Evolutionary kinematics and geological features of the large Pisciotta rock slide (Cilento Geopark, Campania, southern Italy)

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Abstract: In the Pisciotta municipality (Province of Salerno, Cilento Geopark, southern Italy), a large and slow moving landslide is known since several decades for having damaged continuously an important provincial road which crosses its body and to have requested repetitively maintenance works for permitting vehicle traffic. The almost uninterrupted state of activity, existed in the last seventy years at least, the slow kinematics, not yet evolved in a paroxysmal global failure stage, and the exposition to risk also of a railway tunnel make this landslide a special case of geohazard to be analyzed. The landslide involves entirely a hilly slope constituted of a Paleogene turbidite series belonging to the Saraceno Formation (Nord-Calabrese tectonic unit), which is formed by intercalated calcarenites, marls and mudrocks and is completely deformed by a polyphasic folding. In this research, engineering geological, geomorphological and topographical analyses were finalized to understand geological factors and kinematics of the Pisciotta landslide.

Among principal results, the landslide spatial occurrence and its kinematics are controlled by specific geological and stratigraphic factors such as the existence of an argillaceous member, whose dominant attitude of bedding is downslope dipping with a dip that is generally equal or lower than the local slope angle, and of a fault that bounds the landslide on its left flank. Furthermore, results derived by the displacement of the provincial road, since 1955, as well ground displacements measured by an on-purpose monitoring campaign (September 2006-March 2009) allowed to reconstruct the landslide kinematics and to understand further the deep-seated mass movement behavior. Based on such analyses, the Pisciotta landslide is classified as an active, very slow to slow, deep-seated rock slide involving a volume of rock-mass varying between 4 and 6 × 10⁶ m³.

Key-Words: Turbidite series, Argillaceous rocks, Rock slide, Landslide kinematics, Slow slope movements, Life-lines at risk.

1 Introduction

Turbidite and basinal series formations are among terrains most prone to deep-seated landslides both in Italy (Del Prete and Guadagno, 1990) and worldwide (Nemčok et al., 1982; Margielewski, 2006; Klimeš et al., 2009; Baroň et al., 2011) owing to the coexistence of several factors predisposing to slope instability, such as variable argillaceous component, mechanical anisotropy of the rock-masses and predisposition to loss of shear strength induced by deep weathering. This scientific issue is well known in Italy since the ‘70s of the last century, when first researches on slope instabilities of turbidite and basinal series formations led to the identification of a special category of engineering geological units, named structurally complex formations, and a proposal of classification to be used for slope stability issues (Esu, 1977). Deep-seated landslides in structurally complex formations were generally recognized as characterized by initial evolutionary stages with very slow to slow ground movements preceding a paroxysmal global slope failure, with velocities up to the rapid class (Cruden and Varnes, 1996; Corbi et al., 1999; De Vita et al., 2001). For such features, these large mass movements represent commonly a risk higher for the exposed buildings, infrastructures and life-lines, than for human lives. The latter is usually related to typical feasibility to evacuation and easy recognition of signs indicating the imminence of a global slope failure. Nonetheless, secondary risks for human lives, induced indirectly by these large landslide even in the pre-paroxysmal evolutionary stages, consisting in a likely activation of rapid and...
shallow slope instabilities superimposed over the deep-seated ones, cannot be neglected.
This kind of large slope movements has always represented a challenging topic of research for both geotechnical and engineering geological approaches, especially for what concerns the challenging modeling of slope stability by an ordinary geotechnical approach (Hutchinson, 1995), and for requesting a deep comprehension of mechanical features and heterogeneities of rock masses (Guzzetti et al., 1996; Marinos and Hoek, 2001; Picarelli et al., 2005). In fact, complex rupture mechanisms, controlled by pre-existing shear planes, involvement of residual shear strength, progressive rupture mechanism (Bjerrum, 1967; Rose and Hungr, 2007), reduction of shear strength due to weathering (Taylor and Cripps, 1987) as well as stratigraphic and structural factors controlling landslide onset, kinematics and evolutionary stages, make forecasting and modelling the location and evolution of these landslides much harder than shallow landslides.
Following a precedent research (De Vita et al., 2013), in this paper we present further characterizations of the Pisciotta landslide (Cilento Geopark, Campania, southern Italy), which describe principal features, evolutionary stages and kinematics of this large slope mass-movement.

