lateral thickness of the landslide deposit. This is clearly visible along the western part of the cross-section. Although boreholes P4, P5 and P6 are very close together and at the same elevation, the landslide bedrock was found approximately at 6, 8 and 12.5 m b.g.l., respectively, denoting a progressive thickening of the landslide deposit in the lateral direction (Fig. 5). Moreover, despite the proximity of the piezometers installed inside these verticals, different average groundwater table levels were detected. The observations from stratigraphic logs compare well with the outcomes of some seismic wave velocity models (Fig. 4), which in some cases exhibit deep low-velocity zones. For example, as shown in Fig. 4, along the seismic tomogram Ss5, at the profile distance comprised between 20 and 40 m, a V-shaped low velocity anomaly was found. It can be noted that low V_s values (<500 m/s) persist up to a depth of approximately 11 m. Such anomalies could be interpreted as depressions filled by low-stiffness materials.

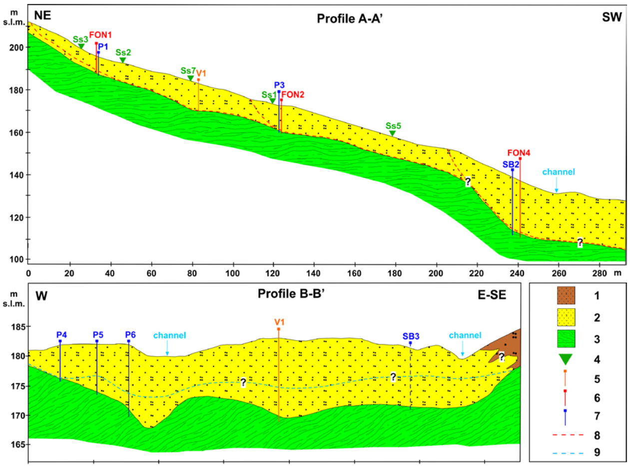

Fig. 5 - *Interpretative engineering-geological cross-sections of the Fontane landslide body (see Fig. 2 for location). LEGEND: 1) eluvial-colluvial deposit; 2) landslide deposit; 3) bedrock (FBS Fm.); 4) seismic survey; 5) stratigraphic borehole; 6) inclinometer; 7) piezometer;8) slip surface; 9) average water table*

Landslide kinematic

The inclinometric measurements carried out periodically from October 2006 to October 2008 (Fig. 6a) in the borehole SB1 show that cumulative horizontal displacements at the tube head can be assumed negligible (<1.5 mm) and comprised within the margin of accuracy of the monitoring device.

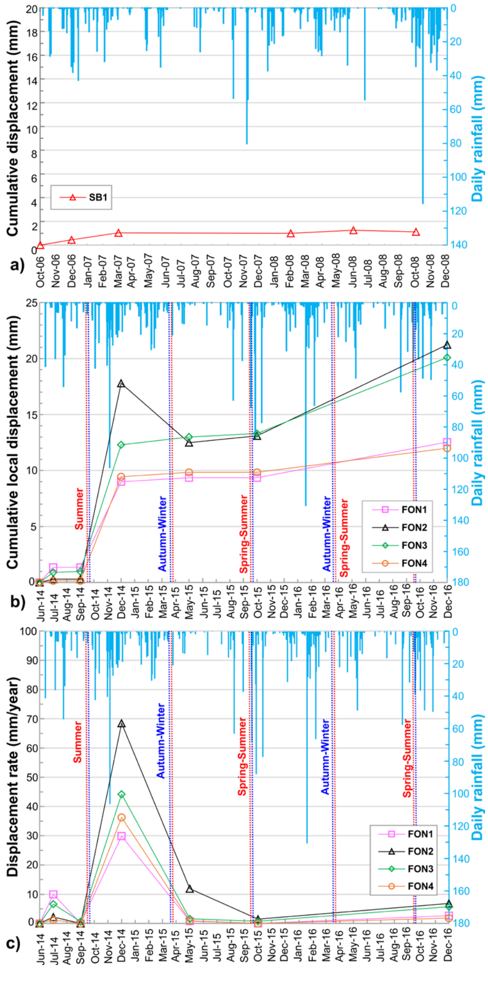

Fig. 6 - *Landslide motion against time and associated rainfall sequence: a) comparison between cumulative displacements at the tube head and daily rainfall (period 2006-2008); b) comparison between cumulative local displacement and daily rainfall (period 2014-2016); c) comparison between displacement rate on the slip surface and daily rainfall (period 2014-2016)*

