Landslide caused problems underground

Rainer Poisel
Vienna University of Technology, Institute for Geotechnics, Vienna, Austria

Kurt Mair am Tinkhof
Vienna University of Technology, Institute for Geotechnics, Vienna, Austria

Alexander Preh
Vienna University of Technology, Institute for Geotechnics, Vienna, Austria

ABSTRACT: On October 5th, 2010, cracks were found in a gallery 1.80 m high and 1.40 m wide. The gallery is 100 years old and runs parallel to a valley flank. After eliminating several possible causes of cracking, a landslide producing the damages had to be taken into consideration. Monitoring revealed that a landslide was occurring, loading the gallery lining. As stabilization of the slope was not an option for several reasons, it was decided to replace the gallery by a new one deeper inside the slope, which will be ready for operation in 2017. Thus the old gallery has to be kept in operation till then and it was decided to reinforce the old gallery by a heavy reinforced shotcrete lining 10 cm thick. However, it has to be realized that stiffening the support of a tunnel in a landslide attracts the stresses and the tunnel is greatly damaged in the long term. Nevertheless, it may be a positive measure in order to allow a structure to survive a particular span of time.

1 INTRODUCTION

On October 5th, 2010, cracks and spalls were found in a 30 m long section of a gallery 100 years old, which had not been observed before (Figure 1). The gallery had been excavated in a tectonically strongly stressed and therefore highly disintegrated, weathered and slightly dipping sandwich of clayey shales, sandstones and marls belonging to the Flysch-zone very close to the thrust by the Northern Calcareous Alps. Geological mapping and reconnaissance drilling revealed that the sandwich described above is covered by 5 m of weathering loam and a rock debris layer 4 m thick. Overburden of the gallery amounts to some 25 m. The excavation had been supported by a timber structure and a U-shaped profile had been cast. The crown had been supported by a cut stone arch (Figure 1).

In order to answer the questions “Will it collapse?” and “What has to be done to keep the gallery stable?” first of all the deformation performance of the structure as well as the causes of cracking had to be found, which were completely unclear when the damages were observed for the first time, though many authors described tunnel damages and their causes (e.g. Mueller 1978, Poisel & Oehreneder 1991, Poisel et al. 1996, Wang 2010).

After eliminating several causes, to which the particular damage pattern (Figure 1) could have been attributed, a landslide deforming the gallery had to be regarded as the most probable cause for the damages (Poisel et al. 1996). Modelling of the system landslide – gallery in a profile along the dip direction of the slope using FLAC (Itasca 2011; Fig. 2) showed an identical damage pattern in the gallery support as observed (Fig. 1).

The gallery is running parallel to a slope some 110 m high (Figure 3). At the toe of the slope a weir is situated which was modernized in 2009 and 2010. In doing so the reservoir level, which is kept constant during operation, has been increased by 1 m, the tailwater level has been decreased by 1.10 m over a length of ca. 300 m and at the toe of the slope some 20,000 m³ had to be excavated in order to make space for a fish migration device. Additionally in the summer of 2009 210 mm of rain fell in 4 days measured at a nearby weather station, which had occurred three times since the construction of the gallery. Therefore it had to be assumed that most probably both events (modernization of the weir as well as the precipitation event of 2009) reactivated an old, dormant landslide.

