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A new appraisal of the Ancona landslide based on geotechnical investigations and stability modelling

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Abstract: On the night of 13 December 1982, Ancona experienced the catastrophic reactivation of an old and large landslide located along the coast to the west of the city. The outcomes of past and new geotechnical investigations and the data from the 30 year readings of the monitoring instruments have been integrated to redefine and update the actual location of the sliding surfaces. According to the new analysis, the landslide involves four main sliding surfaces with different extents and depths. The deepest surfaces converge at depth in a shear band and their toes are positioned near or beyond the coast. Numerical and analytical modelling of the landslide has been carried out using the newly derived sliding surface geometries. The numerical modelling has allowed a qualitative assessment of the deformation pattern, confirming the geometry of the sliding surfaces derived from the geotechnical investigations. The stability analyses have been performed applying the limit equilibrium method to quantify the instability conditions of the landside. The analyses have been carried out for five stratigraphic–geotechnical scenarios. All of these scenarios show a stability condition near the limit equilibrium.

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Slopes along the central Adriatic coast (Marche, Abruzzi and Molise regions; Central Italy) are often affected by landslides. These sliding phenomena are similar in their geomorphological and geological characteristics, mainly involving Plio-Pleistocene marine clay sequences (e.g. Centamore *et al.* 1982; Cancelli *et al.* 1984; Fiorillo 2003). One of the most representative examples is that involving the north-facing slope of Montagnolo hill, in the coastal area to the west of the Ancona (Marche region, Italy) (Fig. 1). Mass movements on this slope have been known for a long time and their onset must be dated in the Quaternary. On 13 December 1982, after a period of intense rainfall, there was a catastrophic acceleration of the landslide movement. This event had an area of more than 3.4 km², which began near the top of the hill (at 170 m above sea level (a.s.l.)) reaching a maximum width of about 2 km near the coastline, and involved about 180×10^6 m³ of material (Crescenti *et al.* 1983, 2005; Coltorti *et al.* 1985, 1986; Cotecchia 2006; Cardellini & Osimani 2008). The 1982 event damaged or destroyed almost 280 buildings, involving also the railway and the roads that run along the coast; fortunately, there were no fatalities. Following this recent reactivation, several geological and geotechnical investigations were carried out to define the extent of the landslide at the surface and at depth, the failure mechanisms and the factors that triggered the event.

In 2002, the Marche Region assigned to the Ancona Municipality the responsibility of creating an early warning system and an emergency plan for people who are still living in the landslide area. The early warning system, which currently is based on monitoring data from automatic recording stations, global positioning system (GPS) stations, inclinometers and modular dynamic system columns, aims to provide an integrated and continuous control at the surface and at depth of the entire landslide area (Cardellini & Osimani 2008). The main goal of the installed warning system is to allow the population to live with the landslide. This policy, adopted by the municipality once it was demonstrated that the stabilization of the landslide was unacceptable because of its very high cost and the significant environmental impact, is directed not at the removal of the risk but at its reduction (Cardellini & Osimani 2008).

The complex network of instruments installed makes the Ancona landslide one of best monitored in the world. However, living with the landslide requires continuous equipment updating and advances in the study and understanding of the phenomenon. In this context, new geotechnical investigations and appraisal of the landslides become necessary on a regular time scale. This paper, after a detailed description of the geological and geomorphological characteristics of the landslide, presents a new revalidation of the main sliding surfaces, based on a comparative analysis of all the old and recent geological data and readings of the installed instruments.

Furthermore, new landslide modelling has been carried out using the newly derived sliding surface geometries. The outcomes have allowed a revised interpretation of deformation patterns and landslide kinematics, as well as of the degree of instability and of geotechnical features related to the instability conditions.

Geological and geomorphological setting

From the regional point of view, the Ancona area is part of the external Marche domain of the thrust system forming the Central Apennines (Bally *et al.* 1986). This complex fold-and-thrust arcuate belt with a NE vergence (Calamita & Deiana 1986; 1988) involved the thick marly calcareous sequences of the Umbro-Marche Domain (Late Trias–Late Miocene) and originated from the Neogene compressional tectonics that were a
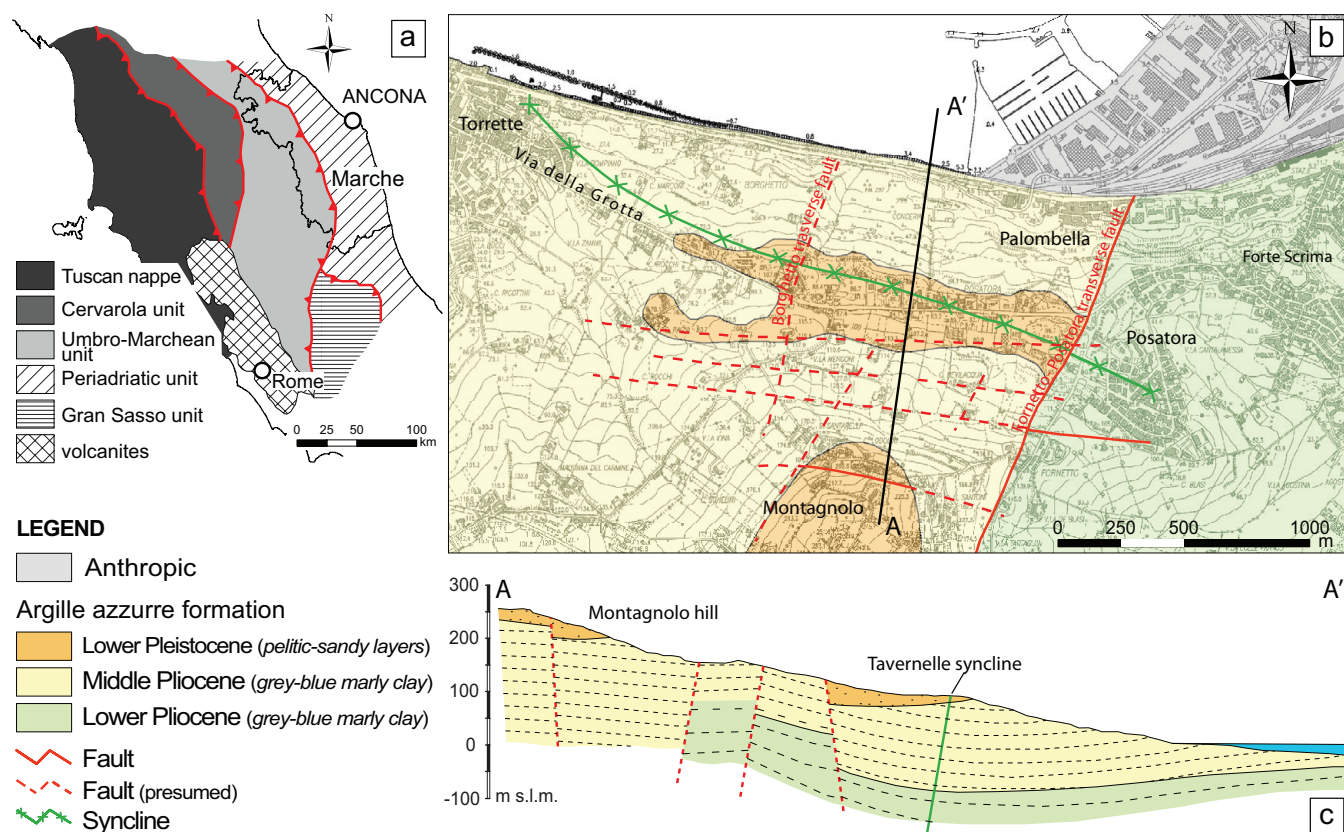
Fig. 1. (**a**) Structural sketch of the northern and central Apennines; (**b**) geological map of the Ancona landslide area (modified from Cotecchia 2006); (**c**) geological section (see (**b**) for location).

consequence of the subduction of the Adriatic plate. In the Periadriatic sector (Fig. 1), all the structures related to the Apennines belt are generally buried by the sediments deposited from the Late Miocene in the Adriatic foredeep (Periadriatic Basin) (Bally *et al.* 1986; Bigi *et al.* 1997). The early sedimentation (Late Miocene and Early Pliocene) was characterized by well-developed turbiditic systems and large volumes of silici-clastic material (Ori *et al.* 1991; Bigi *et al.* 1997). The Plio-Pleistocene sedimentary succession in the Periadritic Basin began with sandy and conglomeratic beach deposits (Bigi *et al.* 1997) and continued with clays, marly and sandy clays, and shallow-marine and non-marine deposits, reaching a total thickness of several hundred metres (Cantalamessa *et al.* 1986). In the Plio-Pleistocene Periadriatic Basin fill several depositional sequences have been defined (Cantalamessa *et al.* 1986; Centamore & Micarelli 1991; Bigi *et al.* 1997; Cantalamessa & Di Celma 2004), the base of which is generally characterized by conglomerate and sandstone deposits (Bigi *et al.* 1997). The evolution of the Periadriatic Basin was strongly controlled by the buried structures connected to the Apenninic chain (Bigi *et al.* 1997; Cantalamessa & Di Celma 2004).

The compressive deformation responsible for the rise of the Central Apennines, migrating toward the foreland, started to involve the Periadriatic sector from the Early Pliocene (Coward *et al.* 1999; Cello & Tondi 2013). This resulted in reverse faults, faint anticlinal structures and normal faults with a downthrow to the east (seaward) that affect the Pleistocene deposits (Cantalamessa *et al.* 1987). The compressional tectonics is still active in the coastal Marche area, as shown by earthquake focal mechanisms (Crescenti *et al.* 1977; Gasparini *et al.* 1985; Riguzzi *et al.* 1989).

Following this deformation, several sectors (characterized by a different tectonosedimentary evolution) have been identified: in

particular, the Ancona sector is one of the shallowest in the entire basin, with reduced sedimentation and thickness and many gaps (Bigi *et al.* 1997).

Starting from the late Pliocene the whole of Central Italy was involved in a widespread uplift (Dramis 1992; Coltorti *et al.* 1996), which in the Ancona sector raised the Plio-Pliostocene deposits by several hundred metres (e.g. 250 m a.s.l. at the top of the Montagnolo hill; Fig. 1) and led to the formation of a monoclinal structure (Cantalamessa *et al.* 1987).

In the study area (containing the landslide) the outcrop consists almost exclusively of sediments of the Plio-Pleistocene foredeep sequence, belonging to the Argille Azzurre formation. The Lower and Middle Pliocene sediments are represented by grey–blue (20−40 cm thick) marly clay (up to 60 cm thick) with thin sandy and silty interlayers. As a consequence of a Middle–Upper Pliocene stratigraphic hiatus (Colalongo *et al.* 1979; Bigi *et al.* 1997; Cello & Tondi 2013), the (Lower) Pleistocene deposits rest unconformably on the Lower and Middle Pliocene sediments. The Pleistocene sequences are characterized by an alternation of pelitic and arenaceous layers (Argille Azzurre arenaceous–pelitic lithofacies), organized in five depositional cycles (Colalongo *et al.* 1979; Cantalamessa *et al.* 1986; Bigi *et al.* 1997). The thickness of the outcropping Argille Azzurre in the area surrounding Ancona is estimated to be about 300 m (Cello & Tondi 2013). These sediments are intensely jointed and overlain by a diffused eluvio-colluvial deposit (Crescenti *et al.* 2005).