2 Geological setting

The Pisciotta landslide is located close to the southwestern sector of the Cilento Geopark coast (Campania region, southern Italy). This area, which has been inscribed among the European Geoparks network since 2010, is a sub-region of the Campania. The geological settings of the Cilento, achieved during the orogeny occurred since the Early Miocene, are representative of the fold and thrust-belt structure of the southern Apennines (D’Argenio et al., 1973; Mazzoli and Helman, 1994; Mostardini and Merlini, 1986; Patacca and Scandone, 2007). Therefore, the morphostructural setting of this area is strongly controlled by features and geometric relationships among principal tectonic units, which are formed by sedimentary series belonging to palaeo-environments of carbonate platforms and interposed marine basins, existed from Triassic to Late Cretaceous.
Specifically, the Pisciotta area is constituted of the Nord-Calabrese tectonic unit, turbidite series deposited in an inner palaeogeographic domain which were involved in the orogeny since the Early Miocene (Bonardi et al., 1988; Ciarcia et al., 2009) and overthrusted over the outer carbonate platform palaeogeographic domains. During the Apennine orogeny, both units were unconformably covered by the wedge-top turbidite flysch deposits of the Cilento Group, Burdigalian-Langhian in age (Bonardi et al., 1988, 2009) and the Monte Sacro Formation (Upper Tortonian in age; Selli, 1962).
Specifically, in the Pisciotta area, the Saraceno Formation outcrops (Vezzani, 1968; De Blasio et al., 1978), which was dated between the Upper Eocene series and the Aquitanian stage (Di Staso and Giardino, 2002). The stratigraphy of the Saraceno Formation comprises a turbidite series formed by alternating calcarenites, calcilutites and mudrocks with a maximum thickness of approximately 600 m. The Saraceno Formation is intensely deformed by a polyphasic folding (Vitale et al., 2010), which was favored by the ductile mechanical behaviour of the flysch rock-mass.

3 Current morphological setting of the unstable slope

The Pisciotta landslide develops in the Rizzico locality, stretching on the left side of the Fiumicello Torrent valley, about 200 m upstream of its outlet into the Tyrrhenian Sea. In the current evolutionary stage (2014) the slope mass movement involves the entire slope of a secondary hill, predominantly facing westward and comprised in the altitudinal range between 237 and 15-25 m a.s.l. (Fig. 1). The middle sector of this unstable slope is crossed by the provincial road SS 447 for a length of about 570 m. The uninterrupted deformations of the road planometric geometry and continuous cracking of the road pavement led to recognize the existence of a slope mass movement since the ‘60s of the last century. During years, the increasing ground displacements became even more evident, especially in the road sectors crossing the landslide flanks, whereas the local inclination increased up to the limit allowed for vehicular traffic. Due the slow ground movement, the functionality of the road was preserved by continuous repairing works consisted in smoothing of cracks opened in the road pavement by earth and asphalt fillings. Only in recent years, the slow slope ground deformations, which initially were related to an undefined shallow mass movement, were attributed to a large and deep-seated landslide due to a clearer recognition of a typical morphological impact affecting the whole hillslope (Fig. 1).
The most evident structural features of the landslide (Fleming and Johnson, 1989; WP/WLI, 1993) were identified in a well-defined main scarp reaching the
middle sector of the slope and describing a typical arc shape (Fig. 1). The main scarp has a stepped morphology being produced by a close series of scarps, with a dip-slip kinematics, forming a total vertical throw of approximately 20 m with an average dip angle of about 75°. The left flank of the landslide, which is derived by the downslope continuation of the main scarp, is clearly identifiable down to about 80 m a.s.l.. In this sector, a trench crossing the SS 447 road with a strike-slip kinematics is clearly observable. Differently, the right flank is less advanced downslope because it is extended down to approximately 150 m a.s.l.. Consequently the left side of the landslide appears relatively more mobile as it is indicated by stronger deformations of the SS 447 road in this sector, especially at the boundary between stable and unstable zones where the most important maintenance works were carried out.

The main body of the landslide, which is relatively accessible only in the middle-upper part, presents a series of surficial structures consisting in secondary scarps and counterscarps, often with a width and depth of few meters, and grabens (Fleming and Johnson, 1989). Moreover, a general bulging of the landslide foot is easily recognizable by a global view from the opposite side of the valley due to the increase in the slope angle of its frontal part and the occurrence of a series of small shallow landslides involving the detrital mantle.

The landslide foot is intersected by two tunnels of the national Battipaglia-Paola railway stretch (Fig. 1). Among them, the most exposed to landslide movements appears the northernmost one because it intersects the central part of the landslide toe.

