CAUSES AND RECONSTRUCTION OF A LANDSLIDE IN LOWER TRIASSIC SANDSTONE BY EXCAVATION OF A CUT ON MOTORWAY A38 (GERMANY)

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Abstract: After the German Reunification numerous road construction projects were designed to develop an advanced and efficient infrastructural system for the whole country. As one of the major projects the new motorway A38 ("Verkehrsprojekt Deutsche Einheit Nr. 13") was built to connect the existing motorways A7 near the city of Göttingen and A9 south of Leipzig.

Between the junctions "Rossla" and "Wallhausen" the new A38 was designed in cuts with depths up to approximately 20 m. The slopes of these cuts were situated in the Lower Triassic Sandstone. During site investigation the stability of the slopes was found to be critical – in particular concerning the angle of incidence of the intact rock layers – and therefore structural measures were taken. Nevertheless in spring 2003, shortly after finishing the earth works, a landslide occurred on a length of approximately 100 m in the area of the maximum cut depth.

After the landslide additional analyses and calculations were made in order to detect the causes of the failure. For this purpose disturbed samples were taken from some of the larger strata joints in order to carry out classification tests. The samples mainly consisted of plastic clay and silt. Additionally two independent institutes conducted a mineralogical analysis of the clay. It was found that the soil contained swellable intra-crystalline clay minerals (17 – 20 percent by weight in total; 40 – 43 percent of the fraction $d < 2$ μm).

Generally swelling-action is caused by a decisive and long-lasting change of stress conditions. Therefore it was assumed that by excavating the cut certain swelling at the strata joints and a further decrease in shear strength were produced. Based on experience values and former calculations the angle of shear friction was defined to 10 – 15°, taking into account the present knowledge about swelling, structure of the rock mass and tectonic stresses. According to the geotechnical survey of the slip joint an average friction angle of about 12° was available there, which corroborates the calculated values.

INTRODUCTION

After the German Reunification numerous road construction projects were designed to develop an efficient infrastructural system for the whole country. As one of the major projects the new motorway A38 ("Verkehrsprojekt Deutsche Einheit Nr. 13") was built to connect the existing motorways A7 near the city of Göttingen and A9 south of Leipzig.

Between the junctions "Rossla" and "Wallhausen" the new A38 was designed in cuts with depths up to approximately 20 m. The slopes of these cuts were situated in the Lower Triassic Sandstone. During site investigation the stability of the slopes was found to be critical – in particular concerning the angle of incidence of the intact rock layers – and therefore structural engineering measures were taken. Nevertheless in spring 2003, shortly after finishing the earth works, a landslide occurred on a length of approximately 100 m in the area of the maximum cut depths.

After the landslide additional analyses and calculations based on further field investigations were carried out in order to detect the causes of the failure (Kempfert + Partner Geotechnik; 2003). The following article is presents the results of these examinations, describes the landslide area with its geological and geotechnical end conditions as well as the causes of the collapse and illustrates the reconstruction concept.

PROJECT AND GENERAL GEOLOGICAL SITUATION

The cut near Hohlstedt extends from about km 14+650 to about km 15+700 and is characterised by slope inclinations of approximately 1:1.75 (angle of slope about 30°) and a maximum depth of about 20 m on the northern side of the motorway. The maximum depth has been established from about km 15+380 to km 15+480 on a length of approximately 100 m. The natural terrain behind the top of the slope bends towards the motorway in an angle of approximately 5° to 10°.

The motorway runs in east-western direction on the northern edge of the “Goldene Aue“, a morphologically depressed area between the southern ends of the lower Harz mountains and the northern ends of the Kyffhäuser mountains. In the region north-west of the city of Hohlstedt three regional tectonic disturbances are crossing each other: the “Hohlstedter Störungszone” (direction E-W), the “Kirchbergstörung” (direction NW-SE) and the “Wallhäuser Störzone” (direction WNW-ESE). Information of the State Office for Geology and Mining of Sachsen-Anhalt (LAGB) did not indicate a geogenic danger for the motorway.

