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EFFICIENCY OF STABILIZATION TECHNIQUES IN ACQUALORETO LANDSLIDE AREA (UMBRIA, ITALY)

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ABSTRACT

This work, based on the results of a series of geotechnical and monitoring studies, analyses two landslides composed of heterogeneous altered marly clayey arenaceous rock and eluvial-colluvial deposits, located near the village of Acqualoreto (Central Italy). The landslides (called here A and B) are characterized by retrogressive movements approaching buildings and roads near the village and by different sliding surfaces between 10 and 25 m b.g.l. Maximum displacement rates were measured after the most significant rainfall events in autumn months. Four years after the installation of drainage systems in both landslides, some considerations on the efficiency of stabilization techniques (horizontal drains and drainage wells) are presented, with analysis of inclinometric and piezometric data, both pre- and post-installation. Results indicate that single alignment of drainage wells in the upper part of landslide A cannot be considered resolutive in reducing the landslide hazard: therefore, new drainage works in the central part of landslide mass and in the accumulation zone should be considered. The horizontal drains in the central/upper part of landslide B did greatly reduce movement, although new drains should be installed along the toe of the landslide for definitive control the groundwater rise.

Key words: *Acqualoreto landslide, horizontal drains, drainage wells, drain efficiency*

INTRODUCTION

Rises in groundwater level after stormwater events or prolonged rainy periods is one of the main triggers for landslides (e.g. Van Asch *et alii*, 1999; Iverson, 2000). According to Bishop & Morgenstern (1960), Ghiassian & Ghareh (2008) and Di Matteo *et alii* (2013a), the most critical situation that a slope may experience with respect to the mass stability is when groundwater level is approaching to the slope profile. As noted by Hutchinson (1977), a proper drainage system is the main method used to stabilize landslides, followed by modification of slope geometry. Surface water (runoff) is less difficult and expensive to control than deep groundwater, especially in the case of deep complex landslides. The efficiency of horizontal drains is generally high, but long-term maintenance may suffer due to fine particles which slowly clog drain pores (Bromhead, 1992; Santi *et alii*, 2001; Mininger *et alii*, 2011). The design and success of horizontal drains are also often governed by local experience alone (Rahardjo *et alii*, 2003). Although the ideal location for horizontal drains is at the toe of the slope (Santoso *et alii*, 2010), this is often not feasible (costs, logistics, etc.). Drains - together with flexible retaining walls for protecting dwellings - are often designed first at the higher part of the main body of landslides, especially when slope failure approaches buildings. Large-diameter drainage wells linked to sub-horizontal drains are also commonly used to lower the groundwater table and increase slope stability (Cencetti *et alii*, 2005; Popescu & Sasahara, 2008; Ronchetti *et alii*, 2009).

The present work, based on the results of a series of geotechnical and monitoring studies, illustrates the stabilization techniques used in two landslides (located near the village of Acqualoreto, Central Italy) and examines their efficiency. The site of Acqualoreto, between the towns of Todi and Orvieto, is taken as a reference, being classified as high landslide risk area (R3). According to risk zoning for landslide in Italy, R3 indicates an area with high risk characterised by victims, functional damage to buildings and infrastructure, as well as partial interruption of economic activities are possible (Cascini *et alii*, 2010). Four years after the installation of drainage systems in the two landslides, the efficiency of stabilization techniques (horizontal drains and drainage wells) was studied, following monitoring data recorded since 2002.

