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ScienceDirect

Procedia Engineering 158 (2016) 194 – 199

Procedia Engineering

www.elsevier.com/locate/procedia

VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING –
Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale,
CNRIG2016

Kinematics of the Maierato landslide (Calabria, Southern Italy)

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Abstract

On 15 February 2010, a landslide of great dimensions occurred at Maierato (Southern Italy) after a long rainy period. Although the zone was continuously affected by movements, no monitoring system was installed before the landslide. However, many photos were taken to document the occurrence of deformations and two videos were filmed during the paroxysmal phase of the event. Photos and videos are used in the present study to reconstruct the kinematics of the landslide. A geotechnical model of the slope is also defined on the basis of the results from field and laboratory tests.

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Keywords: Landslide; failure mechanism; rainfall; geotechnical model of the slope

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1. Introduction

On 15 February 2010, a landslide of great dimensions (Fig. 1) occurred at Maierato which is a village located about 8 km from Vibo Valentia (Calabria, Southern Italy), in a site with elevation ranging from 200 to 320 m a.s.l.. The Maierato landslide was studied by several authors who provided a detailed description of the geological, geomorphological and tectonic setting in which the landslide occurred [1-5]. The dimensions of the landslide body were about 1000 m in length and about 500 m in width. The maximum height of the main scarp was approximately 50 m. The volume of the displaced mass was estimated from 5 to 10×10^6 m^3. On 20 February 2010, an additional soil volume of about 5×10^5 m^3 broke away from the central part of the main scarp, causing a retreat (about 80 m long) of the landslide crown. The landslide can be classified as a slide that evolved into a rapid flow after the

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Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016
doi:10.1016/j.proeng.2016.08.428

activation phase [6]. The event was preceded by a long rainy period that involved the two preceding years (2008 and 2009) and the first two months of 2010.During this period, a great number of landslides occurred in Calabria.

Fig. 1. Aerial view of the 15 February 2010 Maierato landslide and location of the Maierato village (Calabria, Southern Italy). Legend: a, b and c location of the photos in Fig. 2; B1, B3, B5, B11 and B13 location of the boreholes in Fig. 6; ----- trace of section.

The landslide caused the collapse of a bypass road located on the left flank of the landslide body, the destruction of a main road (SP 55) in the lower part of the slope, and the loss of many hectares of farmland. The landslide also moved a building for a distance over 100 m, and caused the formation of a small lake on the right flank of the landslide body. Although the zone was affected by continuous movements especially during the wet seasons, no monitoring system was installed before the occurrence of the 2010 landslide. However, since the landslide was preceded by large deformations affecting mainly the SP 55 road, the area was under observation from some days. Many photos were taken to document the deformation process, and two videos were filmed during the landslide. In addition, a site investigation consisting of boreholes, field and laboratory tests was carried out after the event. Piezometers were also installed in several boreholes to detect the presence of groundwater in the subsoil. All these data are usedto reconstruct the kinematics of the landslide and to define the geotechnical model of the slope.

2. Kinematics of the Maierato landslide

Following Guerricchio et al. [1], the 15 February 2010 landslide falls within a large area (about 25 km^2 wide) affected by a deep-seated gravitational deformation process of the slope on which the Maierato territory extends. In addition to this deformation process, a complex system of faults contributed to determine the morphology of that area and its high susceptibility to the occurrence of landslides [5]. Numerous landslide bodies (either active or dormant) affecting the study area are documented in the official landslide maps [7] and in the published studies on the Maierato landslide [1-5]. Some landslides were likely caused by the tremendous earthquake which shookthe Calabria region in 1783 [1,5].Thanks to the photos taken before the slope collapse and the videos filmed during the paroxysmal phase of the landslide, it was possible to reconstruct the kinematics of the 2010 landslide. The failure process started on 15 February 2010 in the morning, with the occurrence of large deformations that affected the SP 55 road (Fig. 2a) and the portion of the slope extending upstream from this road to a pre-existing scarp at 270 m a.s.l. (Fig. 2c). With time progress, slope movements caused the formation of further cracks and bulges on the ground surface and along the SP 55 road (Fig. 2b).At 4:55 pm, the main scarp was formed and some minutes later, it developed another transversal fracture at an elevation of 285 m a.s.l. (Fig. 3). On the contrary, a pre-existing scarp at 305 m elevation was not involved by the failure process (Fig. 3). While the height of the scarps at 285 and 300 m elevation were progressively increasing, a soil mass consisting mainly of evaporitic limestone broke away from the scarp at 270 m elevation causing the complete collapse of a hairpin road. This soil mass, moving downstream as a debris flow, covered the SP 55 road. At 5:10 pm, the crown of the landslide body was completely developed. At the same time, the most part of the displaced material rapidly evolved into a flow, and some small lakes formed at the foot of the main scarp and along the contour of the landslide body.

Fig.2. (a,b)cracks and bulges along the SP 55 road; (c)increase in the height of a pre-existing scarp at 270 m a.s.l.(location is indicated in Fig.1).

