New Strategy for Landslide Mitigation Considering Cost Sustainability

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In most developed countries the budget devoted to structural risk mitigation of natural hazards such as floods and landslide is reducing. On top of that, mitigation structures constructed decades ago require some maintenance that it is seldom guaranteed since they are widespread in all the territory and inspections are infrequent. In some cases, the cost correlated with the engineering activities could be compensated through the association of works that provide economic return on the long term.
The case study consists of a slope instability phenomenon crossed by a National Road that connects the Veneto and Friuli Venezia Giulia regions. Due to the risk conditions the phenomenon has been investigated and monitored for more than 15 years. The landslide is crossed by a torrent and near the crown of the instability phenomenon some springs are present. The opportunity to use the water removed from the slope to produce energy through a small hydropower plant could help sustain economically the remediation project.

Key words: SABO, slope stability, countermeasure works, micro hydro, economic sustainability

1. INTRODUCTION

While population in mountain areas increase do to anthropic pressure, question arise about how to cope with the risk related to landslide in a cost effective manner [*Blaikie et al.*, 1994*; Eisbacher,* 1982].

Some authors approach the issue using a large scale of analysis, calculating the cost of damage associated with landslides at national scale [*Hilker et al.,* 2009; *Klose et al.,* 2016]. These estimates are of great use for insurance companies or nations that centralize the budget devoted to landslide protection measures. However, other nation de-centralize the jurisdiction for risk mitigation to local authorities such as regions or even municipalities.

In Italy rarely National or Regional authorities undertake the costs associated with countermeasure works for slope stability. For these reason most of the times the financial burden for structural mitigation works must been sustained by municipalities and local communities [*Scolobig et al.*, 2014*; Prenger-Berninghoff et al.*, 2014). However small municipalities rely on small budget and if the landslide does not threaten lives directly, the construction investments are often sub-prioritized. Besides local communities are often against large stabilization intervention with significant impacts on landscapes or that would lead to the expropriation of some of their land [*Scolobig et al.*, 2016]. In this framework the definition of slope stability works that would financially self-sustain themselves could be the only option for reducing risk with local support.

In some cases, it could be feasible to install micro hydro power plants to convoy and collect the water that induces slope instability and use the water drop to generate electric power. These plants on the medium run will then pay themselves and provide some resources for maintenance works of already present structural countermeasure works such as check dams and culverts.

In this work, we present the case study of a medium-size landslide located in the Eastern Italian Alps that has been monitored for more than a decade. The landslide intercepts a National Road but despite that, the mitigation work that have been implemented do not protect the entire exposed road segment due to the lack of resources of the municipality and disputes between the national and local authorities. The countermeasure works design consists in extracting and convoying the water that flows above and within the slope in order to reduce the landslide displacements, then using the available

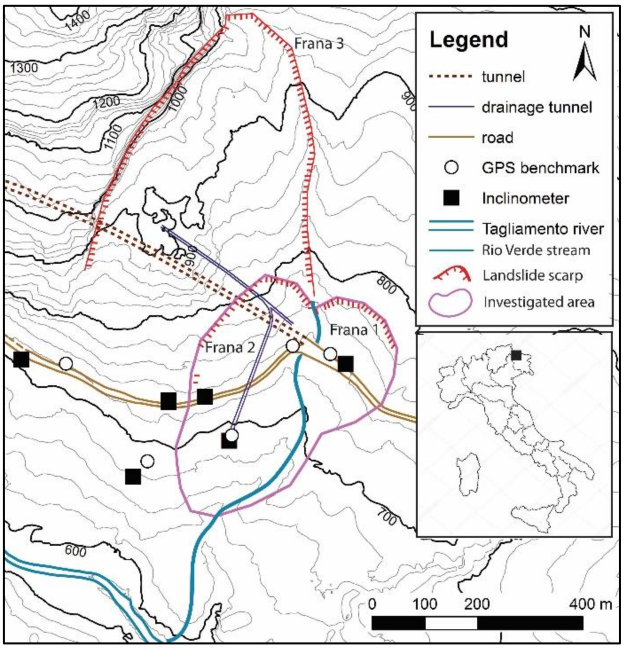

Fig. 1 Study area of Passo della Morte, the bigger scarp on the top of the figure belongs to the blockslide (Frana 3)

130 m drop to produce hydroelectric power. In this way the plant would provide economic return on the long term that would pay the costs of the stabilization and provide funds for maintenances.

