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COLLAPSE OF THE SCHIEBURG TUNNEL IN LUXEMBOURG: GEOLOGICAL CAUSES AND EMERGENCY SECURING WORKS

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Abstract

On 27 August 2022, a collapse occurred in the Schieburg tunnel during repairs on the vault. Around 400m^3 of debris flowed out in a matter of seconds, completely blocking the tunnel and the only railway line serving the north of Luxembourg towards Belgium. The rockfall occurred 60m from the southern entrance, at a point where the overburden above the tunnel is 31m. The geological and geotechnical studies carried out included reconnaissance boreholes with parameter recording to a length of 80m, geophysical prospecting using electrical and seismic tomography, and a structural study of outcrops in the vicinity of the tunnel. These investigations revealed a highly complex geological situation, with the rockfall zone located at the intersection of a system of conjugate faults not recorded on the geological maps. The results made it possible to estimate the volume and shape of the deconsolidated zone above the collapse, and to propose safety measures to reinforce the deconsolidated zone above the tunnel, safely remove the cone of scree and repair the vault. Geotechnical monitoring of the safety works was carried out from start to finish, enabling the tunnel to be reopened less than one year after the collapse, despite very difficult access conditions.

Key words

Tunnel, collapse, rock slump, geological investigations, emergency works, Luxembourg

1 Introduction

A collapse occurred in the Schieburg tunnel (built in the 19th century) in Luxembourg on 27/08/2022 during repair works on the vault, completely blocking the tunnel and traffic on the only railway line linking the north of Luxembourg to Belgium (Figure 1). The rockfall occurred approximately 60m from the southern entrance of the tunnel, at a point where the overburden above the tunnel is 31m, and under a forest canopy.

In the first phase, in order to understand the causes of the rockfall and, on that basis, to be able to restore traffic in the tunnel while guaranteeing its integrity, a geotechnical study was carried out, including reconnaissance boreholes with parameter recording, geophysical investigations using electrical and seismic tomography, as well as camera passes inside the boreholes. At the same time, a geological and structural analysis was carried out on all the rock outcrops around the tunnel.

In a second phase, once the principle of making the tunnel safe again had been established, geotechnical monitoring was carried out throughout the works. Additional electrical tomography was also used throughout the injection phase to monitor the filling of the deconsolidated zone above the tunnel and check the effectiveness of the reinforcement measures. The results of these tomographies were also used to refine the initial geological and hydrogeological model.

Figure 1. Rock slump seen from the southern part of the tunnel

This paper presents the results of the 2 phases mentioned above, as well as the safety measures implemented. These measures enabled the tunnel to be reopened less than one year after the collapse, despite very difficult access conditions, both for reconnaissance boreholes and for carrying out the work.

2 Geological context and investigations carried out

2.1 Geological contexte

The Schieburg tunnel, located to the north of Luxembourg near Kautenbach, is underlain by Lower Devonian (Emsian) formations forming what is known as the "Our Formation - Schuttbourg Member", which is characterised by alternating sandstone, clayey sandstone, sandy phyllite and phyllite. The geological map also shows a regionally significant NNW-SSE trending fault approximately 250m to the east of the tunnel. This fault is subvertical, oriented 151.4° to the north and appears to have a dextral offset (see Figure 6 right).

2.2 Investigations

To understand the geological and geotechnical situation and explain the causes of the rockfall, a geotechnical study was carried out. This included in a first step 10 inclined reconnaissance boreholes drilled from the surface with parameters recorded up to 80m in length, geophysical surveys using electrical tomography and seismic techniques, and camera passes inside the boreholes. At the same time, a structural and stereographic analysis was carried out on all the rock outcrops around the tunnel. The geophysical profiles had the following characteristics: 2 refraction seismic profiles of 100 m with a spacing of 4m between the geophones, 2 seismic profiles of 50m with a spacing of 2m between the geophones and 3 electrical tomographies with a spacing of 3m between the electrodes for 2 of them, and 2.5m for the last one.

In a second phase, additional electrical tomography was carried out to refine the data from the initial study, but also to follow the grout injections through the deconsolidated zone and check the effectiveness of the reinforcement measures. The 2 additional geoelectric profiles, each 315m long, with a spacing of 5m between the electrodes, were perpendicular to each other and oriented at 45° to the axis of the tunnel in line with the rockfall. In addition, geotechnical monitoring was carried out throughout the works, and the geological and structural study has been refined.