Fig. 3. The 15 February 2010 landslide with an indication of the main slip surfaceat300 m elevation (red arrows) and a second slip surface emerging at285 m elevation (blue arrows). The pre-existing scarp at 305 m a.s.l. (yellow arrows) was not involved by the failure process.

3. Rainfall preceding the landslide

The 15 February 2010 landslide occurred after a long rainy period that also involved the years 2008 and 2009. In particular, from 1 September 2009 to 15 February 2010 (for a total of 168 days), a cumulative rain of about 900 mm was recorded at the rain-gauge station of Vibo Valentia. Daily rainfall recorded in this period is presented in Figure4. As can be seen, although the rain depths are not particularly high (the maximum value is 35.6 mm), precipitation is well distributed over the time period considered. Such a characteristic should in principle favour infiltration (rather than surface flow) and consequently groundwater supply. Figure 5 shows the cumulative rain in the wettest 168 consecutive days of each year of the time series, from 1919 to the date of the landslide. As can be observed, a value of 900 mm was exceeded few times. In addition, two consecutive years with rainfall comparable with that recorded in the years 2009-2010 (black arrow) only occurred in the years 1939-1940 and 1944-1946 (white arrows), i.e. over 60 years before the 2010 landslide, when the land conditions were different from the current ones. In the last decades, in fact, a large area surrounding the landslide site was urbanized.

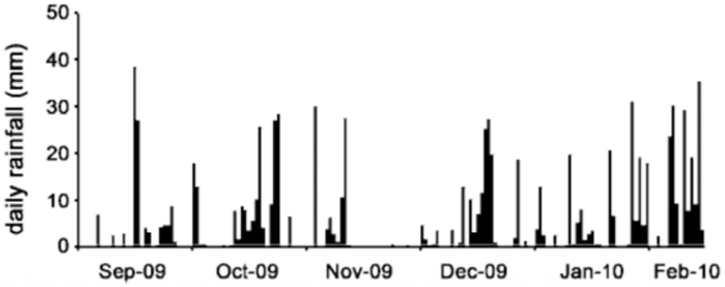

Fig. 4.Daily rainfall recorded at Vibo Valentia station from 1 September 2009 to 15 February 2010.

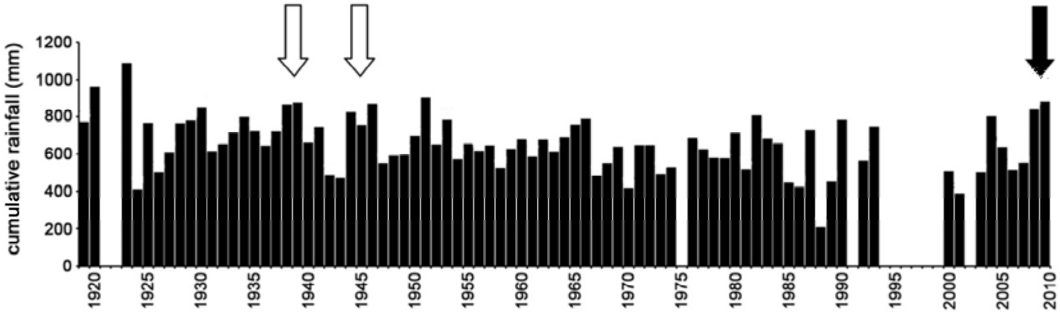

Fig. 5.Cumulative rain in the wettest 168 consecutive days of each yearof the time series, from 1919 to 2010.

4. Geotechnical model of the slope

A site investigation consisting of boreholes, laboratory and field tests was performed after the 15 February 2010 landslide. Figure 6 shows the soil profile of some boreholes which were instrumented by piezometers sealed at different depths. The mean piezometric level measured after the landslide, in the period 2011-2012, is also indicated in Fig. 6, for each piezometer considered. As it can be seen, the subsoil consists of the following sequence (from top to bottom) of soils and rocks: (1) Pliocene deposit formed by layers of silty sand and clayey silt. This deposit has a thickness variable from 5 m to 25 m; (2) Miocene evaporitic limestone with a thickness of 25-45 m; (3) Miocene marly clay the thickness of which ranges from a few meters to 20 m; (4) Miocene sandstone, slightly cemented, with a thickness varying from 10 to 40 m; (5) Miocene conglomerate formed by sand and gravel with clasts and blocks deriving from the underlying formation; (6) Paleozoic basement consisting of gneiss generally with a high degree of weathering. As shown in Fig. 6, a different groundwater, often under pressure, is located in the evaporitic limestone, sandstone and gneiss.Field tests consisting of standard penetration tests (SPT), Ménardpressuremeter tests (MPT) and Lefranc tests were carried out at various depths along some boreholes. In particular, SPTs were performed in the sandy layers of the Pliocene deposit and in the Miocene sandstone. Values of N_{SPT} from 19 to 40 blows/30cm were recorded in the Pliocene sand, whereas all the tests performed in the Miocene sandstone yielded a refusal after a penetration of few centimetres. In the evaporitic limestone, both the Ménard modulus, E_M, and the limit pressure, p_{LIM}, generally increase with depth. In particular, E_M varies from 12 to 28 MPa, and p_{LIM} from 1.4 to 3.7 MPa. Higher values of these parameters were found in the sandstone and conglomerate. Marchetti Dilatometer Tests (MDT) were also carried out. Average values of the lateral stress index K_d=14 and dilatometer modulus E_d=30 MPa can be attributed to the marly clay. In the evaporitic limestone, both K_d and Ed have a trend to increase with depth. In particular, K_d varies approximately from 5 to 10 and E_d from 30 to 100 MPa. The test conducted in the sandstone was stopped at a depth of about 4.5 m, because of the high mechanical properties of this geological formation. The average values of K_d and E_d for this material were 30 and 150 MPa, respectively. Lefranc tests provided the values of the coefficient of permeability, k, indicated in Table 1 [3]. Finally, direct shear tests were conducted to evaluate the soil strength parameters at peak (c'_p;φ'_p) and residual (φ'_r). On the basis of the experimental data available, the subsoil model shown in Fig. 7 has been reconstructed. The mechanical properties assigned to each soil layer are specified in Table 1, in which γ,E'andv' denote the unit weight, Young’s modulus and Poisson’s ratio, respectively. The values indicated in Table 1 have been obtained directly from the results of the laboratory tests or using empirical relationships between soil properties and the results from the field tests available [8-10]. Some finite element analyses in which suitable constitutive models are incorporated [11-15], are in progress to interpret the failure mechanism documented by the images and to establish the main factors of triggering of the landslide.