2. THE STUDY AREA

Passo della Morte is a narrow gorge of the Tagliamento river in the municipality of Forni di Sotto (UD); the former National Road, that was the only route along the valley, was subject to rockfalls and snow -avalanches in the area. For these reason a new road tunnel was designed and then constructed since 1994 and opened in 2008. The eastern tunnel portal was located just after the crossing of a small stream called Rio Verde.

In 1996 the road tunnel was disrupted at during a major rainfall events. In fact a large block slide (called “Frana 3”) is present and the increase of displacements due to the meteoric events caused the collapse of the structure at about 300 m from the eastern entrance [*Bossi et al.*, 2017]. During the same event a se condary slope instability (called “Frana 2”) affected the tunnel portal. Concurrently also 200 m of national road before the entrance has been displaced and subsided of some centimeters due to the activity of a landslide called (“Frana 1”). The peculiarity of Frana 1 and Frana 2 is that while they have distinct scarps they converge at the toe forming a heart shaped slope instability that needs to be investigated as a whole (**Fig. 1**). The two scarps are divided by the Rio Verde torrent, a small stream that flows just before the eastern tunnel entrance.

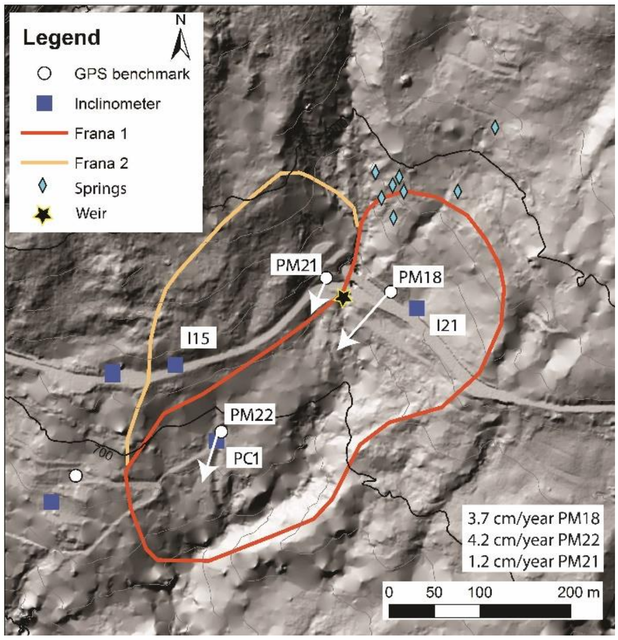

Fig. 2 Monitoring network for Frana 1 and Frana 2 and location of the springs. The white arrows represent the displacement directions of the GPS benchmarks

The tunnel and the old national road cross the Rio Verde above two concrete box culverts.

In the following years a new project for the tunnel restoration was designed; the construction, that started in 2004 and was finished in 2008, was coupled with a drainage tunnel located underneath the road tunnel in order to drain the water from the slope and mitigate the displacements of Frana 3 and Frana 2.

2.1 Societal background

Managing the damage induced by the landslides of the study area and associated risk for the road tunnel is responsibility of the Italian National Road Authority (ANAS) that is the formal owner of the infrastructure.

