Subsurface Investigation and Landslide Monitoring as a Basis for Planning Protection Measures - Case Study Doren Landslide -

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Large or widespread slope movements are often characterised by a very complex interplay of various mass movement processes which are in turn caused by saturated water conductivity regimes in the underground that are difficult to assess or model. The planning of protection measures is therefore often met with great challenges. The importance of monitoring measures for determining protection measures is to be demonstrated using the example of the Doren landslide in Austria. The oral tradition about this landslide, situated on the orographic right hand side of the Weißach river, dates back to the year 1847. The first geological investigations, stabilization measures and monitoring measures were carried out after a mass movement in 1935. Due to unfavourable rock properties and a complex water regime, stabiliziation measures which were successfully implemented in other landslides in Austria failed in the Doren landslide. In the summer and autumn of 2014 two different systems to stabilize the head scarp of the Doren landslide were tested.

Key words: mass movement, monitoring, Doren landslide, head scarp, erosion control

1. GENERAL INFORMATION

Fig. 1 Landslide area of Doren after the event of 1988. At the left side of the upper image border the center of the village Doren is visible.

The oral tradition about a landslide area on the orographic righthand side of the Weißach river in close vicinity to the town center of Doren/Austria reach back to the year 1847. Mass movements in 1927, 1935, 1988 (see **Fig. 1**) and 2007 in each case involved the movement of 2 – 3 million m³ of material. In 1935 and 2007 the Weißach was completely dammed up by this material, causing a lake of approximately 500 m in length behind the landslide deposit. Following the mass movement of 1935, the first geological investigations were carried out and drainage tunnels of circa 700 m length were mechanically bored and filled with coarse boulders for stability. The aim of the study is to find out the advantages and disadvantages of each system.

2. CLIMATIC CONDITIONS

Doren is situated on the fringes of the Northern Alps. Distinct oceanic influence is shown by the high rainfall, the moderately warm summers and the moderately cold winters. The average annual rainfall totals 1875 mm.

The maximum precipitation recorded within a period of 24 hours totalled 143 mm on May 30th 1940.

3. GEOLOGY

The geological subsurface in the landslide area consists of rocks of the so-called Weißach layers of the Lower Freshwater Molasse. The landslide area is divided into various sections (see **Fig. 2**):

Section A: Terrace covered with quaternary sedimentsthat lead to subordinate secondary slides in the upper sections of the head scarp.

Section B: A scarp face of up to 70 m height with slope parallel marlstone and sandstone layers of the Lower Freshwater Molasse. The marl layers contain up to 45% swellable clay minerals and produce solid rock slips along the steeply inclined bedding planes that dip towards the valley bottom. These bedding planes consist alternatingly of formerly competent layers and incompetent layers.

Section C: Rotational slide bodies at the foot of the scarp face that consist of loose rock masses, bedrock components that have slid downslope as well as moraine deposits that formerly overlay those bedrock components.

Section D: Further downslope an approximately 600 m long earth and rock waste stream of loose rock masses that are predominantly saturated to the tributary Weißach. [*Van Husen et al.*, 2008]

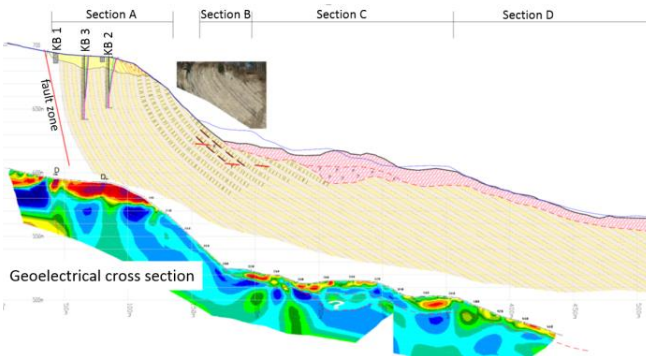

Fig. 2 Schematical geotechnical cross section of the landslide with the different sections A, B, C and D.

The layers of marl weather very rapidly into their components. Spring outlets at the interface between the Weißach layers and moraine deposits continuously supply water so that weathering products are soon eroded.Weathering along with the three landslide processes (bedrock slipage in the scarp, rotational slides at the foot of the scarp face, as well as the immediately adjoining earth and rock waste stream) which interact with one another lead to a retrogressive erosion of the scarp face on the order of 1 m per annum.