From a tectonic point of view, the study area is the result of several tectonic phases (Crescenti *et al.* 1983; Cotecchia 2006; Cello & Tondi 2013). The oldest one, an Early–Middle Pliocene compressional phase, gave rise to the major structures present in the area, which are roughly NW–SE-oriented folds (Cello & Coppola 1989; Crescenti *et al.* 1983) associated with the regional
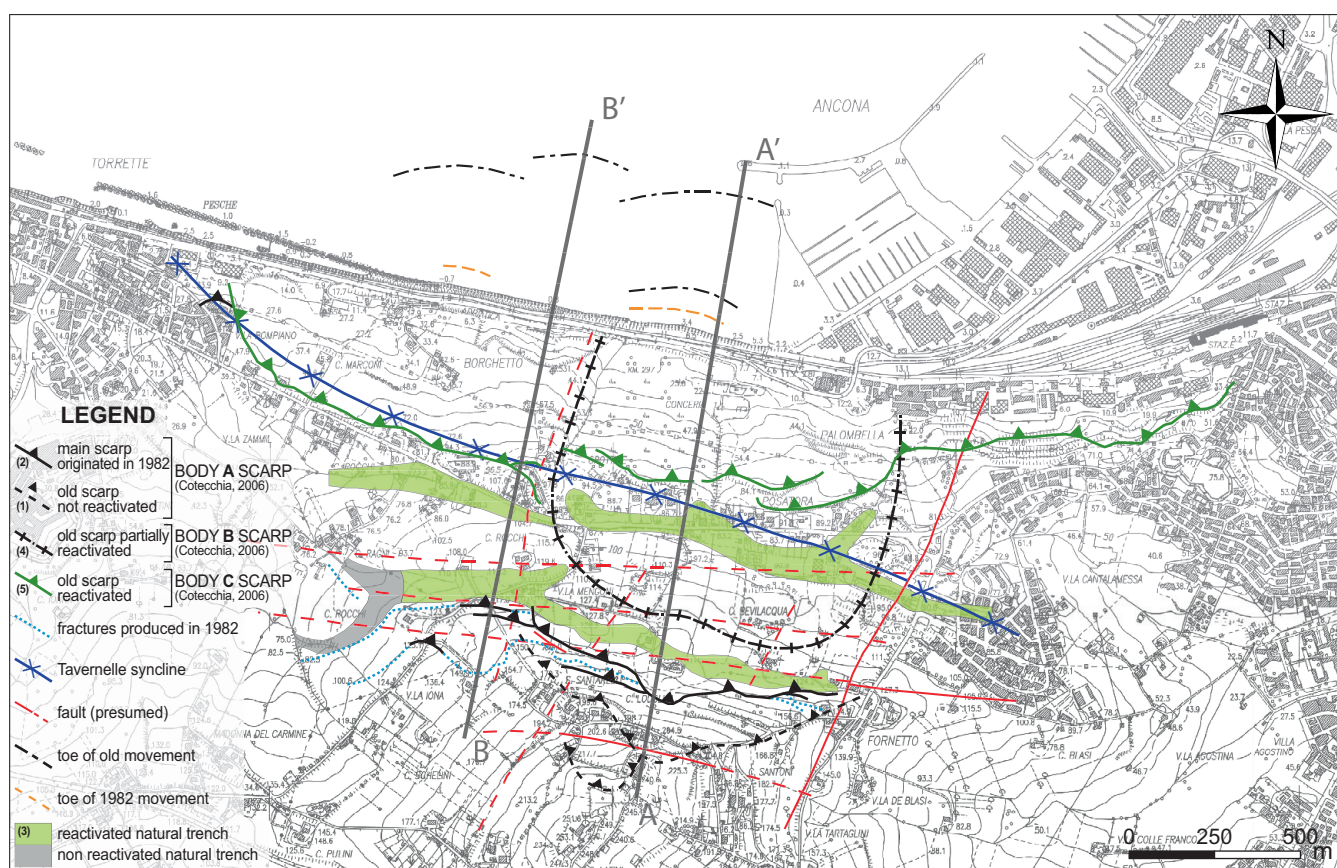
Fig. 2. Main geological and geomorphological features of the Ancona landslide area and main landslide bodies as defined by Cotecchia (2006).

thrusts (Cello & Tondi 2013). Among these folds, the most important structure is the Tavarnelle syncline. This crosses the whole landslide area (Figs 1 and 2), with its axis running almost parallel to the coastline, and exerts a major structural constraint on the layer arrangement in the entire area (Fig. 2): strata are generally subhorizontal or seaward dipping upslope and slightly counterslope downslope (Stucchi & Mazzotti 2009). Later products of this tectonic phase are several normal faults oriented NW–SE, which have been interpreted as collapse structures at the thrust front or at the back of the thrust-associated anticlines (Cello & Coppola 1989). The orientation of these structures is consistent with a roughly NE direction of tectonic movement, which is still active at present. The normal faults that cut the Montagnolo slope with a roughly east–west local orientation (Fig. 1) are taken as one of these collapse structures: they strongly lowered the sediments toward the sea, with a maximum displacement between 50 and 150−200 m (Crescenti et al. 1983; Cello & Tondi 2013).

The latest tectonic phase (Pleistocene to present) is responsible for the transverse faults with anti-Apenninic NNE–SSW orientation (Crescenti et al. 1983; Cello & Coppola 1989; Cello & Tondi 2013) that are found in the coastal area. These structures cut and displace the previous folds, giving rise to isolated structures (Nanni 1980). The landslide area is crossed by two of these faults, the Borghetto and the Fornetto–Posatora transverse faults (Figs 1 and 2), which dislocate the Tavarnelle syncline (Cotecchia 2006). Furthermore, these structures are probably still active and a probable source of earthquakes; for example, the 1972−1974 earthquake swarm epicentres are roughly aligned along these structures (Crescenti et al. 1977; Michetti & Brunamonte 2002).

The tectonic evolution, in particular the uplift, started in the late Pliocene–early Pleistocene, and the lithostructural characteristics of the sediments strongly conditioned the geomorphology of the coastal area to the west of Ancona. The uplift resulted in an increased linear erosion and a rapid increase of relief with consequent production of steep and rough slopes, which in the past may have favoured the development of deep-seated gravitational deformations (i.e. Dramis et al. 1983; Dramis 1992). The slopes in these Plio-Pleistocene sediments are generally gentle, with moderate elevation (rarely exceeding 200−300 m) and slope angles varying between 5 and 15° (Cello & Tondi 2013). In detail, the Montagnolo slope, occupied by the landslide, has steeper areas, with inclination that reaches 25−30°, and morphological elements such as scarps, steps, closed depressions (trenches) and reverse slopes (Coltorti et al. 1986) characteristic of deep-seated movements (i.e. Coltorti et al. 1985; Dramis et al. 1983, 2002). It is also noteworthy that, in the Ancona outskirts, where pelitic sediments of the Argille Azzurre predominantly crop out, almost 70% of the area is covered by landslides (Cello & Tondi 2013).

Landslide description

The investigated slope has a history of gravitational movements: significant mass movements, with large areal extent, were recorded in 1578, 1768 and 1858 (Bracci 1773; De Bosis 1859; Segré 1920; Crescenti 1986). The instability conditions associated with these movements were also responsible for the development of smaller and shallower landslides, such as the two recorded in 1919 (Segré 1920): one near the top of the Montagnolo hill, and a lower one, the Barducci landslide, which developed halfway up the slope and extended to the coastline, involved the sea floor, and damaged the coastal road and railway. Moreover, Crescenti (1986) cited the great reduction in the number of the buildings on the slope, com-

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pared with a cadastral map of 1915, as evidence of the historical activity of this mass movement.

The instability conditions and the first gravitational movements on the Montagnolo slope began several thousand years ago and are probably linked to the regional uplift that brought the foredeep sediments to their present elevation (Coltorti *et al.* 1986; Dramis *et al.* 2002). In detail, the onset of these movements could be post-dated to 5000–6000 years ago, before the Flandrian Transgression, when the sea level was much lower (Crescenti *et al.* 1984, 2005; Coltorti *et al.* 1985; Curzi & Stefanon 1986).

The 1982 reactivation of this massive gravitational phenomenon started without warning, lasted only a few hours and affected the whole area simultaneously. At the end of the event, about 8 m of horizontal displacement and 3 m of uplift were recorded at the base of the slope, along the coastline; upslope, the recorded horizontal displacement was up to 5 m, together with settlements of the order of 2.5 m (Crescenti *et al.* 1983; Cotecchia 2006; Cardellini & Osimani 2008). The main direction of displacement was roughly south to north (Cunietti *et al.* 1986) and was generally relatively independent of the surface morphology (i.e. some of the scarps and fractures extend outside the displaced area) (Coltorti *et al.* 1985, 1986). A general lowering (up to 3 m) was also observed along Via delle Grotte through topographic levelling (Coltorti *et al.* 1985).

This phenomenon reactivated most of the main pre-existing morphological characters, inherited from earlier landslides, and resulted also in some new sliding surface and deformation zones (Cotecchia 2006). In particular, as sketched in Figure 2, from the top of Montagnolo hill toward the sea, the following features can be observed.

(1) An old main crown scarp, with an arcuate shape, that occurs close to the top of the slope was not reactivated in 1982 and coincides with the upper landslide described by Segré (1920).

(2) A WNW–ESE-oriented, 1000 m long system of scarps and minor scarplets (and associated fractures and fissures) was produced during the 1982 event, with a maximum high of 8 m in its central portion.

(3) Two long and wide subparallel undrained trenches exist at elevations of about 140 m (about 700 m long and 80 m width; T1) and 80 m a.s.l. (about 1200 m long and 80 m width; T2) respectively. These graben-like structures are the most striking geomorphological elements of the Montagnolo hill (Crescenti *et al.* 1983, 2005); they were both only partially reactivated in 1982, resulting in widening and deepening of the depressions. Their genesis and development have been correlated with the early stages of the mass movement and with its evolution over time, and may also have been favoured and controlled by the presence of tectonic structures such as the Pliocene normal faults along which the upper trench is aligned (Crescenti *et al.* 1984) and/or seismic activity (Coltorti *et al.* 1985). Such features have been reported as evidence of a translational component of movement (Skempton & Hutchinson 1969).

(4) Just below the first trench, an old scarp, partially reactivated, defines a landslide whose lateral extent is bounded by the Borghetto and the Fornetto–Posatora transverse faults.

(5) A very long scarp (running from Torrette to the west to Palombella to the east), divided into three main sections, was reactivated during the 1982 event.

(6) From the last scarp to the coastline, a series of scarps and scarplets are associated with superficial landslides, of flow and slide type, which mainly involved the superficial eluvio-colluvial deposits (Crescenti *et al.* 1983, 2005; Coltorti *et al.* 1985). These superficial landslides mostly occurred downslope and were responsible for the largest local displacement and damage. Among them, the most representative is the above-mentioned Barducci landslide, at the base of which a horizontal displacement of about 12 m was observed, comparing measurements taken after the 1982 event with

those of a previous monitoring (Fangi & Radicioni 1984; Cunietti *et al.* 1986).

Based on historical data and morphological evidence, it should also be noted that the extent of the 1982 movements was less than previous ones; in particular, it seems that the older movement involved an area east of Posatora to Scrima Fort, 500 m beyond the 1982 limit, and the upper part of the Montagnolo hill, where an old scarp mentioned above is still recognizable (De Bosis 1859; Segré 1920; Crescenti *et al.* 1983; Coltorti *et al.* 1985, 1986).

The extent of the area involved, the simultaneous occurrence of deformations, the presence of typical features such as the trenches, a very old onset of the movements, step-wise evolution and independence of the movement from the surface morphology are all characteristics that indicate that the main movement of the studied landslide was deep-seated, at probably more than 100 m depth (Crescenti *et al.* 1983, 1984, 2005; Coltorti *et al.* 1985, 1986; Dramis *et al.* 2002). The deep-seated nature of the Ancona landslide was confirmed by extensive studies that followed the 1982 paroxysmal event and that were carried out by means of exploratory boreholes, micro-palaeontological studies, inclinometers, topographic levelling and geophysical investigation, aimed at understanding the characteristics of the phenomenon and evaluating the execution of stabilization measures (i.e. Cassinis *et al.* 1985; Cotecchia 2006; Cotecchia *et al.* 1995; Cotecchia & Simeone 1996; Santaloia *et al.* 2004; Crescenti *et al.* 2005; Cardellini & Osimani 2008; Stucchi & Mazzotti 2009; P. Colombo *et al.*, unpublished data; V. Cotecchia *et al.*, unpublished data). These studies allowed a conceptual scheme of the landslide to be drawn (Fig. 2), characterized by three main bodies with movement intermediate between rotational and translational (Cotecchia 2006): Body A, very deep and with very large areal dimensions, defined by the upper scarps (1 and 2) at the hilltop and extending from Palombella to Torrette, characterized by rather limited movements during the 1982 event; Body B (scarp 4), superimposed on Body A, involving the central part of the slope, which underwent more intense deformations during the 1982 event; Body C, delimited by the lower long scarp (5), which was partly reactivated in 1982.

