

Application of the observational method for the optimization of supports: examples of the extension of the Knuedler car park and the Hosingen bypass in Luxembourg

Steve Gruslin, Tiffany Hennebaut

Department of Geotechnics & Engineering Geology, GEOCONSEILS, Luxembourg, steve.gruslin@geoconseils.lu

ABSTRACT: The observational method was applied throughout the construction works to optimize the supports for two projects: the extension of an underground car park in Luxembourg and the bypass of Hosingen. For each project, geotechnical calculations were carried out to verify the stability of the walls, considering the different load cases depending on the locations. Several scenarios were envisaged, based on the results of the geotechnical investigations, each corresponding to a type of support to apply. Then, as the work progressed, an in-situ analysis of the rock (geomechanical characterization and classification (RMR, Q, AFTES), Rock Schmidt measurements, etc.) was carried out. Regular monitoring made it possible to classify the rock in one of the predefined cases at each stage, making it possible to secure the rock faces without losing time or stopping the works. For the car park in Luxembourg, several very specific constraints had to be considered, in particular the presence of archaeological remains and a monument to be preserved in situ. In addition, the existing car park had to remain in use. An umbrella vault was installed, under which the earthworks were carried out. The worksite was divided into 3 phases: a general earthworks phase, another to secure the side walls, and a phase linked to the underpinning of the existing car park and the partial earthworks beneath it. For the bypass of Hosingen (325m long covered trench), the method was used in a highly folded and faulted context, with slopes up to 25m high. By making it possible to check the exact geological conditions of the rock as the work progressed, and to adapt the securing required to the situation encountered, the application of the observational method made it possible to optimize the work and limit costs while guaranteeing completion deadlines.

KEYWORDS: Observational method, design and optimization of supports, geotechnical monitoring of structures.

1 INTRODUCTION

The aim of this article is to describe how the application of the observational method to two projects in Luxembourg, by means of regular monitoring and the application of recommendations based on rock classification systems, enabled the support to be optimized, and hence the duration and costs of the project.

In general, design offices design support structures based on a geotechnical model that takes into account the average geotechnical characteristics of the soils and rocks. This means that safety measures are generally oversized to account for the worst-case scenario. The observational method can be used to optimize the dimensioning of supports.

After a brief description of the projects in question and their geological context, we will explain the methodology used before giving a few examples of applications to different cases encountered.

2 DESCRIPTION OF THE PROJECTS

2.1 Extension of the Knuedler car park

The project featured in this article is the eastward extension of the underground car park beneath Place Guillaume II in Luxembourg City (Parking Knuedler). The dimensions of this extension are 50 m by 40 m. While the existing car park has only 3 levels, this extension was built over 5 basement levels, with levels -4 and -5 being built partially under the existing car park, requiring the foundations to be rebuilt underneath.

From the outset of the project, a number of very specific constraints were identified. Firstly, preventive archaeological digs uncovered archaeological remains. It was decided to preserve these remains in situ. As a result, the initial project involving open-cast earthworks had to be modified. The final solution was to create an umbrella vault using micropiles below the level of the remains, with mole excavation underneath. An additional constraint was that the statue of Grand Duke Guillaume II in the square could not be moved under any circumstances during the works. Given that the umbrella vault could not support such a weight, a column of rock was kept under the statue until the final level of the car park, and had to be secured as the earthworks progressed. In addition, the

existing car park had to be kept in service for as long as possible. By contrast, the entire project is above the water table.

