

Giuseppe Delmonaco⁽¹⁾, Fabio Garbin ⁽²⁾, Maria Marsella⁽³⁾, Claudio Margottini ⁽¹⁾, Alberico Sonnessa ⁽⁴⁾, Daniele Spizzichino ⁽¹⁾

Laser scanning analysis and landslide risk assessment on transportation network: the Lugnano in Teverina (Umbria Region, Italy), landslide case study

- (1) ISPRA, Italian Institute For Environmental Protection And Research, Geological Survey Of Italy, Rome, Via Curtatone 3, +39 0650074087, daniele.spizzichino@isprambiente.it
- (2) Geoplanning, Rome, Italy
- (3) Università, La Sapienza, Dicea, Rome, Italy
- (4) Surveylab, Università La Sapienza, Dicea, Rome, Italy

Abstract The present paper reports a multi-disciplinary team work, involving professionals, research institutes and public administration, for defining and applying lowimpact techniques for risk assessment and mitigation of landslide areas. A study area located at Lugnano in Teverina (Umbria Region, Italy) and interested by landslides triggered by heavy rainfall and affecting important railway and road networks, was considered. A geological field survey has been carried out (including in situ and laboratory tests) in order to define strength parameters to be used in the stability analysis, for the detection of the most active area (residual risk) and implementation of preliminary design. In order to identify landslide surface and estimate the involved volumes, 3D laser scanner acquisition has been performed at different times. The obtained results stress the importance of performing different analysis in the light of reducing the impact of landslides on critical infrastructures by promoting low-environmental and sustainable solutions.

Keywords landslide, transportation network, laser scanning, slope stability model

Introduction and site description

This study reports the main outcomes of geological, geomorphological and geotechnical analyses carried out for the selection and executive design of landslide mitigation works of the slope located in the municipality of Lugnano in Teverina, Umbria (Italy), historically and recently affected by slope instability . The study has been planned following two distinct levels: i) collection of historical information on topographical, geological, geomorphological, hydrological and hydrogeological data and maps at various scales, ii) implementation of geotechnical investigations (direct and indirect) and studies at local scale for the reconstruction of local geomorphological active dynamics and physical-mechanical characteristics of the soils.

The study area is located approx. 5km SW from Lugnano in Teverina along the provincial road 87 in the

locality of Ramici-Molinaccio, at 120m. a.s.l., very close to the alluvial plain of the Tiber river (Fig.1).

Geology and geomorphology

Lugnano in Teverina is located in the middle Tiber river valley where recent alluvial soils overlap a Pleistocene sandy-clayey formation that constitutes the bedrock of all the area (Barchi et alii, 1991) (Bertini et alii, 1971).

The landscape is characterised by large outcropping of badlands. The study area is located uphill the provincial road 87, at an elevation range between 70m a.s.l. (road level) and 200m a.s.l., at the top of the hill, with an average slope angle of 35°. A 150m-length tunnel of the high-speed rail crosses the slope.

Outcropping terrains, from the most recent to the oldest, are:

- Terraced alluvial soils (Quaternary): they outcrop along the Tiber river alluvial plain and are characterised



Figure 1 Location Lugnano landslide case study

by deposits of the ancient Tiber terraces and recent alluvial soils with variable granulometry, from pebbles and gravel to fine sands and clay:

- Yellow sands and sandy clays (Pleistocene): largely surveyed in the middle part of the area, they represent, from a palaeo-geographical point of view, the

Giuseppe Delmonaco, Fabio Garbin , Maria Marsella, Claudio Margottini , Alberico Sonnessa , Daniele Spizzichino - Laser scanning analysis and LRA on transportation network

closure facies of the Pliocene marine cycle. The succession is formed by yellow loose or slightly cemented sands and sandy clays interbedded with generally soft grey clays and discontinuous thin layers of gravels.

The area is affected by old and active geomorphological processes promoted mainly by the litological and stratigraphical setting; hilly areas, that prevail in the local landscape, are located where Pleistocene clays outcrop. Clayey areas, due to high erosion rate of soils, are characterised by deep hydrographic network. In the study area, the Pescara stream, sited W of the urban area, is the most important water course and is presently affected by very active erosion. The stream originates some kilometres E, fed by circulating waters along the contact between calcareous formations and the clay bedrock. It presents a general W-E direction and flows into the Tiber as one of the left tributaries in this region. In detail, the stream network of the Plio-Pleistocene clay bedrock promotes slopes with generally high angles in the upper parts of the slopes (35- 45°) and lower angles (15-20°) on the contact between the slope toe and the floodplain.