The sliding surfaces of the three main deep landslides converge at depth into a single wide shear band with ductile behaviour and low strength (Cotecchia 2006). This band was recognized in boreholes (chaotic and highly disturbed material), inclinometer readings and geophysical survey; its origin may be related to the high strain experienced during the long-lasting history of the landslide, or, conversely, it may be a pre-existing geological feature that guided the deepest sliding surfaces to converge at depth. Although clear movements of the sea floor attributable to the 1982 event were not observed (Crescenti *et al.* 1984; Curzi & Stefanon 1986), except that in the vicinity of the coastline (about 50 m; Cotecchia 2006), the sliding surfaces of the main landslides emerge offshore, at a maximum distance from the coastline of over 250 m (Fig. 2; Coltorti *et al.* 1985, 1986; Cotecchia 2006). The presence of the pre-existing sliding surface was confirmed by the analysis of boreholes (Cotecchia 2006; V. Cotecchia, unpublished data). It must be stressed that there are many examples of very large landslides in Plio-Pleistocene sediments along the Adriatic coast whose sliding surfaces develop below sea level, sometimes more than 200 m from the coastline and that, in certain cases, uplift parts of the sea floor (Colapietro 1822; Segré 1918; Centamore *et al.* 1982).

The 1982 reactivation is strongly correlated with the heavy rainfall of the previous weeks (Crescenti *et al.* 1983; Cotecchia 2006). However, this meteoric event was not exceptional and the rainfall alone would not have been able to produce a similar paroxysmal event. A larger role in the reactivation was probably played by the early 1970s earthquakes, which remobilized the fractures and thus increased the permeability at the scale of the whole slope (Crescenti *et al.* 1977; Michetti & Brunamonte 2002).

Based on its characteristics, the Ancona landslide can be defined, according to Cruden & Varnes (1996), as a deep-seated, multiple, compound (rotational–translational movement) and recurrent (slow, continuous movement, with short and sudden accelerations) landslide. Considering also the superficial flow and slide type landslides, the whole phenomenon can also be considered as a composite mass movement (different types of movements in different areas of the displaced mass).

Methods

Landslide investigation and soil geotechnical parameters

The Ancona landslide has been extensively studied and several methods have been used to define the causes and conditions of landslides (Cotecchia 2006). Among these, more than 150 exploratory boreholes have been drilled since the event of 1982; about 140 on land and 10 offshore. The Ancona municipality carried out the latest investigation campaign in 2011 to better define the submarine extent of the landslide, with the drilling of six new boreholes, five offshore and one on land. The maximum drilled depth of the boreholes is about 170 m b.g.l. Sixty-eight boreholes have been equipped with inclinometers. The measurement period started in 1983 and has continued to the present. Forty-two boreholes have been equipped with piezometers to define the water levels and groundwater system, which is strongly influenced by the complex structural setting that includes trenches, fractures and discontinuities (generated both by landsliding and tectonic movements) (Cotecchia 2006). The measurement period is variable for each piezometer and in general ranges from 1993 to the present. Piezometric data indicate the presence of a prevalent seepage domain in the slope, probably related to the high degree of fissuring in the clays (Cotecchia 2006). The presence of a single seepage domain is supported by the piezometric levels, which show a decrease in depth in the uphill piezometers and an increase with depth in the piezometers near the coast. This behaviour is indicated by a strong curvature of the flow lines at the toe of the slope and by the resulting shape of equipotential lines (Cotecchia 2006).

Numerous geotechnical *in situ* and laboratory tests have been carried out on Pliocene clays to determine the input parameters for the stability analyses. The consistency index of these clays is generally just below unity, with some samples displaying lower consistency owing to their location in areas possibly disturbed by the sliding process. The Pliocene clays are overconsolidated and their compressibility, as obtained from oedometer test results, was rather low ($Cc = 0.30-0.35$) but increases for samples taken at around 100 m depth, confirming the possible disturbed nature of the soils. Direct shear and triaxial tests, for both the on-land and offshore clays, indicated that the friction angles (ϕ) and cohesion (c) vary with increasing vertical effective stress, associated with the consolidation pressure and reducing void ratio. At medium to high pressures, the range where the on-land samples were mostly tested, the friction angle is around 21°. The residual friction angles obtained from direct shear testing were around 15° for the on-land samples, decreasing to 13° for the offshore samples. Geotechnical parameters were also estimated by back-analysis (Cotecchia 2006) by assuming, given the current slope kinematics, a limit equilibrium condition for the main landslide bodies. The back-analysis results showed a friction angle of around 13° at failure. Back-analysis results were found to be in general agreement with the laboratory residual strengths, clearly showing that the operational strength in the slope at Ancona is below the peak value. Details have been given by Cotecchia (2006).

In 2011 a new geotechnical laboratory testing programme was carried out on samples taken at depths of 50 m (sample 1), 100 m (sample 2) and 150 m (sample 3) in the new borehole drilled on land (TM1; Fig. 3). The results are reported in Table 1. According to the Unified Soil Classification System of Wagner (1957), samples 1 and 3 can be classified as inorganic clay of high plasticity (CH) whereas sample 2 can be classified as inorganic clay of low plasticity (CL). The unit weight (γ) varies between 20.3 and 21.7 kN m^{-3}, depending on the degree of saturation, and the consistency index is around unity. Effective shear strength angles, ranging between 20 and 27°, have been obtained through a direct shear test, whereas effective residual shear angles, ranging between 11 and 15°, have been obtained from a ring shear apparatus.

Integrated analysis of the geotechnical investigations

The geological and geotechnical results at our disposal, coming from past and new investigations and from the 30 year readings of the monitoring instruments, have been reworked and reinterpreted to redefine and update the actual location of the main sliding surfaces of the Ancona landslides. The sliding surfaces proposed in all the previous studies (Segré 1920; Coltorti *et al.* 1985; Esu 1986; Cotecchia 2006; V. Cotecchia, unpublished data) have been taken in account. The geometry, depth and organization of the sliding surfaces were reconstructed along two sections (AA' and BB'; see Figs 2 and 3) running approximately perpendicular to the coastline, from the top of Montagnolo hill to a few hundred metres beyond the coastline (Figs 2 and 3). The choice of the section location aimed at obtaining two transects that were representative of the central and wider portion of the investigated phenomenon and that crossed all the main surfaces and structures described in the literature; moreover, many subsurface data were available in these positions (Fig. 3). The two sections are also roughly parallel to the local direction of movement (Cunietti *et al.* 1986).

To obtain a preliminary idea of the complex subsurface situation, all the geomorphological features crossed by the section traces have been recorded. Because the areal extent of the Ancona landslide is very large a great transverse variability is expected (i.e. perpendicular to the movement direction and roughly parallel to the coastline) both for the depth of the various sliding surfaces and for the superficial extent (Fig. 2). On the basis of these observations, geotechnical investigations that lie along the section traces or in their proximity (i.e. in a zone of around 200 m from the section trace) have been taken into account in the reconstruction.

The detection of the depth at which evidence of movement has been found mainly relied on inclinometer readings and the identification, on borehole and piezometer stratigraphic logs, of structures ascribable to kinematic phenomena (i.e. highly fractured bands, high-plasticity levels, chaotic levels with sudden changes of strata orientation not correlated with the local geological attitude, alteration surfaces).

To precisely locate each geotechnical investigation along a trace, the position of all the utilized wellheads has been projected orthogonally to the traces themselves. This choice follows the observation that each body of the Ancona landslide developed along rotational–translational surfaces, and because the section traces are roughly parallel to the landslide movement direction, the projections (orthogonal to the traces) are parallel to the rotation axis of the sliding surfaces. This allows us to assume an almost flat local geometry in a direction orthogonal to the general landslide movement (i.e. a pseudo-cylindrical surface) and that a sliding surface depth does not critically vary in the chosen neighbourhood. With these assumptions it is consequently legitimate to consider that each movement
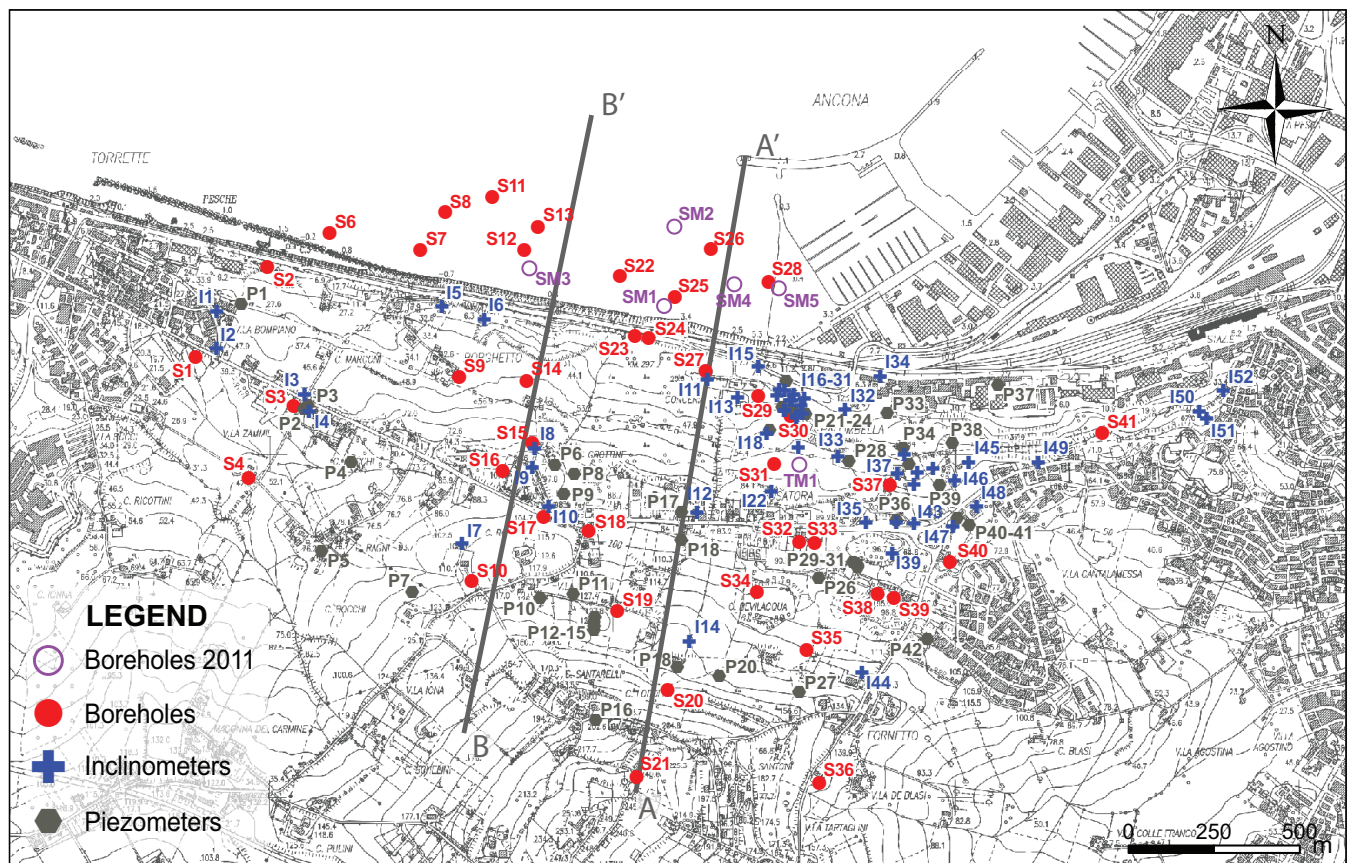
Fig. 3. Boreholes, inclinometers and piezometers based and installed inside the landslide perimeter.

Table 1. *Soil geotechnical parameters for the three samples from the TM1 borehole*

Sample	1	2	3
Depth (m)	50	100	150
Gravel (%)	0	0	0
Sand (%)	4.2	6.5	5.2
Silt (%)	51.1	60.1	51.9
Clay (%)	44.7	33.4	42.9
w_L (%)	67.9	44	78.9
w_P (%)	24	19.5	19.3
I_P (%)	43.9	24.6	59.6
I_L	−0.1	0.07	0.07
I_C	1.1	1.07	1.07
Soil classification USCS	CH	CL	CH
γ (kN m^{-3})	20.3	21.5	21.7
c_r (kPa)	0.17	0.09	0.11
c' (kPa)	1.04	2.62	2.31
ϕ' (deg.)	20	26	24
ϕ_r' (deg.)	11	15	11

recorded along the length of a geotechnical investigation located within a zone of around 200 m from a section is at an equivalent elevation below the trace on which it has been projected. Such evidence of movement can thus be considered as fully representative of the depth of the sliding surface below the section.

The topographic difference between the altitude of a wellhead and the altitude of its projection along a trace has been considered. The depth of an identified movement has thus been changed in its absolute elevation with respect to the sea level (i.e. wellhead altitude minus the depth of evidence of movement).

Each identified movement has been weighted on the basis of its soundness and reliability as well as its distance from the section trace (i.e. the higher the distance, the less the reliability). This means that where two or more projections along a section trace almost overlap, we considered the information from the investigation closer to the section trace to be more reliable. Information from geotechnical investigations beyond the 200 m threshold from a section trace has been given the lowest weight.

