Hydrogeological parameterization of the landslide of Lamosano, (Eastern Italian Alps)

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Short Note

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ABSTRACT

The area of the village of Lamosano, in the province of Belluno (North-East Italy), has been critically affected for several decades by a landslide that has caused significant damages to buildings and infrastructures. This instability process, involving almost the whole village, is set in a 30-meter thin layer of Quaternary deposits and marls. Groundwater flow within these deposits has been identified as one of the primary causes of the slope movement.

With the purpose of identifying fundamental and useful parameters for the intelligent design of landslide countermeasures, a series of geological and hydrogeological investigations have been carried out.

Through the analysis of 18 stratigraphic logs, a geological model for the subsoil was provided.

The hydrogeological characterization concerned the realization of slug tests and point dilution tests to properly estimate the hydraulic conductivity (K) and the groundwater flow velocity (v_d), respectively. Both investigations have been conducted on the five piezometers available in the study area. A satisfactory agreement has been detected between the K values and v_d.

The data provided in this study can be used as a basis for the efficient implementation of a coupled hydrogeological-mechanical model, which would considerably contribute to the mitigation of the landslide risk.

KEY-WORDS: Lamosano, landslide, geology, hydrogeology, 3d model.

INTRODUCTION

Hydrogeological numerical modelling is an increasingly used technique in support for the design of landslide mitigation solutions. There are several examples of their potential application all over the word (Eberhardt et al., 2007; Lo et al., 2020; Matti et al., 2012; Petronici et al., 2016; Piccinini et al., 2014; Shrestha et al., 2008). Despite that, the reliability of the simulations results is strictly related to the quality of the spatial discretization process, initial and boundary conditions (Konikow & Mercer, 1988; Peak et al., 1988). As consequence, it is critical to conduct with reasonable accuracy the preliminary parameterization campaign in the target area. On top of that, the presence of a solid monitoring network, that provided the slope movement trend before and after the remediation, can be very useful to test the effectiveness of these models (Ronchetti et al., 2020).

With this purpose, the village of Lamosano, in the municipality of Chies d'Alpago (Belluno), is a perfect benchmark location, as it has been critically involved for several years by various slope movement phenomena. In addition, the small town has been continuously monitored over the past 30 years due to the high landslide risk. The monitoring network includes: inclinometers, Periodical Global Navigation Satellite System surveys, piezometers, rain gauge and temperature sensors. As a matter of fact, the village is located in the proximity of the well-known Tessina landslide (Mantovani et al., 2000). The latter is a rotational slide, triggered in 1960, that can frequently evolve in debris-flow events such as the ones occurred between 1990 and 1998. Exceptionally significant was the collapse of 2,000,000 m^3 in 1992 which caused a high-risk situation for the villages of Funés and Lamosano. As a direct result of this event, the Istituto di Ricerca per la Protezione Idrogeologica (CNR-IRPI) has started the installation of a monitoring network in the area. The initial intention was to investigate the correlation between critical rainfall events, variation in groundwater level, and rates of slope movement. To properly manage that a meteorological station was deployed and, in 1997, a piezometer has been installed for the continuous hydraulic head monitoring.

As it happens, the Lamosano area was discovered to be involved in a slow slope movement that is strictly related to groundwater level variations due to precipitation events (Genevois, 2008). For that reason, an appropriate drainage project to reduce the hydraulic head in village proximity is programmed for the next years. The design of that will be supported by the implementation of a high-quality hydrogeological numerical model. The latter requires a series of preliminarily investigation in order to be effectiveness. Since there was a completely lack in literature relating to hydrogeological parameters and groundwater movement in the area, we realized a high-resolution 3D subsoil model to identify the trend of the main hydrogeological units using lithostratigraphic logs carried out in three previous studies (Broili, 1990; Genevois, 2008; Onofri, 1995); we executed of a series of slug tests in available piezometers to obtain an estimate of hydraulic conductivity (K); we performed a series of point dilution tests (PDT) to estimate the Darcy velocity (v_d) near each piezometer.