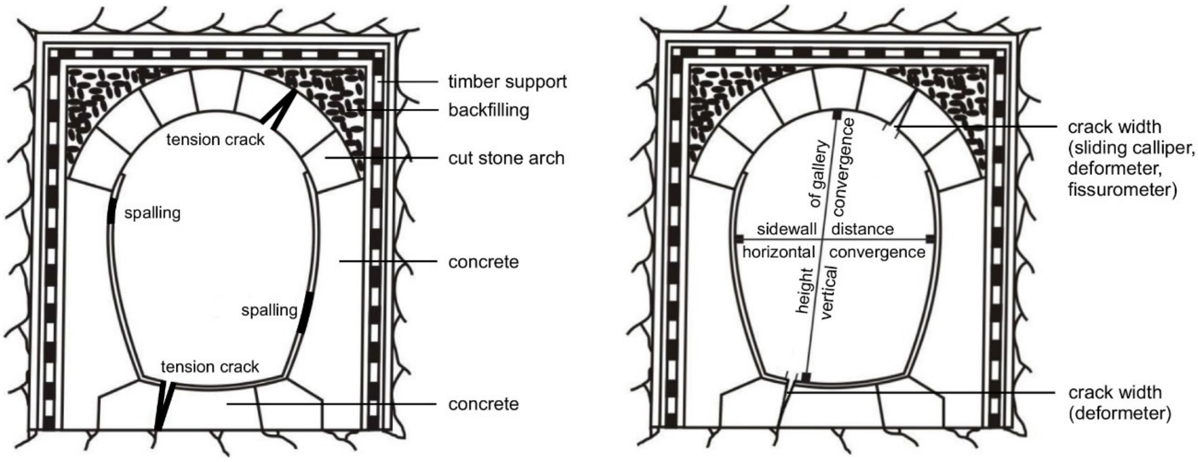

Figure 1. Gallery cross section with damage pattern and monitoring programme (measured distances).

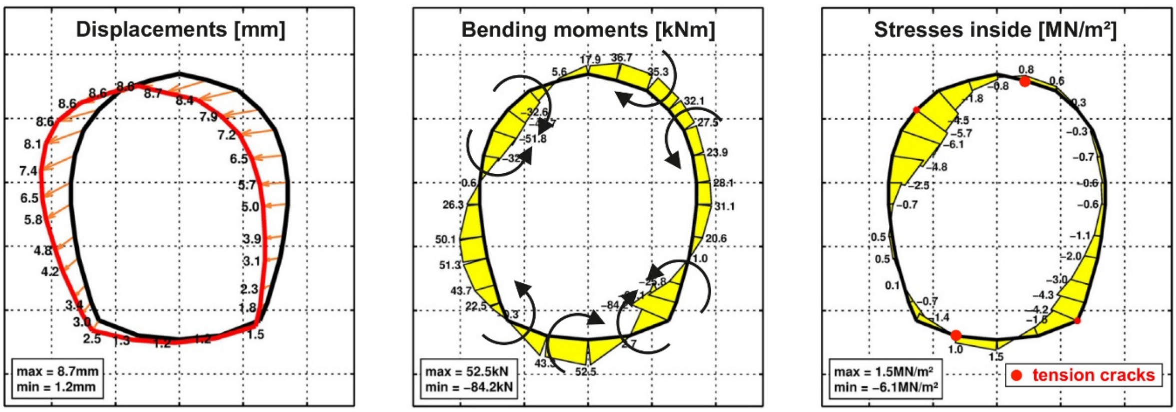

Figure 2. Calculated displacements, bending moments and stresses in the gallery support resulting from a simulation of the system landslide – gallery in a profile along the dip direction of the slope using FLAC (Itasca 2011)

2 MONITORING OF THE GALLERY BEHAVIOUR

Monitoring of crack widths started in October 2010 and showed that crack widths were increasing 1.5 mm per year. In March 2012, fissurometers measuring relative displacements of crack surfaces in 3 dimensions were installed at the crack in the roof parallel to the gallery axis (Figure 1). Convergence measurements started in October 2010 and showed that sidewall distances (horizontal convergence) were increasing 3.5 mm per year whereas the height of the gallery (vertical convergence) was decreasing 2.5 mm per year (Figure 4).