4. SLIDING PHENOMENON

Primarily the slide affected the bedrock (interbedded strata of clay/marl/calcareous marl/sandstone), as well as the quaternary sediment cover. Today the landslide scar has the form of a conch and rotational slides are prevailing. The material in the accumulation area is creeping and flowing towards the axis of the river (earth/debris flow). The quaternary sediment cover atop of the Weißach strata provides supply of material to the earth/debris flow. The earth/debris flow is periodically mobilised by seeping water in the quaternary sediment cover and surface runoff. **Fig. 3** shows the change in altitude between 2006 and 2007.

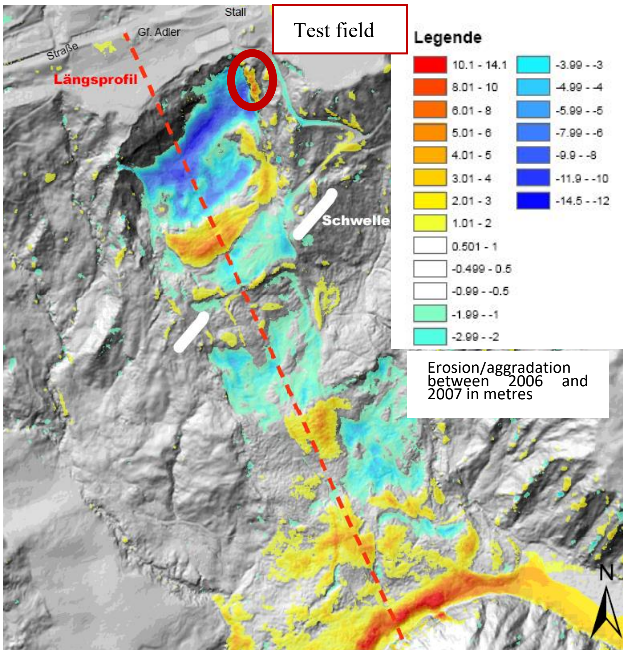

Fig. 3 Differences in the ground height between 2006 and 2007

5. SLOPE WATER SITUATION

The marls of the Weissach strata are nearly impermeable because of the high content of fine grained material. Coarse clastics within the heterogenously composed quaternary sediment body act as groundwater and slope water bearing horizons. 4 different groundwater conductors (aquifers) can be distinguished:

- Water bearing horizons within the redeposits
- Water bearing horizons at the border between redeposits and glacial deposits
- Water bearing horizons within the glacial deposits
- Water bearing horizons at the border between glacial deposits and bedrock [Weißach strata]

The existing water bearing horizons are dependent to small tubular and lenticular ground water conductors, a compact slope water conductor is not evolved.

6. SUBSURFACE MODEL

To survey the depth and the extent of the impermeable rocks and the depth of the earth/debris flow geoelectrical measures with multielectrode configuration were carried out.

All profiles on the terrace showed a clear double segmentation in the distribution of resistivity (see **Fig. 4**). A horizont which shows a remarkable low resistivity [< 40 ohm.m] is coated with a horizont of higher resistivity [80 – 200 ohm.m].

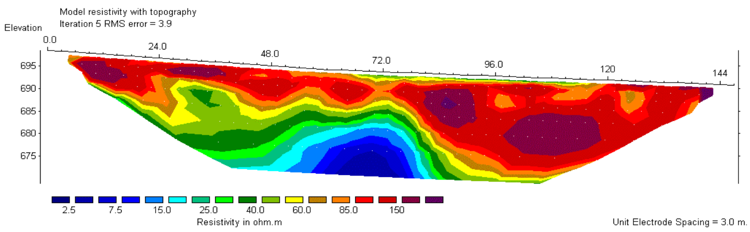

Fig. 4 The cross section on the terrace shows a clear double segmentation in resistiviy

The depth of the cover which shows high resistiviy (glacial deposits) ranges between 1,09 m and > 22 m.

According to the results of the geoelectrical measurement, the depth of the actually moving earth/debris flow at the base of the scar is 10 -15 m. Noticeable is the steep slope of the earth/debris flow in an altitude of 600 m (see **Fig. 7** geoelectric). This escarpment is visible in all aerial photographs since 1950. A rock escarpment seems to exist.