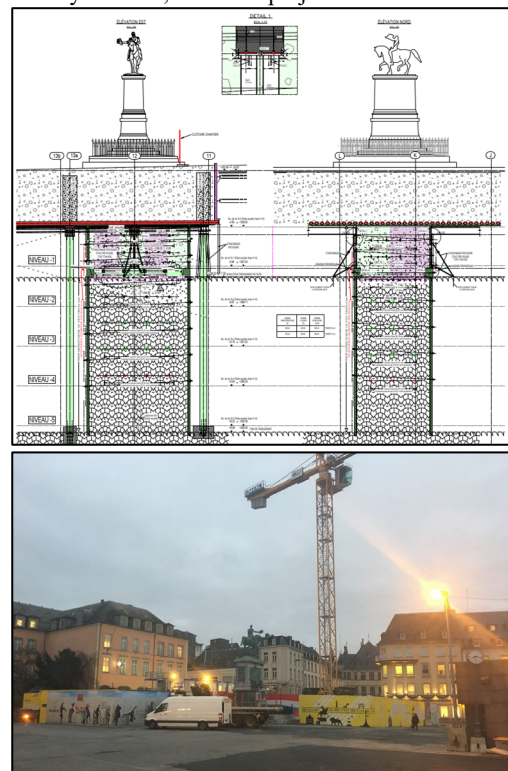


Figure 1. Protected statue above the parking and the general overview of the project

The project was divided into 3 phases: a general earthworks phase on large scale and to secure the column of rock beneath the monument, another to secure the side walls of the future car park made of piles and micropiles, and finally a phase involving the underpinning of the existing car park and partial earthworks beneath it. The earthworks will run from 2018 to 2022.

Following a first geotechnical study, which highlighted a number of deconsolidated zones, the engineering office, which

designed the project, initially planned to use homogeneous grouting based on the case of weathered rock. At the project owner's request, we then carried out a detailed geotechnical study using boreholes cores, which were drilled prior to the construction of the piles to be used as columns (9x12m and 15x26m boreholes), and which revealed that the deconsolidated zones remained very limited in extent. As a result, and in consultation with the engineering office, it was proposed to use the observational method throughout the worksite in order to react on a case-by-case basis, rather than planning a general safety system based on an unfavourable case. The core drillings also enabled a number of uniaxial compression tests to be carried out, and the RQDs to be determined, which constitute 2 input parameters for the classification systems commonly used.

2.2 Hosingen By-pass

One of the main road of the north of Luxembourg called "N7" is a national road that go through the village of Hosingen. The aim of the bypass Hosingen is to divert the traffic currently passing through the village by creating a traffic lane better suited to the flow of traffic.

For this project, the project owner has decided to build part of the section using a cut-and-cover tunnel. To realize this cut-and-over tunnel, some massive rock excavation had to be made.



Figure 2. By-pass location in red on the global project.

The geotechnical study in this area was carried out, at the client's request, from 5 core drillings to a depth of 30 m with logging measurements such as optical and acoustic imaging, natural gamma radiation, density, and sonic. 3 of those boreholes have been equipped with piezometers for groundwater monitoring. These boreholes enabled us to determine the RQDs on which we based our determination of the rock's geomechanical parameters. A surface geophysical surveys using electrical resistivity and seismic refraction have also been made.

The aim of our assignment was to optimize the safety measures pre-dimensioned in the tender phase based on our geotechnical study. And following the several steps of the works.



Figure 3. General view of the project

3 GEOLOGICAL CONTEXT

Geologically, Luxembourg is divided into two regions with different landscapes and substrata, bearing witness to the country's geological history. In the north, the Oesling region is characterized by deep valleys incised into Devonian rocks (from the Pragian and Emsian periods) folded during the Variscan Orogeny. From the Lower Triassic (Buntsandstein) to the Dogger, marine transgressions covered the (then eroded) Devonian basement and successively deposited sediments. Subsequently, new uplift processes (Alpine Orogeny) led to the erosion of these sediments, leaving the Devonian rocks exposed in the north of the country. However, in the Gutland region to the south of Luxembourg, some of these sediments have remained. Gutland is thus characterized by a succession of hard and soft consolidated sedimentary rocks, plunging gradually towards the southern end of the country. The hard rocks are characterized by relatively high fracturing, resistance to weathering and relatively high permeability. Impacted by the process of erosion, they form steep slopes (cliffs) with a gentle reverse slope corresponding to the inclination of the layers known as 'cuestas', a typical Gutland landscape (State Geological Survey, 2009).

3.1 Knuedler car park

The Knuedler car park extension project is located in the Gutland region, more specifically in the Luxembourg Sandstone (li2). The Luxembourg Sandstone dates from the Lower Liassic (Lower Jurassic) and was formed 210 million years ago as a result of the sedimentation process on the seabed mentioned above. Sandstone is often visible as a brown rock outcrop and is part of Luxembourg's cultural heritage.