Landslide characteristics

The outcropping of weak clayey rocks and superficial water circulation are the most important causative factors for landslides whereas heavy precipitation is the main triggering factor, causing the decaying of shear strength parameters of the clays. The main landslide types, affecting the study area, are rotational and translational slides (Cruden and Varnes, 1996), in the upper portion of the slopes, evolving in mud/earth-flows (Cruden, 1991.), in the middle-low parts (Fig.2 - 3).



Figure 2 Detail of the crown area of Lugnano landslide

The average depth of failure surface is between 1-3m, as estimated by D.P.M. tests and seismic refraction.

The heavy rainfall event of 15-16 May 2010 that affected a wide area of the river Tiber upper-middle catchment area (peak rainfall of 150mm in 2 days) caused in the study area the triggering of 2 distinct mudflows that interrupted the road 87, menacing, as well, a sector of the high-speed rail, in accordance with the slope stability simulation that have been implemented for the mitigation measures project.



Figure 3 Middle portion of the landslide

The average depth of failure surface is between 1-3m, as estimated by D.P.M. tests and seismic refraction.

The heavy rainfall event of 15-16 May 2010 that affected a wide area of the river Tiber upper-middle catchment area (peak rainfall of 150mm in 2 days) caused in the study area the triggering of 2 distinct mudflows that interrupted the road 87, menacing, as well, a sector of the high-speed rail, in accordance with the slope stability simulation that have been implemented for the mitigation measures project.

Laboratory test and geotechnical analysis

The following geognostic investigation for geotechnical characterisation of outcropping geological formations in the landslide area has been carried out consisting in:

a) n. 20 field tests for reconstruction of UCS with pocket penetrometer;

b) n. 30 field tests for definition of undrained shear strength with field vane test;

- c) n. 2 dynamic penetrometer tests by D.P.M.;
- d) sampling and analysis of n. 2 soil samples;
- e) implementation of n. 2 seismic refraction tests.

The bedrock of the area can be sub-divided into 3 distinct units, based on litological, structural and physical-mechanical characteristics.

(1) Alluvial soils: medium to high relative density sands and gravels ($Dr = 0.4 \div 0.8$) with medium consistency and low plasticity (ML-SM) silty-sandy clay decimetric levels on the top. The geotechnical behaviour of the litotype is generally cohesionless.

(2) Landslide deposits: grey-yellowish sandy and clayey silts with variable consistency depending on water content and remoulded state of materials (from very soft clay S1 to soft clay S2) and ML-CL (USCS). The thickness of the deposit is 1.0-1.5m in the upper part of the slope and 2.5m in the landslide toe.



Figure 4 Pre event laser scanning 3D model of the Ramici Landslide

(3) Clayey bedrock: from silts with sandy clays in the superficial layers to overconsolidated clays with sandy silts in the depth. Consistency is between S1, in the superficial layers, and S3 for the bedrock (ISRM) and ML-CL plasticity. The depth of the litotype is >100m in the study area.

Table 1. Geotechnical parameters of soils outcropping in the study area.

| Parameter | Alluvial soil | Landslide | Clay bedrock |
|-------------------------------------|------------------------|------------------------------------|------------------------|
| | | deposit | |
| γ_{nat} (kN/m ³) | 19,0÷20,0 | 18,0÷20,0 | 20,9÷21,2 |
| φ' (°) | 32÷38 | 26÷29 | 27÷33 |
| φ' _{res} (°) | - | 24÷26 | 16÷19 |
| c' (kPa) | 0÷10 | 0÷10 | 10÷30 |
| c' _{res} (kPa) | - | 0 | 2÷10 |
| CU' (kPa) | - | 19÷31 | 163÷175 |
| k (m/s) | $10^{-6} \div 10^{-4}$ | 10 ⁻⁷ ÷10 ⁻⁸ | $10^{-8} \div 10^{-9}$ |
| V _p (m/s) | - | 200÷500 | 1800 |
| E' (MPa) | - | - | 42 |