- The reason for the "global slide" is a failure of the base of the steep rock layers in the scar
- The failure occurs by an overload of the competent parts (sandstone) of the layer.
- The increase of stress up to the failure is caused by the water pressure, which is efficacious along joints and faults. The incompetent layers (marl) are impermeable to water.
- After the failure of the base the sliding mass becomes part of the earth/debris flow. Due to the characteristics of the materials (marl/sandstone = ductile/prattle) and the influx of water the mass is extremely plastified and flows downwards to the river.

7. MITIGATION EFFORTS

The first mitigation efforts were carried out for the Doren landslide starting in 1938, following the mass movement event of 1935. The Viennese geologist Josef Stiny (Vienna University of Technology) carried out the first geological surveys of the site and planned mitigation measures on the basis of these investigations. In order to drain the landslide's catchment area, a 700 m long drainage tunnel was mined at approximately 10 m depth to the north-east of the scarp head, and filled with coarse rock material. This drainage system drained between 150 and 520 m³ of water per day between 1938 and 1940. Today, 80 years later, this drainage system is still continually discharging a few liters per second and therefore a sum of water in the same order of magnitude as in those first years.
Following the mass movement event of 1988 an additional subsurface drainage system was installed north of the scarp head.

Geophysical investigations carried out in 2002 and 2007 revealed that the drainage tunnels were not situated in bedrock only, for which reason, they were presumably underflowed in part; slope seepage water situated below the system can also not be collected and discharged through it.
Further mitigation efforts aimed primarily to drain the earth and rock waste stream situated at the foot of the scarp. The ultimate aim of such measures are to secure the foot of the scarp against further erosion, which would destabilize the entire upslope area. However, also these measures were not successful and did not bring about the wished for stabilization, which became very apparent in 2007 when, following a long period without precipitation, mass movements occured once again.

8. ESTABLISHING A MONITORING SYS TEM IN THE DOREN LANDSLIDE

The first monitoring efforts at the Doren landslide site encompass the discharge measurements from the drainage tunnels between 1938 and 1940.

Following the massive reactivation of the landslide in the spring of 1988, the installation of the monitoring system currently in use was begun. A probe drill hole as well as two drill holes fitted with inclinometer tubes were constructed in order to better understand the underground and the processes taking place in it. The monitoring system was expanded step by step in the years thereafter, although the drill holes from 1988 have since become unmeasurable. Measurements are made in yearly increments. In conjunction with the inclinometer data, the position and elevation of the inclinometer head was also determined, so that the posibility of a sliding plane beneath the foot of the inclinometer could be excluded. The monitoring system at present includes the following measurement instruments:

8.1. Terrace above the scarp

- GPS survey point, manual
- 5 inclinometers (2002, 2007), manual
- 6 piezometers in 3 drill holes (2007), manual
- 5 piezometers in 1 drill hole (2009), automatic
- 2 level gauges (2001, 2013), automatic
- 1 level gauge (2013), manual
- 1 gauge of the water volume discharged from the vacuum well, automatic using a water meter.
- 1 gauge of the subsurface drainage system discharge, automatic using a measuring weir and gauge

8.2. Foot of the scarp face, rotational slide bodies and earth- and rock waste stream

The survey points used to assess movement of the landslide had to be newly set numerous times following the high rates of movement in the years 2005 and 2007. Following the large surge of movement during Easter 2007, an automatic movement monitoring system was installed in May of the same year (see **Fig. 5**). In February 2010 it was decided to revert back to periodic manual measurements (of movement). This was due to financial reasons. At the first hints of a reactivation of the landslide, an automatic measurement can be reimplimented immediately, however.

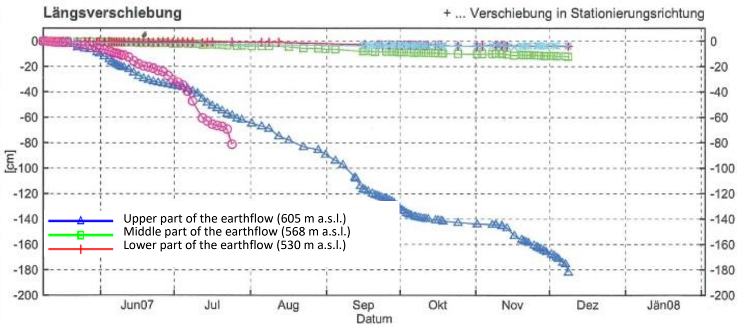

Fig. 5 Longitudinal displacement of monitoring points in the Western part of the landslide Doren 2007.