STUDY AREA

Lamosano (46.172 N, 12.386 E) is part of the geographical unit of the Alpago basin, to east of Belluno City, bordering the province of Treviso to the south and the province of Pordenone to the west (Fig. 1). The Alpago Basin is surrounded by prominent mountains to the north, east, and south sides, while to the west it is separated from Belluno Valley by a hilly relief (Mantovani et al., 1976). On an annual basis, the average meteoric inflow is equal to 1667 mm. The typical number of rainy days progressively increases between January and April. Subsequently, it gradually decreases from May with a peak of precipitation in November. The average temperature regime is characterized by a maximum in July of 18.5° C and a minimum in January of 0.7° C. The annual average temperature is equivalent to 9.5° C.

In the surrounding, there are two main landslide systems: a deep one, within the Bolago Marls, involving the western of the area; and a shallower one, within the Quaternary deposits and the most superficial portion of the marls, which is responsible for a depression in the eastern part of the village. These two phenomena are characterized by different depths of the sliding surfaces: 70 m in the deep one and no more than 25-30 m in the shallow one. These slope movements are presumably related to each other. Indeed, the marly layer slipping determines the deformations within the Quaternary deposits (Genevois, 2008). This mechanism causes an average surface rate of movement of about 0.5 cm/year, with peaks of 2.5 cm/year in some area. In this context, groundwater circulation performs a crucial role in the complex dynamics of the slope (Broili, 1990; Onofri, 1995).

GEOLOGICAL AND HYDROGEOLOGICAL FRAMEWORK

In accordance with previous studies and surveys (Broili, 1990; Genevois, 2008; Onofri, 1995), the ridge where the village of Lamosano rises consists of two principal geological units. Belluno Glauconitic Sandstones: which are located into the lower portion of the dorsal and appear sandy, greyish, sometimes with medium cementation and conglomeratic levels. Marls of Bolago: which represent the upper formation outcropping around the village. These are described as sequences of clayey-silty marl, often fractured, sometimes with clayey horizons due to alteration or friction process. Quaternary moraine and eluvial deposits as alteration of the marly substrate mantle the outcropping formations. Consistent with this geological setting, the present of four hydrogeological units have