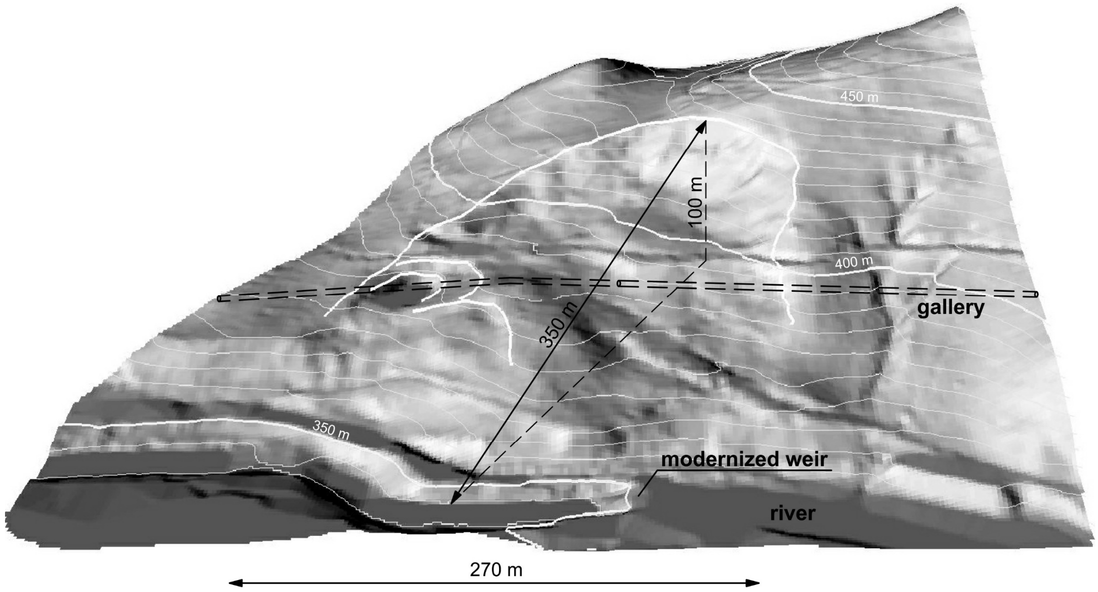

Figure 3. Morphology of the slope (laserscan data recorded in 2011).

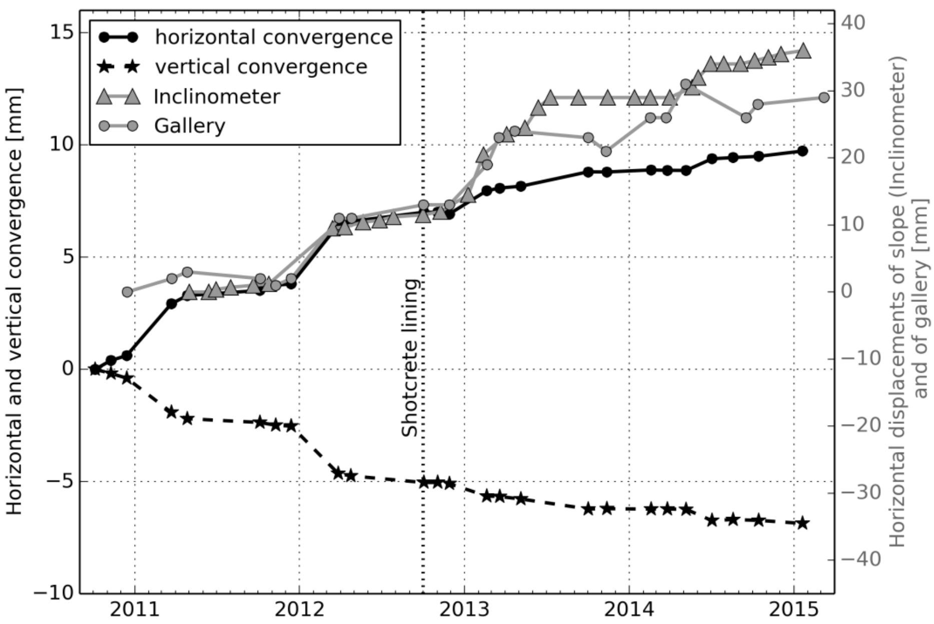

Figure 4. Horizontal and vertical convergences of gallery in the damaged section, horizontal gallery displacements of damaged section and horizontal slope displacements (inclinometer) over time.