3 Results of the investigations

3.1 Geological and structural situation and faults

After the collapse, and while the first geotechnical study was in preparation, the priority was to understand the geological and structural situation of the area. The rock in the area around the tunnel consists of alternating sandstone and quartzite beds of decimetre to multi-decimetre thickness, with intercalations of shale beds. These beds (particularly the more competent sandstone and quartzite beds) are intersected by 2 families of diaclases perpendicular to each other and perpendicular to the bedding planes, which helps to break up the rock into roughly parallelepiped blocks of varying dimensions. The dip of the stratification planes is generally subvertical and oriented to the SE. Several erratic discontinuities also intersect these beds in a more random fashion, favouring the appearance of dihedrals.

Analysis of the scree cone inside the tunnel shows the presence of blocks and boulders of widely varying sizes, as well as elements that can be assimilated to soils. We also noted the presence of banks that had been completely altered in clay, but still had a remnant of sheets, or even folds and quartz inclusions. Completely transformed and vitrified-looking beds were noted, either in the form of rocky pieces, or in the form of veneers on sandstone beds. Striations indicating displacement (following the passage of a fault, for example) were observed. The clay alterations intercalated between the rock banks can act like a soap layer between the blocks and are very sensitive to variations in water content.

Structural and stereographic analysis revealed a steeper dip (70°) for the stratification near the scree cone than near the northern exit of the tunnel (48°). Two outcrops are directly accessible at the southern entrance to the tunnel, on either side of the train track. At this point, the stratification on the outcrop on the east side dips to the south at 70° to 75°, while the stratification on the outcrop on the west side dips more steeply at 86° to 89°. This variation in the dip of the stratification over such a short distance could be linked to the influence of a fault. Along the logging road above the tunnel, we see that the dip of the stratification decreases from west to east as we approach the tunnel, and then increases sharply directly east of the northern entrance to the tunnel, from 57° to 23° and then increasing to 51° directly east of the tunnel. There is also a change in the strike for the least inclined beds. This trend was also observed just above the northern entrance to the tunnel, where the dip of the stratification varies between 57° to the west and 17° to the east. Several fault planes were observed along the access path to the northern entrance of the tunnel. Directly to the east of the tunnel, the rock mass is no longer visible, and a zone covered with vegetation and soft ground can be observed. This zone corresponds to the supposed passage of a fault plane. Beyond this zone along the road, the dip of the stratification increases again to 51°.

The various observations mentioned above (see also Figure 2) have clearly revealed a variation in the orientation (strike and dip) of the stratification over very short distances, suggesting the presence of a fault or a fault system probably associated with the main fault shown on the geological map. These fault systems in this kind of rocks are generally linked to folds close to the fault planes and bank-to-bank slides. The presence of beds completely transformed into clay, vitrified elements and the mixture of blocks of variable dimensions in a clay matrix also suggest the influence of a zone crushed by a fault.