In recent years, the worsening of the road SS 447 conditions and the potential scenario of a rapid paroxysmal global failure of the slope, led the Salerno Province to set an alert system for warning the vehicular traffic, since September 2006. Therefore, a campaign to monitor ground and underground deformations was undertaken by the Salerno Province through the predisposition of a bi-weekly topographic monitoring. For such a scope 50 optical targets were distributed in the upper part of the landslide body, between the SS 447 road and the main scarp. Moreover, three boreholes, equipped by inclinometers, and the installation of three wire-extensometers across the main cracks were carried out.

Fig. 1 – The Pisciotta landslide (modified from Google Earth, 2004).

4 Approaches of study

Different approaches were applied to reconstruct a geological and evolutionary model of the landslide. Geological and geomorphological surveys were executed over an extent of approximately 15 km², comprising the landslide area and its stable surroundings. Structural surveys were conducted in all the accessible outcrops of the Saraceno Formation to provide systematic measurements of the bedrock attitudes. To this end an indirect window sampling technique based on terrestrial stereoscopic photographs (De Vita et al., 2012) was applied. Moreover, stratigraphic data derived by boreholes, resistivity and seismic refraction geophysical tomographies were also used to reconstruct the geological model of the landslide (De Vita et al., 2013).

The kinematic and evolutionary phases of the unstable slope were reconstructed by a geomorphological analysis (Corbi et al., 1999; De Vita et al., 2001) of all available aerial photographs taken in: 1943, 1955, 1956, 1971, 1982, 1991, 1995, 2003 and 2006 (orthophoto). The comparison of variable paths of the road SS 447 during years, derived by topographic maps and orthophotos available in the period 1955-2006, allowed a long-term quantitative kinematic analysis of displacements and ground deformations. Moreover, kinematic analyses were also carried out in a shorter time period by analyzing topographical measurements started in September 2006 and lasted approximately for 18 months, till March 2009.
5 Results

5.1 Long-term kinematic evolutionary stages (1943–2006)
An earlier evolutionary stage of the landslide was recognized since 1943, whose aerial photograph showed first traces of the main scarp, in the upper part of the slope, as well as no bulging of the slope foot. Following, between 1955 and 1956, the expansion of the main scarp, which described a more complete arc shape and a clearer appearance of secondary scarps were observed. For the successive years (1971, 1982 and 1991), an additional increase of the morphological impact of the main scarp was identified by a significant enlargement of its vertical throw and planimetrical trace, especially in the left side of the landslide. During such a time span, also the landslide foot became progressively more evident by the bulging of the foot slope. This ground deformation has led to the increase of the local slope angle and to the predisposition to shallow landsliding of the surficial detrital mantle. Such morphological impacts of the principal landslide structures became even more evident and pronounced in the following years. Furthermore, new ground fractures with strike-slip kinematics and secondary scarps were detected. Finally, by the most recent aerial photograph (orthophoto) taken in 2006, a global worsening of the impact of the mass movement over the slope was recognized by the expansion of the vertical displacement of the main scarp as well as of secondary scarps and the development of a series of longitudinal and transverse cracks.

By mapping the SS 447 road track, the horizontal displacements of the middle sector of the unstable slope were estimated with reference to four fixed transects, set normal to the road axis (A–A’, B–B’, C–C’ and D–D’ in Fig. 2). In addition, these kinematic data were integrated with topographical monitoring of the upper part of the slope accomplished in the period September 2006 - March 2009. For the whole observation period (1955-2009), the cumulative horizontal displacements of the road axis showed an unexpected maximum total value of 53 m for the A–A’ transect, with an average velocity of 2.7 mm day$^{-1}$ (0.81 m year$^{-1}$). Instead, displacements and velocities were observed to diminish progressively for the other road transects located toward the right flank of the landslide, with minimum values reached for the D–D’ transect: 22 m and average velocity of 1.1 mm day$^{-1}$ (0.41 m year$^{-1}$). Additionally, by observing the whole time series, different rates of horizontal displacements were detected for the years preceding and following 1994. In detail, in the A–A’ road transect, average velocities of 2.2 mm day$^{-1}$ (0.81 m year$^{-1}$) and of 4.0 mm day$^{-1}$ (1.46 m year$^{-1}$) were estimated for periods preceding and following 1994, respectively.