These monitoring data indicate that, despite some rainstorms occurred, the state of activity of the landslide may be classified as "dormant". Afterwards, no quantitative data on the landslide kinematic are available up to the second half of 2014, when a new monitoring network was implemented. Before that, a phase of activity is known from interviews with local inhabitants. Precursory signals of movements were observed between November and December 2013. These movements culminated with the important reactivation of the landslide occurred between January and February 2014. The analysis of rainfall data revealed that these months were particularly wet. In November and December 2013, cumulative monthly rainfall equalled 145.2 and 147.4 mm, respectively. On the other hand, the total rainfall accumulated in January and February 2014 reached 645 mm, which represents approximately 45% of the local mean annual rainfall (1450 mm). The geotechnical monitoring of subsurface displacements during the period following the landslide reactivation highlighted that the movement mechanisms continued to be active (Fig. 6b, c). From the profiles of the horizontal cumulative displacement measured within inclinometers, zones of intense deformation can be clearly detected (Fig. 7).

Above these localized deformations, the shape of inclinometric profiles appears somewhat regular because of homogeneous displacements, especially along the verticals FON3 and FON4 (Fig. 7). Some secondary deformations can be identified along the profiles measured within tubes FON1 and FON2. These observations suggest that the movements produced limited internal deformations of the moving mass. Therefore, the displacements measured on the slip surfaces can be assumed as highly representative of the kinematic features of the landslide. Moving from the landslide head to the landslide foot, the slip surfaces were found at increasing depth (Fig. 7). In the upper part of the landslide body, the slip surface developed at approximately 6 m b.g.l. (i.e., tube FON1). In the middle sector (i.e., tubes FON2 and FON3), the zones of concentrated deformation are situated at approximately 12 m b.g.l., while in the lower one (i.e., tube FON4), the slip surface was identified at 24 m b.g.l. (Fig. 7). All inclinometric measurements showed SW oriented displacements that are fundamentally consistent with the average dip direction of the slope. From the plot of cumulative displacements measured at the slip surfaces against time, it can be noted that the landslide kinematic is characterized by the alternation of phases of faster and slower displacements (Fig. 6b, c). However, despite some differences in the magnitude of measured displacements, the patterns of movement are somewhat uniform across the different sectors of the landslide. The most important accelerations of the slope movements occurred between 2014 and 2015. By comparing the cumulative local displacements to daily rainfall (Fig. 6b), the main patterns of movement can be assumed, to a first approximation, as seasonal. In fact, the most important displacements were recorded during the autumn and winter seasons. The seasonal variation affecting the landslide kinematic can be easily recognizable from traditional inclinometric measurements covering the period June 2014-May 2015 (Fig. 6b, c). For example, in Autumn 2014, all inclinometers recorded accelerations of the movements. In detail, from September to December, the maximum local displacement (approximately 18 mm) was recorded along the vertical FON2 while the minimum one (approximately 8 mm) along the tube FON1. In this time interval, a severe rainstorm hit central-eastern Liguria on November 10th (Cevasco *et alii*, 2015; 2017; Roccati *et alii*, 2018). At the Sara rain gauge station, which is the closest to the study area, a cumulative daily rainfall of approximately 106 mm was recorded. Moreover, it is interesting to point out that, the week before, this rainstorm was preceded by some days