Lastly, the information from each investigation has been analysed and compared with that from the other closest investigations and with respect to the geomorphological features (main scarps, natural trenches, fractures, etc.) identified in its immediate neighbourhood.

This data analysis has allowed us to draw a new and comprehensive reconstruction of the landslide geometry and to define four main sliding surfaces (Fig. 4).

Landslide modelling

Two types of landslide modelling have been carried out: numerical modelling and analytical modelling. The numerical modelling was implemented through a finite-difference method and has been carried out to reconstruct the kinematics and the initial deformation patterns of the slope, and consequently to qualitatively confirm that the proposed sliding surfaces (Fig. 4) are consistent with the kinematic evolution of the slope. The analytical modelling was implemented through the limit equilibrium method to quantitatively define the instability of the Ancona landslide.

The main problem related to the modelling of the Ancona landslide is the transition from the geological model to the geotechnical model of the slope. Given the geological and geomorphological complexity of the landslide, the geotechnical parameters obtained from laboratory
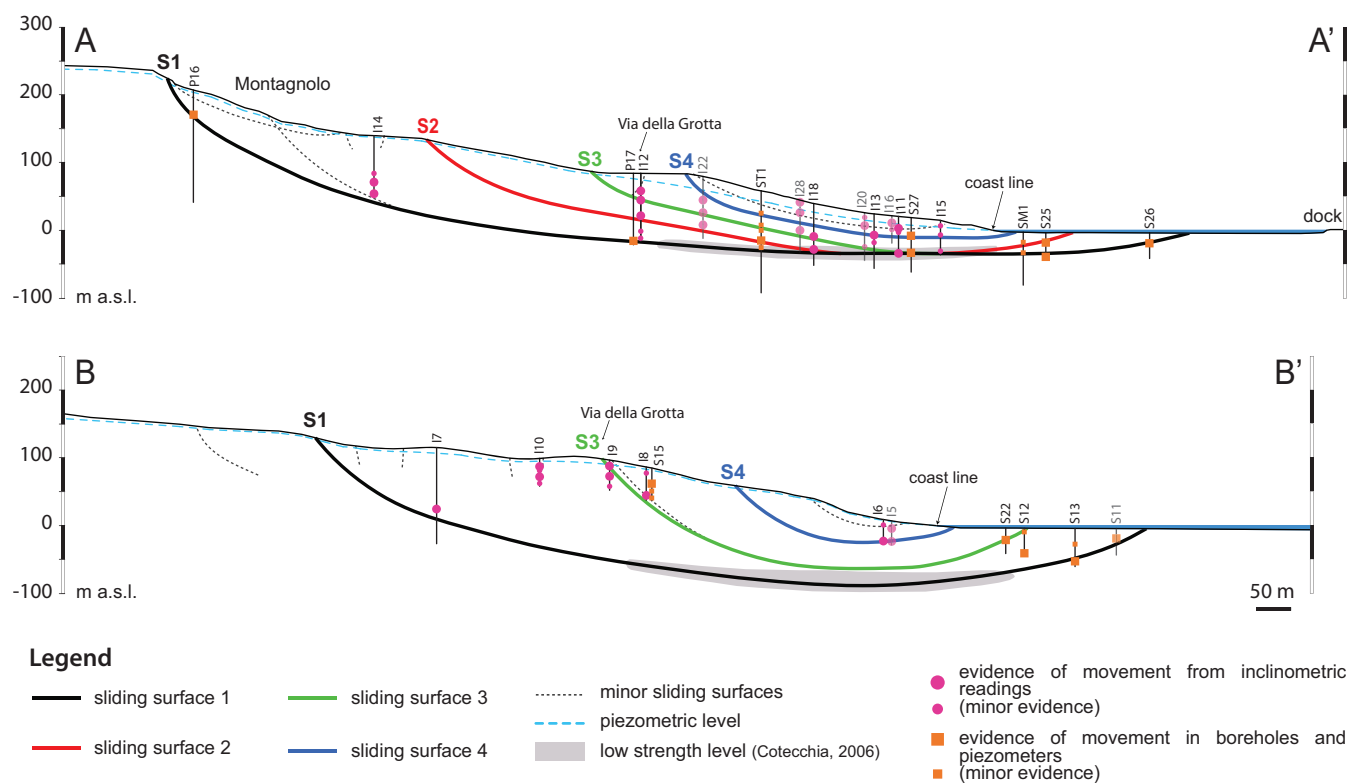
Fig. 4. Schematic representation of sections AA' and BB' (see Figs 2 and 3 for location): the sliding surfaces individuated through the integrated analysis of the geotechnical investigations are represented. Boreholes, piezometers and inclinometers used in the reconstruction of the landslide geometry are also indicated; geotechnical investigations beyond 200 m from the section trace are in a lighter shade. The evidence of movement recognized along each log is indicated with circles for inclinometers, and squares for boreholes and piezometers; smaller symbols indicate evidence of minor movement.

tests are roughly adaptable to the complexity, owing to fractured clays and reworked materials, of the landslide body. The mechanical behaviour of the slope is thus controlled not only by the intrinsic strength of the clay, but a major role is also played by the geometry, frequency and strength of the discontinuities (Cotecchia 2006).

The finite-difference numerical model for the simulation of the triggering mechanism of the Ancona landslide was carried out by means of the FLAC code (Itasca 2000), along the two profiles AA' and BB', reconstructed through the interpretation of the abovementioned investigations (for operational needs the AA' profile was extended westward; Fig. 5). In this case, as the aim was to obtain qualitative results, the geotechnical model used was very simple: following the results of the stratigraphical analysis, the whole slope has been simulated by means of a single material type, which has been assigned a strain softening behaviour. The peak ($c' = 10$ kPa and $\phi' = 23°$) and residual ($c' = 0$ kPa and $\phi' = 12°$) properties, and the unit weight ($\gamma = 20$ kN m^{-3}), have been chosen taking the mean values of the laboratory testing results carried out on the three samples taken from borehole TM1.

For both sections, a grid made up of 110 rows and 80 columns was created, and this grid was extended to prevent interaction phenomena between the edges of the model and the central area of interest (Fig. 5). The size of the cells, furthermore, has been scaled so as to have a higher resolution at the centre of the model, where plastic deformation within the material is expected to occur.

The *in situ* initial stress state was calculated by initially assigning the material high strength properties to avoid plastic deformations, and leading the model to equilibrium under its own weight; after that, the material strength was changed to actual values. Under these conditions, the system is unstable and multiple surfaces of plastic deformations are created for both profiles (Fig. 6).

The analytical model performed with SLOPE/W software (i.e. Casagli *et al.* 2006; Tofani *et al.* 2006) has been carried out for both sections (AA' and BB') and for all the main sliding surfaces identified (Fig. 7). To define the actual stability we have accounted for a more complex and complete geotechnical representation of the slope, which include the effects of the water level and the deep level of Pliocene clay (located at a depth between 100 and 150 m and affecting sliding surface S1, S2 and S3 in section AA' and sliding surfaces S1 and S3 in section BB'), together with low strength parameters and ductile behaviour recognized by Cotecchia (2006).

In the model, the water level has been reconstructed based on the long-term piezometric monitoring described in the section 'Landslide investigation and soil geotechnical parameters', and pore water pressures along the sliding surface have been computed hydrostatically based on the distance from the water level. Moreover, the effect of the water weight on the submerged portion of the slope has been taken into account, considering a unit weight for seawater as 10.052 kN m^{-3} (Fig. 7).

To obtain more representative strength parameters, back-analysis of the slope failure has been carried out. The back-analysis has been conducted with SLOPE/W software (Krahn 2004), applying the Morgenstern–Price limit equilibrium method (Morgenstern & Price 1965) to all the sliding surfaces of section AA'. The results reported in Figure 8 show that the residual friction angles range from about 16° for the deepest sliding surface (S1) to about 12° for the shallowest sliding surface (S4). These parameters are in agreement with those reported by Cotecchia (2006). These obtained values have to be considered residual values for the shallowest sliding surfaces (S2, S3, S4) whereas for the deepest sliding surface (S1) they have to considered as 'intermediate' shear strength values (i.e. between peak and residual).
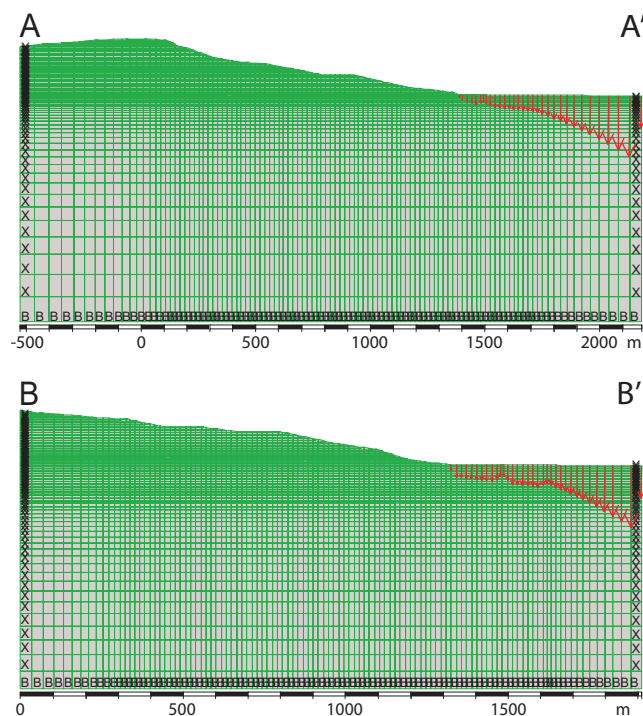
Fig. 5. Finite-difference grid of the numerical model for profiles AA' and BB'. The boundary conditions are also displayed: X, fixed velocity in the *x* direction; B, fixed velocity in the *x* and *y* directions; vertical arrows represent the net applied forces owing to the weight of seawater.

The geotechnical parameters used in the analysis, derived from laboratory tests and back-analysis, are reported in Table 2. In addition to peak and residual strength parameters, intermediate strength parameters have also been considered to take into account the probable recovery of strength of the Pliocene clay from the last event of 1982 (mostly to be ascribed to a progressive reduction of the fracture widths).

On the basis of the above-mentioned geotechnical features of the Ancona landslide, five geotechnical and stratigraphic scenarios have been analysed, as follows.

Scenario 1: homogeneous Pliocene clay with peak strength parameters (c' = 10 kPa and ϕ' = 23°).

Scenario 2: homogeneous Pliocene clay with residual strength parameters (c' = 0 kPa and ϕ' = 12°).

Scenario 3: Pliocene clay with peak strength parameters (c' = 10 kPa and ϕ' = 23°) and a low-strength level with residual strength parameters (c' = 0 kPa and ϕ' = 12°).

Scenario 4: homogeneous Pliocene clay with 'intermediate' strength parameters (c' = 10 kPa and ϕ' = 17°) as indicated by V. Cotecchia (unpublished data).

Scenario 5: Pliocene clay with 'intermediate' strength parameters (c' = 10 kPa and ϕ' = 17°) and a low-strength level with residual strength parameters (c' = 0 kPa and ϕ' = 12°).

Results

Reconstruction and validation of the main sliding surfaces

The integration of the various data available led to the identification and definition of four main sliding surfaces (Fig. 4). The reconstruction of the landslide geometry and the sliding surfaces along section AA' used the evidence of movement obtained from 10 inclinometers and seven boreholes (two of them equipped with piezometers) (Table 3), and from six inclinometers and five boreholes for the surfaces along section BB' (Table 4).

Section AA' crosses all the main landslide bodies and the four proposed main sliding surfaces (Fig. 4). The deepest sliding surface (S1, 110 m b.g.l.) emerges offshore at a maximum distance estimated at about 300 m from the coastline, as already proposed by Cotecchia (2006). Surfaces S1, S2 and S3 coalesce at depth (*c*. 40 m below the sea level) in the deep low-strength clay level with ductile behaviour.

Section BB' crosses the landslide bodies defined by the sliding surfaces S1, S3 and S4. Sliding surface S2 does not intersect this section as its extent is limited and probably controlled by two NE–SW transverse faults (Figs 1 and 2). Along this section, the Ancona landslide has a maximum depth of about 85 m below sea level and the greatest distance from the shoreline to the toe of the landslide is some 250 m. Sliding surfaces along section BB' do not converge along the low-strength level although surface S1 crosses it for a large portion of its length.