SETTING AND DESCRIPTION OF STUDY AREA

In the Acqualoreto area (42° 44' 0", 12° 20' 0"), a large well-known landslide occupies the left bank of the river Tiber (Fig. 1): the village of Acqualoreto has been one of the areas to be stabilized in the Umbria region since 1966. The study area is characterized by rocks belonging to the Tuscan Domain (marly clayey arenaceous rock and calcarenite of the "Scaglia Toscana Formation - Calcareniti di Dudda") and Umbria-Marche Domain (marly limestone). Eluvial-colluvial deposits and talus extend over the body of the landslide, which has a maximum width of 3.5 km. The landslide is composed by heterogeneous altered flysch rocks and heterogeneous eluvial-colluvial deposits and talus. Figure 1 shows the location of the study area, with the main lithological and geomorphological features. The extension and geometry of the Acqualoreto landslide were studied by multiple and multi-scale observation of aerial photos, together with extensive geotechnical investigations and monitoring (Faralli *et alii*, 2004). The present work takes as its reference part of two landslides where some stabilization techniques have been designed: both are located in the main body of the larger landslide and are characterized by retrogressive movements approaching buildings and roads near the village (Fig. 1). They are called here "landslide A" and "landslide B" (Fig. 2): the latter is located downstream of Acqualoreto. Several geotechnical surveys to determine the geometry of both landslides were carried out between October 2002 and July 2008: site investigations included boreholes; nucleus destruction boreholes; seismic refraction profiles and DPSH/SPT dynamic penetration tests; pressuremeter tests (DRT) and Lugeon and Lefranc permeability tests. Figure 3 shows a lithological sketch oriented roughly NW-SE (longitudinal to the body of landslide B). Several samples of undisturbed soils were also collected for geotechnical laboratory testing. The results were extensively discussed by Faralli *et alii* (2004). For information on landslide kinematics, displacement measures and groundwater observations were collected. According to data from about 16 inclinometers, landslide movements occur between 10 and 25 m below ground level (b.g.l.) (Fig. 3). The landslide movements are mainly roto-trans-

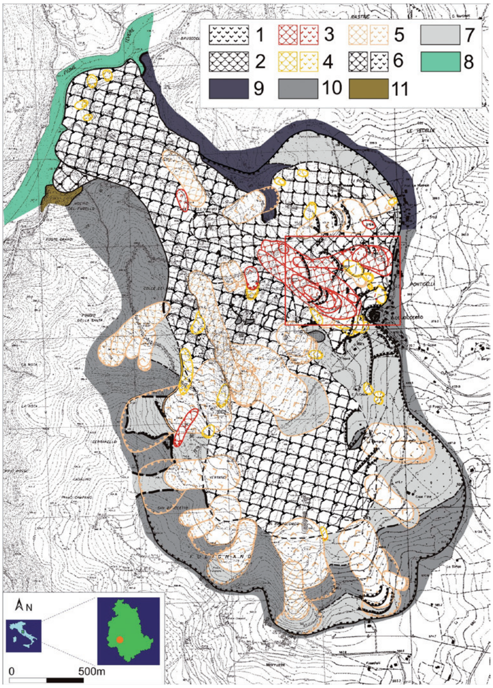

Fig. 1 - Lithological and geomorphological features of Acqualoreto area (modified from Balducci et alii, *2013). Red rectangle: location of landslides studied here. LEGEND: 1a) active complex landslide; 1b) active slide landslide; 2a) suspended complex landslide; 2b) suspended slide landslide; 3a) dormant complex landslide; 3b) dormant slide landslide 4a) stabilised and relict complex landslide; 4b) stabilised and relict slide landslide; 5) eluvial and colluvial deposits; 6) alluvional deposits; 7) arenaceous bedrock; 8) marly bedrock; 9) calcareous bedrock*

