Sliding surfaces and displacement rates of extremely-slow landslides: reliability of inclinometer measurements

Surfaces de glissement et taux de déplacement des glissements de terrain extrêmement lents: fiabilité des mesures de l'inclinomètre

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ABSTRACT: Movements of extremely-slow landslides may be detected only with instrumentation providing measurements with adequate precision and accuracy. In fact, if a reliable estimate of the velocity is requested in a short time (e.g. some months) by using displacements of only few millimeters, the errors that affect the measurements should be at least one order of magnitude smaller. Otherwise, a specific data processing has to be defined in order to reduce their influence on the displacement evaluation. This paper describes the data processing procedure that was effectively applied to detect the sliding surfaces and to estimate the displacement rates with inclinometer measurements collected in two extremely-slow landslides by using different probes. The procedure includes the identification of: precision, accuracy, interval of integration, and validation of results. The procedure was firstly defined and validated to study the V70 landslide, in the Isarco valley in Northern Italy, that involves a motorway viaduct at the toe of the slope. Then it was applied to an extremely-slow landslide, located on the south-eastern slope of the Monteverde/Gianicolo Hill in Rome (Italy), where a sliding surface with displacements at a rate of 1 mm/year was identified only after one year of measurements.

RÉSUMÉ: Les mouvements des glissements de terrain extrêmement lents peuvent être identifiés seulement avec une instrumentation fournissant des mesures avec la précision et l'exactitude adéquates. En effect, si une estimation fiable de la vitesse est demandée dans un court laps de temps (par example quelques mois) en utilisant des déplacements de quelques millimètres seulement, les erreurs qui affectent les mesures devraient être au plus d'un ordre de grandeur inférieure. D'une autre manière, une elaboration spécifique des données doit être défini pour réduire leur influence sur l'évaluation du déplacement. Cet article décrit la procédure d'elaboration des données qui a été effectivement appliqué pour détecter les surfaces de glissement et pour estimer les taux de déplacement avec des mesures d'inclinomètre collectées dans deux glissements de terrain extrêmement lents en utilisant différentes sondes. La procédure comprend l'évaluation de: précision, exactitude, intervalle d'intégration et validation des résultats. La procédure a d'abord été définie et validée pour étudier le glissement de terrain V70, dans la Vallée d'Isarco dans l'Italie du nord, qui implique un viaduc d'autoroute au pied de la pente. Ensuite, elle a été appliquée à un glissement de terrain extrêmement lent situé sur la pente sud-orientale de la colline Monteverde / Gianicolo à Rome (Italie), où une surface de glissement avec un taux de déplacement de 1 mm/an n'a été identifiée qu'après un an de mesures.

KEYWORDS: extremely-slow landslides, displacements, monitoring, inclinometer, errors, measurement reliability.

1 INTRODUCTION. FIRST LEVEL HEADING

According to the velocity scale given by the International Geotechnical Society's UNESCO Working Party on World Landslide Inventory (WP/WLI) (1995) and in Cruden and Varnes (1996), extremely-slow landslides move with rates less than 16 mm/year and their displacements are detectable only with instrumentation because the revealing factors that would provide evidence of movement are not easily recognizable. Some examples of displacement monitoring of extremely-slow to slow landslides are given in Simeoni and Mongiovì (2007), Di Maio et al. (2010), Puzrin and Schmidt (2012) and Macfarlane (2009) by using geodetic and inclinometer systems, in Massey et al. (2009), Cohen-Waeber and Sitar (2013), Bovenga et al. (2013) and Corominas (2014) for the use of non-contact techniques such as GNSS and SAR. The difficulties in monitoring extremely-slow landslides reside in the presence of systematic errors of the same order of magnitude of the displacements (Simeoni and Ferro 2015).

This paper describes the data processing procedure that was effectively applied to detect the sliding surfaces and to estimate the displacement rates with inclinometer measurements collected in two extremely-slow landslides in Italy: the V70 landslide, in the Isarco valley in Northern Italy, and the landslide at Monteverde/Gianicolo Hill in Rome. Measurements were collected with two different probes and were processed in order to identify: precision and accuracy of measurements, interval of displacement integration, and reliability of results.

2 LANDSLIDES AND MONITORING SYSTEMS

The characteristics of the two landslides and of the monitoring systems have been described in Simeoni et al. (2015) for the V70 landslide and in Amanti et al. (2014) for the Monteverde/Gianicolo Hill. They are briefly summarized in the following.

2 .1 *V70 landslide*

V70 landslide, in the Isarco valley in Northern Italy, involves a motorway viaduct at the toe of a slope where a Deep-seated Gravitational Slope Deformation (DGSD) has developed after the last glacial periods, including other landslide units such as deep and shallow rotational/translational slides of rocks, debris and coarse soils (Figure 1).