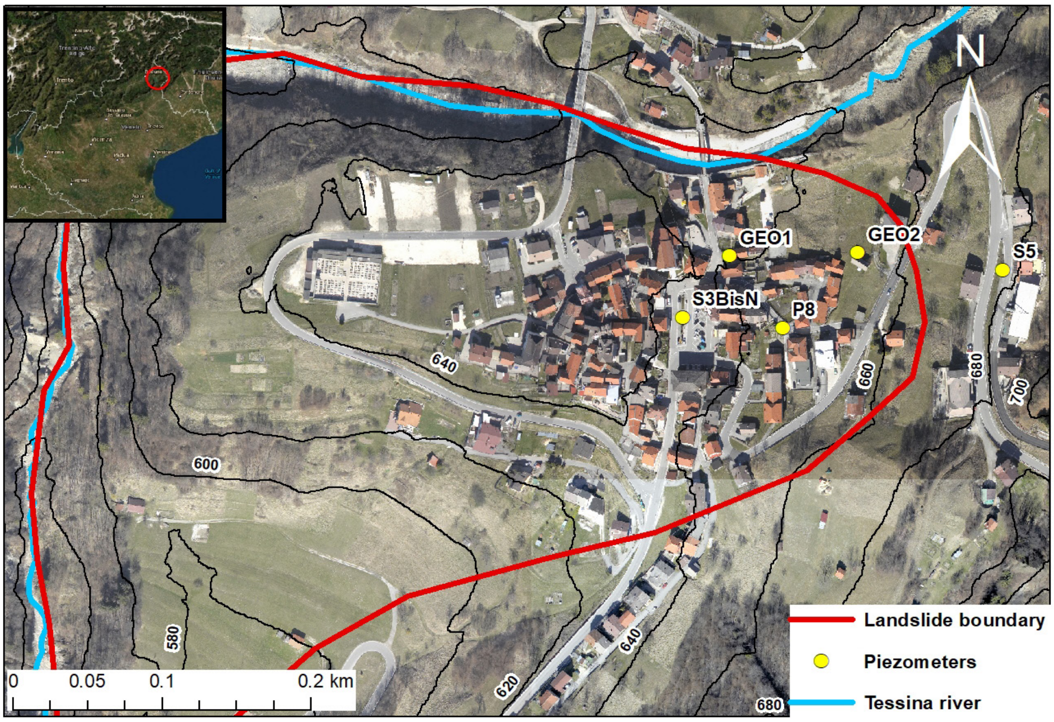

Fig. 1 - Study area with piezometers location and landslide boundary.

been underlined. In fact, the Bolago marls have been divided into two distinct units: one in the superior portion and fractured, whereas the second in the lower and more compact portion. Within these hydrogeological units the presence of two aquifers was hypothesized. A first one in the Quaternary deposits characterized by high excursions of the hydraulic head and a second one in the marly formation with a steadier piezometric trend (Broili, 1990). The groundwater flow is from east to west, following the trend of the slope and the hydrogeological units. The hydrogeological balance, as regards the inflow component, is primarily due to the precipitation recharge. Contrary, the outflow component is related to the excellent drainage of the aquifers by the Tessina stream.

MATERIAL AND METHODS

Geological Model

To accurately reconstruct the trend of hydrogeological units in the study area, a triangle mesh-based 3D model (average edge 25m) was created using MOVE software (Midland Valley Ltd 2016.1.2). The model domain was design with a: E-W extension of 1000 m, N-S extension of 400 m, and a reasonable depth of 400 m from the ground level. The latter ensured the presence of all the formations identified in literature. Within the model domain, 18 lithostratigraphic logs from previous studies (Broili, 1990; Genevois, 2008; Onofri, 1995) were interpreted, analysed and used to perform the hydrogeological reconstruction (Fig. 2). In this phase ArcGis software from Esri was utilized to realise 4 preliminary hydrostratigraphic sections as reference. These last and the lidar of the area from Regione Veneto (1x1 m resolution) were then imported into MOVE and, by linearly interpolating the lines present in the 2D sections, the separation surfaces of the hydrogeological units were identified. Through this procedure, it was possible to estimate the volumes of the hydrogeological units and export three interpretative east-west sections (Fig 4).

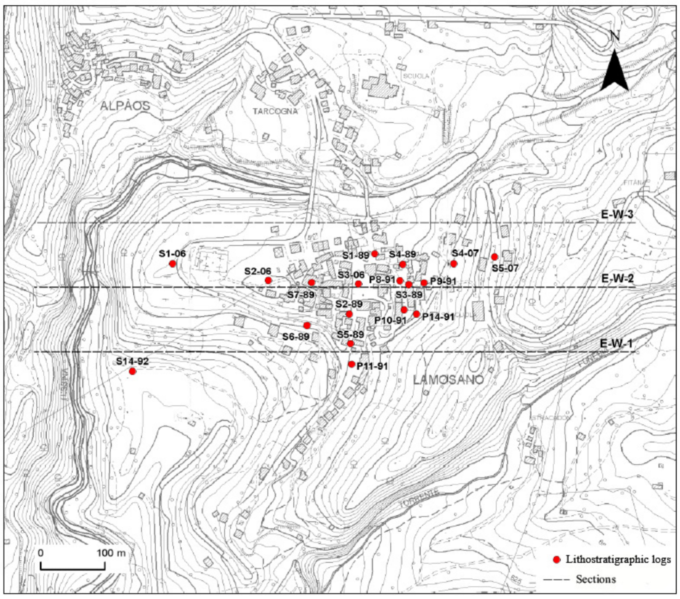

Fig. 2 -Location of lithostratigraphic logs and hydrostratigraphic sections.