3D laser scanning analysis

Laser scanning surveying were performed to accurately map the landslide geometry and estimate the involved volumes (Heritage and Large, 2009) . The collected data allowed to extract a Digital Terrain Model of the landslide body after having removed artefacts and sparse vegetation form laser point clouds. Such a model (Fig 4) was obtained at the beginning of investigations for a detailed description of the area aimed at assessing the landslide area and volume as well at precisely locating the potential surrounding interference with the failure, such as the railway tunnel and the provincial road 87. After the 15-16 May 2010 event, the Municipality of Lugnano in Teverina, commissioned a new laser scanning investigation, for the reconstruction of postevent morphology (Fig. 5). To estimate the volumes remobilised by landslides (Delmonaco et alli, 2006) the differences between pre and post DTMs were analysed (Fig. 6). The analysis of the post event DTM permitted to verify the interaction between the new landslide body and railway and road network (Fig. 7).



Figure 4 Pre event laser scanning 3D model of the Ramici Landslide



Reference cross sections for the implementation of slope stability analysis have been extrapolated from the two 3D model. A post-event back-analysis calibrated on landslide sections, derived by high-resolution DTM (fig. 8), has provided actual shear-strength parameters, mobilised during the event along the failure surface. Giuseppe Delmonaco, Fabio Garbin , Maria Marsella, Claudio Margottini , Alberico Sonnessa , Daniele Spizzichino - Laser scanning analysis and LRA on transportation network



Figure 6 Estimation on mobilized volume during the May 2010 event Slope stability analysis affect

A finite-difference modelling code from Itasca (2008) was implemented in order to detect the safety factors, (Dawson et al., 1999) along two distinct potential landslides sections, under dry and partially-saturated condition. The limit equilibrium analysis has been performed by using a FLAC tool (FLAC-Slope) that is a mini-version of FLAC designed specifically to perform FoS calculations through a shear strength reduction technique. In comparison with FLAC, consolidation phase (typical of FLAC procedure) is not specifically considered by the programme.

The model has been set on the basis of soils and geotechnical parameters described in the following Tab. 2.

Table 2. Geotechnical parameters of soils outcropping in the study area.

| Soil Type | Friction angle | Cohesion | Unit weight |
|-------------------|-------------------------|---------------------------|---------------------------------|
| Landslide deposit | φ' _{res} = 18° | c' _{res} = 5 kPa | $\gamma = 18$ KN/m ³ |
| Clay bedrock | φ' = 28° | c' _{res} (kPa) | $\gamma = 21 \text{KN/m}^3$ |

Under dry condition, the landslide crown is at 100m a.s.l. affecting the upper part of the landslide accumulation, located uphill the concrete wall, along the road 87, surveyed at the beginning of investigation. The potential failure is at 1.5-2.0m depth, whereas shear strain and maximum value zone of velocity appears on the slope toe, at ca. 90m a.s.l. Maximum value zone of plasticity affects both landslide accumulation and crown areas, at an average height of 130m a.s.l., where the actual rototranslational slide is located. The calculated safety factor is 1,07 (Fig. 9).



The second iteration has been undertaken considering a realistic 70% saturation of the clayey landslide deposit. In the upper part of the slope, near the crown area, the depth of water level is on the contact between clay bedrock and superficial clays, simulating a saturation of materials from the bottom to the top surface. This is due the presence of tension-cracks, surveyed uphill, that promote water infiltration inside the landslide body, and potential pore-pressure generation along an assumed multiple landslide failure surface, located at ca. 130m a.s.l. and 1.0-1.5 depth.



Figure 8 Topographical 3D model reconstruction for the stability model





The safety factor for the above condition drops to 0.81. Shear strain and maximum value zone of velocity are distributed along the present failure surface (Fig. 10). The crown area of the landslide n. 2, that has been reactivated in May 2010, has resulted as the most critical situation according to numerical analysis. The model has substantially verified the observations made during the geomorphological analysis undertaken before the rainfall event of 15-16 May 2010 and the implementation of the slope stability analysis that detected the middle-lower part as the most hazardous sector of the slope. This situation has to be correlated with the highest thickness of remobilised material with very bad geotechnical characteristics, also under dry condition. The analysis has also defined the residual risk of the slope and addressed the choice of engineering solutions designed for the stabilisation of the landslide body taking into account the

presence of the railway tunnel under the failure surface and mainly addressed to the reduction of critical pore pressure and increase of shear strength of clay materials.