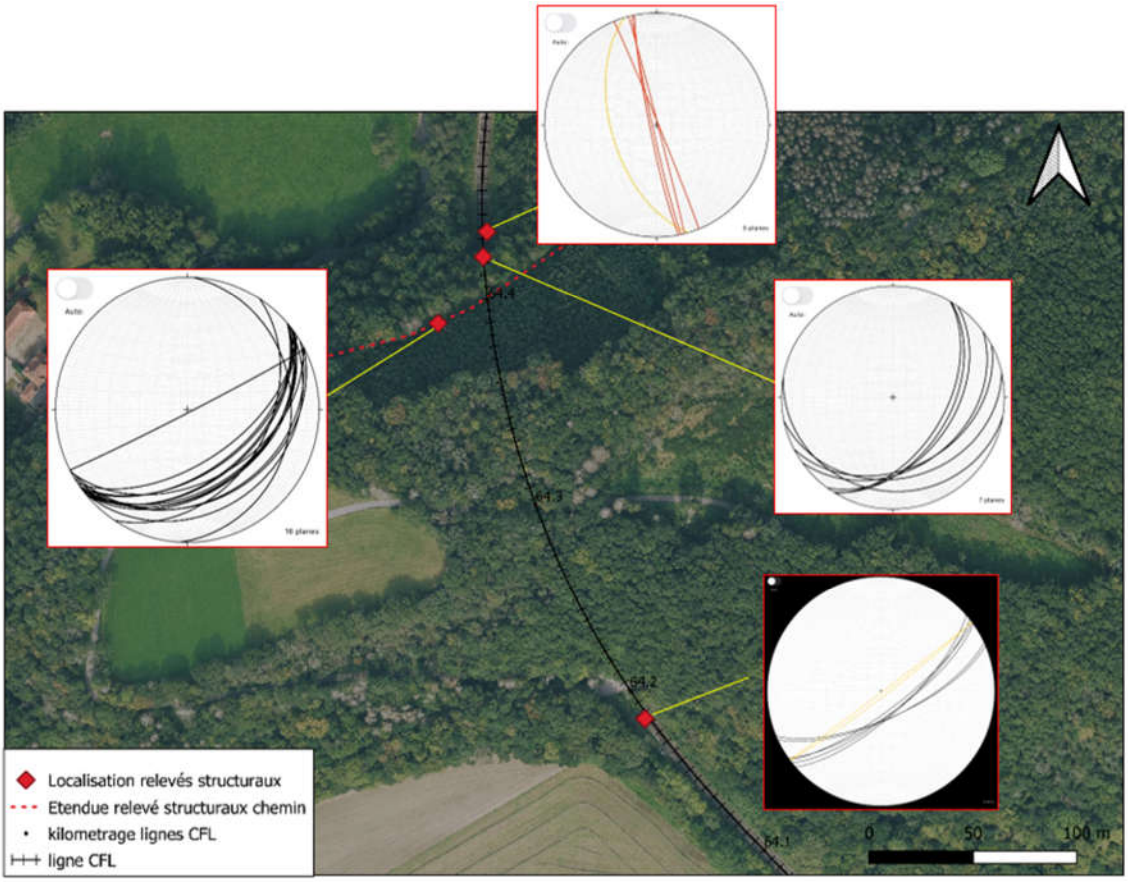

Figure 2. Variation of the strike and the dip of the stratification (black) all around the tunnel. The fault planes observed to the north of the tunnel are shown in red and yellow on the stereogram in the top center

Several camera passes were made in the boreholes. In the deconsolidated zone, the images obtained show the presence of more or less angular blocks and boulders in a clay matrix, as well as numerous voids between the blocks following the rearrangement after the rock slump. The nature of the material is compatible with an area that was crushed following the passage of a fault and subsequently altered by water circulation.

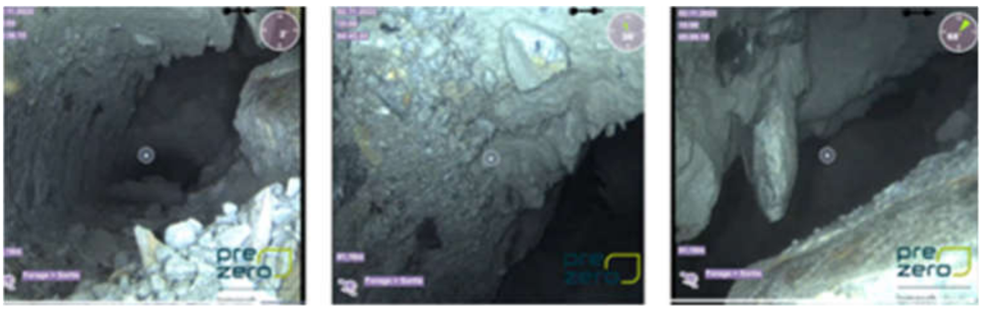

Figure 3. Camera pass through borehole 2 showing blocks and boulders of varying sizes in a clay matrix

Finally, the data from the reconnaissance boreholes and the geophysical studies are compatible with observations suggesting the presence of a faulted/deconsolidated zone located to the east of the tunnel and intersecting it close to the collapsed zone (NE-SW direction). The boreholes also show that the funtis resulting from the collapsed zone rises upwards in the form of a "chimney" rather than spreading laterally. This is compatible with a slide that would have occurred along weathered, clay-filled planes that would have been destabilised by the removal of the vault. In addition, the works on the vault were carried out just after a long period of dry weather, which led to the clay joints being transformed into cohesionless dry joints. Figure 4 summaries the results that can be interpreted from the reconnaissance boreholes.