On the other hand, there is no direct responsible for the 200 meters of road before the eastern entrance as there are several institutions that may and may not have interest in the slope stabilization. In this framework, CNR–IRPI was involved to monitor and modelling the landslides of the area and provide reliable risk scenarios. This would help also in assessing the public body that will be responsible for the Frana 1-Frana 2 issue. The municipality of Forni di Sotto is particularly interested in solving the problem since, if the road suffers disruptions, the traffic would be diverted in another valley with local commuters facing more than one hour of additional travel-time. However small municipalities in Italy are subject to several budget constrains so a

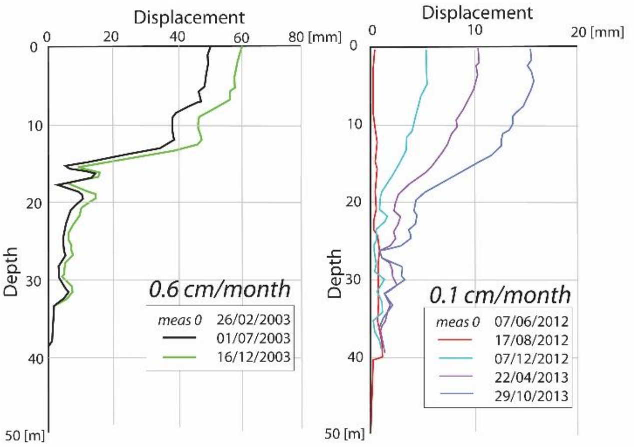

Fig. 3 Displacements and velocities measured in inclinometer I15 series (Frana 2). On the left before the construction of the drainage tunnel; on the right after the drainage tunnel was finished and operative.

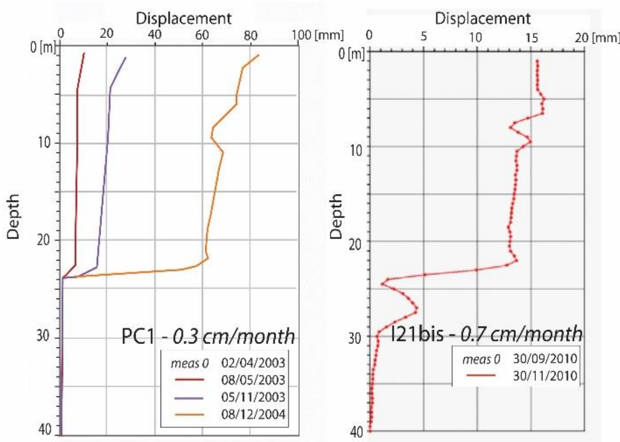

Fig. 4 Displacements and velocities measured in inclinometers PCbis and I21bis (Frana 1).

cost-effective mitigation strategy that would also provide some economic return for the local community is the only win-win strategy that would guarantee the remediation of the Frana 1-Frana 2 problem.

3. INVESTIGATION

3.1 Monitoring

The landslides of Passo della Morte have been monitored for more than a decade with piezometers, inclinometers (periodic and in place) and GNSS surveys. Some instruments were deployed by ANAS while others were installed by the National Research Council of Italy (CNR-IRPI) since 2002.

The monitoring instruments were deployed to control the movements of the landslides and to understand the slope kinematics; moreover, to see if the mitigation works were effective and to provide data on which design new countermeasure if the already implemented ones were not sufficient (**Fig. 2**).

Periodical Global Navigation Satellite System (GNSS) survey provided information about superficial displacements.

Several inclinometric tubes have been installed within the years. That helped define with good accuracy the tri-dimentional shape of the slip surface. The protocol adopted by CNR-IRPI called for the deployment of in-place inclinometers once the location of the slip surface was defined through periodic inclinometric surveys. Moreover, when a borehole broke another one was drilled nearby to follow the evolution of the landslides for several years in order to gain a large dataset. At the moment there are still active three inclinometers in the heart-shaped landslide. Each inclinometer hole is also coupled with a piezometer equipped with a sensor to acquire data in real-time. The monitoring system was integrated in 2012 with a sharp crested thin plate weir that was installed in the Rio Verde to assess the water discharge of the torrent. The regular shape of the culverts made easier the installation of the weir and of the piezometer that measures the water height.