Slug tests

A campaign of characterization of K was carried out by performing a series of slug tests on 5 accessible open-pipe Norton-type piezometers: S3BisN, P8, GEO1, GEO2, and S5 (Fig. 1). The screen interval is accurately known just for P8 (from 5 to 9.6 m depths). For the other piezometers, the screen interval was attributed by comparing the location of the bottom of the hole with the depth of the hydrostratigraphic units identified in the subsoil model. The hydrostratigraphic units intercepted by the piezometers are reported in the Tab. 1. K represents a fundamental hydrogeological parameter that must be known to implement groundwater flow simulations in steady and transient state. The slug test method involves the instantaneous injection (falling test) or withdrawal (rising test) of a volume (or a slug) of water or solid cylinder of known volume into a piezometer. The artificial fluctuation of the hydraulic head is then measured in a manual or automatic manner. It is therefore a single-well test, performed in a transient regime, whose purpose is to calculate K in the vicinity of the well/piezometer. The campaign was carried out between 20/07/2017 and 02/07/2018. Four solutions were used for the interpretation of the collected data: Hvorslev (1951), Bouwer & Rice (1976), Dagan (1978) and Hyder et al. (1994). PAST statistical software was utilised to establish the most representative K value for each piezometer (Hammer et al., 2001). These K values can be properly treated as a continuous random variable. For this reason, it was possible to attribute to each sample a probability distribution of normal type. The hypothesis of normality was confirmed through three distinct phases of determination: (i) exploratory graphic analysis through boxplot for the identification of outliers; (ii) graphical confirmation of the hypothesis of normality via normal probability plot of the samples excluding the outliers; and (iii) final validation of normality through the test Shapiro-Wilk (Shapiro & Wilk, 1965).

Point Dilution Tests

PDTs were carried out on the piezometers P8, S3BisN, GEO1, GEO2 and S5. The PDT is a single-well technique for estimating Darcy velocity (v_d) surrounding a well. This is a relevant parameter that, in contexts where the hydraulic gradient is predominantly controlled by the trend of the topographic surface, can be used to highlight areas where groundwater flow is most active. The Lamosano area is under these conditions. As consequence, we can compare the variability of K with the one of v_d cross-checking both results.

The PDTs were performed starting from the injection of a NaCl solution and then recording the decline over time of specific electrical conductivity at 25°C (EC_{25}). In this step a high-accuracy multi-probe sensor CTD-Diver (Schlumberger Water Service; range 0-30 mS/cm, accuracy ±1% of reading and resolution 0.1% of reading) at determined depths was used. The conversion from EC_{25} (mS/cm) to equivalent NaCl concentration (g/L) was carried out according to the experimental relationship (Piccinini et al., 2016):

$$C_{NaCl} = 0.002 {Ec_{25}}^2 + 0.54 EC_{25}$$

Traditionally, v_d calculation assumes that the decreasing tracer concentration is proportional both to the apparent velocity (v_a) into the test section and to v_d in the subsoil according to:

$$\ln C = -\left(\frac{2v_a}{\pi r}\right) \cdot t + \ln C_0$$

where C is the tracer concentration at time t > 0, C_0 is the concentration at t = 0 and r is the radius of the well. Field data are analysed by plotting the natural logarithm of the ratio of tracer concentration (C) with the initial concentration (C_0) vs time. If the tracer dilution is only caused by water flowing through the test section, the logarithm of this ratio (C/C_0) exhibits a linear trend, and its slope (m) is proportional to v_d based on:

$$v_d = m \cdot \left(\frac{\pi r}{2\alpha}\right)$$

where α is the factor that consider the flow distortion due to the well screen and gravel/sand pack around the well. This is typically established equal to 2 for open-pipe piezometers (Drost et al., 1968).