Many of the measurement instruments were destroyed during larger mass movement events in 2016:

- 2 well gauges, manual (2012)
- 1 automatic level gauge (2012)
- 5 electric contact gauges (2012)
- Manual measurent of water discharge from 6 horizontel drill holes (2012, 2013)
- Water discharge from 2 vertical bore holes (2012)

8.3. Orthophotos and Laserscans

The comparison of orthophotos taken since 1950 in conjuntion with numerous laserscans since 2003 has provided information about the landslide’s mass balance, whose head scarp has over the past 65 years moved an average of 1 m in the direction of the town center, and it has furthermore shown the importance of securing the scarp face.

9. PROBLEMS

Due to the surges of movement, which can hardly be predicted, measurement instruments installed in the earth- and rock waste stream downslope of the scarp face are soon destroyed. For this reason, manual measurements are preferred in this lower section of the landslide, or, as an alternative, low cost mobile measurement instruments (for example, mobile gauge level loggers). The inclinometers installed directly below scarp head likewise have very limited lifespan.

The possible extent of a rise in groundwater was also underestimated so that the level gauge installed in the conglomerate zone was unable to measure the peak value that occured on 02.06.2013 (see **Fig. 3**).

10. RESULTS

A number of mitigation measures have been employed in the Doren landslide since 1935. The objective of these measures have been, on the one hand, to safely drain subsurface water out of the upper scarp face (drainage tunnels 1938, depth drainage measures 1988 and 2002-3) and from the lower section of the scarp (surface drainage, horizontal drill holes at the foot of the scarp face), and on the other hand, to protect the scarp face from weathering (afforestation in the 1950s, securing the scarp face with erosion protection systems since 2014). All of these mitigation measures raised hopes of a stabilization in the short run, however, in the long run were unable to prevent further surges of mass movements.

Little is known about the origin of groundwater streams. In the meantime it is known, that the groundwater has different conductivities. One problem is the water at the foot of the scarp face. For construction of better mitigation measures it is necessary to learn more about the origin of groundwater streams.

In order to adapt the mitigation measures accordingly, it is important to have more information about the subsurface hydrological balance, water conductivity and how these relate to mass movement surges in this landslide. An important function of the monitoring system is to evaluate the efficacy of the mitigation measures employed (for example by measuring the discharge of the subsurface drainage system).

10.1 Subsurface hydrological balance and water conductivity

The water level in the probe drill hole (2010-13) was measured in part automatically with a gauge and in part manually with an electric contact gauge. Well discharges in the earth- and rock waste stream, discharges from horizontal drill holes at the foot of the scarp face as well as overflow of the vertical drill holes were all measured manually. All of the data does gathered provided important information about the ground water level within the landslide. During the heavy precipitation event from the 31st of May to the 1st of June 2013 the groundwater level in the drill hole situated in the conglomerates rose, with a temporal delay of only a few hours to the precipitation, approximately 12 m over the course of two and a half days (see **Fig. 6**).

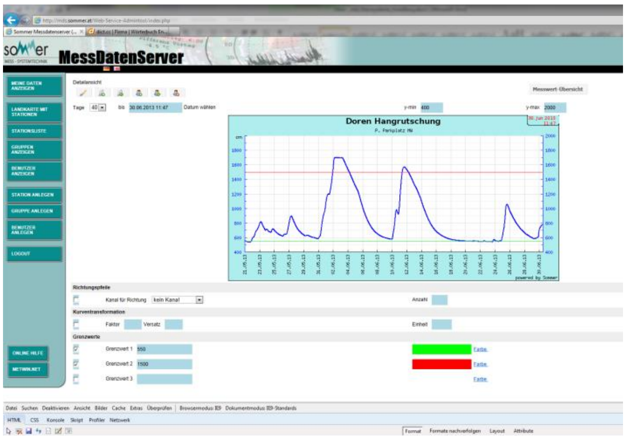

Fig. 6 Chart of a groundwater gauge situated slightly above the Doren landslide during the floods in June 2013.