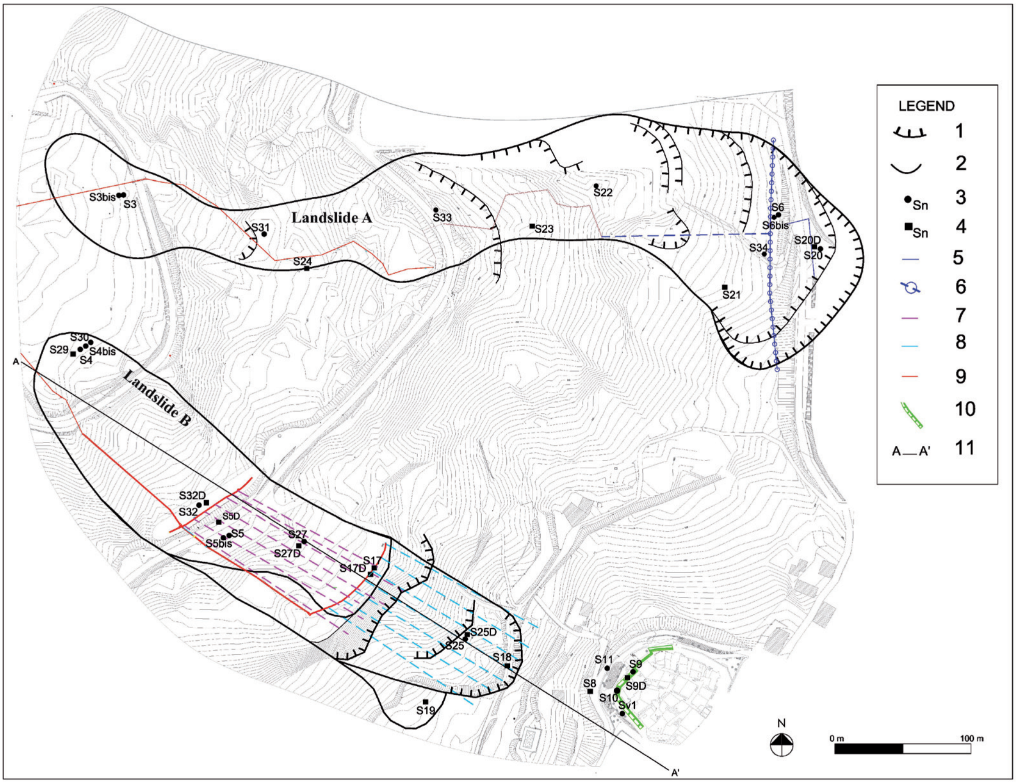

Fig. 2 - Boundaries of landslides A and B. LEGEND: 1) landslide crowns; 2) landslide boundaries; 3) inclinometer; 4) piezometer; 5) HHD pipe outlet; 6) drainage wells; 7) first-order HDD drains; 8) second-order HDD drains; 9) superficial drainage network; 10) retaining walls; 11) line of lithological section

lational sometimes associated with flow-type motion (Balducci *et alii*, 2013). These kind of kinematics is widespread in flyschoid complexes in the Umbria region (Guzzetti *et alii*, 1996).

Data from 12 open standpipe and Casagrande piezometers indicate that an unconfined aquifer is hosted in the dismembered rock slide body. Permeability data from 15 Lugeon and Lefranc tests show that the permeability coefficient varies from 10^{-6} to 10^{-9} m/s (Faralli *et alii*, 2004): high variability of the permeability coefficient, typical of landslide areas characterized by altered flysch rocks (Ronchetti *et alii*, 2009), was also observed, in both vertical and horizontal directions.

According to data from the Corbara raingauges (140 m a.s.l.), located about 10 km SW of village of Acqualoreto, the mean annual precipitation in the area is about 730 mm (1963-2012 period). Analysis of monthly data indicated that the main precipitation peak is recorded in autumn (October-December), with a mean value of about 270 mm (Fig. 4).

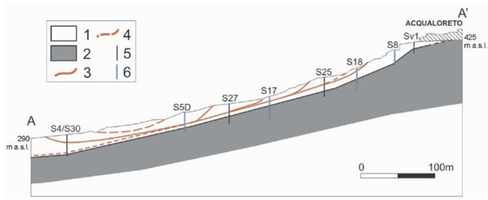

Fig. 3 - Lithological sketch oriented longitudinally to body of landslide B (line of section shown in Fig. 2). LEGEND: 1) altered marly-clayey arenaceous rock and calcarenite, eluvial-colluvial deposits and talus; 2) bedrock (marly-clayey arenaceous rock and calcarenite); 3) sliding surface; 4) hypothetical sliding surface; 5) inclinometer; 6) piezometer

STABILIZATION TECHNIQUES

A series of flexible retaining walls was constructed to protect the village of Acqualoreto (Fig. 2). Drainage systems were built into the main body of both landslides. As shown in Fig. 2, a group of drainage wells connected to a Horizontal Directional Drilling (HDD) pipe outlet were drilled in the upper part of landslide A. Two sets of HDD drains were constructed in the central/upper part of landslide B.

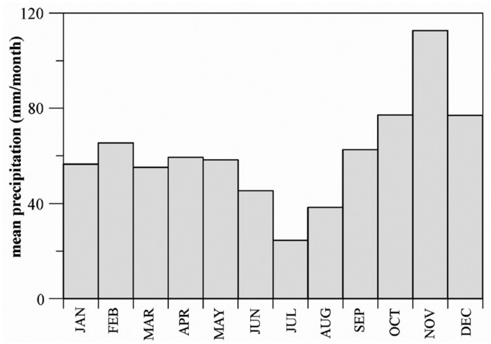

Fig. 4 - Mean monthly precipitation at Corbara raingauge for 1963-2012 period

DRAINAGE WELLS (LANDSLIDE A)

Due to the size of landslide A (up to 500 m long and 150 m wide) and considering that the main crown is very close to buildings and roads (Fig. 2), a group of 28 drainage wells 1.20 m in diameter and at a distance of 6 m from each other was built in the upper part of the landslide at altitudes between 380 and 390 m a.s.l. Each well reached a maximum depth of about 15 m (Fig. 5). In order to redirect groundwater outside the landslide mass, the wells were linked to form an interconnected subsurface and surface drainage network (Figs. 2 and 5).