3 SLOPE MONITORING

Monitoring of the slope started with a geodetic survey in November 2010; which provided displacement vectors with a length of some 50 mm between November 2010 and October 2014 shown in Figure 5.

Inclinometer 1 (later replaced by inclinometer 2) was installed in April 2011 near the gallery in the upper part of the slope (Figure 5). Inclinometer 3 was installed in December 2012 in the lower part of the slope. The results of the inclinometer measurements revealed that an almost rigid block moves downslope on an approximately 2 to 3 m thick, fully developed shear zone.

Combining the morphology of the slope (Figure 3), results of geodetic as well as of inclinometer (Figure 5) measurements and the position of the damaged section of the gallery, a spatial model of the landslide can be developed (Figure 5), which leads to the geometry of a bowl shaped, rotational landslide with a volume of about 1 Mio m³.

A comparison of slope displacements (Figure 6) and gallery deformations (Figure 4) over time reveals that phases of larger slope displacements and phases of larger gallery deformations coincided until October 2012 when shotcrete support was constructed (afterwards gallery deformations occurred only to a very limited extent.). Thus, most probably the landslide causes the gallery damage.

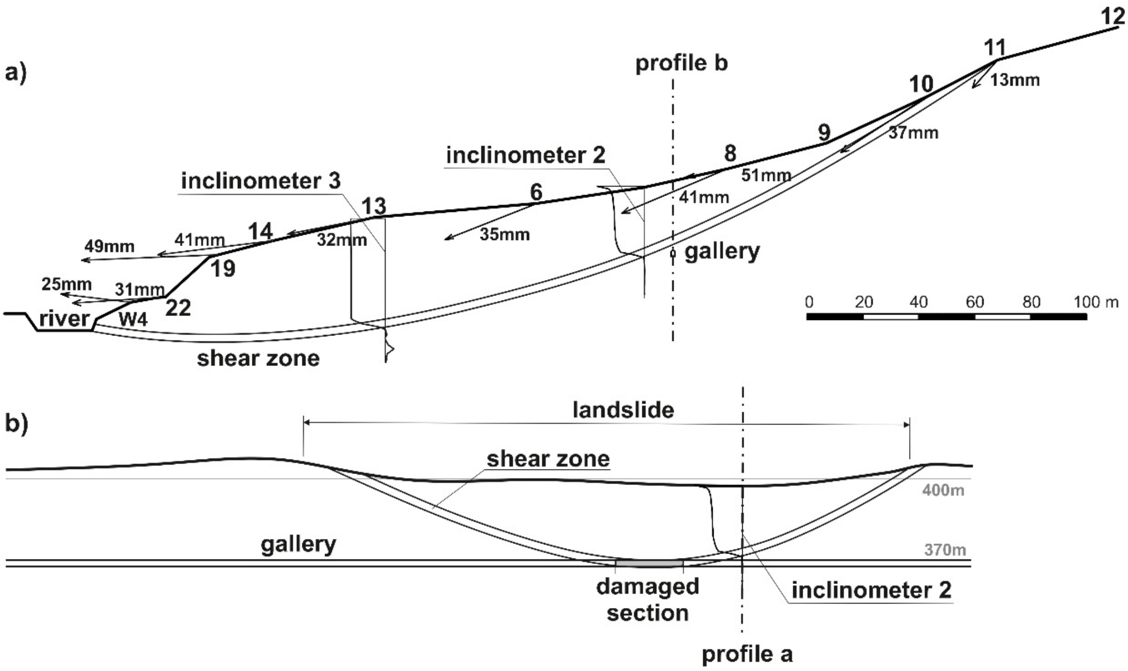

Figure 5. a) Profile along dip direction of slope and results of geodetic survey (after Rudorfer 2014); interpretation of geomorphology, geodetic survey and of results of inclinometer measurements
b) Profile along axis of gallery; interpretation of geomorphology, of geodetic survey and of results of inclinometer measurements.