Robust gauge data loggers have proven to be very useful for speedy and mobile deployment. For example, they were used to establish the interrelation between the ground water level of two bore holes spaced 125 m apart, while boring was taking place at the site (see **Fig. 4**).

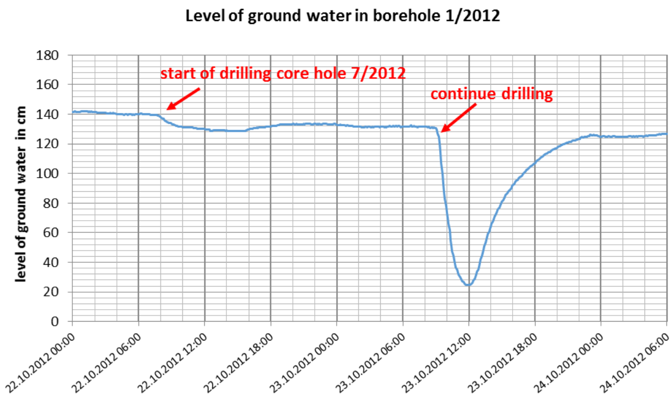

Fig.7 Response of the groundwater in the Doren landslide to drilling operations at a distance of 125 m.

10.2 Evaluating the mitigation measures used

Measurements of the discharge from the subsurface drainage system allow inferences to be made about the size of the catchment area as well as the efficacy of the mitigations measures employed.

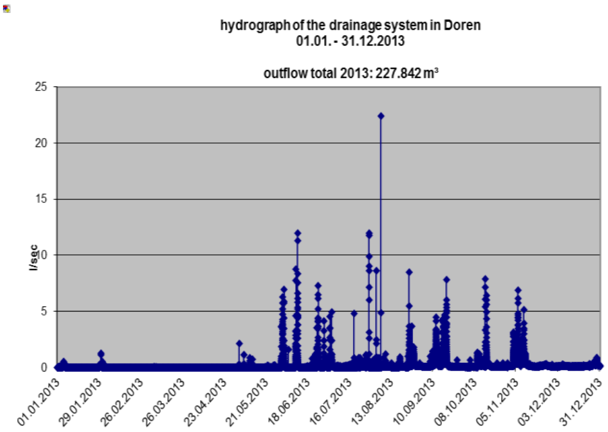

Fig.8 Hydrograph of the drainage in the landslide Doren 2013.

11. TEST SITE FOR SLOPE STABILIZATI ON

A characteristic feature of the Doren landslide is the speed at which weathering of the marl layers is occuring. The composition of this material causes it to swell upon wetting, following which it is eroded by concentrated ingress of water, by frost or other forms of loading. The marl layers were overlain with moraine deposits of numerous meters thickness during glacial periods. Due to their high permeability, these moraine deposits allow precipitated water to penetrate to the marl subsurface. During heavy precipitation events this water is discharged in the boundary layer between marl and moraine layers, thus eroding the weathering layer situated there. On average, the regression of the upper edge of the marl layer constitutes 1 m per annum over the last 50 years. To prevent further regression, the surface of the landslide must be protected from weathering.

Further difficulties are caused by the subsurface drainage of the landslide area. The entire area of the landslide as well as the adjacent area above it contains wellsprings, subsurface flows, infiltrations, etc., the exact position and drainage of which is unclear. This water causes an upslope hydraulic pressure, which contributes to the erosion of the rock face and the regression of the upslope terrain. The combination of weathering and upslope hydraulic pressure provides a precarious challange, since the slope must on the one hand be protected from weathering, whilst the water must on the other hand be able to be discharged from these upper sections of the landslide. The slope can therefore not be secured in the classical sense, since securing the slope with a net will not solve the weathering problem, whilst using shotcrete would prevent water from being discharged through the surface.

11.1 Products used in the test site of the Doren landslide

In an attempt to secure and stabilize the landslide of Doren with nets or meshes, two systems have been tested to date: the "Krismer-3D"® system, which is a three-dimensional mesh, and the "Tecco"® system, a high strength square wire mesh produced by Geobrugg. Both of these products were tested in the Doren landslide area, by installing the respective meshes on test sites demarkated within the larger landslide area, in order to evaluate the long-term performance of these two products. The criteria chosen for evaluating the functioning of these systems were structural safety as well as weathering protection, in addition to which the installation of each system was also considered.