The subsoil in the considered area is formed by minor layers of quarternary loose soils laying on top of sediments of the Lower Triassic Sandstone, the latter consisting of a change of laminated clay and silt stone and platy-stratified sandstone and limestone respectively with a thickness of more than 100 m. The groundwater level is situated below the base of the cut. Due to subterranean leaching of water soluble layers of the “Zechstein” (karst formation) under the Lower Triassic sandstone layers in the geological past there was a laminary descent of the overhanging layers, which led to deformation of the Lower Triassic Sandstone layers and in some areas to steep folding.

For site investigation 35 m deep core drillings and 6 m deep trial holes were put down each in a distance of about 150 m to document the geotechnical structure. In order to calculate the stability of the slopes, the shear strength of the strata joints which were running southeast to southwest was then estimated to φ_{SS} = 17° with c_{SS} = 0 kN/m² by means of experience and literature values. According to these first calculations extensive bolting would have been necessary on a length of approximately 650 m to guarantee the slope stability. Thereupon additional trial pits with sampling of rock layers were carried out in order to obtain the in situ shear strength of the strata joints. Tests on these samples yielded to a friction angle of φ_{SS} = 22° (at c_{SS} = 0 kN/m²), which was used in further design stages. The required stability of the slopes finally could be reached by flattening the slope inclination to 30° combined with bolting in areas of local disturbances (for further information: Hecht, Mittag; 2002).

DESCRIPTION OF THE COLLAPSE

The earth works for the excavation of the cut where the landslide occurred began on 27th November 2002. The cut was excavated quickly and almost continuously. The installation of three vertical inclinometer cases and the bolting which should have followed immediately was delayed due to several circumstances, most of all because of uncertainties concerning the protection against corrosion of the bolting.

- The inclinometer No. 1 was installed from 28th January 2003 to 6th February 2003 at km 15+500 outside the body of the slide.
- The excavation of the cut were nearly done on 11th of February 2003 but no bolting was established yet.
- The drilling of the bore hole for inclinometer No. 2 started on 11th February 2003. On February the 17th, at a depth of approximately 20 m, the core barrel could not be moved anymore. It had to be retrieved.
- On 18th February 2003 a heave was recognized on the surface of the slope.
- The drilling for inclinometer No. 3 started on 20th February 2003. The designed depth of 16 m was reached on 24th February 2003.
- During the night of 24th to 25th of February enormous deformations occurred between about km 15+360 and km 15+400, which finally led to a landslide in the area of km 15+360 to km 15+460. Smaller landslides were noticed earlier in an adjacent area (km 15+100 to km 15+160) where the cut had a depth of about 14 m.

A top view of the main slide body with the detected fissuration is shown in figure 1. The viewable slide body can be described as a prismatic tetrahedron or wedge-shaped body with a synclinal floor area (figure 2).