The spatial continuity of the landslide associated with the sliding surface 4 is nevertheless doubtful. Most probably the slope in its lowest portions (between Via della Grotta and the coastline) is affected by several surficial landslides, the longitudinal extent of which is limited. Among these, we may cite the Barducci landslide, crossed by section AA', the crown of which almost coincides with that proposed for surface S4 (see Segré 1920).

The coherence of the proposed sliding surfaces (Fig. 4) with the kinematic evolution of the slope was qualitatively confirmed and validated by the results of the numerical modelling (Figs 5 and 6). In addition, these results allowed us to reconstruct the kinematics and the initial deformation patterns of the slope, and consequently give confirmation to the hypothesized failure mechanisms. In detail, the analysis of Figure 6 allows the identification of those areas of the models where plastic strains are concentrated.

In particular, the simulation carried out along section AA' shows the occurrence of shear surfaces concentrated mainly in the upper part of the slope (which in the past has experienced the higher deformations). However, with the progress of the computing cycles, new deep shear bands develop, the most extensive of which originates almost from the coastline.

For profile BB', most of the plastic deformations are concentrated in the portion of the slope closest to the coastline, with some areas of secondary plasticization that develop further upstream.

It is important to stress that the results of the numerical modelling must be interpreted only from a qualitative point of view. The differences between the simulated and actual phenomena mainly relate to the simplification in the choice of a single homogeneous model to characterize the material forming the investigated slope.

Analytical modelling

To quantify the degree of stability of the slope, detailed stability analysis was performed using the limit equilibrium method. The results of the stability analysis carried out on the two sections AA' and BB' and for all the sliding surfaces are reported in Figures 9 and 10.

For section AA', sliding surface 1 shows for all the scenarios analysed the lowest values of factors of safety (FS) and thus it can be considered as the most critical in terms of instability conditions. Scenario 1 shows the highest values of FS for all the sliding surfaces whereas scenario 2 shows the lowest ones. Intermediate values of FS, although still above unity, are reported for all the other scenarios. The only exception is sliding surface S4, which does not involve the low-strength clay level, and for this reason the factor of safety values are identical for scenarios 4 and 5 and for scenarios 1 and 3.

FS values related to all the sliding surfaces of section BB' are in general lower than those for section AA'. The sliding surfaces S3 and S4 show values near unity except for the scenarios 1 and 3,
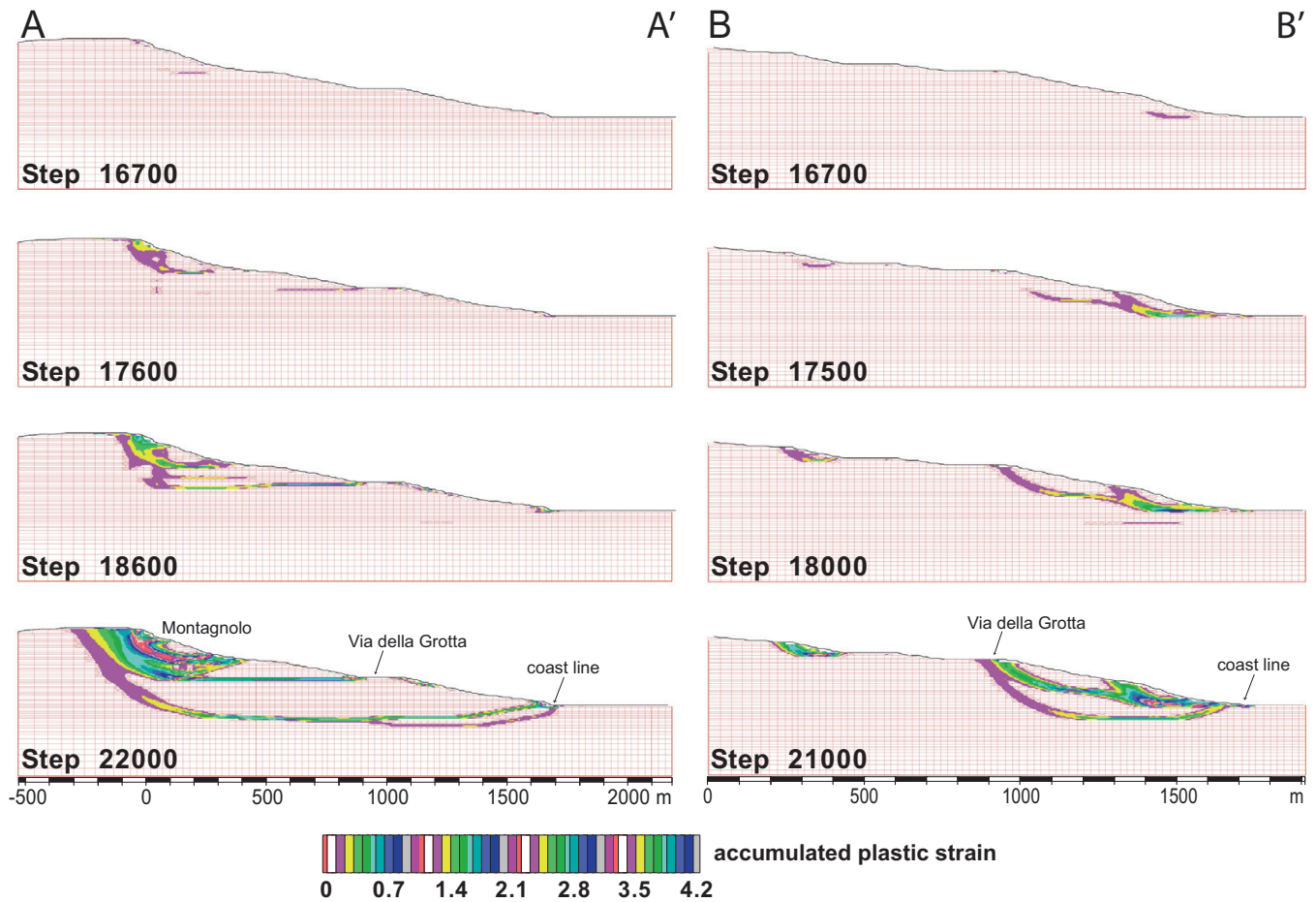
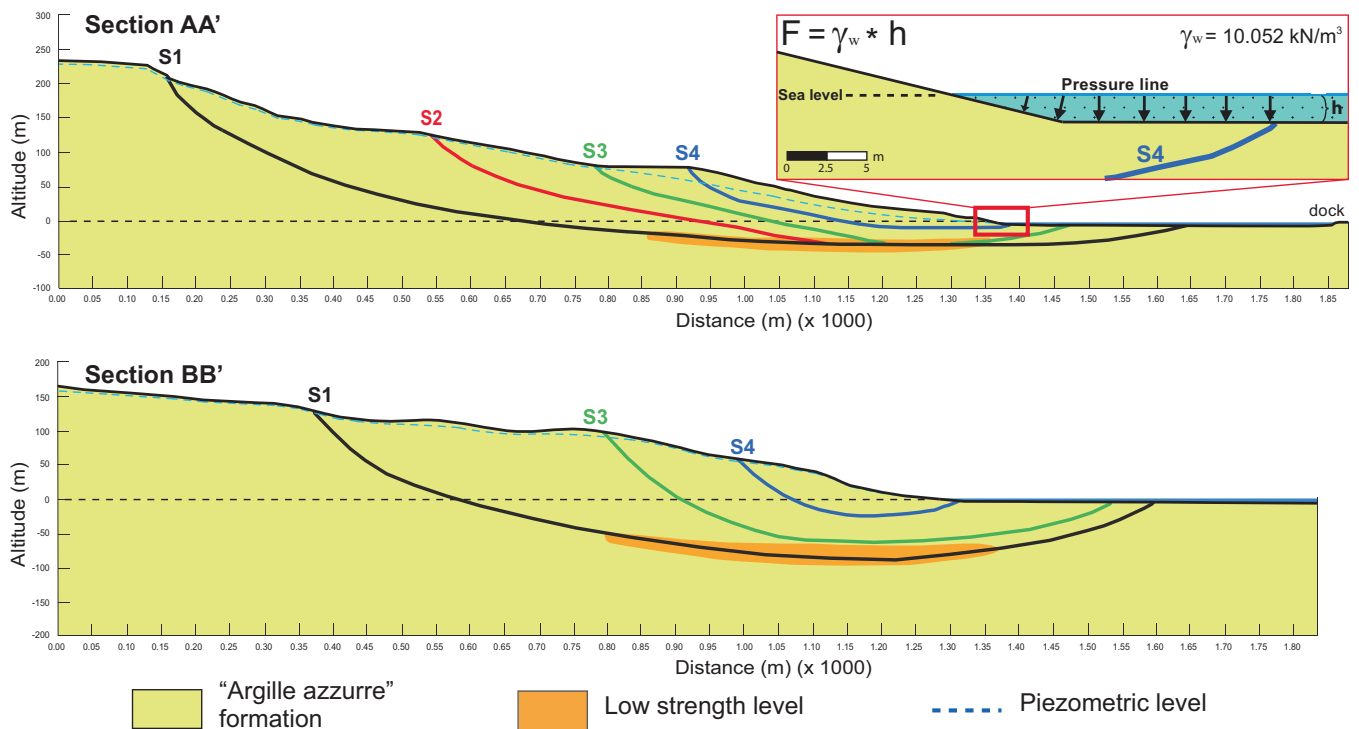**Fig. 6.** Accumulated plastic strain during calculation for sections AA' (left) and BB' (right).

Fig. 7. Definition of the geometries used with SLOPE/W software for sections AA' and BB'. Details of the seawater weight modelling are given in the enlarged view at upper right.
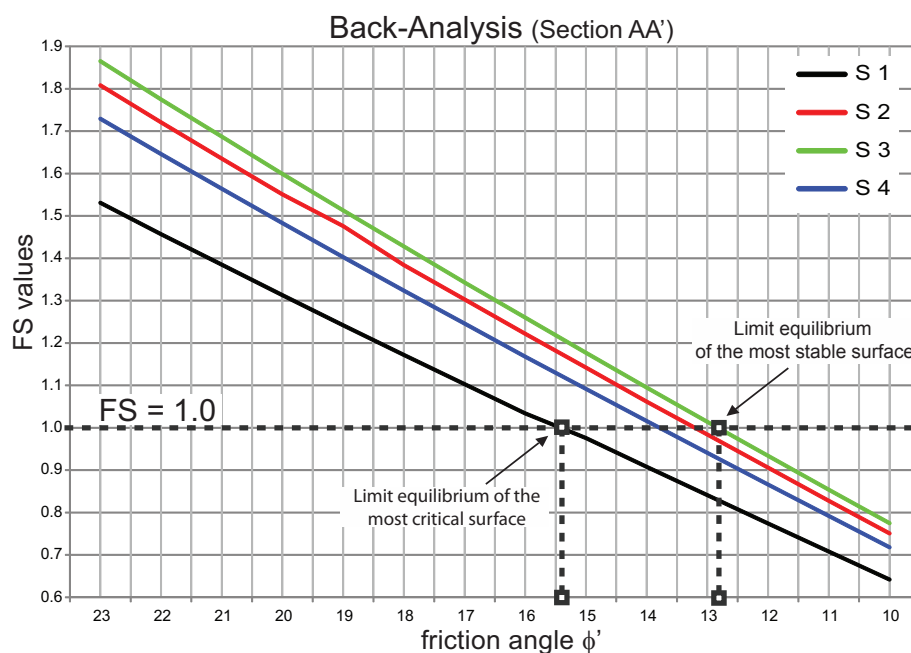
Fig. 8. Results of the back-analysis executed on the four sliding surfaces identified along the section AA'.

which consider peak strength parameters. These results are in agreement with the movements observed in the event of 1982, during which the most significant displacements are registered for the shallowest sliding surface.

Discussion

The analysis of the existing information from boreholes and inclinometers has allowed us to redefine the sliding surfaces of the Ancona landslide along two sections. Given the extreme complexity of the studied phenomena, the proposed sliding surfaces are the ones that best summarize the Ancona landslide as a whole. This obviously does not exclude the presence of several minor and shallower phenomena such as earth flows, which are both more limited in space and intermittent in time, and present different triggering conditions with respect to the major phenomena. We have not accounted for these types of phenomena as they are not usually monitored with the conventional monitoring techniques used in this study. However, they have been extensively reported and described through time; an example is the Barducci landslide, in the lower part of section AA', or the landslide reported by Segré (1920) close to the top of Montagnolo hill (Fig. 4).