RESULTS

Geological Model

The 3D geological model allowed to improve the representation of the structure of the hydrostratigraphic units. Particularly: two shallow units; Quaternary deposits and fractured marls, and two deep units; consisting of compact marls and sandstone (Fig. 3, Fig 4). The Quaternary deposits are concentrated in the topmost and southern part of the hill of Lamosano village. They have variable shape and thickness, which reach the maximum values of 35 m in the central area of the relief. The fractured marls are a homogeneous body, locally dipping toward the west, characterized by a decrease in thickness from west (80 m) to east ending in the eastern portion of the domain. This unit is cut to the north and west by the bed of the Tessina torrent (Fig. 1). The compact marls unit has a homogeneous thickness. The trend of this unit is consistent with the fractured marls. They outcrop mainly in the north-eastern part of the domain where they attain the maximum thickness of 60 m. The sandstone unit again follows the trend of the marls. It outcrops at the eastern crest of the domain. The estimate volumes of the units result from the model are: 1.3 Mm³ for Quaternary deposits, 5.2 Mm³ for Fractured marls and 8.5 Mm³ for Compact marls. The volume of the sandstone has been unevaluated because the model does not reach the bottom of this unit.

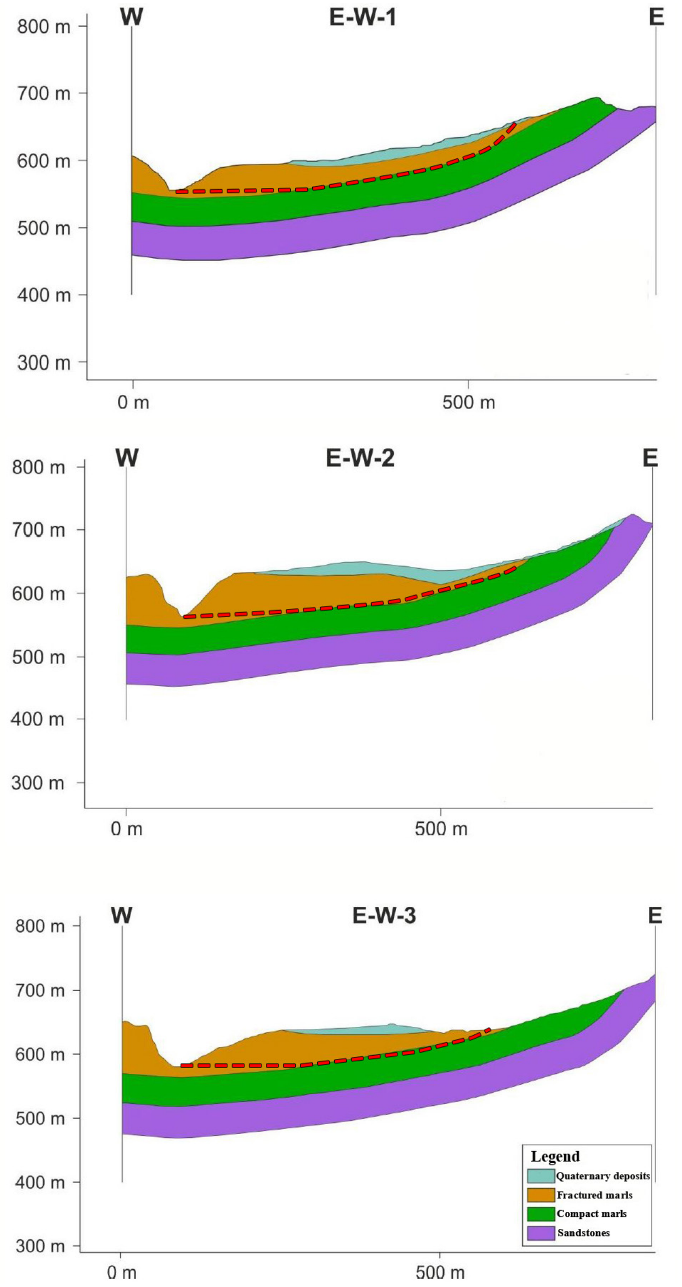

Fig. 4 - E - W sections exported from the 3D model with the landslide slip surface hypothesized by Onofri (1995).