Table 1. Soil parameters

Material	γ (kN/m^3)	c'_p (kPa)	φ'_p (°)	φ'_r (°)	E' (MPa)	v'	k (m/s)
silty sand	19	0	37	-	90	0.30	$1\cdot10^{-6}$
clayey silt	19	15	26	15	20	0.30	$2\cdot10^{-9}$
evaporitic limestone	19	15	36	28	50	0.30	$1\cdot10^{-7}$
marly clay	18	57	25	13	20	0.30	$1\cdot10^{-9}$
sandstone	20	0	45		400	0.30	$5\cdot10^{-8}$
gneiss	20				500	0.30	$1\cdot10^{-8}$

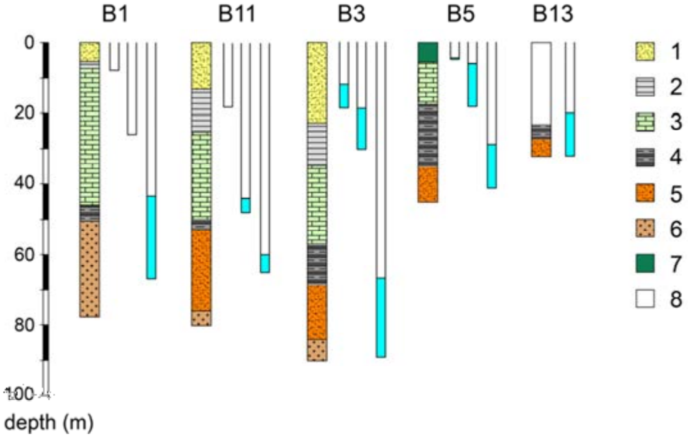

Fig. 6.Soil profiles from some boreholes (location is indicated in Fig. 1) with an indication of the piezometric levels measured after the landslide. Legend: 1) silty sand; 2) clayey silt; 3) evaporitic limestone; 4) marly clay; 5) sandstone; 6) gneiss; 7) cover soil; 8) landslide debris.

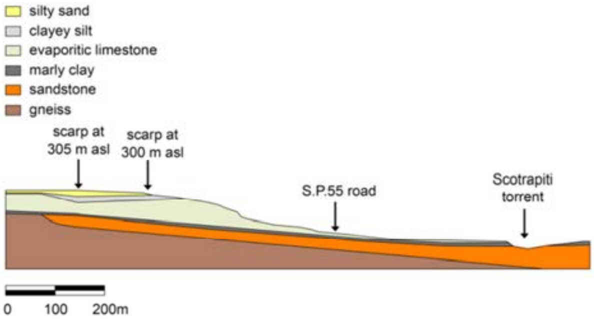

Fig. 7.Geotechnical model of the slope before the 2010 landslide (the trace of this section is indicated in Fig. 1).

5. Concluding remarks

The 15 February 2010 Maierato landslide has become the symbol of the hydrogeological instability in Calabria (Southern Italy) also thanks to some impressive images filmed during the paroxysmal phase of the event. These images have been considered in this study to establish the kinematics of the landslide. In particular, it was ascertained that the lower part of the slope was the first zone to move. Subsequently, the main slip surface emerged at the ground surface in correspondence of a pre-existing scarp at 300 m elevation. On the basis of the results from field and laboratory tests carried out after the event, a geotechnical model of the slope has been defined to perform a comprehensive analysis which accounts for the complex failure process occurred.

Acknowledgements

Authors wish to express their gratitude to Eng. M. Trimmeliti for having provided the photos and the videos used in the present study.Geotechnical data were collected within the framework of the activities carried out for the Regione Calabria - Supportotecnico-scientifico al CommissarioDelegato O.P.C.M. n. 3862/2010.

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