To identify which of the landslide units have been causing the movement of the viaduct, displacements of parts of the viaduct have been measured since 1993 by using different instrumentation such as theodolite and stadia rods, biaxial clinometers, direct pendula, Total Station, while inclinometers were used to measure the subsurface displacements in the periods 1993-2000 and since 2008 to 2010. Figure 2 shows the location of the inclinometers respect to the piers of the viaduct.

The body of the V70 landslide consists of weathered rock fragments and blocks of tuff and ignimbrite accumulated at the foot of the cliffs (talus and rockfall deposit) and mixed with glacial sandy to clayey deposits and alluvial lens at the base of the slope. The bedrock of ignimbrite gently deepens towards North from a depth of 18 m at the pier 26 to a depth of 36 m at the pier 21.

Since 2005, displacements of three targets installed on each pier from 21 through 26 have been periodically measured with a Total Station. From 2008 to 2010 inclinometer measurements were carried out by collecting readings on all of the four tube grooves.

2 .2 *Monteverde/Gianicolo Hill landslide*

The eastern flank of Monteverde/Gianicolo Hill (Figure 3) represent an “historically unstable area” subjected to surficial sliding and roto-traslational mass movements since 1894.

The main event occurred in 1963 when a landslide of about five hectares seriously injured retaining walls, streets and sewer. The remedial works were realized by the Municipality only in 1984-85, consisting in an embedded wall of bored piles (d=1200mm) breaking the landslide body, a network of trenches and some retaining walls to stabilize the superficial cover (Amanti et al. 2014). This latter consist of backfill and reworked pyroclastic materials with a variable thickness ranging from 2 to 15 meters, lying over continental deposits of the Monte Mario formation (MTM) (Funiciello and Giordano 2008) made by sand, sandy-loam and clay. Deeper, the stratigraphic sequence end with a firm silty clay known as Monte Vaticano formation (MVA) (Funiciello and Giordano 2008).

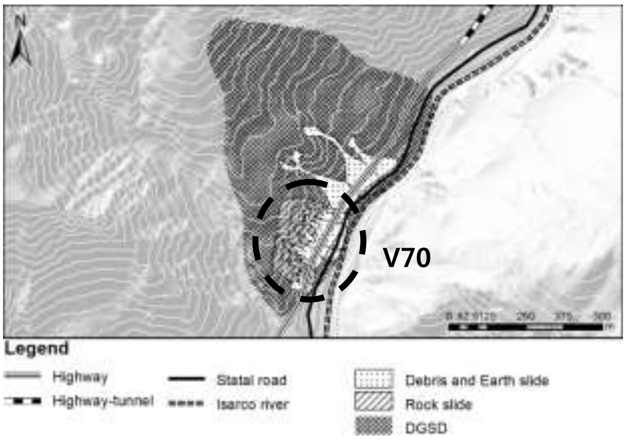

Figure 1. V70 Landslide units

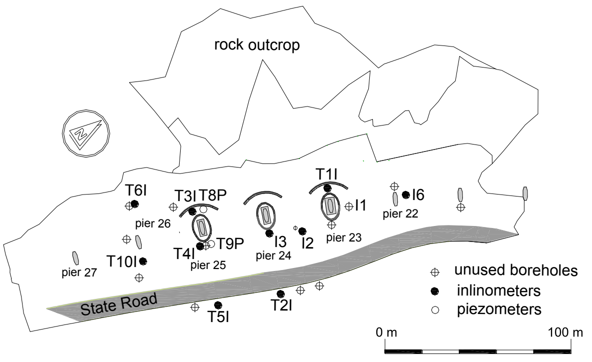

Figure 2. Location of boreholes and instrumentation at V70 landslide.

Despite the high number of instruments (piezometers and inclinometers) and many monitoring activities from 1964 to 2009, the kinematics of the landslide still remained undefined for a reliable evaluation of the residual risk at present. The new monitoring activity started in 2011, reactivating nine existing inclinometers some of which older than 20 years.

Measurements have been carried out collecting readings on all of the four tube grooves, monitoring instruments downstream the embedded wall every 3 months on average (more frequently if heavy rains occurred). The readings along I3_96, I9_96 and I2_96 upstream the embedded wall were conducted every 6-8 months.

3 INCLINOMETER DATA ANALYSIS

In both sites inclinometer measurements were carried out by lowering the bi-axial probe along all the four grooves 1, 2, 3 and 4 of the tube. Accordingly, four couples (A, B) of readings were available and four different processing methods could be used: 1) data collected in the opposite grooves 1 and 3; 2) data collected in the opposite grooves 2 and 4; 3) data collected by sensor A in the four grooves; 4) data collected by sensor B in the four grooves.