The reconstruction of the actual underground 3D location of the sliding surfaces of the Ancona landslide is impossible owing to the lack of a complete database of movement measurements. However, it has been possible, based on geomorphological evidence and on pre-existing inventory maps, to infer the landslide perimeter outside the analysed sections. In particular, four main bodies and associated perimeters, related to the four main sliding surfaces detected, have been defined and mapped (Fig. 11).

The perimeter of body 1 is in accordance with the official perimeter of the landslide reported in the Marche Region Hydrogeological Setting Plan. Outside this perimeter, near the coastline, there are some areas that show evidence of movements (Fig. 11) detected through geological survey, topographic levelling and satellite monitoring by means of the PS-InSAR technique (Colesanti *et al.* 2003; V. Cotecchia, unpublished data) and that in the past have been already considered as potentially affected by the landslide activity (Segrè 1920). In particular, these areas show an

Table 2. *Soil geotechnical parameters used in the limit equilibrium analysis*

	Peak strength parameters	Intermediate strength parameters	Residual strength parameters
γ (kN m^{-3})	20	20	20
c' (kPa)	10	10	0
ϕ' (°)	23	17	12

uplift movement with average velocity, along the line of sight of the satellite, between about 2 mm a^{-1} in the western area and 2.5 mm a^{-1} in the eastern area (Fig. 11), with an almost linear trend (Colesanti *et al.* 2003). Some further investigation and monitoring analysis are necessary to clarify if this uplift is related to landslide.

The perimeter of body 2 (in the middle part of the slope) is well defined by an evident scarp that was partially reactivated in 1982 (Fig. 2); its extent is limited and probably controlled by two NE–SW faults, the Borghetto and the Fornetto–Posatora transverse faults (Figs 1 and 2).

Owing to their probably discontinuous lateral extent, the perimeter of body 3 and especially the perimeter of body 4 have been drawn only in the zones where geomorphological and geotechnical data allow a high degree of certainty. For these two bodies, we thus preferred to not infer their continuation beyond the coastline, restricting the sketch of the perimeters only to the proximity of the section.

The numerical model performed through the FLAC software along the two sections supports the assumed failure mechanism. In particular, the results support the occurrence of multiple sliding surfaces with shape and extent similar to those derived from the analysis of the geotechnical investigation.

The stability analysis, carried out along the identified sliding surfaces, has been performed through the SLOPE/W software, which uses the limit equilibrium method. Five stratigraphic–geotechnical scenarios have been assumed. Scenario 5, which presents Pliocene clay with intermediate strength parameters and a low-strength level with residual strength parameters, shows factor of safety values closest to the limit equilibrium for both of the sections and for all the sliding surfaces. Given that the Ancona landslide is

Table 3. *Geotechnical investigations used in the reconstruction of the sliding surfaces along section AA', ordered from south to north (see Figs 4 and 7 for location)*

			Surface							
			1		2		3		4	
Number	Type	Distance from the section (m)	Depth b.g.l. (m)	Height a.s.l. (m)	Depth b.g.l. (m)	Height a.s.l. (m)	Depth b.g.l. (m)	Height a.s.l. (m)	Depth b.g.l. (m)	Height a.s.l. (m)
P16	P	151	35[1]	170[1]		–				
I14	I	77	64	74	80	58	–	–		
P17	P	4	100[1]	–15.5[1]						
I12	I	43	27[3]	57.5[3]	40[3]	44.5[3]	60[2]	24[2]	94.5[1]	–10[1]
I22	I	237	7[4]	73[4]	36[4]	44[4]	54[3]	26[3]	72[2]	8[2]
ST1	B	307	*41/45[4]*	*24/20[4]*	63/69[3]	2/–4[3]	80/90[2]	–5/–15[2]	*94[1]*	*–29[1]*
I28	I	288	20	41	35	26	49	12		
I18	I	198	58[3]	–9[3]	77[2]	–28[2]				
I20	I	236	*19*	*19*	31[4]	7[4]	*62[3]*	*–24[3]*		
I13	I	97	33[4]	–7[4]	*44*	*–18*				
I16	I	209	15	11	*25*	*1*				
I11	I	0	17	3	22[4]	–2[4]	55*[1]	–35*[1]		
B27	B	7	26[4]	–8[4]	51*[3]	–33*[3]				
I15	I	140	7	6	20[4]	–7[4]	46*[2]	–33*[2]		
SM1	B	160	–14.5[3]	–17.5[3]	*30[1]*	*–33[1]*				
B25	B	134	15[3]	–18[3]	36[1]	–39[1]				
B26	B	54	15[1]	–19[1]						

P, piezometer; I, inclinometer; B, borehole. Depth values indicate the depth below ground level (b.g.l.) of the evidence of observed movement; height values indicate their altitude above sea level. Superscript numbers match sliding surfaces and their associated movement evidence: [1]surface 1; [2]surface 2; [3]surface 3; [4]surface 4. Numbers in italics refer to secondary or minor movement evidence.
*Two or more coincident sliding surfaces are at the same depth.

Table 4. *Geotechnical investigations used in the reconstruction of the sliding surfaces along section BB', ordered from south to north (see Figs 4 and 7 for location)*

			Surface					
			1		2		3	
Number	Type	Distance from the section (m)	Depth b.g.l. (m)	Height a.s.l. (m)	Depth b.g.l. (m)	Height a.s.l. (m)	Depth b.g.l. (m)	Height a.s.l. (m)
I7	I	119	75[1]	87[1]				
I10	I	107	12	88	*18*	*82*	*27*	*73*
I9	I	38	10[2]	82[2]	24	68	*39*	*53*
I8	I	32	*9*	*78*	42[2]	45[2]		
B15	B	24	23	62.5	*34*	*51.5*	*44*	*41.5*
I6	I	187	*37[3]*	*–233[3]*	–	–	–	–
I5	I	315	11	1	30[3]	–18[3]		
B22	B	177	20[2]	–23[2]				
B12	B	113	3/8[2]	–7/–12[2]	–37	–41		
B13	B	87	20/24	–24/–28	49[1]	–53.5[1]		
B11	B	235	–15[1]	–19.5[1]				

I, inclinometer; B, borehole. Depth values indicate the depth below ground level (b.g.l.) of the evidence of observed movement; height values indicate their altitude above sea level. Superscript numbers match sliding surfaces and their associated movement evidence: [1]surface 1; [2]surface 3; [3]surface 4. Numbers in italics refer to secondary or minor movement evidence.

an active one, it is credible to suppose that this scenario could represent the most reliable reconstruction of the underground and geotechnical conditions of the landslide. This analysis can be confirmed also by the fact that the low-strength level has also been identified in some boreholes and by the fact that a recovery of strength is plausible in the case of an intermittent kinematic behaviour such as that of the Ancona landslide (where long periods of inactivity or with only minor movements allow, for example, a progressive reduction of the width of fractures that may result in an increase in the overall material strength, except for the deep shear band where several sliding surfaces converge and the strain is concentrated).

Conclusion

The Ancona landslide is a deep-seated multiple, compound (rotational–translational movement) and recurrent (slow, continuous movement, with short and sudden accelerations) landslide.
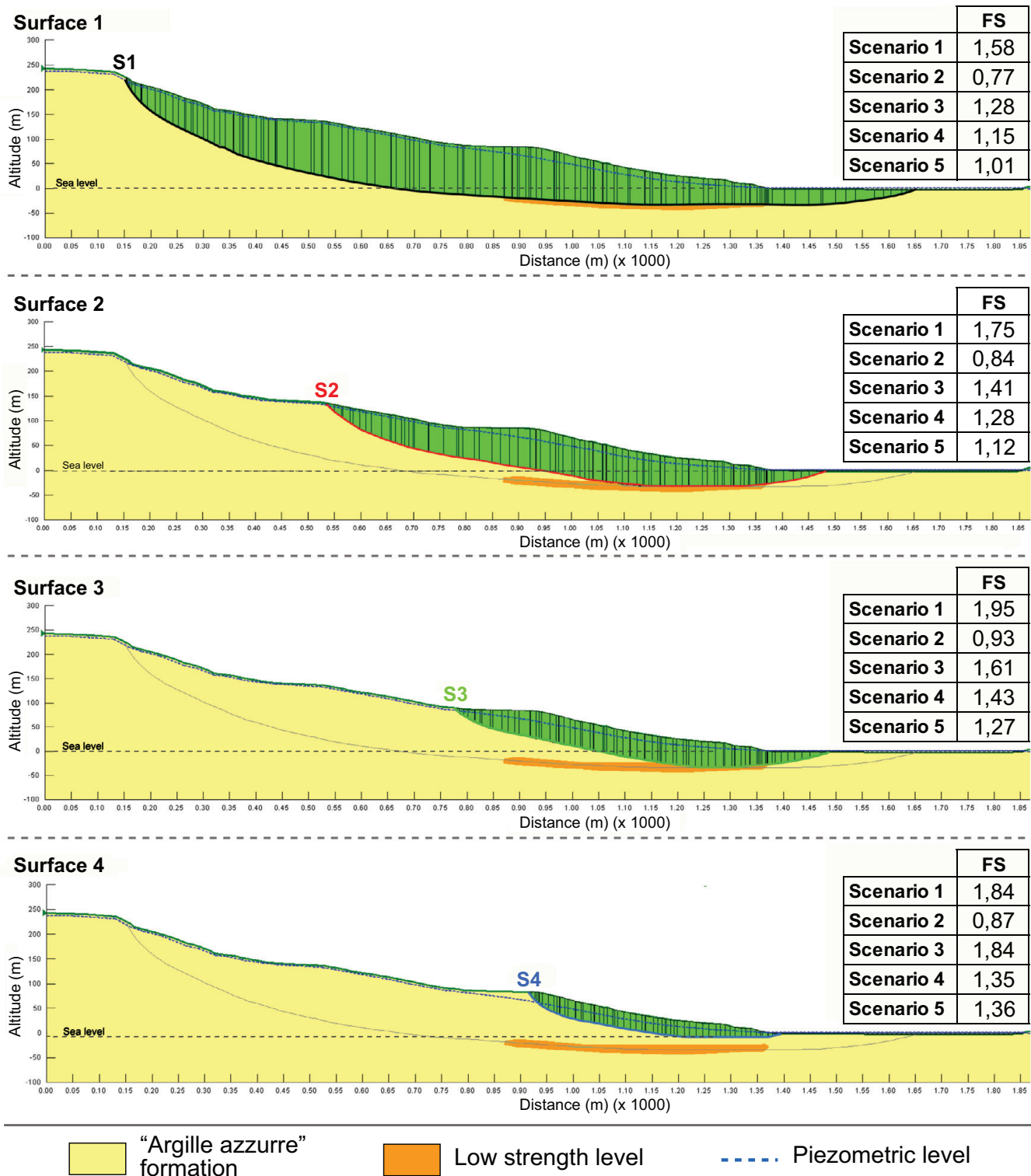
	FS
Surface 1	
Scenario 1	1,58
Scenario 2	0,77
Scenario 3	1,28
Scenario 4	1,15
Scenario 5	1,01

	FS
Surface 2	
Scenario 1	1,75
Scenario 2	0,84
Scenario 3	1,41
Scenario 4	1,28
Scenario 5	1,12

	FS
Surface 3	
Scenario 1	1,95
Scenario 2	0,93
Scenario 3	1,61
Scenario 4	1,43
Scenario 5	1,27

	FS
Surface 4	
Scenario 1	1,84
Scenario 2	0,87
Scenario 3	1,84
Scenario 4	1,35
Scenario 5	1,36

Legend: "Argille azzurre" formation — Low strength level — Piezometric level

Fig. 9. Results of the stability analysis performed on the four sliding surfaces identified along section AA'. Factor of safety (FS) values in the tables refer to the results of the analysis performed with the parameters of the five scenarios.

On the night of 13 December 1982, the landslide reactivated; this event had a volume of about $180 \times 10^6 \, m^3$, and the affected surface area was about $3.4 \, km^2$, accounting for 11% of the total urban area of the Ancona municipality. After the 1982 event, several geological and geotechnical investigations were carried out to define the surface and depth extents of the landslide, failure mechanisms and the factors that triggered the event. Since 1983

monitoring instrumentation such as piezometers and inclinometers has been installed; data obtained from these instruments have been of key importance in identifying the sliding surfaces and monitoring the deep continuing deformations.