HORIZONTAL DIRECTIONAL DRILLING (LANDSLIDE B)

For efficient drainage of the body of landslide B, HDD technology was applied (Fig. 6), with the implementation of controlled Paratrack and Vector Magnetics devices, which allowed the pilot well to be targeted with an error of less than 5 cm. A system of drainage pipes up to 140 m long was distributed throughout the central/upper part of landslide body, for increased drainage efficiency. Planimetric and altimetric locations of drains and their interactions were designed according to well-known methods (Hutchinson, 1977; Di Maio *et alii*, 1988). HDD technology was applied to install two orders of drainage pipes on two pitches at 323 and 343 m a.s.l., at about 100 m from each other. For maximum efficiency, the tubes were placed in the portions of the sliding surface where soil permeability was higher.

The drains were placed parallel to the landslide axis, at 10 m from each other. Two orders of drains were overlapped, to limit groundwater rising in the transition area between the two groups of drains, to lower the groundwater level and to control pore water pressure along the slope.

Fig. 5 - Detail of installation of drainage wells in landslide A. Scheme of well groups from Balducci et alii (2013)

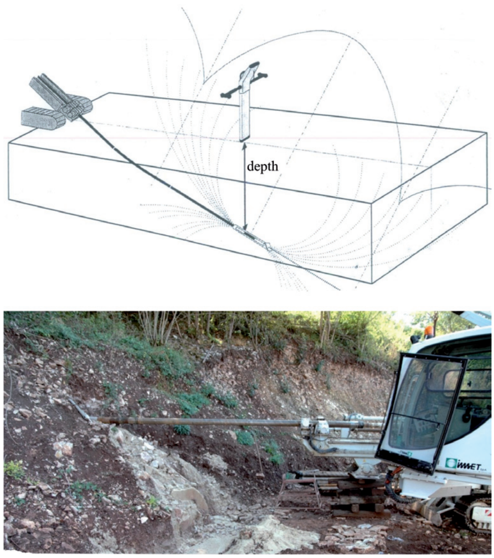

Fig. 6 - Sketch of HDD Techniques (modified from Balducci et alii, 2013) and detail of drainage works in landslide B

ANALYSIS OF EFFICIENCY OF DRAINAGE SYSTEMS

To study the efficiency of the drainage systems constructed in both landslides, displacement rates and piezometric responses to precipitation were analysed during both pre- and post-installation periods.

PIEZOMETRIC DATA

Before HDD and drainage wells were installed (before September 2008 for landslide A and before January 2009 for landslide B), the response to precipitation of some piezometers, measured at approximately monthly intervals, was studied. Field data (collected from February 2004) indicated that the seasonal groundwater response to precipitation before installation of the drainage systems was different between the foot and the lowest part of the main body of the landslides, with maximum fluctuation in the accumulation zone (up to 10 m after heavy autumn rain). Taking as reference the lowest part of the main body of landslide B (piezometer S5D; Fig. 7), during the study period there was a 5-m increase in groundwater level, due to heavy autumn rain in 2004 and 2005 (400-500 mm, corresponding to about two-thirds of the average annual value). Piezometer S5D was chosen because it had the longer data set.

During the study period, 1-month responses of groundwater level to precipitation were identified for piezometers located in the main body of the landslides, and 2-month responses for those in the accumulation zone. Although piezometric data before February 2004 were not available, the piezometric heads in the body of the landslides were expected to be lower than those of the 2004-2009 period: during 2000-2003, a prolonged drought affected the study area and the central Apennines in general (Di Matteo *et alii*, 2013b). After the installation of the first-order HDD in the main body of landslide B (September 2008-January 2009), the response of groundwater level to precipitation changed considerably. As shown in Fig. 7, autumn rain was heavy in 2008 (about 500 mm, similar to autumn 2004 and 2005), but produced a rise in the water table of only 1.30 m. In the period September 2008-July 2011, the groundwater level fluctuated at around 322-324 m a.s.l.: these values correspond to the lowest and highest elevations of the first-order HDD. Due to the lack of piezometric data prior the installation of drainage wells in landslide A, the analysis of the effect of drainage system on groundwater was not carried out.