For example, standard readings in the opposite directions 1 and 3, A1 and A3 on plane A (plane *yz* in the Cartesian three-space, with *z*=depth), B1 and B3 on plane B (plane *xz*), may be expressed as:

$$\begin{aligned} A_1 &= A+\varepsilon^s_{A1}+\varepsilon^r_{A1} \quad \text{and} \quad A_3 = -A+\varepsilon^s_{A3}+\varepsilon^r_{A3} \\ B_1 &= B+\varepsilon^s_{B1}+\varepsilon^r_{B1} \quad \text{and} \quad B_3 = -B+\varepsilon^s_{B3}+\varepsilon^r_{B3} \end{aligned} \tag{1}$$

where A and B are the true values; $\varepsilon^s_{A\alpha}$ and $\varepsilon^s_{B\alpha}$ are the systematic errors, with α=1 or 3; $\varepsilon^r_{A\alpha}$ and $\varepsilon^r_{B\alpha}$ are the normally distributed random errors. The true values A and B are usually estimated by the differences $\overline{A}$ and $\overline{B}$:

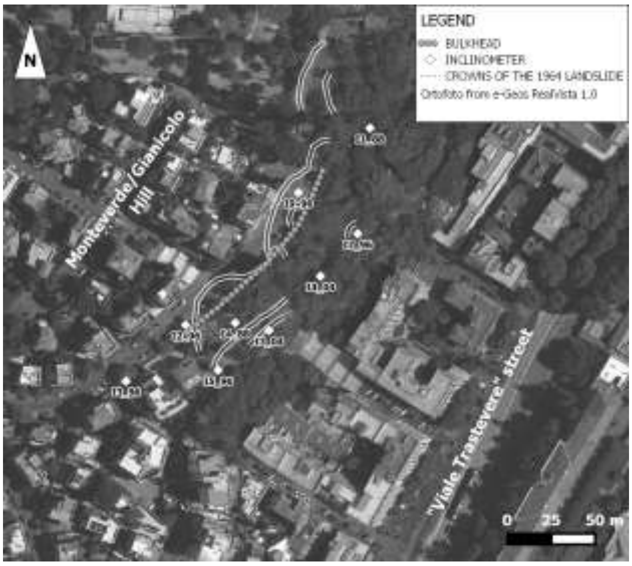

Figure 3. Location of monitoring network along Monteverde/Gianicolo Hill landslide.

$$\bar{A} = \frac{A_1 - A_3}{2} = A + \frac{\varepsilon^s_{A1} - \varepsilon^s_{A3}}{2} + \frac{\varepsilon^r_{A1} - \varepsilon^r_{A3}}{2}$$
$$\bar{B} = \frac{B_1 - B_3}{2} = B + \frac{\varepsilon^s_{B1} - \varepsilon^s_{B3}}{2} + \frac{\varepsilon^r_{B1} - \varepsilon^r_{B3}}{2} \qquad (2)$$

in which the systematic errors are usually assumed unchanging during the rotation of the probe and then disappear in the equation 2. Differences $\bar{A}$ and $\bar{B}$ still contain the random errors, whose standard deviations may be calculated from the checksums S_A and S_B and used to evaluate the precision of the inclinometer measures and displacements (Simeoni and Mongiovì 2007).

If systematic errors were null (i.e. very good measurement accuracy) the displacement should not depend on which of the processing methods has been used. Actually differences generally occur. For example, in inclinometer I3 of the V70 landslide the cumulative displacements calculated on plane *yz*, from June 2008 to October 2009, by using modes (1) or (2), differed of more than 8 mm at the ground surface (Simeoni and Ferro 2015). This difference did not reduce when measurements were corrected from a systematic error due to the instrument bias or any other systematic error suggested by Mikkelsen (2003).

Since the main objective of this study was to identify the sliding surfaces responsible for the movement of the viaduct in the V70 landslide or still moving despite the remedial works in the Monteverde/Gianicolo Hill, the effects of the systematic errors were reduced by integrating the displacements only in the depth intervals where the sliding surfaces were identified. In other words, displacements were integrated only in the intervals were their magnitudes where significantly greater than the precision and directions were coherent with the geomorphology. An example is given in the following for the inclinometer I1_88 of the Monteverde/Gianicolo Hill.

4 DISPLACEMENT INTEGRATION

Figure 4 shows the local displacements calculated at the inclinometer I1_88 of the Monteverde/Gianicolo Hill from October 2011 to July 2013 by using the data collected on grooves 1-3 or 2-4.

It is seen that in the depth interval 7-9 m the magnitude of the local displacements is the greatest and that the directions vary between 100° and 110° accordingly the downslope direction (Figure 3). Moreover, in this depth interval the magnitude of displacements resulted greater than its precision, estimated of about 0.06 mm according to the error propagation theory given in Simeoni and Mongiovì (2007).