Figure 10 Simulation results of shear strain, velocity and plasticity under partially saturated condition

The slope has been distinguished into three distinct sectors (crown area, track area and landslide toe) where different works have been designed specifically: erosion control and reduction of potentially remobilising volumes mainly through geo-grids in the upper sector; drainage system with trenches in the middle part and slope angle reduction coupled with environmental engineering techniques in the lower part.

Conclusions

The case study of Lugnano in Teverina, highlights the importance of multi-discipline team, analysis and approach in the light of reducing the impact of landslides on critical infrastructures by promoting lowenvironmental and sustainable solutions.

In particular, the adoption of 3D laser scanning technique has resulted in a reduction of field survey time, by preserving high resolution of data, and implementation of models capable to reconstruct very precise information such as topographical sections for i.e. slope stability back analysis, calculation of mobilised Giuseppe Delmonaco, Fabio Garbin , Maria Marsella, Claudio Margottini , Alberico Sonnessa , Daniele Spizzichino - Laser scanning analysis and LRA on transportation network

volumes, potential failure surfaces, interaction of slope stability models with infrastructures.

The rigorous topographical control in the study area during the design and implementation stages of the mitigation project has avoided potential dangerous interaction between the landslide area and the railway infrastructures.

Simulations undertaken with FLAC-Slope under dry and partially-saturated conditions of the clay soils outcropping in the landslide study area report, respectively, two distinct scenarios in terms of potentially unstable conditions, only apparently in contrast.

The landslide body located in the middle part of the slope presents the highest instability under dry conditions, due to highest depth of altered materials, defined by penetrometer tests, whereas the landslide crown area exhibits the maximum instability in case of pore-pressure increase. The presence of tension cracks in the upper part of the slope surveyed during the field analysis can promote rapid infiltration of superficial water in the weathered clayey mass, like in the rainfall event of May 2010. The downslope movement of the upper remobilised mass along with the pseudo-static conditions of the middle landslide body has caused the collapse of that portion where maximum shear stress is concentrated and facilitated slip along the contact between altered materials and intact clay bedrock.

Finally, the present work demonstrates that a rigorous geomorphological survey coupled with analysis of soil mechanics and landslide kinematics can provide reliable forecasting models of slope evolution like those provided before the landslide event of May 2010, that are essential for providing sustainable and effective mitigation works.

Acknowledgments

Authors are grateful to the Municipality of Lugnano in Teverina and Regione Umbria for support and help.

References

- Barchi M, Brozzetti F and Lavecchia G (1991) Analisi strutturale e geometrica dei bacini della media valle del Tevere e della valle umbra. Bollettino Società Geologica Italiana, 110, 65-76.
- Bertini M, D'Amico C, Deriu M, Girotti O, Tagliavini S, Vernia L (1971) Note illustrative della Carta Geologica d'Italia alla scala 1:100.000. Foglio 137 Viterbo. Roma, Nuova Tecnica Grafica, pp. 109.
- Cruden D M , Varnes D J (1996) Landslide types and processes. In: A.K. Turner, R.L. Schuster (eds.) Landslides investigation and mitigation (Special report 247, pp. 36-75). Transportation Research Board, Washington, D.C.
- Cruden D M 1991 A Simple Definition of a Landslide. Bulletin of the International Association of Engineering Geology, No. 43, pp. 27 29.
- Dawson E M, Roth W H and Drescher A (1999) Slope Stability Analysis by Strength Reduction, Geotechnique, vol. 49, (6), pp. 835-840.

- Delmonaco G, Falconi L, Leoni G, Margottini C, Puglisi C, Spizzichino D (2006) Multi-temporal and quantitative geomorphological analysis on the large landslide of Craco village. In: (K. Sassa, H. Fukuoka, F. Wang & G. Wang, Eds.) Landslides: Risk Analysis and Sustainable Disaster Management. Springer, pp. 113-118.
- Glenn N F, Streutker D, Chadwick J, Thackray G, Dorsch S (2006) Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. Geomorphology, 73, 131-148.Glenn, N.F., Streutker, D., Chadwick, J., Thackray, G., Dorsch, S., 2006. Analysis of LiDARderived topographic information for characterizing and differentiating landslide morphology and activity. Geomorphology, 73, 131-148.
- Heritage G L and Large A R G 2009 Laser scanning for the Environmental Sciences, Wiley-Blackwell, 278 pp.
- Itasca (2008) FLAC/Slope version 5.0. Itasca Consulting Group, Minneapolis, MN.