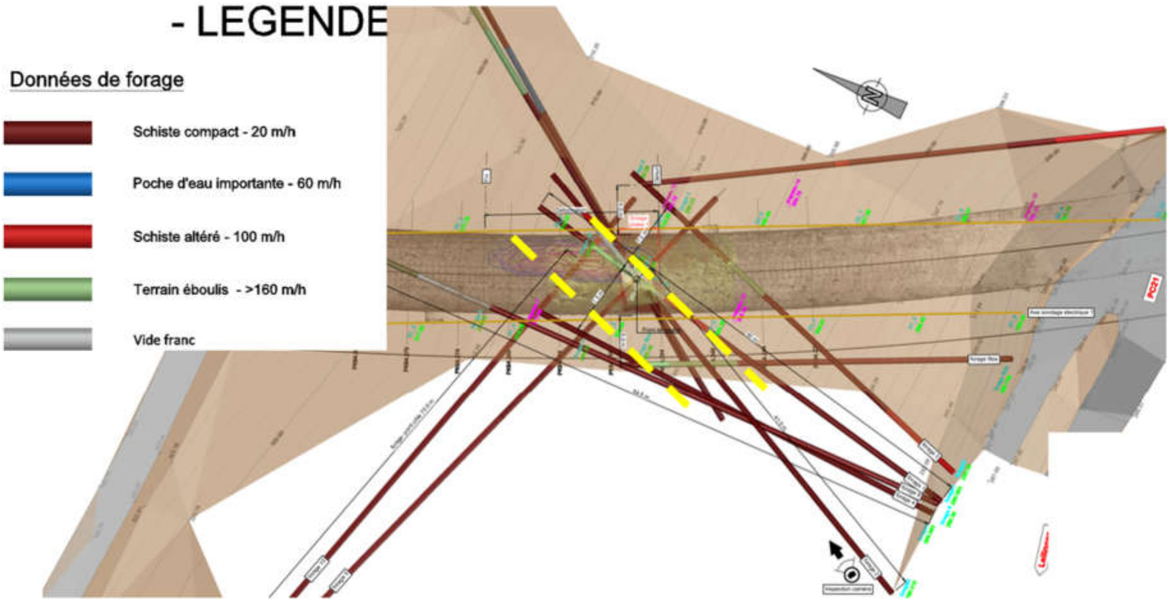

Figure 4. Possible orientation of the deconsolidated/faulted zone (in yellow) based on reconnaissance boreholes

The geophysical measurements carried out during phase 1 of the study confirm the existence of an altered and/or highly fractured zone in line with and around the collapsed zone. This zone is not punctual, has an irregular geometry and appears to be expanding eastwards and possibly northwards.

Additional geophysical measurements (electrical tomographies) have enabled us to refine our understanding of the structural situation at the study site. The various results of the geophysical studies suggest the presence of several deconsolidated zones (one in the immediate vicinity of the tunnel and another further east), probably linked to the presence of one or more faults.