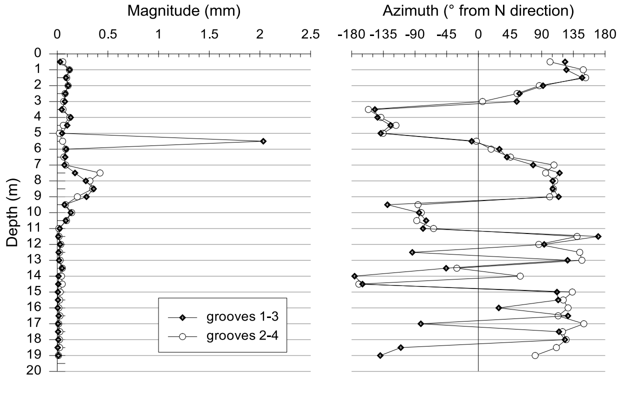

Figure 4. Local displacements since October 2011 to July 2013 at the inclinometer I1_88 of the Monteverde/Gianicolo Hill.

The local displacement of about 2 mm and -10° from North calculated with data collected on grooves 2-4 at depth of 5.5 m, also shown in Figure 4, was recognized to be affected by a gross error since at the same depth the checksum S_B differed significantly from its average value. This displacement was therefore neglected and the sliding surface was definitely located in the depth interval 7-9 m.

5 RESULTS

At the V70 landslide the displacements integrated locally according to the procedure described in the previous section were compared in terms of displacement rates to the movement of the base of the viaduct piers measured with the Total Station.

It is seen in Table 1 that a very good redundancy was obtained and therefore it was proved that: a) the data processing with locally integrated displacements identified correctly the sliding surface of the landslide; b) the viaduct piers are dragged by the landslide; c) the landslide is a partial reactivation of the DGSD.

Table 1. V70 landslide. Displacement rates at the viaduct pier bases calculated from total station (TS) or inclinometer (Inc) measurement.

	mm/year				
	Pier 22 (I6)	Pier 23 (T1I)	Pier 24 (I3)	Pier 25 (T3I)	Pier 26 (T6I)
TS	8.2	8.6	10.1	8.9	6.7
Inc	7.5	8.2	8.0	9.3	9.6

At the Monteverde/Gianicolo Hill site the described data-processing procedure allowed to retrieve reliable information about the kinematics of the old landslide. The monitoring activity proved that : a) the landslide body could be considered stabilized, due to the absence of meaningful horizontal displacements beside the embedded wall realized in 1984; b) as shown in Figure 5, very slow movements have been detected along the slope downstream of the embedded wall; c) reliable displacements only took place in a well identified depth range, corresponding to the middle of MTM formation, also in

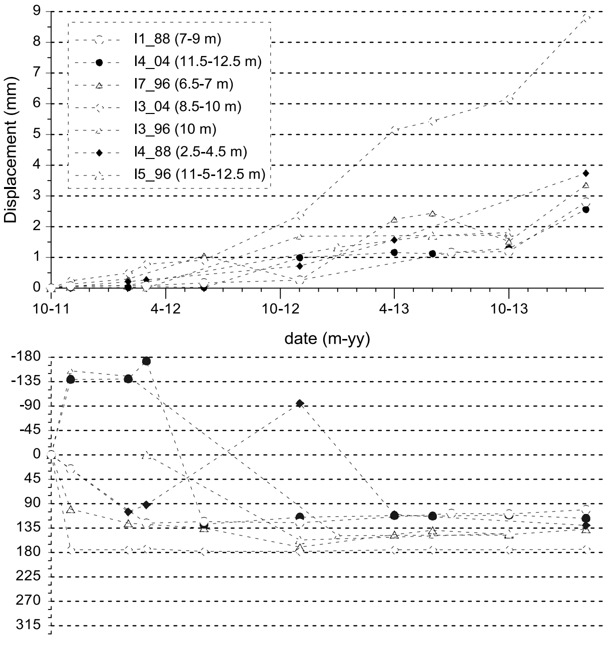

Figure 5. Displacements on the sliding surface at the Monteverde/Gianicolo Hill landslide

good agreement with downslope direction. On the other hand, the sliding surface resulted from those measurements would seem to be deeper than the ancient one, and therefore further geotechnical investigations are necessary to better define its shape.

6 CONCLUSION

Extremely slow landslides move at a rate less than 16 mm/year and may be recognized only by measuring the displacements, but measurements may include random and systematic errors of the same order of the magnitude of the movements that occur in a short time if proper installation and data processing are not adopted.

This paper proved that:

- Carrying out measurements along all the four grooves,
- Processing the measurements with the four available methods, and
- Integrating displacements only locally,

in only 1 year of measurements it was possible to identify sliding surfaces with displacements at a rate of 1 mm/year.

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