4. RESULTS

Analyzing data from the inclinometers installed on Frana 2 it is possible to see that the construction of the drainage tunnel changed the displacement pattern of the landslide (**Fig. 3**). In the measures of 2003 there is a distinct slip surface and the velocity of the movement is of 6 mm per month. In contrast, in 2012 the drainage tunnel was operative since 5 years and the rate of movement reduced to 1 mm/month (**Fig. 3**). Moreover, while before the drainage tunnel a distinct slip surface was detectable, in the 2012-2013 inclinometer the displacements are distributed along the whole landslide body as the slope moves under creep.

On the other hand, inclinometers PC1 and I21 shows a very distinct slip surface (**Fig. 4**). This evidence allowed to define the range of each of the two landslides as it is indicated in **Fig. 2**. This hypothesis is also supported by the different degree of activity measured by the GNSS benchmarks. PM18 moves with an average velocity of 3.7 cm/year, PM22 of 4.2 cm/year while PM21 of 1.2 cm/year. The velocities obtained from I21bis are above the annual average because the autumn of 2010 was particularly rainy.

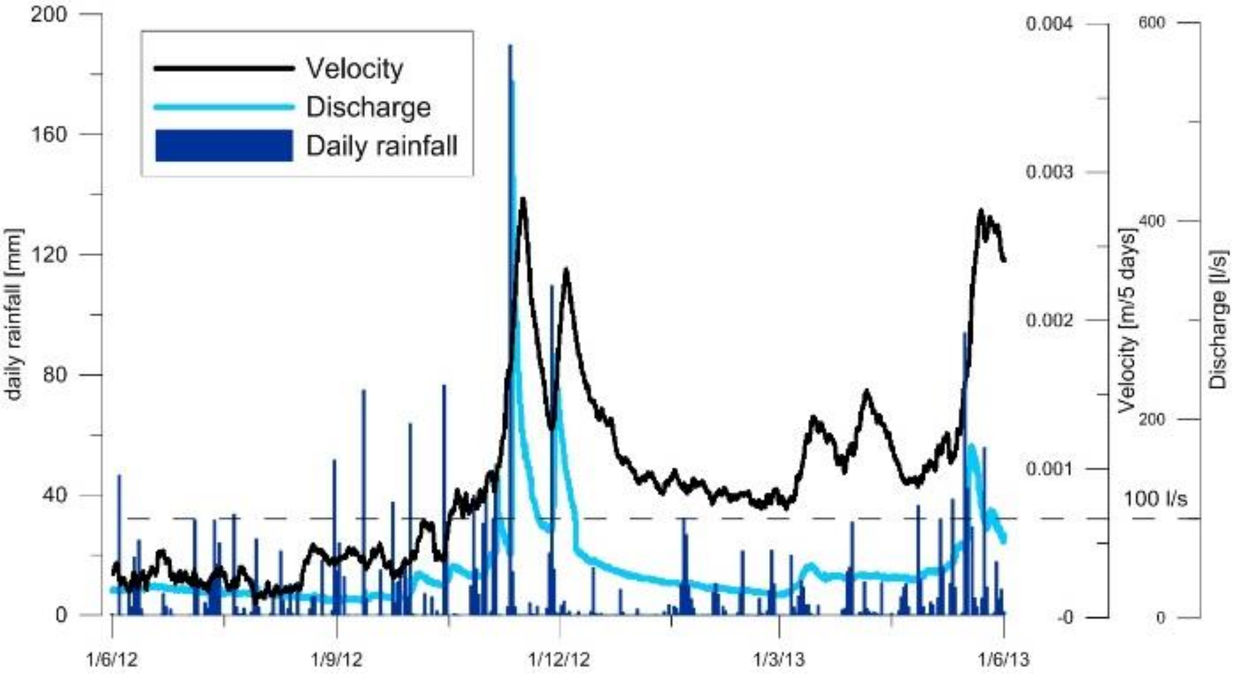

Fig. 5 Velocity of the landslide along the slip surface in I21bis in comparison with the daily rainfall and the discharge in the Rio Verde – the dashed line represents the proposed plant's maximum discharge

Piezometers show that the water table does not reach the slip surface of Frana 1. This evidence it is particularly interesting since it excludes one of the main causes of landslide activity such the variation of the phreatic level inside the landslide body.