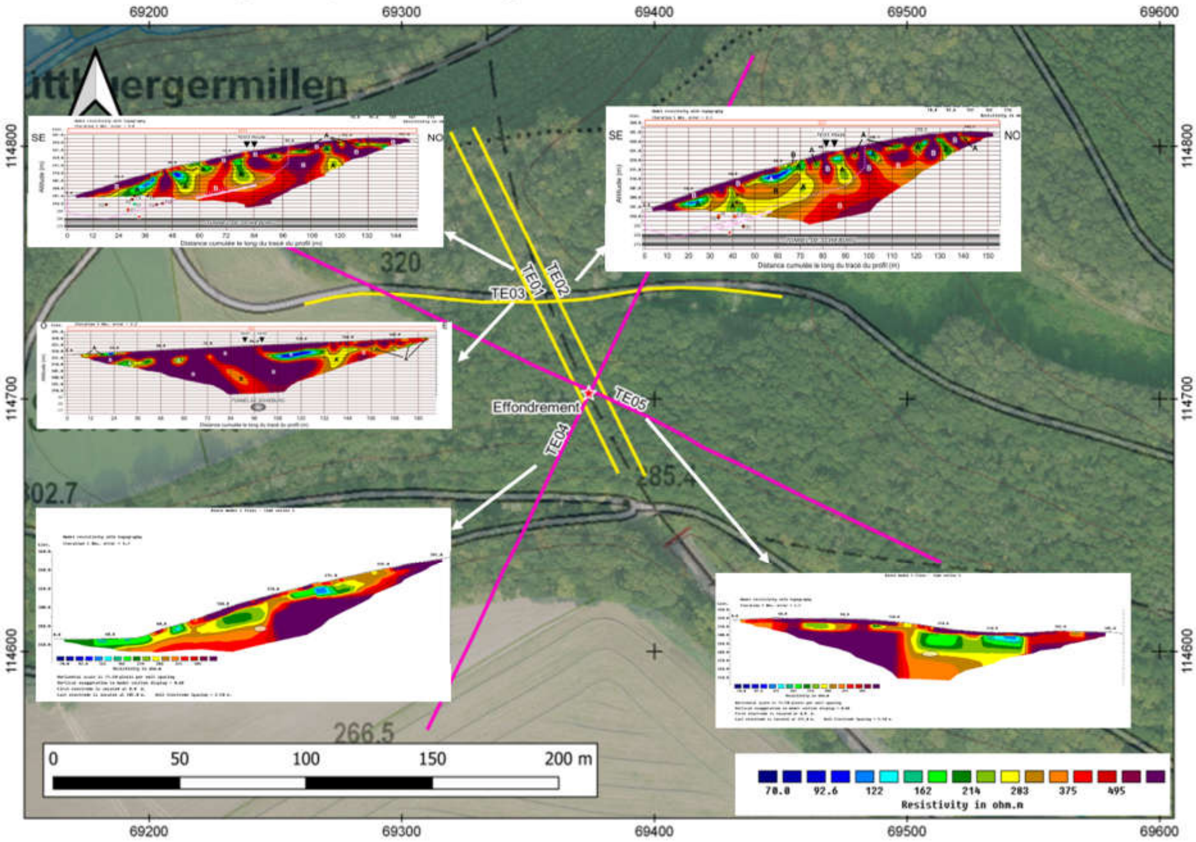

Figure 5. Location of electrical tomographies (yellow lines: 1st phase, magenta lines: 2nd phase) and results obtained

By linking these results with field observations, as well as the position and orientation of the fault shown on the geological map, geomorphological evidence of the presence of fault zones in the vicinity of the tunnel, and the orientation of the deconsolidated zone, which can be estimated on the basis of the results of reconnaissance boreholes, the interpretations shown in Figure 6 left can be made.

We thus have both a fault parallel to the main fault shown on the geological map and passing to the east of the tunnel (fault shown in red in Figure 6) and a fault perpendicular to the above-mentioned fault, which was also revealed by drilling (see Figure 4), and which intersects the axis of the tunnel in the collapse zone (fault shown in black in Figure 6). These 2 faults are thought to form part of a system of strike-slip faults (although it cannot be ruled out that they are also vertically dipping) linked to the various faults shown and supposed on the regional geological map, as illustrated in Figure 6, right.