The aim of this study has been the definition of a new appraisal of the Ancona landslide based on the geotechnical investigations and on numerical modelling. In particular, the results of past and
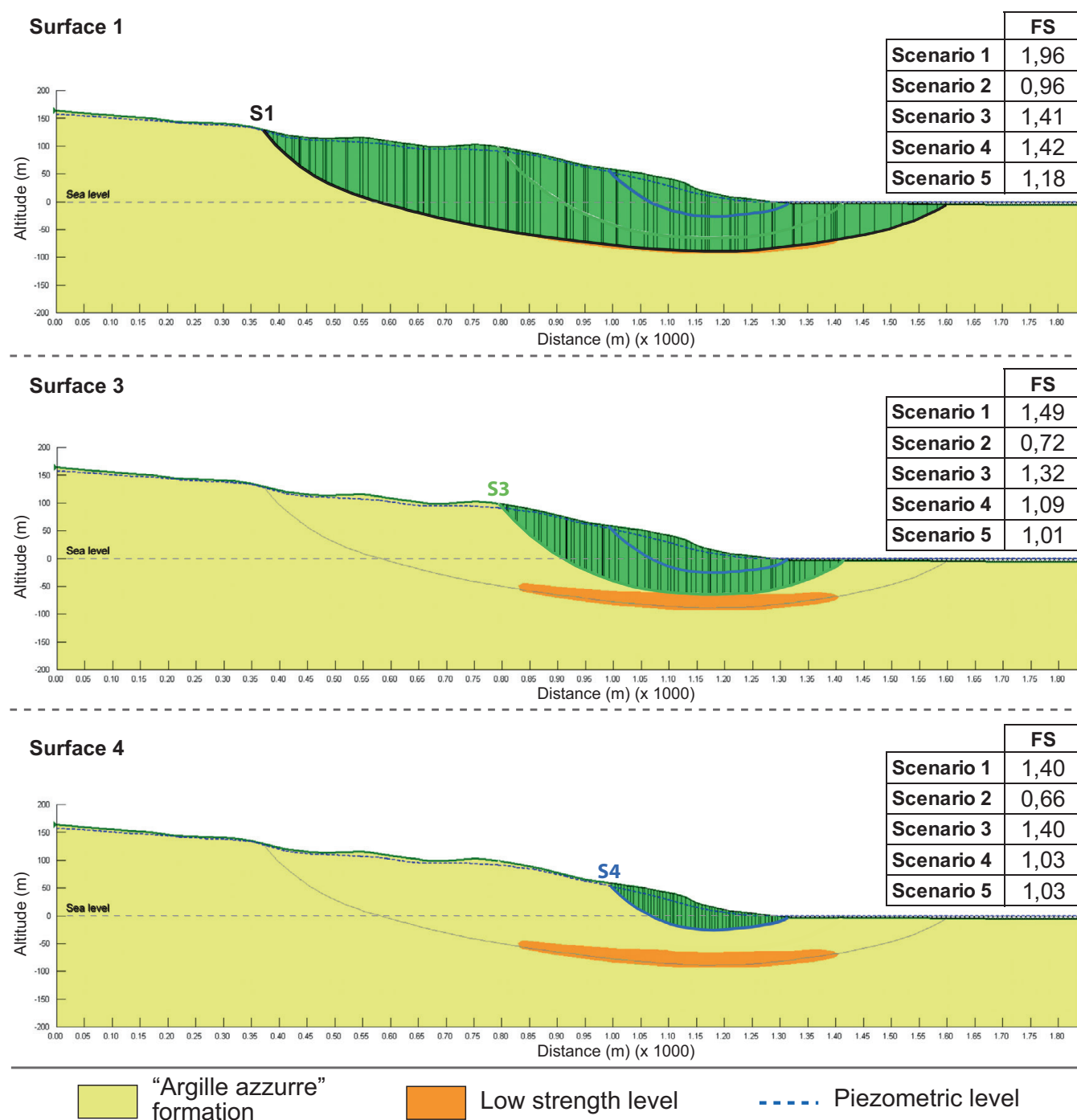
Fig. 10. Results of the stability analysis performed on the three sliding surfaces identified along section BB'. Factor of safety (FS) values in the tables refer to the results of the analysis performed with the parameters of the five scenarios.

new geotechnical investigations and all the data from the 30 year readings of the monitoring instruments have been integrated to redefine and update the actual location of the sliding surfaces along two longitudinal sections of the landslide. Furthermore, numerical and analytical modelling of the landslide has been carried out using the newly derived geometries of the sliding surfaces.

The main outcomes of the study are as follows.

(1) Four main sliding surfaces with different extents and depths, which range from around 110 m b.g.l. to 30 m b.g.l., have been identified. The deepest surfaces converge at depth in a low-strength level as hypothesized by Cotecchia (2006) and emerge near or beyond the coastline (with a maximum distance of around 300 m).

(2) The numerical modelling, carried out using the finite-difference method implemented in the FLAC program, has allowed a qualitative assessment of the deformation pattern of the landslide, which correlates well with the geometry of the sliding surfaces derived from the geotechnical investigations.

(3) The results of the stability analysis, carried out with the SLOPE/W software and applied to five stratigraphic–geotechnical scenarios, describe a slope condition near the limit equilibrium, with FS values equal to unity or slightly higher.

(4) The scenario that best describes the stability condition of the Ancona landslide involves Pliocene clay with intermediate strength parameters and a deep low-strength level with residual strength parameters.
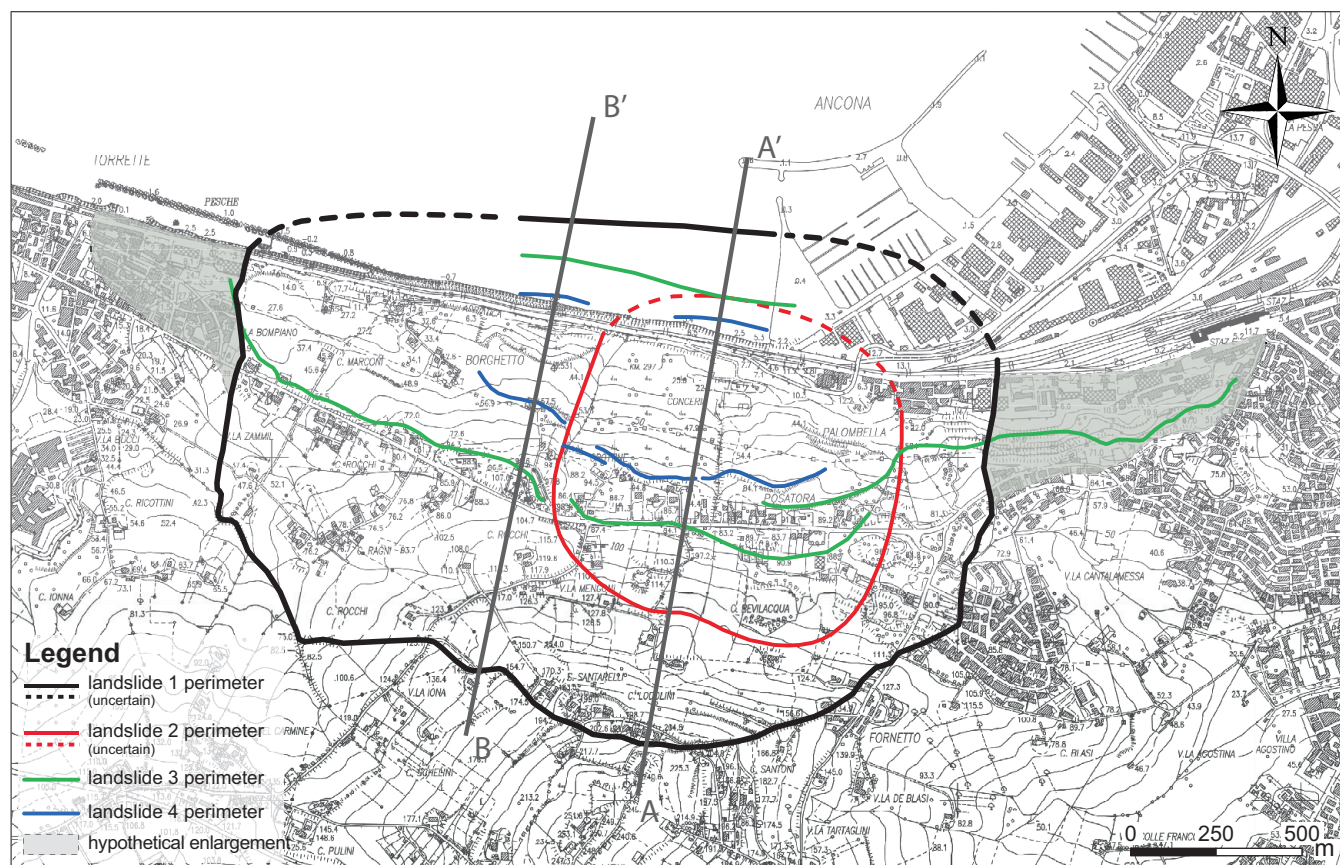
Fig. 11. Perimeters of the four main bodies of the Ancona landslide (uncertain perimeters are indicated with a dashed line). Available data do not allow us to draw complete perimeters for landslides 3 and 4. Grey areas indicate hypothetical enlargement of the landslide area on the basis of PSI data (Colesanti *et al.*, 2003).

The outcomes of this study will be of help to further develop the early warning system of the landslide adopted as the current risk management strategy, as the identification of the most hazardous scenario and the location of the sliding surfaces will help in optimizing the installation of new monitoring instruments and/or will reinforce the value of the existing ones. Furthermore, the new landslide perimeters identified should be considered as input data for any land planning policies to provide recommendations and prescriptions in the area with highest landslide risk.

References

BALLY, A.W., BURBI, L., COOPER, C. & GHELARDONI, R. 1986. Balanced section and seismic reflection profiles across the Central Apennines. *Memorie della Società Geologica Italiana*, **35**, 237–310.

BIGI, S., CANTALAMESSA, G., ET AL. 1997. The Periadriatic Basin (Marche–Abruzzi sector, Central Italy) during the Plio-Pleistocene. *Giornale di Geologia*, **59**, 245–259.

BRACCI, V. 1773. *Relazione alla visita fatta per ordine della Congregazione de B. Governo nei mesi di aprile e maggio 1773 a un tratto di strada Flaminia*. Archivio di Stato, Ancona, **sez. IV**.

CALAMITA, F. & DEIANA, G. 1986. Evoluzione strutturale Neogenico-Quaternaria dell'Appennino Umbro-Marchigiano. *Studi Geologici Camerti, Volume Speciale*, 91–98.

CALAMITA, F. & DEIANA, G. 1988. The arcuate shape of the Umbria–Marche–Sabine Apennines (Central Italy). *Tectonophysics*, **146**, 131–147.

CANCELLI, A., MARABINI, F., PELLEGRINI, M. & TONNETTI, G. 1984. Incidenze delle frane sull'evoluzione della costa adriatica da Pesaro a Vasto. *Memorie della Società Geologica Italiana*, **27**, 555–568.

CANTALAMESSA, E. & DI CELMA, C. 2004. Sequence response to syndepositional regional uplift: Insights from high-resolution stratigraphy of late Early Pleistocene strata, Periadriatic Basin, central Italy. *Sedimentary Geology*, **164**, 283–309.

CANTALAMESSA, G., CENTAMORE, E., ET AL. 1986. Il Plio-Pleistocene delle Marche. *Studi Geologici Camerti, Volume Speciale*, 61–81.

CANTALAMESSA, G., CENTAMORE, E., ET AL. 1987. Nuovi dati sulla geologia dell'area di Porto San Giorgio (Ascoli Piceno, Marche). *Geologica Romana*, **26**, 359–369.

CARDELLINI, S. & OSIMANI, P. 2008. Living with Landslide: The Ancona Case History and Early Warning System. *In*: CASAGLI, N., FANTI, R. & TOFANI, V. (eds) *Proceedings of the First World Landslide Forum, Tokyo*, ICL & ISDR, Tokyo, 473–476.

CASAGLI, N., DAPPORTO, S., IBSEN, M.L., TOFANI, V. & VANNOCCI, P. 2006. Analysis of the landslide triggering mechanism during the storm of 20th–21th November 2000, in Northern Tuscany. *Landslide*, **3**, 13–21, doi:10.1007/s10346-005-0007-y.

CASSINIS, R., TABACCO, I., BRUZZI, G.F., CORNO, C., BRANDOLINI, A. & CARABELLI, E. 1985. The contribution of geophysical methods to the study of the great Ancona landslide (December 13, 1982). *Geoexploration*, **23**, 363–386.

CELLO, G. & COPPOLA, L. 1989. Modalità e stili deformativi dell'area Anconetana. *Studi Geologici Camerti*, **11**, 37–47.