DYWI® Drill hollow bar anchors were used to anchor the respective mesh systems in the Doren landslide test sites. These are self-drilling hollow bolts that are installed either during the drilling process itself or thereafter by means of grout injection. This system is typically employed when dealing with unstable boreholes. The hollow bolts of this system can be assembled modularly, like building blocks, in order to meet the requirements of the mesh system and the particular site in question. Using sleeves, the hollow bolts can be extended as much as is required, while the drill bit is chosen in accordance with the material conditions of the underground that needs to be drilled.

These anchors (DYWI self-drilling hollow bolts) were used to secure both products tested. Drilling into the slope was carried out on a raster of 1.5 m x 1.5 m, which has the advantage that should one of the systems fail or fail to provide adequate weathering protection, another mesh net could be installed over it or even completely replace the inadequate product.

11.2. The Krismer-3D system

The Krismer-3D system is a three-dimensional steel wire mesh mat that forms a wire frame directly on top of the slope that needs to be secured. This wire frame is filled with angular particles of sizes 35-60 mm, over which a 1-2 mm thick humus layer is then applied and vegetated (see **Fig. 9** and **10**). This layered construction should provide a fast growing and well rooted biological protection measure against weathering. The criteria of geotechnical measurements are also met by this system. However, geologists in the provincial service have expressed misgivings that the system might in practice not be strong enough to withstand the resulting loads. Another disadvantage of the Krismer system concerns its installation: the steel wire mesh mats are delivered as separate parts, each 6 m² in size. These panels must be individually installed after all the nails or anchors have been set in the slope, following which, they must as a second step be filled. On slopes that are not too steep this presents no problem, however, on steeper slopes like that found in individual sectors of the Doren landslide (with over 80°), bringing the elements into place can be problematic and involves a significant effort. Moreover, on such steep slopes the filling material crumbles out of the wire frame holding it, thus losing its protective function against weathering processes.

All in all, the Krismer-3D system constitutes an appropriate solution to the problem in question here, as it forms a protective layer on the slope to be stabilized yet is water permeable, allowing water to be discharged from the slope through it.

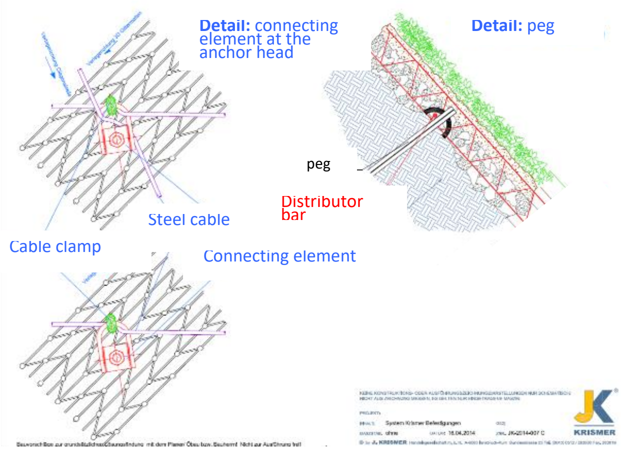

Fig. 9: Detail diagram of the Krismer-3D system


Fig. 10 Krismer-3D system

11.3 The TECCO system

The TECCO system is a high strength square wire mesh that in principle is a classical slope net system. Nevertheless, certain sections of the Doren landslide was fitted with this system for testing purposes. The fear is that due to its large mesh size (65 mm), the products of weathering could readily fall through this net and also that a vegetation layer would only develop with difficulty on this mesh, if at all.

For this reason, Teccmat, a structured mat made of randomly arranged polypropylene filaments, produced by Geobrugg, was laid beneath parts of the square wire mesh covering. The lifespan of these filaments is roughly two years. This three dimensional mat was intended to provide additional erosion protection immediately following the installation, as well as support for the vegetation process. However, this additional part of the trial was soon aborted, as the mat was dislodged by a heavy precipitation event prior to its having been completely anchored, falling toward the foot of the scarp.

REFERENCES

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