INCLINOMETRIC DATA

Analysis of displacement rates of the inclinometers located in both landslides indicates that most of the

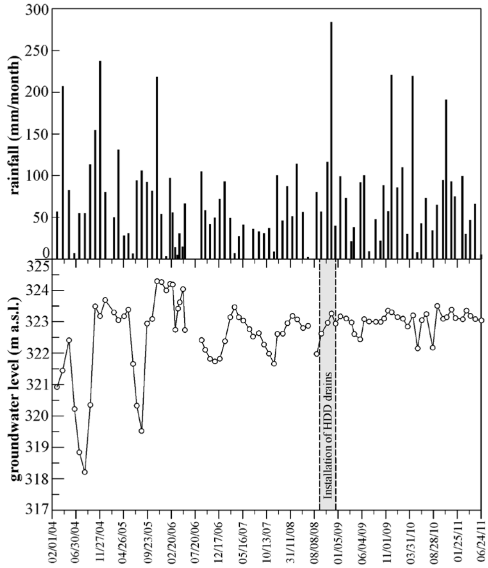

Fig. 7 - Effect of precipitation on groundwater level (piezometer S5D), February 2004 - July 2011, for lowest part of main body of landslide B (data measured at approximately monthly intervals). Data recorded at Corbara raingauge

movements are concentrated along the main slip surface (Fig. 3), although secondary surface movements are produced by superficial splay. Most of the casings of the inclinometers were broken, so that only a few instruments remained to monitor displacement rates before and after the installation of the drainage systems. In order to update the monitoring system, new inclinometers were then set up near the damaged instruments.

Displacement data from inclinometers S6, S6b, S34 and S22 were used for landslide A (see Fig. 2 for location of instruments). Figure 8a,b shows the cumulate displacement of inclinometers S6, S6b and S34 at two deformation depths (around 11 and 16 m b.g.l.): data was collected at 1- and 2-month intervals. During the study period, maximum cumulate deformations were recorded at a depth of 11 m for all inclinometers. As Fig. 8a shows, the mean monthly displacement rates before the drainage wells were drilled (between 1.5 and 1.9 mm/month over 18 months) were much higher than those observed after installation (around 0.1 mm/month over 23 months). In particular, the decrease recorded by S34 occurred after a prolonged rainy period (2008-2010 in Fig. 7), indicating that the drainage system contributed to reducing landslide motion, at least in the highest part of the main body. This was confirmed by the recent

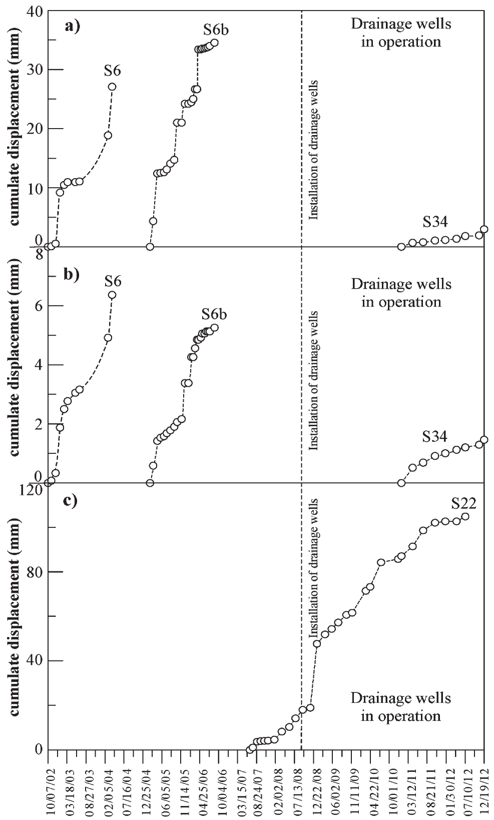

Fig. 8 - Cumulate displacement rates in 4 inclinometers in landslide A (S6, S6b, S34, and S22). Inclinometers S6, S6b, S34 are located close to drainage system, while the inclinometer S22 is located about 120 m below the drainage system (the location of inclinometers is shown in Fig. 3). a) data registered at inclinometers S6, S6b, S34 at a deformation depth of 11 m b.g.l.; b) data registered at inclinometers S6, S6b, S34 at a deformation depth of 16 m b.g.l.; c) data registered at inclinometer S22 at a deformation depth of 11 m b.g.l.