![Figure 2: Cumulative displacements of the provincial road SS447 assessed for four transects normal to the road axis from 1955 to 2009.](image)

5.2 Kinematics of the upper landslide body (September 2006 to March 2009)
The bi-weekly topographic monitoring of the 50 optical targets distributed upslope of the road SS 447 allowed to assess the ground displacements and their spatial distribution. Data were transformed in maps of fundamental kinematic variables: horizontal cumulative displacement; vertical cumulative displacement; total cumulative displacement; average velocity over the whole observation period (18 months); maximum velocity measured for each optical target between two consecutive topographic measurements.

The maps of the cumulative displacements showed a general progressive downslope increase up to 4.36 m (8.1 mm day$^{-1}$ on average) and -2.06 m (-3.8 mm day$^{-1}$ on average), respectively for horizontal and vertical components of the most mobile optical target. In the direction normal to the slope movement, a tendency to increase of ground displacements and velocities towards the left flank of the landslide was observed. More in detail, the highest values appeared to be concentrated in a narrow strip, shifted towards the left flank of the landslide and approximately parallel to it.

The statistical analysis of all the recorded velocity data, calculated between two consecutive measurements and related to all the available optical targets (2016 records for the 42 optical targets located into the landslide body), permitted to estimate the spatial and temporal variability of the ground velocities: 0.8 mm day$^{-1}$ (2.5th percentile),
4.7 mm day$^{-1}$ (50th percentile – median value) and 15 mm day$^{-1}$ (97.5th percentile).

5.3. Reconstruction of the landslide geological model

Geological surveys, carried out in the surroundings of the landslide area, stratigraphic data gathered by boreholes and geophysical tomographies, permitted the reconstruction of the landslide geological model and the identification of stratigraphic intervals involved in the slope instability as well as structural constraints controlling the landslide geometry.

In the lowest stratigraphic positions, the typical turbidite calcarenite lithofacies of the Saraceno Formation was found. In this lower stratigraphic interval, the bedrock lithologies were observed to be comprised of calcarenites and subordinate calcilutite beds, with lenses and nodules of chert. Due to the turbidite sedimentological facies, these lithologies were observed being rhythmically alternated with mudrock interbeds. The ratio between the lithoid (calcarenite and calcilutite) and the mudrock components was estimated to be the highest among the whole series (up to 5:1 – 10:1).

In higher stratigraphic positions, such as those surrounding the landslide main body and within the unstable zone itself, calcareous marls, marls and subordinate calcarenites, alternated with an abundant mudrock component, were found. In this higher stratigraphic interval, the ratio between the lithoid and mudrock components was observed reaching lowest values (down to 2:1 – 1:1). For both stratigraphic intervals, a polyphasic ductile deformation was recognized, according to what previously discovered by other studies (Vitale et al., 2010). The Geological Strength Index (Marinos and Hoek, 2001) was estimated ranging from 35 to 45 (B to C classes) for the lower stratigraphic interval and varying from 10 to 20 (F to H classes).

On the basis of such stratigraphic setting, two distinct engineering geological units (Dearman, 1991) were identified: a) calcarenite lower member; b) marly limestone upper member. Owing to the lack of any outcrop of the bottom of the lower member, the only stratigraphic thickness was estimated for the upper unit as varying between 40 and 60 m.

More stratigraphic details were obtained by boreholes, which confirmed an upward greater abundance of mudrocks and marly limestones alternated to calcarenites. The water table was intercepted only in the lowest borehole (B1) at approximately 25 m depth and at an altitude (35 m a.s.l.), a little higher than the valley bottom.

The statistical analysis of all bedding attitude data indicated a significant clustering for dip direction and dip angle values around 250°N to 290°N and 10° to 12° respectively, besides of a dispersion of bedding data due to the polyphasic folding. Therefore the global attitude of the Saraceno Formation was found to be WNW dipping, with an average dip lower than the slope angle, for the left-hand side of the Fiumicello Valley. By the stratigraphic and morphological observations, two principal normal fault systems, NW-SE and NE-SW striking, were identified. A normal fault passing through the upper zone of the left flank was supposed to control strongly the landslide geometry by putting the marly limestone upper member in lateral contact with the lower calcarenite member.

The inclinometer measurements indicated discrete sliding surfaces at different depths: 19 m for B1 borehole at the landslide foot; 34 m for B2 borehole in the middle-right sector of the landslide; and 5, 10, 19 and 32 m for B3 borehole. The closeness (less than 10 m) of the latter borehole to the left landslide boundary and the deepest deformation datum (32 m deep) led to reconstruct a subvertical geometry of the rupture surface in this sector. Such an
observation supported further the interpretation that the normal and subvertical fault forms the left boundary of the landslide exerting a strong structural control on the mass movement.