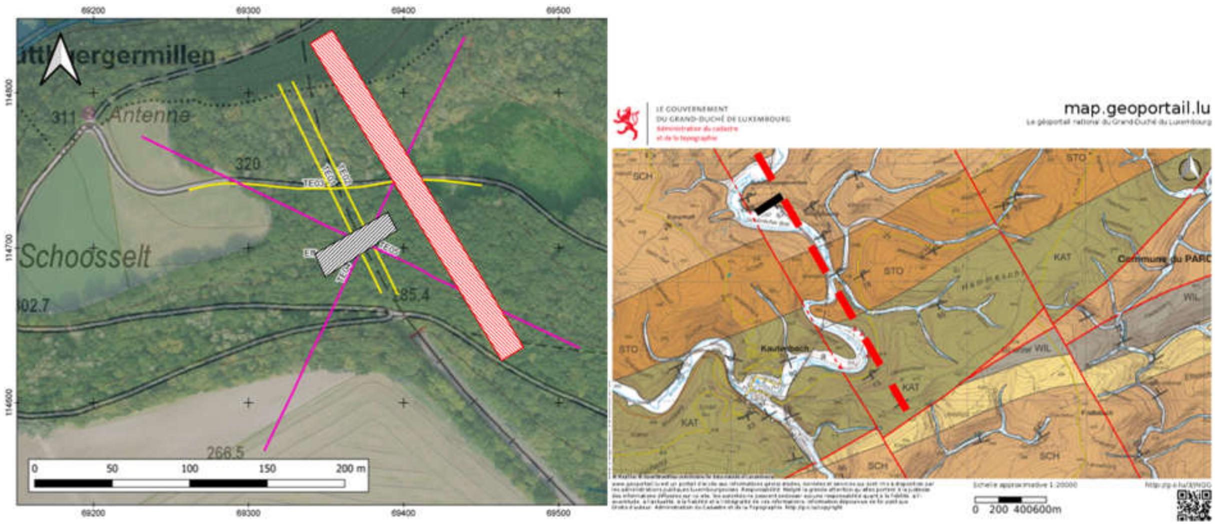

Figure 6. On the left: interpretation of the position of potential faults (red and black) based on electrical tomography and field observations. The yellow and magenta lines represent the axes of the electrical tomographies (see Figure 5). On the right: transfer of these faults (red and black dashes) on an extract of the geological map (faults are represented on the geological map by red lines)

3.2 Conclusions of the geological and geotechnical investigations

Taking into account all the results obtained, the causes that can be retained to explain the rockslide are as follows.

Firstly, the presence of a local geological event combining a zone intersected by 2 fault zones and a folded zone responsible for the alteration of certain banks into clay and the deconsolidation of the rock marked by numerous blocks of very variable dimensions. The division into relatively small blocks is accentuated by the existence of several families of discontinuities (stratification, diaclases, schistosity, fractures, etc.).

Secondly, the stratification is very upright (> 70° in the area of the collapse), which is conducive to instability if the support is removed (by removing the vault for example) and if alteration (water) or drying due to a period of drought greatly reduces the cohesion between the stratification planes.

The rockfall would be the result of a slide along these clay-filled planes (soap layer in the case of water, or loss of cohesion through shrinkage in the case of drying). The extremely dry period prior to the works resulted in a sharp reduction in the cohesion of the clay planes.

The rockfall was probably initiated by the collapse of the banks that had been transformed into clay, which broke away, accentuating the deconfinement of the rest of the altered/decomposed zone. The incident was therefore the result of a combination of geological, tectonic and climatic factors.

4 Emergency securing works

4.1 Securing principle

Based on the complicated topographical situation, the presence of the cone of scree in the tunnel and the technical capabilities of the companies involved, the following methodology was adopted, in consultation with the Lux Ouvrages d'Art design office:

1. Injection of the extrados of the vault on either side of the cone of scree (north and south sides) to fill the voids between the vault and the ground.

2. Injections through the cone of scree to ensure its stability during excavation, and gunning with anchors of the walls of the cone.

3. Injections of cement grout into boreholes drilled from the top of the ground (31m above the tunnel) to fill the voids between the destabilised blocks and boulders above the vault. The injections were carried out in several planes: 0.5m, 1.5m, 3m, 5m, 7.5m, 10m and 15m above the vault.

4. Placement of anchor bars from above in order to hold the injected zone in place (bars of sufficient length to cross the entire deconsolidated zone and anchor in the sound rock beyond it).

5. Anchoring and injections from the tunnel to create a kind of forepole umbrella system and hold the injected soil in place above the hole in the vault.

6. Complete removal of the scree heap.

7. Definitive securing of the vault around the collapsed area using arches formed from galvanised steel “T” sections embedded in the existing vault, between which galvanised steel plates have been welded.