What appears from data from the in-place inclinometers is that after the construction of the drainage tunnel the lower part of Frana 2 is an epiphenomenon of Frana 1. In fact Frana 1 dynamic is characterize by sudden accelerations that are then followed by a smaller increase of activity in Frana 2. The movement of Frana 1 disturbs the creeping dynamic Frana 2 than sacks down of few millimeters.

The displacement pattern of the in-place inclinometer in PC and I21 was analyzed and confronted with rainfall data and the discharge measured in the thin plate weir along Rio Verde.

Data support the hypothesis that the displacement pattern of the landslide is influenced by the water discharge of the Rio Verde rather than rainfall. A Pearson test results with a correlation of 0.85 for water discharge. Lesser correlation values have been observed confronting directly displacements with precipitation or cumulated precipitation in the 1, 2, 3, 6, 10 days intervals.

This could be explained by toe erosion and internal erosion near the toe of Frana 1-2 during high discharge events. The well graded soil forming the landslide body has been in fact analyzed with geotechnical tests and has been proven to be extremely sensitive to water content. Besides the groundwater circulation near the slip surface in the lower part of Frana 1 transports the finer particles of the landslide body away inducing displacements and sagging.

In **Fig. 5** more than a year of monitoring data is represented: usually during autumn and spring snowmelt the aquifer that feeds the stream recharges and higher discharges are observed. The discharge of Rio Verde originates from the springs located at the crown of Frana 1 and only on rare major rainfall events has a contribute from the upper basin. This is due to the complex hydrogeology of the area where highly fractured limestones collect and convoy rainfall disregarding superficial topography.

5. MITIGATION

In Italy micro hydro plants (5 kW to 100 kW) are subsidized on a National basis, giving 0.22 €/kWh. Mountain municipalities are therefore incentivized to exploit every drop available to generate electric power to sell to the national network.

For the Forni di Sotto municipality using the discharge of the Rio Verde torrent could be a win-win strategy. The power plant would pay for itself in few years and concurrently the measure would stabilize the heart-shaped landslide "Frana 1-2" of Passo della Morte.

5.1 Hydrology and hydraulics

The Rio Verde Basin covers an area of about 2 km^2 with a drop between 2122 m a.l.s. of Mt. Tinisa to 580 at the outlet in the Tagliamento river.

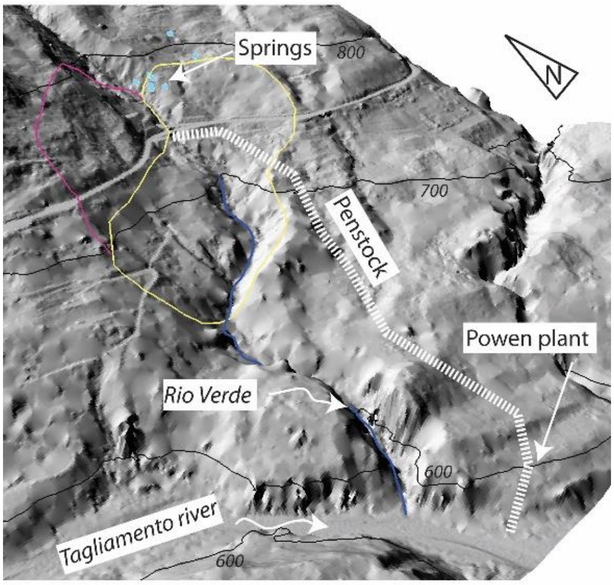

Fig. 6 Intervention areas, capitation of water from the springs and buried penstock layout

Water discharge in the Rio Verde however is more sustained by the flow exiting from the springs on the left hand side of Rio Verde (**Fig. 2**) rather than from superficial runout from the upper basin. For most of the year in fact the river bed upstream of the springs is dry and does not carry any water.