6 Discussion and conclusions

The analysis of the morphological evolution of the Pisciotta landslide reveals the existence of an early stage, since 1943, in which the slope gravitational deformation is represented by an initial trace of the main scarp only, limited to the upper part of the slope. Similar early evolutionary stages were identified for other deep-seated landslides involving flysch deposits (Margielewski and Urban, 2003; Margielewski, 2006). In these first landslide stages, the rupture mechanism was supposed to terminate into the rock mass due to a downward progressive accommodation of the shear stress by a viscous behavior (Radbruch-Hall, 1978; Chigira, 1992).

Accordingly, the Pisciotta landslide can be considered of a confined-type (Hutchinson, 1988) in its initial evolutionary phase. In the successive steps, the progressive widening of the main scarp and its downslope continuation into the landslide flanks, with a strike-slip kinematics, support to hypothesize the enlargement of the basal rupture surface and a landslide distribution of advancing type (WP/WLI, 1993). The increase of the rate of ground movements after 1994, as it is assessed by velocities of the SS 447 road displacements (Fig. 2) can be related to the progressive enlargement of the basal rupture surface and it is supposed to be controlled by a downslope progressive failure mechanism (Leroueil et al., 2012). In the current stage, the development of the basal rupture surface still appears not fully completed, as it is testified by the downslope discontinuity of the lateral landslide boundaries and by the absence of a clear outcrop of the basal rupture surface at the landslide toe.

The current morphological features of the landslide, coupled to the reconstructed geological model, allow classifying this large slope mass movement as a deep-seated translational rock slide (Hutchinson, 1995; Cruden and Varnes, 1996). Taking into consideration the variability of the depth of the basal rupture surface, the sum of the depleted mass and the accumulation volume were assessed ranging between 4 and 6×10^{6} m^{3}.

The assessment of landslide evolutionary stages, derived by coupling aerial photographs since 1943 and the topographical monitoring of the upper landslide body (September 2006 – March 2009), indicates on a long-term time span (about 66 years) movements and deformation regimes variable in space and time. Besides the progressive increase of deformation rates and widening of landslide structures, the non-uniform movements inside the landslide main body determine an increase of displacements and velocities toward its left part. The differential movements inside the landslide body are demonstrated by a series of transversal morpho-structures with strike-slip kinematics. These kinematic features are interpreted to be caused by movements of rock-mass blocks, characterized by differential downslope displacements and velocities and controlled by the different driving forces.

Accordingly, higher displacements and velocities of the left side of the landslide are supposed to be determined by greater driving forces due to the larger thickness of the unstable mass. This assumption is motivated by peculiar geometry of the intersection between the bedding and the normal fault that delimits the left flank of the landslide. This geometric condition determines an increase of the thickness of the unstable upper marly member toward the left flank of the landslide. In addition, the existence of a morphological ridge shifted toward the left flank is another factor that contributes to increase the thickness of the unstable rock-mass, namely of driving forces.

Taking into consideration both the long-term continuous activity (1943-2014) and the low seismicity of the Cilento area, the triggering of the landslide and its spatial and temporal evolutions cannot be related to specific events. Also the erosional process of the Fiumicello Torrent seems to have played a marginal role because its path appeared over years not deviated by the landslide activity as it still is. The last conclusion is consistent with the hypothesis of a not complete development of the basal rupture surface and its not outcropping condition at the landslide foot.

The available data cannot allow to understand clearly the role of groundwater on kinematic evolutionary stages. The water table was detected only in the lowest borehole and deeper than the sliding surface. Notwithstanding this apparent independence of the groundwater circulation and the unstable rock mass, a delayed positive relationship between cumulative rainfall and ground velocities indicates that infiltration process influences not negligibly the landslide movement rates and determines a rough seasonal control.

The multidisciplinary study of the Pisciotta landslide proposes the analysis of a further case of deep-seated landslide in flysch rock-masses.
attempts to advance knowledge about these complex phenomena. Besides of particular geological constraints that have predisposed to the instability of a definite slope sector, the Pisciotta landslide appears a singular phenomenon due to its peculiar kinematics that is both characterized by a slow constant activity over about seventy years and the lack of a paroxysmal evolutionary phase, notwithstanding the large cumulative displacements recorded since 1955. These characteristics appear relevant to be investigated further by focusing future research activities on the comprehension of the complex rupture mechanism through experimentation of appropriate rheological and numerical modelling. The latter could represent a significant tool to forecast future scenarios with specific regards to the stability of the bulged landslide foot that appears to be at limit of equilibrium, at the current evolutionary stage.

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