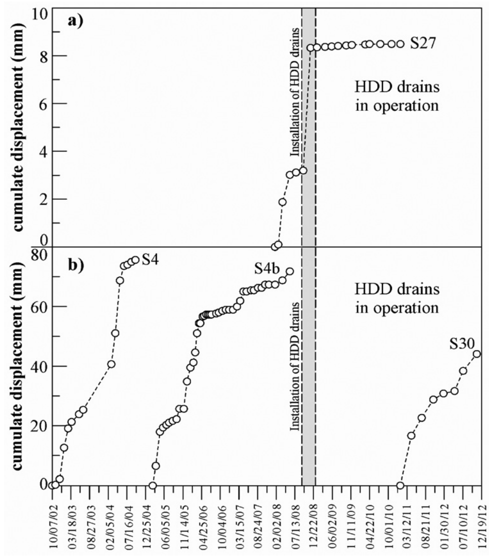

Fig. 9 - Cumulate displacement rates in 4 inclinometers in landslide B (S27, S4, S4b, and S30). Inclinometer S27 is located close to HDD drains while inclinometers S4, S4b, and S30 are located in the lowest part of landslide (the location of inclinometers is shown in Fig. 3). a) data registered at inclinometer S27 at a deformation depth of 11 m b.g.l.; b) data registered at inclinometers S4, S6b,and S30 at a deformation depth of 12 m b.g.l.

heavy rainfall data for autumn 2012 (about 500 mm), which did not produce any significant movement in landslide A. The efficiency of the drainage system was not observed at inclinometers located about 120 m below it (e.g., inclinometer S22 in Fig. 8c).

Data from S27, S4, S4b and S30 were analysed for landslide B (Fig. 9a,b). Maximum deformation from inclinometer S27, located close to the first-order HDD drains, was also recorded at a depth of 11 m. As shown in Fig. 9a, the displacement rates reached a maximum of 2.6 mm/month, due to the rain of September-November 2008 (250 mm): the installation of the first-order HDD (September 2008) followed by that of the second (January 2009), practically halted landslide motion. By using observations from S4, S4b and S30, two deformation depths were recorded along the toe of landslide B at 12 an 25 m b.g.l. respectively (Fig. 3). As shown in Fig. 9b, the displacement rates have not decreased after the installation of HDD drains.

CONCLUSIONS

The present work contributes to understanding of the efficiency of drainage systems, with particular reference to drainage wells and horizontal drains: although the latter are widely used to stabilize landslides, there are very few reliable studies reporting their efficiency (e.g., Ahmed *et alii*, 2011). Both landslides investigated here are characterized by different sliding surfaces, the main of which occurs between 10 and 25 m below ground level. By correlating deformations recorded by inclinometers with precipitation, maximum displacement rates were measured after the most significant rainfalls during autumn months. Observations from instrumental site monitoring after the installation of drainage systems allow the following considerations on displacement rates:

- *Landslide A*: drainage wells installed about four years ago contributed to reducing landslide movement, at least in the highest part of the main body. In particular, the prolonged rainy period of 2008-2010 and recent heavy autumn rainfall in 2012 did not cause significant movement.

- *Landslide B*: two orders of HDD drains constructed between September 2008 and January 2009 in the central/upper part of the landslide body did not allow the rises of groundwater table, improving slope stability in the short and medium term. Of note is the fact that the recent heavy autumn rain in 2012 only produced a displacement rate of 0.17 mm/month. Taking autumn 2004 as a reference period with rainfall similar to that of autumn 2012, most of the inclinometers in the central part of landslide body were damaged. This comparison is interesting, because both seasons considered were preceded by well known very dry periods. The effects of HDD drains did not produce any substantial reduction in displacement rates in the accumulation body, far from the drainage system.

In conclusion, single alignment of drainage wells in the upper part of landslide A cannot be considered resolutive in reducing the landslide hazard: therefore, new drainage works in the central part of landslide mass and in the accumulation zone should be considered. The horizontal drains in the central/upper part of landslide B did greatly reduce movement, but their long-term maintenance, together with new HDD drains to be installed along the toe of the landslide, must be pursued in the next few years.

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