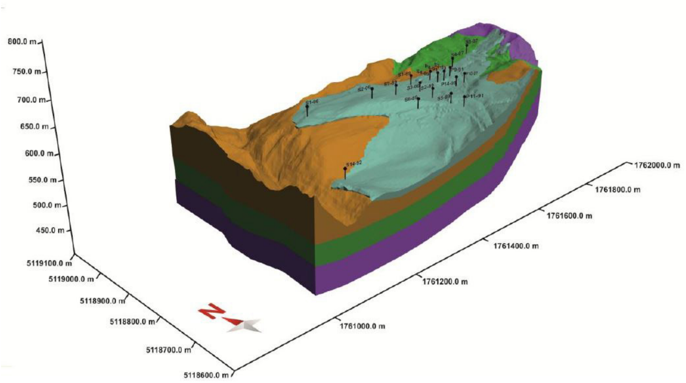

Fig. 3 - 3D model of the area of Lamosano. Four hydrostratigraphic units were distinguished: Quaternary deposits (blue), fractured marls (orange), compact marl (green) and sandstones (purple).

Slug test

The slug test campaign allows estimating the value of K of the hydrostratigraphic units in the area. From the statistical analysis conducted with PAST, it emerged that the normal distribution is the most suitable for each population of samples. As shown in the Tab. 1: Quaternary deposits (S3BisN and GEO1) are characterized

Table 1 - Mean (m) and standard deviation (σ) of the K values, va and vd calculated on the piezometers P8, GEO1, GEO2, S3BisN and S5. (H= average hydraulic head; Unit=hydrostratigraphics unit; MF=fractured marls; M=marls; Q=Quaternary deposits; A=sandstone).

ID	Depth (m)	H (m MSL)	m (m/s)	σ (m/s)	v_a (m/s)	v_d (m/s)	Unit
P8	9.6	642.93	9.65E-07	1.64E-07	1.96E-07	9.81E-08	MF
GEO1	20	635.89	2.41E-05	4.77E-06	3.30E-05	1.65E-05	Q
GEO2	26	651.09	2.60E-08	5.36E-09	3.30E-08	1.65E-08	M
S3BisN	15	643.35	1.08E-06	1.02E-07	7.85E-07	3.93E-07	Q
S5	64	632.07	2.22E-08	1.75E-08	1.19E-07	5.97E-08	M/A

by medium-low K values. The K of the fractured marls (P8) has a value comparable to that of the Quaternary deposits. This fact is in accordance with the hypothesis that also this unit is characterized by groundwater circulation. On the contrary, the deeper compact units (S5) are distinguished by very low K values. This result is consistent with weak groundwater circulation in these formations. Finally, the low K value calculated on the GEO2 piezometer suggests that it is probably filtering the compact marls unit as the magnitude of K is similar to S5.

Point dilution tests

The PDTs allow identifying the value of v_d in the same piezometers used for the slug tests doublechecking the result of both methods. As a matter of fact, the variability of v_d values shows in Tab. 1 is comparable to the one of K values. GEO1 and S3BisN present the highest magnitude of v_d. On the contrary, the v_d values calculated from GEO2 and S5 are the lowest. The P8 piezometer is the only one that clearly differs from the trend determined with the slug test. In fact, it presents a v_d value in the same magnitude of GEO2 and S5. This can be justified by the presence of a peculiar local hydraulic gradient in the vicinity of this point.

CONCLUSIONS

Proper knowledge of the physical, geological, and hydrogeological aspects must always be taken into account in landslide risk regions. This would help to prevent disturbances of the territory balance caused by improperly designed infrastructure, which can also increase the slope movement, creating an unnecessary risk in nearby urban areas and infrastructures themselves. The amount of data obtained in this study allowed the hydrogeological characterization the Lamosano village area. These data can be used as a basis for the creation of a hydrogeological numerical model. The latter, once calibrated, will be able to identify the preliminaries consequences on the groundwater flow of the construction of countermeasure works; allowing to improve the stability conditions of the slopes.

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