8. Injection of a cement grout behind the welded plates to ensure contact between the arch and the old vault.

9. Drilling of drainage boreholes all around the final arches.

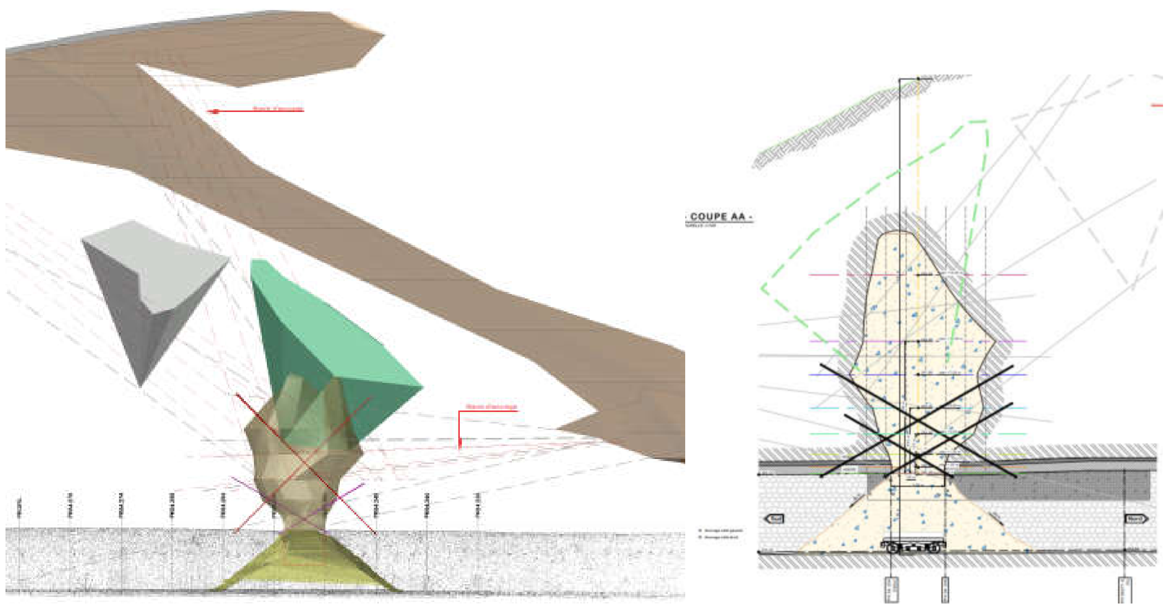

Figure 7. Principle of injection from above (left) and anchoring the injected heap (right)

Figure 8. On the left: drilling from above ton inject the grout. On the right: drilling from the tunnel for anchoring the deconsolidated soil injected above the hole in the vault

Figure 9 shows the situation at the end of the safety works, with the final belts in place.

Figure 9. Situation at the end of the safety works (same point of view as Figure 1)

4.2 Geotechnical and geophysical monitoring

Geotechnical assistance was provided throughout the safety worksite. This was done by checking the injections using electrical tomography and core sampling from the tunnel at various key stages once the works inside the tunnel were possible under safe conditions. For the geophysical monitoring, the 325m tomographic profiles mentioned above were used, applying 2 different analysis protocols (Wenner and Schlumberger), with an initial intervention serving as a "0" measurement and control measurements at different time intervals. A comparison between the initial and final measurements clearly shows an increase in resistivity in the vicinity of the tunnel. This is particularly evident in the profile shown in Figure 10. The increase was most noticeable after the injection work from the vault inside the tunnel.

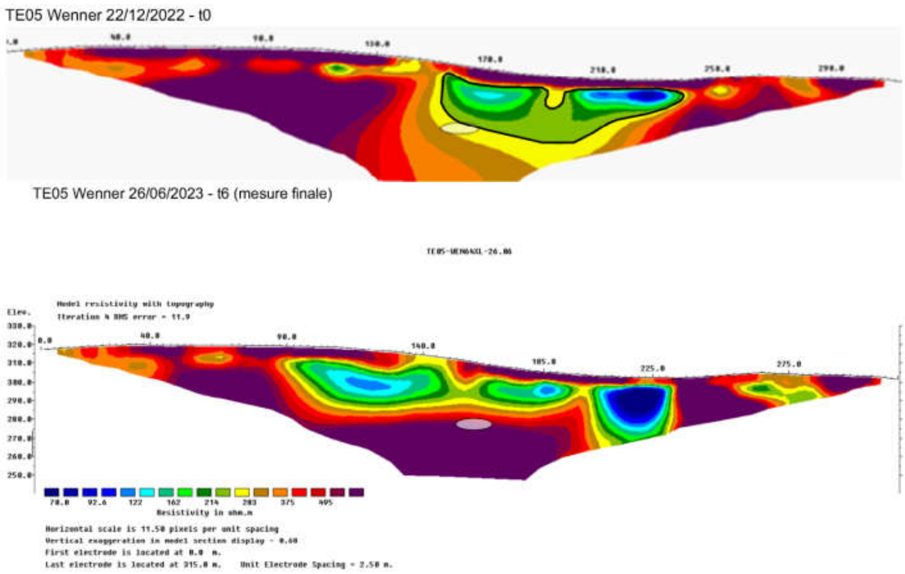

Figure 10. Comparison between the initial measurement and the final measurement showing the increase in resistivity around the tunnel

The geophysics also confirms that the injections did not remain localised to the boreholes, but that the grout probably spread over a fairly large area around the tunnel, which is also confirmed by grout spills observed along the path rising above the tunnel.