The risk regarding excessive sediment transport that may compromise the plant operation is negligible. The stream is characterize by low sediment transport, the main channel has a well developed natural armour since for most of its track it is directly in contact with limestone. The springs do not carry much sediment, just a little amount of sand that could be easily segregated in a transversal deposition tank that would treat the water before entering into the penstock. The tank could be easily placed in the box culvets below the roads.

Not considering the contribution of the peaks induced by extreme rainfall events runoff the average discharge of the stream has been quantified in 45 l/s. The minimum discharge measured in three years was 12 l/s after an extremely dry year.

The project propose to intercept a maximum of 100 l/s and leave to flow in the Rio Verde the exceeding discharge that may occur during intense rainstorm. The value of 100 l/s represent a balance between economic long-term sustainability and expected effect since based on our measures when the water discharge is sufficiently low the movements of the landslide stop (**Fig. 5**).

The intake catch box will be placed below the bridge that leads to the road tunnel at 735 m a.s.l. A HDPE (High Density Polyethylene) penstocks would carry the water in pressure to the powerhouse located at 603 m a.s.l..

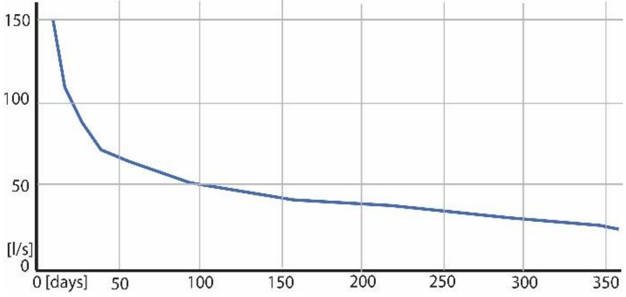

Fig. 7 Flow duration curve of the extractable discharge from the springs and Rio Verde torrent

The restitution of water to the natural network will occur at 575 m a.s.l. through a natural channel that will need to be protected with local stones from erosion.

5.2 Economic evaluation

A flow duration curve has been derived from the seven year dataset (**Fig. 7**). The available data does not cover a long time-span, however the climate regime of the observation period was sufficiently various to allow a statistical analysis. Moreover, the springs regime is seldom as variable as the superficial discharge.

For the plant the minimum intake is 14 l/s, the maximum intake is 90 l/s. Since the average intake is 45 l/s it is possible to calculate the average nominal power at 58.27 kW with a drop of 132 m. Therefore the yearly average production will be of 378000 kWh. If we consider an average price of 219 €/MWh the annual gross income generated by the plant will be of 65745 €.

The cost of construction for the plant will be around 300.000 €. The turbine will be installed in an old isolated building property of the municipality to reduce the impact of landscape and reduce costs. The excavation of the soil to bury the penstock will be very easy since it may be performed by light trencher digging in the soft colluvium located on right hand side of the Rio Verde. All these elements allow to reduce the costs and the impact on landscape of the micro hydro plant.

6. CONCLUSIONS

A mitigation strategy of the landslide that affects the only route that serves the Upper Tagliamento valley has been defined by investigation of its cinematic through long-term monitoring. Evidence gathered in the ten year observation period show that the displacements of Frana 1-2 are strongly influenced by the water discharge in the Rio Verde. Collecting the water from the stream and use it to generate hydro power could be a win-win intervention for an economically self-sustained slope stabilization measure. Moreover, the countermeasure would produce lesser environmental impact than extensive engineering stabilization works but it may be coupled in a second phase with lesser impacting SABO works collecting all the water directly from the springs.

Since anthropic pressure in mountain environment is increasing so it is the request for protection from natural hazard of new allotments and infrastructures. At the same time the SABO works serving the most dangerous areas, which in general have been constructed more than fifty years ago, start to require maintenances or downright reconstruction. The conjunction between the need for maintenances of fundamental mitigation works and the increasing request of safety by mountain population represents a great challenge in times of budget constraints for local and national governments. In this framework the possibility to provide design solution for countermeasure works that would economically self-sustain themselves and eventually produce revenues, like micro hydro plants, should always be considered.

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