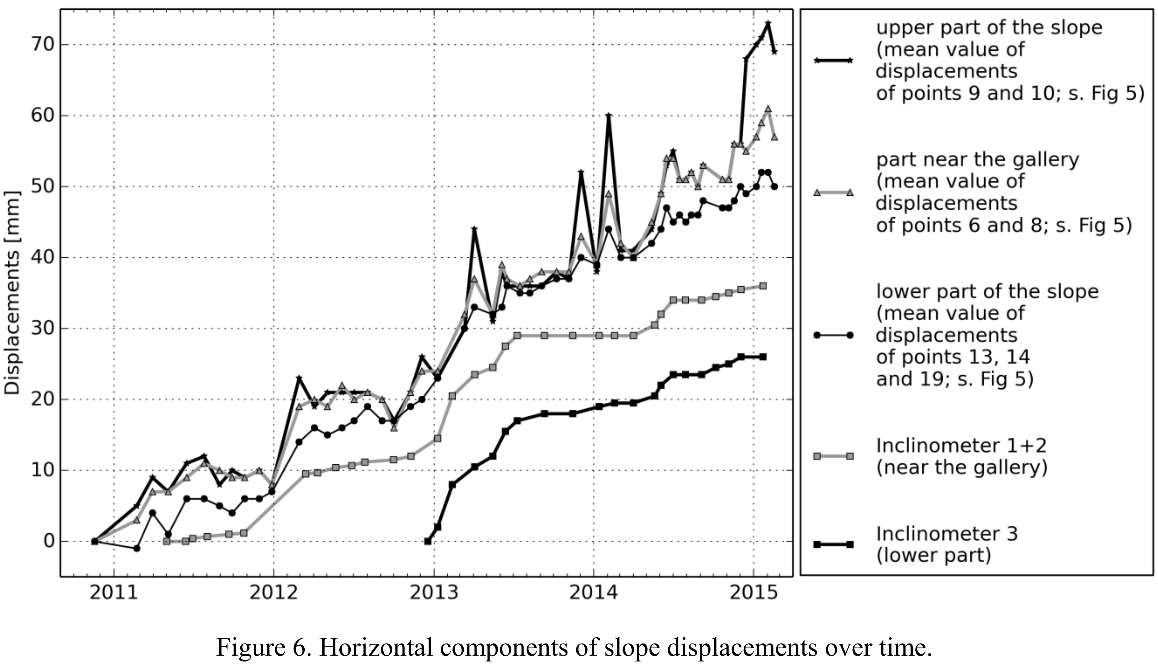

Figure 6. Horizontal components of slope displacements over time.

The perforated pipe of inclinometer 1 was used to monitor the groundwater level. During excavation of the borehole for inclinometer 1 water was found in the rock debris layer below five meters of weathering loam and above the sandwich of clayey shales, sandstones and marls which was followed by a rising of the ground water level of 3 m. It is assumed that the artesian ground water level predominantly in the rock debris layer is monitored by the piezometer, because the tectonically strongly stressed, weathered and slightly dipping sandwich of clayey shales, sandstones and marls is regarded as impermeable.

4 INTERPRETATION OF MONITORING RESULTS

Landslides moving rapidly during late spring and summer can only be found in higher altitudes (e.g. Barla et al. 2010, Weidner et al. 2011, Crosta et al. 2014). However, the landslide discussed in this paper is situated at an altitude of only a few hundred meters and is moving more rapidly in late autumn and during winter time (Figure 6). Other authors (e.g. Cornforth 2012, Simeoni et al. 2014) reported the same behaviour of landslides at an altitude of only a few hundred meters. This behavior is caused by evapotranspiration reduced during wintertime, as well as surface freezing, leading to rising groundwater levels, thus triggering larger displacement velocities (Weber 2013). Obviously, the winters of 2013/14 and of 2014/15 were not cold enough in order to produce a frozen surface over large areas, thus the groundwater level did not rise and slope displacements did not occur during winter time, which was usual in the winters before. Moreover, rain of more than 90 mm accumulated over 4 days also proved to cause a rise of the ground water level above 389.30 m a.s.l., which was found to lead to accelerations of slope displacements.