In addition to the monitoring by electrical tomography, several phases of control coring were carried out: coring of the vault and pedestals to check the grouting of the interface between the masonry and the ground in place, coring from the tunnel to check the injections carried out from above and coring to disassociate the gunite between the scree heap and the vault, which also enabled the injections to be checked and improved. The various check cores confirmed the low permeability of the ground and scree (significant presence of clay materials in which boulders of varying sizes are embedded), with grout concentrated mainly in the voids between blocks and boulders or along discontinuity planes. This left a number of areas in which the grout was unable to penetrate, and which were therefore not grouted. Nevertheless, the grouted areas provided sufficient overall stability, which was ensured by the installation of anchor bars (from the surface, but also from the tunnel on the north and south sides), the purpose of which was to hold the plug thus created in place so that the scree cone could be removed, and the final arches installed.

Grout was also found further to the south than the area targeted by the injection boreholes drilled from the surface, indicating that the relatively fluid grout initially used by the company tended to follow the planes of discontinuities present in the massif (stratification/schistosity planes dipping to the SE, fault planes or cracks in the rock beds) and to spread over a larger volume than the volume to be treated initially.

In total, 450m^3 of grout was injected. Additional evidence confirming the presence of a fault (striations and quartz crystallisations) was also found in the drill cores.

4.3 Hydrogeological situation

From a hydrogeological point of view, the following observations were made following the study carried out prior to the safety works: a relatively large amount of water at a depth of 25m in borehole 1, an equally large amount of water at a depth of 26m in borehole 6, a verbal indication from the project owner of the presence of a diverted spring near the southern entrance to the tunnel, traces of dampness in several places in the tunnel, traces of dampness in several places in the tunnel, especially on the east side (the side of the supposed fault), traces of dampness at the top of the scree cone on the north side and just before it on the east side of the tunnel and, lastly, circulations of water observed along planes of discontinuities along a path below the tunnel.

A number of indications suggesting a change in flow conditions in the massif were noted as the work progressed. This change in flow could be linked either to the drains created by the boreholes creating preferential flow zones, or to a change in the permeability of the massif by the clogging of certain discontinuities by the injection grout, or to a combination of these 2 influencing factors. The following signs were observed: the locations of the moisture zones visible in the tunnel at vault level have been moved north and south (on either side of the grouted zone) and are present in greater numbers; more water has entered the tunnel, even partially flooding the track at one point in the absence of pumping; a great deal of water was entering the scree heap; water entering the eastern masonry retaining wall at the southern entrance to the tunnel, which had previously remained relatively dry; water arriving in several places on the paths around the tunnel, which had previously remained dry; and lastly, water seeping into the embankment bordering the path passing over the tunnel, one of which is linked to the presence of a reconnaissance borehole that is also bringing back water, confirming the creation of a preferential flow zone linked to the boreholes.

All these findings led to the decision to drill drainage boreholes in the vault and pedestals all around the area secured by the arches. This drainage system is all the more important given that the protection is mainly made of steel.

5 Conclusion

The geological, geotechnical and geophysical investigations carried out determined that the collapse was the result of a local combination of several factors: the presence of 2 faults (one of which runs right through the collapse) and a folded zone responsible for strong fracturing and clay alteration of certain rock banks, the division into relatively small blocks due to the existence of several families of discontinuities, as well as a very upright stratification (> 70° in the area of the fallen zone), which is conducive to instability if the support is removed and if alteration (water) or drying due to a period of drought greatly reduces the cohesion of the stratification planes. The extremely dry period prior to the works certainly had an influence on the cohesion of the clay planes. The incident is therefore the result of a combination of geological, tectonic and climatic factors.

Monitoring of the works and additional investigations carried out in parallel with the work to make the Schieburg tunnel safe have enabled the hypotheses put forward at the end of the initial study phase to be refined and clarified. Geophysical measurements confirmed the presence of suspected faults. These measurements, combined with the observations made during the initial study, provided a better understanding of the situation and suggested the presence of 2 faults, one of which would actually intersect the tunnel at approximately right angles to it. The extent of the deconsolidated zone linked to this presumed fault could be determined.

These conclusions, in relation to the extent of the deconsolidated zone and the faulted geological context, show that extensive safety work was necessary to enable the tunnel to be reopened, and enhance the importance to realise a geological and structural investigations in such a complicated geological or work context. This allowed the tunnel to be reopened less than one year after the collapse, despite very difficult access conditions for both the exploratory drilling and the safety work.

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