CELLO, G. & TONDI, E. 2013. *Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, foglio 282 Ancona*. SELCA Firenze.

CENTAMORE, E. & MICARELLI, A. 1991. Stratigrafia. *In: L'ambiente fisico delle Marche*. SELCA, Firenze.

CENTAMORE, E., COLTORTI, M., ET AL. 1982. Aspetti neotettonici e geomorfologici del Foglio 133–134 (Ascoli Piceno–Giulianova). CNR-Progetto Finalizzato 'Geodinamica': Contributi conclusivi per la realizzazione della Carta Neotettonica d'Italia, **2**, 371–386.

COLALONGO, M.L., NANNI, T. & RICCILUCCHI, F. 1979. Sedimentazione ciclica nel Pleistocene anconetano. *Geologia Romana*, **18**, 71–96.

COLAPIETRO, E. 1822. Su le rovine della città di Vasto in Abruzzo Citeriore avvenute nel mese di aprile dello scorso 1816. *Atti del Regio Istituto d'Incorraggiamento alle Scienze Naturale di Napoli*, Napoli.

COLESANTI, C., FERRETTI, A., PRATI, C. & ROCCA, F. 2003. Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. *Engineering Geology*, **68**, 3–14.

COLTORTI, M., DRAMIS, F., GENTILI, B., PAMBIANCHI, G., CRESCENTI, U. & SORRISO-VALVO, M. 1985. The December 1982 Ancona landslide: A case of deep-seated gravitational slope deformation evolving at unsteady rate. *Zeitschrift für Geomorphologie*, **29**, 335–345.

COLTORTI, M., DRAMIS, F., GENTILI, B., PAMBIANCHI, G. & SORRISO-VALVO, M. 1986. Aspetti geomorfologici della frana di Ancona. *Studi Geologici Camerti, Numero Speciale*, 29–40.

COLTORTI, M., FARABOLLINI, P., GENTILI, B. & PAMBIANCHI, G. 1996. Geomorphological evidence for anti-Apennine faults in the Umbro-Marchean Apennines and in the peri-Adriatic basin, Italy. *Geomorphology*, **15**, 33–45.

COTECCHIA, V. 2006. The Second Hans Cloos Lecture. Experience drawn from the great Ancona landslide of 1982. *Bulletin of Engineering Geology and the Environment*, **65**, 1–41.

COTECCHIA, V. & SIMEONE, V. 1996. Studio dell'incidenza degli eventi di pioggia sulla grande frana di Ancona del 13.12.1982. *In*: *Proceedings of the International Conference on Prevention of Hydrogeological Hazards: the Role of Scientific Research*, 19–29.

COTECCHIA, V., GRASSI, D. & MERENDA, L. 1995. Fragilità dell'area urbana occidentale di Ancona dovuta a movimenti di massa profondi e superficiali ripetutesi nel 1982. *Geologia Applicata ed Idrogeologia*, **30**, 633–657.

COWARD, M.P., DEDONATIS, M., MAZZOLI, S., PALTRINIERI, W. & WEZEL, F. 1999. Frontal part of the northern Apennines fold and thrust belt in the Romagna–Marche area (Italy): Shallow and deep structural styles. *Tectonics*, **18**, 559–574, http://dx.doi.org/10.1029/1999TC900003.

CRESCENTI, U. 1986. Notizie Precedenti. *Studi Geologici Camerti, Numero Speciale*, 13–23.

CRESCENTI, U., NANNI, T., RAMPOLDI, R. & STUCCHI, M. 1977. Ancona: Considerazioni sismo-tettoniche. *Bollettino di Geofisica Teorica e Applicata*, **73-74**, 33–48.

CRESCENTI, U., CIANCETTI, G.F., ET AL. 1983. La grande frana di Ancona del 1982. Collana 'Problemi del territorio', Spoleto, 4–7 maggio 1983. Ancona Municipality and Ancona University.

CRESCENTI, U., CURZI, P.V., GALLIGNANI, P., GASPERINI, M., RAINONE, M. & STEFANON, A. 1984. La frana di Ancona del 13 dicembre 1982: Indagini a mare. *Memorie della Società Geologica Italiana*, **27**, 545–553.

CRESCENTI, U., CALISTA, M., MANGIFESTA, M. & SCIARRA, N. 2005. The Ancona landslide of December 1982. *Giornale di Geologia Applicata*, **1**, 53–62.

CRUDEN, D.M. & VARNES, D.J. 1996. Landslide types and processes. *In*: TURNER, A.K. & SCHUSTER, R.L. (eds) *Landslides Investigation and Mitigation*. Transportation Research Board, Special Report, **247**.

CUNIETTI, M., BONDI, G., ET AL. 1986. Misure topografiche ed aerofotogrammetriche. *Studi Geologici Camerti, Numero Speciale*, 41–82.

CURZI, P.V. & STEFANON, A. 1986. Indagini a mare. *Studi Geologici Camerti, Numero Speciale*, 135–144.

DE BOSIS, F. 1859. *Il Montagnolo: studi ed osservazioni*. Encicl Contemp. Gabrielli, Fano.

DRAMIS, F. 1992. Il ruolo dei sollevamenti tettonici a largo raggio nella genesi del rilievo appenninico. *Studi Geologici Camerti, Volume Speciale*, 9–15.

DRAMIS, F., MAIFREDI, P. & SORRISO-VALVO, M. 1983. Deformazioni gravitative profonde di versante. Aspetti geomorfologici e loro diffusione in Italia. *Geologia Applicata e Idrogeologia*, **18**, 355–368.

DRAMIS, F., FARABOLLINI, P., GENTILI, B. & PAMBIANCHI, G. 2002. Neotectonics and large-scale gravitational phenomena in the Umbria–Marche Apennines, Italy. *In: Seismically Induced Ground Ruptures and Large Scale Mass Movements. Field Excursion and Meeting 21–27 September 2001.* APAT, Atti, **4/2002**, Rome, 17–30.

ESU, F. 1986. Analisi delle condizioni di stabilità. *Studi Geologici Camerti, Numero Speciale*, 29–40.

FANGI, G. & RADICIONI, R. 1984. *Ancona: confronto tra profili altimetrici precedenti e successivi alla frana del dicembre 1982*. Bollettino della SIFET, 2

FIORILLO, F. 2003. Geological features and landslide mechanisms of an unstable coastal slope (Petacciato, Italy). *Engineering Geology*, **67**, 255–267.

GASPARINI, C., JANNACONE, G. & SCARPA, R. 1985. Fault-plane solutions and seismicity of the Italian peninsula. *Tectonophysics*, **117**, 59–78.

ITASCA 2000. *FLAC: Fast Lagrangian Analysis of Continua—Version 4.0. User's Manual*. Itasca Consulting Group, Minneapolis, MN.

KRAHN, J. 2004. *Stability Modeling with SLOPE/W. An Engineering Methodology*. GEO-SLOPE/W International, Calgary.

MICHETTI, A.M. & BRUNAMONTE, F. 2002. Some remarks on the relations between the 1972 Ancona earthquake sequence and the Ancona landslide. *In: Seismically Induced Ground Ruptures and Large Scale Mass Movements. Field Excursion and Meeting 21–27 September 2001.* APAT, Atti, **4/2002**, 31–34.

MORGENSTERN, N.R. & PRICE, W.E. 1965. The analysis of the stability of general slip surfaces. *Géotechnique*, **15**, 79–93.

NANNI, T. 1980. *Note illustrative sulla geologia dell'Anconetano*. Ed. a cura della Regione Marche, Ancona.

ORI, G.G., SERAFINI, G., VISENTIN, C., RICCILUCCHI, F., CASNEDI, R., COLALOGNO, M. & MOSNA, S. 1991. *The Pliocene–Pleistocene Adriatic foredeep (Marche and Abruzzo, Italy): An integrated approach to surface and subsurface geology. Third EAPG Conference, Adriatic Foredeep Field Guidebook*, Florence.

RIGUZZI, F., TERTULLIANI, A. & GASPARINI, C. 1989. Study of the seismic sequence of Porto S. Giorgio (Marche)—3 July 1987. *Il Nuovo Cimento della Società Italiana di Fisica*, **12**, 453–466.

SANTALOIA, F., COTECCHIA, V. & MONTERISI, L. 2004. Geological evolution and landslide mechanisms along the central Adriatic coastal slopes. *In*: JARDINE, R.J., POTTS, D.M., HIGGINS, K.G. (eds) *Proceedings of the Skempton Conference, London, Vol. 2*, Thomas Telford Publishing, London, 943–954.

SEGRÈ, C. 1918. Considerazioni geognostiche circa il comportamento della ferrovia nei tratti franosi del litorale adriatico, con speciale riguardo alla frana di Torino di Sangro. Rivista Tecnica delle Ferrovie Italiane, **14**.

SEGRÉ, C. 1920. Criteri geognostici per il consolidamento della falda franosa del Montagnolo, litorale Ancona–Falconara. *Bolletino della Società Geologica Italiana*, **38**, 99–131.

SKEMPTON, A.W. & HUTCHINSON, J.N. 1969. Stability of natural slopes and embankment foundation. State of the Art Report. *In*: *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City*.

STUCCHI, E. & MAZZOTTI, A. 2009. 2D seismic exploration of the Ancona landslide (Adriatic Coast, Italy). *Geophysics*, **74**, B139–B151.

TOFANI, V., DAPPORTO, S., VANNOCCI, P. & CASAGLI, N. 2006. Infiltration, seepage and slope instability mechanisms during the 20–21 November 2000 rainstorm in Tuscany, central Italy. *Natural Hazards and Earth System Sciences*, **6**, 1025–1033.

WAGNER, A. 1957. The use of the Unified Soil Classification System by the Bureau of Reclamation. *In*: *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering, London*, **Vol. 1**, 125.
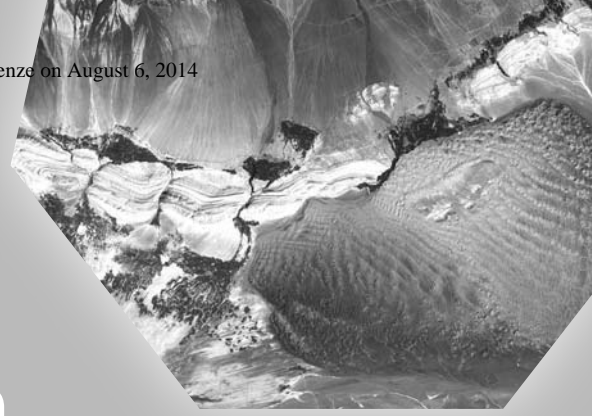
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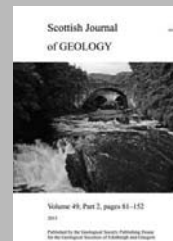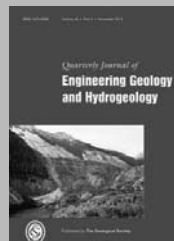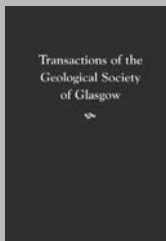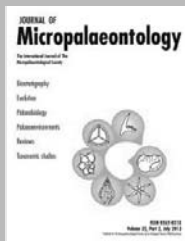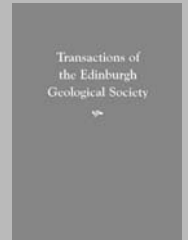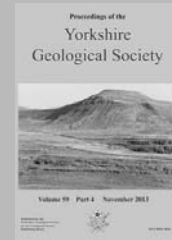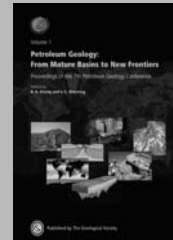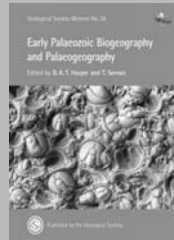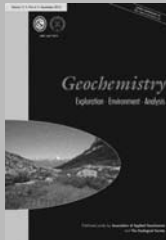
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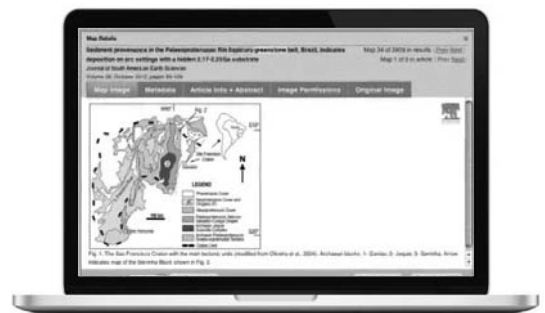
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