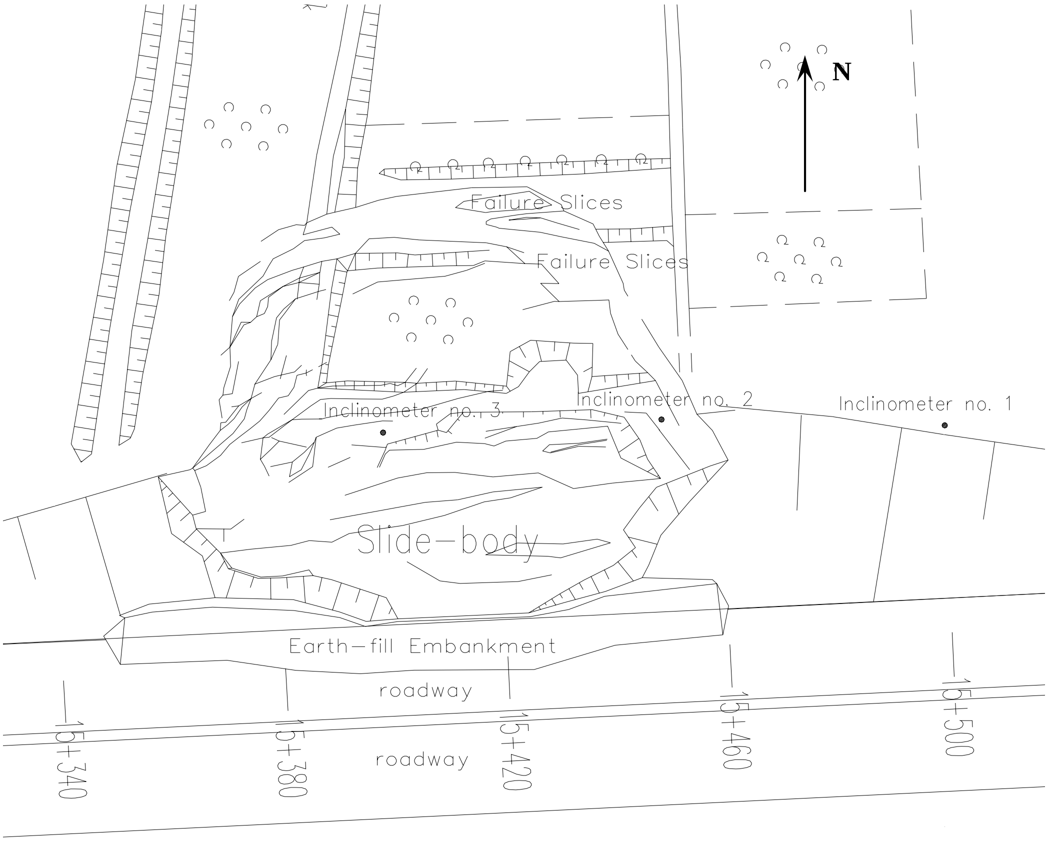


Figure 1. Major landslide with fissuration

Figure 2. Overview of the major landslide

Figure 3 (left). Area of the former top of the slope

Figure 4 (right). Rear tear-off edge of the slide body about 40 to 45 m behind the former top of the slope

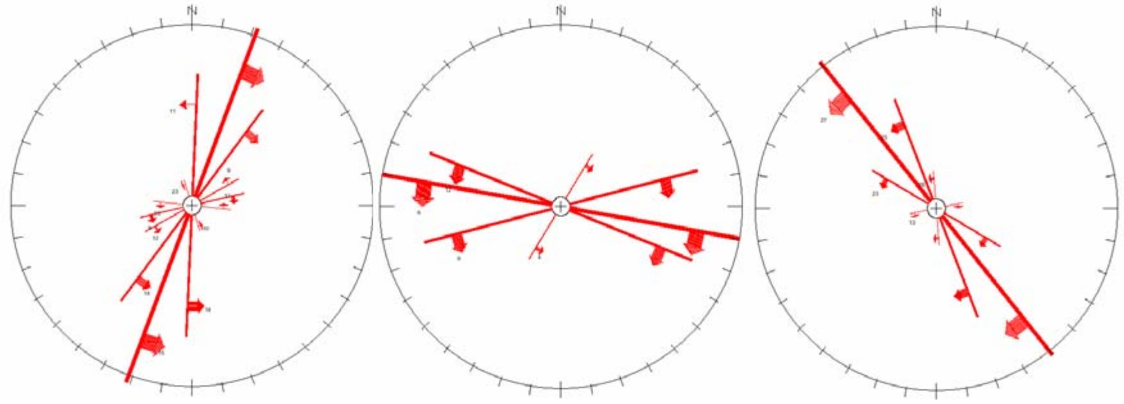
In the lower parts of the slope rock soil and rock masses bulged up to 2 m higher than the former ground surface. As an immediate measure a temporary embankment was built on the lower parts and at the toe of the slope to stabilize the bulge (figure 1). In the area of the former slope top numerous wide fissures and terraces were visible. Most of them basically ran parallel to the former top of the slope. Behind the top of the slope next to an adjacent tree population there was an almost vertical tear-off edge with a height of several meters. In front of the tear-off edge a displacement of several meters had emerged (figure 3). In a distance of about 40 to 45 m to the original top of the slope amidst the adjacent tree population an enormous fissure with a width of more than 5 m and several clods and slices of earth were detected. The rear boundary of the slide body consisted of a vertical tear-off edge with a height of more than 4 m (figure 4).