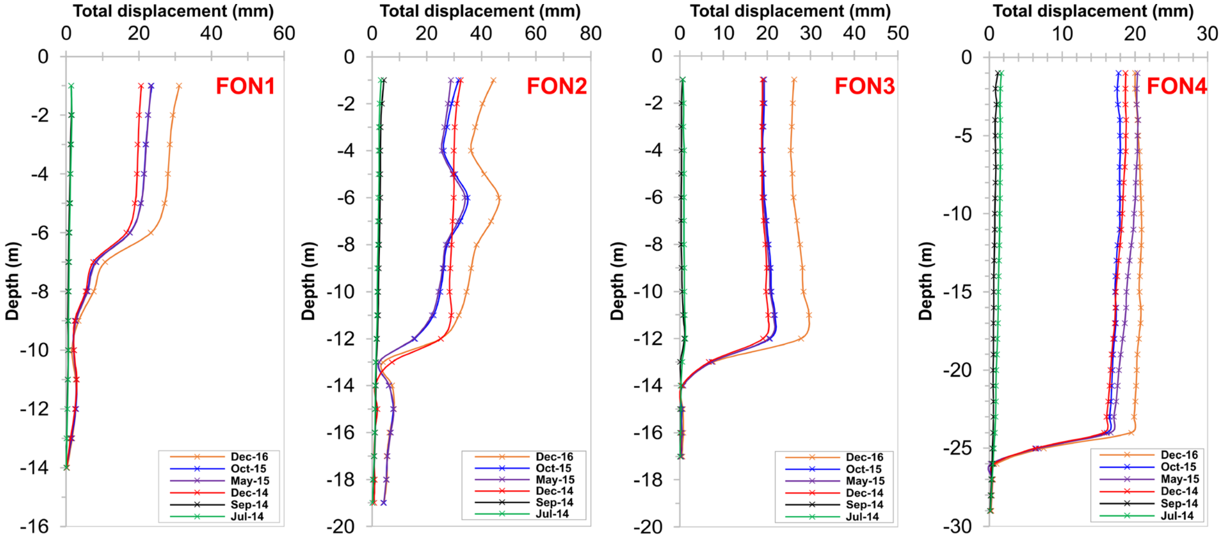

Fig. 7 - Inclinometer profiles of tubes FON1, FON2, FON3 and FON4 showing measurements performed in the period July 2014-December 2016

of prolonged rainfall. In the previously mentioned time window, measured average displacement rates range from approximately 30 mm/year to approximately 69 mm/year, and thus movements are classifiable as "very slow" according to Cruden & Varnes (1996). Conversely, very small (<1.5 mm) or null displacements were detected during spring and summer periods (e.g., from June to September 2014 and from May to October 2015) (Fig. 6b). Overall, these data revealed that the landslide during the driest months is characterized by "extremely slow" average movement velocities (Fig. 6c). During the following monitoring period, namely from October 2015 to December 2016, the seasonal kinematic of the mass movement is not clearly appreciable because of poor temporal resolution of traditional inclinometer measurements (Fig. 6b, c). Nevertheless, the relationships between hydrological regime and landslide motion can be still found by examining continuous data series acquired from automatic monitoring systems. In particular, it is interesting to analyse shear displacements registered by the fixed inclinometer probe installed within tube FON2 and pore-water pressure data measured by pressure transducer P3. As can be seen from Fig. 8, the sequences of movement measured by the in-place inclinometer probe agrees with those of periodical traditional measurements.

During the dry period, extremely low (<0.5 mm) or null daily displacements were measured on the slip surface. Subsequently, starting from the early winter season, a slight increase in the trend of the landslide motion can be observed. Interestingly, two main displacement peaks occurred in February 2016 (Fig. 8). Throughout the month, the rain gauge positioned over the landslide body recorded significant rainfall amounts. The cumulative monthly rainfall was approximately 337 mm, with the occurrence of two main rainfall episodes. The most severe rainstorm occurred on February 6th, when cumulative daily rainfall attained 130.4 mm. Approximately 20 days after, a less intense event occurred, characterized by a maximum cumulative daily rainfall of 66.2 mm. Both episodes were followed by some days of moderate and light rainfall. As can be seen from Fig. 8, the two main displacements peaks are associated with two sharp pore-water pressure increases on the slip surface. However, it is relevant to point out that these peaks are not synchronous with maximum rainfall levels. In detail, it can be noted a delayed response that was estimated as long as 15 days after the most severe rainy day, and approximately 10 days after the second rain episode (Fig. 8). As pore water pressure approaches the maximum values, the displacement on the slip surface increases noticeably.