5 FURTHER STEPS - MITIGATION MEASURES

Authorities, the owner of the land, the owner of the gallery and the owner of the modernized weir – they all have different priorities. This complex situation led to the consequence that stabilization of the landslide was not an option due to political reasons.

As slope displacements as well as deformations of the gallery have been going on, the owner of the gallery decided to replace the old gallery by a new one deeper inside the slope (outside of the landslide) and ready for operation in 2017. Therefore, the old gallery has to be kept in operation till then and it was decided to strengthen the old gallery by a 10 cm thick, heavily reinforced shotcrete lining, which was put in place in October 2012.

Strengthening the old gallery by a shotcrete lining led to a significant decrease of gallery deformations (Figure 4) as simulated by numerical modeling. Therefore, the shotcrete in the central part of the damaged section of the gallery shows no cracks until now. However, strengthening could not reduce displacements of the gallery as a whole due to landslide displacements immediately after construction of the shotcrete lining until spring 2013 (Figure 4). As a consequence, diagonal tension cracks opened in the roof of the gallery in the transition zones unmoved ground – landslide. Two causes can be assigned for the formation of these cracks. Firstly, the strengthened gallery acts like a beam loaded by the landslide movement. Thus, diagonal tension cracks are formed by shear stresses. Secondly, the gallery is rotating in the section affected by the landslide because landslide displacements are decreasing with depth. Therefore, the gallery is fixed in unmoved ground and rotated inside the landslide shear zone. This leads to torsional stresses and formation of tensile cracks in the transition zones unmoved ground – landslide and landslide – unmoved ground. The question is whether the oblique tension cracks in the transition zones (and not the central part, where the gallery is completely inside the shear zone) due to shearing and torsion will impair the operational reliability of the gallery, even though the gallery is needed only for a limited time span.

Before spring 2013 gallery displacements coincided with the displacements of the slope. Afterwards the gallery displacements almost stopped. Most probably the strengthened structure built up a higher resistance forcing the landslide to “overflow” the gallery, as was shown by numerical simulations. Since the middle of 2013, the crack pattern has not changed.

6 CONCLUSIONS

Comparing the weight of the moving mass of a deep seated landslide and the resistance of a tunnel against deformation and displacement, it has to be realized that alternatives, such as slope stabilization or realigning of the tunnel, which means excavating the tunnel deeper inside the mountain and outside of the moving mass, may require increased primary investment, but have a favorable influence on long term stability, design life and life cycle cost. Stiffening the support of a tunnel in a landslide can have two consequences:

1. The strengthened structure can build up a higher resistance forcing the landslide to "overflow" the tunnel, if the tunnel does not cross the landslide but is only tangent to it.
2. Stiffening the tunnel support attracts the stresses and the tunnel is greatly damaged, causing high renovation costs in the course of time. It may be a positive measure in order to allow a structure to survive a particular span of time.

It is very difficult to decide, whether consequence 1 or 2 will apply in a particular case. Most probably the determination is a very delicate one depending on marginal parameter differences which cannot be found out by material tests. Moreover, the determination cannot be analyzed by calculations, but has to be analyzed by the observational method (Peck 1969, Eurocode 7).

The same loading in the transition zones stable bedrock – landslide produced a crack parallel to the gallery axis in the old structure (cast, U-shaped profile, cut stone arch in the crown; the crack did not only follow joints between cut stones but also broke through cut stones). However, the same loading in the transition zones produced oblique tension cracks in the shotcrete support. This discrepancy shows that not only the damage pattern has to be investigated when analyzing the damage cause but also the tunnel support has to be taken into consideration.

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