SOIL INVESTIGATION AFTER THE LANDSLIDE

Borings and visual inspection of the slide

During the installation of two more inclinometers outside the apparent slide body, the soil type of the drill core was classified by a geologist. A zone of decomposed rock was followed by a layer of profound weathered rock of the Lower Triassic Sandstone, which can be described as an irregular, highly varying sequence of mostly laminated to thin platy silt-, clay- and sandstone-layers with thin stratified to stratified, obviously firm or rather hard calcareous sandstone formations in between. Various strata joints with an average thickness of 1 cm and filled with micaceous loose soil were detected within the clay-, silt- and sandstone-layers. Parts of the top level of the clay- / silt-stone layers were completely decomposed to silt and clay.

The geological model could be completed by observations made during the geological survey of the surface and tear-off edge of the slide body of in the course of the removal of the slid material. The geological survey revealed that the course of the strata joints in the area of the slide body followed the apparently synclinal run. Over a limited length in the centre of the slide body the strata joints were bending almost perpendicularly towards the motorway, in an angle of incidence of about 10° (figure 6 and 7).



western area
15+330 to 15+415
EFR/EFW: 111/13

middle
15+415 to 15+420
EFR/EFW: 190/6 resp. 200/11

eastern area
15+420 to 15+490
EFR/EFW: 230/24

Figure 5. Graphs of the strata joints (highest statistical frequency); direction of dip EFR, dip angle EFW

In the course of the geological survey and the inspection of the front and rear tear-off edge of the slide, strata joints of several centimetres filled with clay / silt were observed. They were mainly situated between clay-, silt- or sandstone-layers and the calcareous sandstone (see figure 6). Disturbed samples were taken from these bigger strata joints in order to carry out classification tests. According to the classification the samples consist of plastic clay and silt. Additionally two independent institutes conducted a mineralogical analysis of the clay. In these analyses it was found that the soil consists of swellable intra-crystalline clay minerals (Illite and Smectite: 17 – 20 percent by weight in total, i.e. 40 – 43 percent by weight of the clay fraction with d < 2 μm). Due to this high percentage of swellable clay minerals a significant influence of the soil-physical properties on the failure was assumed.

Conclusions during the removal and exploration of the slide-plane

The reconstruction of the damage was carried out by removing the slid rock masses in the area of the main slide. The removal was supervised by geotechnical engineers and geologists to verify the geological model and in particular to document the position of the slip joint. With the purpose of investigating the accurate depth and run of the slip joint as well as stratification and tectonic conditions, 6 trial holes with depths up to 10 m were excavated at different working stages of the removal.

In summary the following conclusions to define the slide body can be made:

- The landslide was limited to the East, North and West by tectonic disturbances with east-western and north-southern course respectively. The tear-off edges also following the course of these disturbances. North of the disturbance boundary the formation changes from syncline to anticline.
- In general the sliding zone could be described as an area of about 50 cm thickness with one main slip joint e.g. a strata joint filled with silt / clay and a thickness of several centimetres (figure 6).
- The sliding zone shows an average gradient of approximately 12° in the middle of the slope and runs at about 1 to 1.5 m below the toe of slope and up to the area of the planned motorway (figure 7).
- The sliding zone shows a stepped trend in north-southern direction. The main step was probably formed by a disturbance approximately in the middle of the slide body with east-western direction.