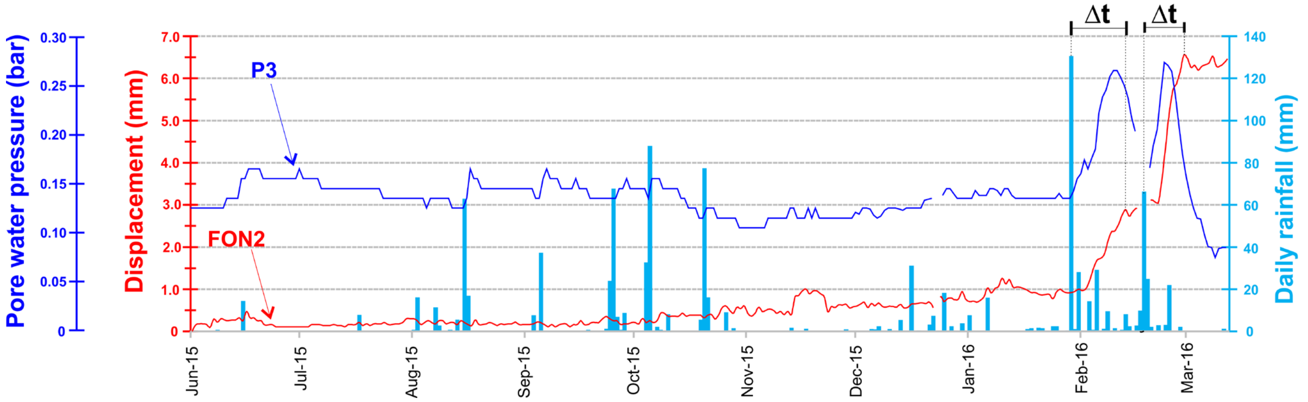

Fig. 8 - Comparison between daily local displacement, daily pore-water pressure and cumulative daily rainfall for the period June 2015-April 2016. The two main time lags (Δt) between maximum rainfall levels and displacement peaks are marked

DISCUSSIONS AND FINAL REMARKS

The purpose of this study is to contribute to the understanding of both the engineering-geological model and kinematic features of the Fontane landslide. The outcomes from site investigations showed that the landslide terrains are markedly heterogeneous and that the thickness of the landslide deposit is extremely variable, especially in the lateral direction (Fig. 5). This latter evidence suggests that the landslide bedrock is characterized by a complex morphology. Based on stratigraphic logs and of seismic profiles, the lateral changes in the thicknesses of the landslide accumulation may be associated to infilled depressions within the underlying bedrock. Taking into account the peculiar shape of the seismic-wave low-velocity anomalies (Fig. 4), such concave morphologies may be interpreted as buried hollows/channels carving the landslide substratum. As described in technical literature (Jongmans & Garambois, 2007), geophysical methods proved very useful in investigating the geometry and structure of the landslide bedrock. By means of gravimetric surveys, Del Gaudio *et alii* (2000) detected a hollow affecting the substratum of an earthflow located in southern Italy. As noted by the same authors, such bedrock concavities could negatively influence slope stability. Indeed, these buried morphologies could represent preferential ways of groundwater circulation and they could give rise to major groundwater flows that in turn can result in excess pore-water pressure, especially in case of intense rainfall events. Although no evident clues are still available, it can be supposed that the detected buried hollows may have some roles in influencing the kinematic of the Fontane landslide. In this regard, the analysis of time series of geotechnical monitoring data revealed some important correlations between slope movements, rainfall and pore-water pressure changes. The outcomes showed that, over the last fifteen years, the landslide kinematic alternated dormant phases to active ones together with occasional reactivations (Fig. 6). However, it was found that during the active phases, the landslide movements follow seasonal cycles that mainly depend on the local hydrological regime. Slope displacements experienced accelerations during the rainy seasons (i.e., autumn/winter). Conversely, extremely slow up to null movements have been recorded in drier periods (i.e., late springer/summer). This kinematic behaviour is typical of slow-moving landslides and it is consistent with several experiences reported in literature (Coe *et alii*, 2003; Handwerger *et alii*, 2013; Massey *et alii*, 2013). The examination of automated continuous monitoring data, acquired along an active slip surface, highlighted that a possible explanation of the onset of displacements can be linked to peaks in pore-water pressure driven by rainfall. It was observed that the movements accelerated significantly as pore-water pressure approached its maximum values (Fig. 8). However, a time lag of several days was observed between the highest rainfall levels and the displacement peaks. Consequently, this evidence suggests a delay in response of the landslide movements to severe rainstorms. As observed by some studies on slow-moving landslide mechanisms (Schulz *et alii*, 2009; Handwerger *et alii*, 2013), the delayed reaction of slope movements to external hydrological input can be ascribed to the rate of pore water pressure diffusion within the landslide body and especially toward the slip surface. However, since light and moderate rainfall were observed following the most severe rainfall episodes, the influence of multi-day rainfall periods will be investigated in future studies (Vassallo *et alii*, 2016; Doglioni *et alii*, 2020). The results of this study reveal that the motion of the Fontane landslide depends on the combination of different driving factors that give rise to a complex sequence of processes. The findings of this research can provide very useful insights to define a landslide early warning system for civil protection purposes. In this regard, the implementation of both pore-water pressure and displacement continuous monitoring should represent an essential component of the warning scheme (Intrieri *et alii*, 2012; Pecoraro & Calvello, 2021). Finally, the kinematic characterization of the landslide along with the generated interpretative engineering-geological models can represent a fundamental source of information for the design of effective structural risk mitigation measures.

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