Figure 6. Cross section with sliding zone

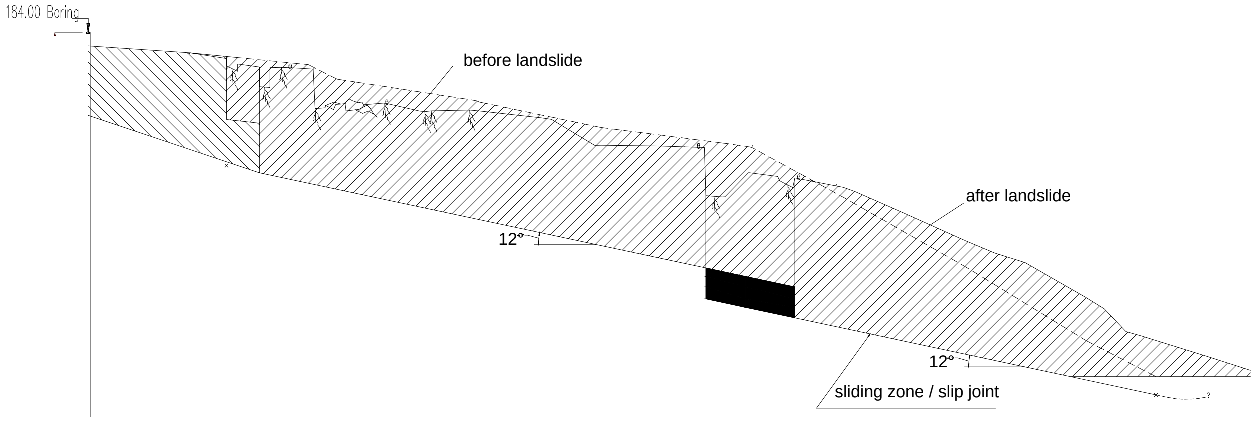


Figure 7. Slip joint in trial hole No. 6

GEOTECHNICAL MODEL AND ANALYSIS OF THE SLIDE

Mathematical analysis

After defining the main strata joints and evaluating the geotechnical survey statistically, several simplified geotechnical models were analysed by the program SOLIDROCK (HarbourDom, Cologne). This program calculates the stability according to Kovari & Fritz 1976. Initially plane slide-bodies were tested. This examination requires that individual bodies are sliding successively. Since minor stabilities were calculated particularly in the eastern area, first of all the eastern and middle part should have slid followed by the western part because of the lacking lateral support. This examination is not adequate to analyse the failure as at the beginning of the slide a certain blocking between the bodies can be premised. Higher stabilities were calculated by consideration of three-dimensional slide-bodies. A safety factor of $\eta \approx 1.1$ was determined by using a wedge shaped body (figure 8) and an assumed unfavourable angle of shear friction of $\varphi_{SS} = 10°$.

Due to slip planes parallel to the slope in the middle of the slide body, which could not be considered in the calculation, it was probable that in situ the stability was smaller than the calculated value. After comparison with other calculations, the slope stability of the situation was assumed to be below $\eta = 1,0$.

Table 1. Results of the stability analysis for the big slide

model	**stratification plane direction of dip / dip angle [°]**	**angle of friction φ_{SS} [°]**	**stability η [-]**
plane body	190/6 (middle)	20	3.5
		10	1.7[1]
	200/11 (middle)	20	1.9
		10	1.0[1]
	230/24 (east)	20	0.8
		10	0.7[1]
	111/13 (west)	20	1.6
		10	0.8[2]
three dimensional body (figure 8)	111/13 (west) und 224/24 (east)	20	2.3
		10	1.1[1]

[1] with specification of the sliding direction towards the motorway

[2] without specification of a definite direction

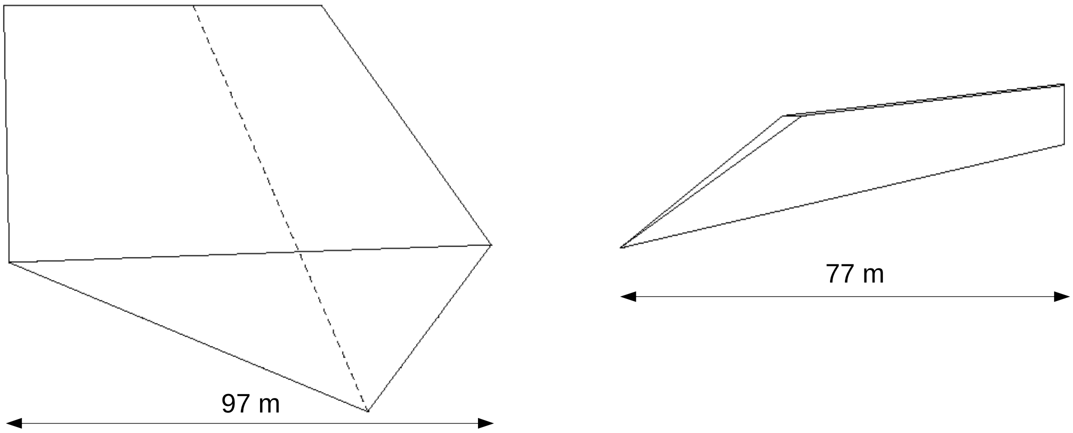


Figure 8. Three dimensional body (schematically)

Conclusion for the shear strength of the strata joints

The samples which were taken for shear tests during the original soil investigation could only be taken from trial holes near the surface, whereas deeper strata joints were not reached. In the course of post-failure investigations it was found that shear tests conducted during planning and the former estimated angle of friction of $\varphi_{SS} = 22°$ were only valid for thin strata joints. After the landslide it was found that in greater depths there are strata joints with a filling of several centimetres of swellable silt / clay between clay-, silt- or sandstone-layers and limestone banks.

Because swelling-action is generally caused by a decisive and long-lasting change of stress conditions, it was assumed that certain swelling at the strata joints was generated by excavating the cut, which could have also led to a further decrease of shear strength. In post-failure calculations the angle of shear friction was determined to 10 – 15° taking into account the present knowledge about swelling, structure of the rock mass and tectonic stresses. According to the geotechnical survey of the slip joint an average friction angle of about 12° was available there, which corroborates the calculated values. Thus the decisive shear strength had been overestimated during design.

RECONSTRUCTION

As enough space was available the general plan was to flatten the slope down to the inclination of the slip surface. In the central area of the synclinal failure the slid material was removed completely above the slide plane (figure 9), so that no additional structural measures had to be taken.

North of the former tear-off edge and in the eastern transition area to the undamaged slope, additional bolting was planned at the new slope which was rebuilt with an inclination of 1:3. Altogether about 500 bolts (system GEWI) with a grid space from 1.5 to 2.5 m and a length between 6 and 12 m were installed in the area of the slide (figure 9).

In addition an exploration of the structure of the intact Lower Triassic Sandstone was conducted while the rock masses were cleared. Based on newly-experienced knowledge of the depth and formation of the slip plane, the height and geometry of the new slope and the conception of the bolting was defined during reconstruction.

Figure 9. Reconstruction a) flattened slope b) bolting

CONCLUSION

During the construction of a cut for the new motorway A38 between Halle and Göttingen in spring 2003 a landslide appeared north of the city of Hohlstedt (Sachsen-Anhalt, Germany). The main slide body extended on a length of about 100 m and involved the whole cut slope with its height of up to 20 m. The chief causes of the collapse were found to be the synclinal course of the strata joints, its inclination towards the cut surface and the small shear strength of φSS = 10 - 15° at strata joints between solid rock layers which were filled with clay. This small shear strength could not be recognised during the planning stages, because the crucial strata joint was not detected within the normal and professional soil investigation. The relevant strata joints were filled with swellable materials, so that the excavation of the cut and the resulting unloading led to a decisive decrease of shear strength. This phenomenon has never been observed in the regional geology before. Consequently there was no possibility to avoid the landslide by using conventional and usual geotechnical investigations. But after that case history the requirement of a mineralogical analysis is now known. In fact the landslide would also have occurred if the designed bolting of the cut had been installed without delay. For this reason the damage has to be categorised as “Subsoil Risk“. It can be assumed that the magnitude of the damage would have been reduced, if the vertical inclinometers were installed in time before excavating the cut, so that after a small excavation unscheduled deformations would have been recognised and counteractive measures could have been taken at an earlier stage.

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