The Luxembourg sandstones are composed of alternating very calcareous compact levels, with very good cementation and a greyer colour, and more sandy levels with good to medium cementation and a lower limestone content. These sandstone levels are whitish to brown in colour. Because of their lower limestone content, they are softer than the limestone levels, which are indurated and therefore more competent.

Although the most calcareous parts are the most massive, they are much more subject to alteration than the sandstone parts. This erosion phenomenon, which occurs according to the fracturing families in the bedrock, can cause karst phenomena. Karsts are natural cavities (open cavities or agglomerations of loose material) formed by the dissolution of carbonate elements. This karst phenomenon gives rise to characteristic surface relief and can cause major structural disorders, such as sinkholes, or the encounter of deconsolidated zones during underground work. This is therefore a parameter that needs to be taken into account during the design and construction monitoring phases.

In addition, the Luxembourg Sandstone, due to its high porosity, is the main aquifer in Luxembourg, where water circulation due to infiltration is all the more important.

The Luxembourg Sandstone is characterized by subhorizontal stratification (maximum 5° to the SW), with two families of perpendicular subvertical joints running through it. This stratigraphy and these families of joints give rise to the formation of parallelepiped blocks.

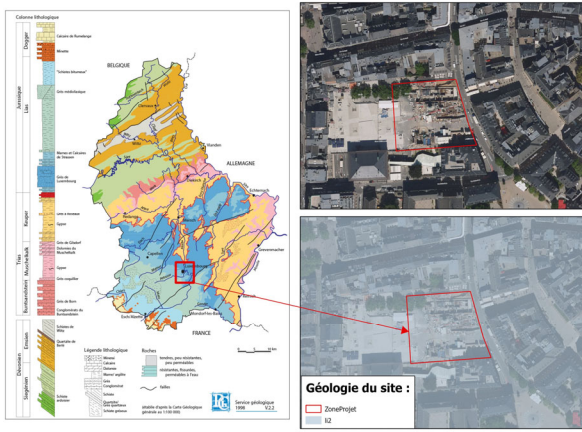


Figure 4. Geology and location of the project

3.2 Hosingen

The entire bypass area is underlain by Lower Devonian soils dating back to the Middle Emsian (“E2”), with the Berlé quartzite “q” to the north.

The E2 (Variegated layers of Clervaux) consists of variegated shales and sandstones. It should be noted that the term “shales” refer here to or sedimentary rock of a clayey or pelitic nature with a layered flow.

In 2020, after distribution of the geotechnical study, a geological map has been published. The new map shows some differences with the old version dating from 1948. The main differences is first, the new geological nomenclature with the “E2” lithology standing for “Clervaux Formation – CLE”.

The Clervaux Formation consists of a mixture of light grey, light green, pale olive-green or variegated (red, green) shales interspersed with sandstones and quartzites. Sandstones parts can vary in color (dark green, bluish, rarely red) and are often micaceous. Quartzites are generally whitish grey. Lithological variations are sudden and probably due to variations in the sedimentation zone (marine, coastal and continental).

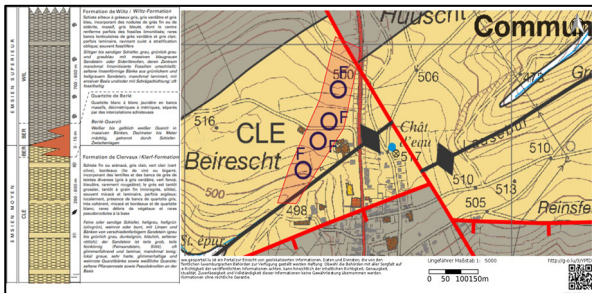


Figure 5. General geology of the project (2021).

The major difference, however, is the presence of 2 faults that are listed on the 2020 map and completely absent from the 1949 map, the only one that was available at the time of the study. The first fault, running NW-SE, is the Hosingen fault, which indicates a dextral separation of the geological strata along it. The second, running SW-NE, is the Schmidtzdelt fault. The new map also highlights the axis of an anticlinal fold (Preischeid anticline) in the southern part of the rocky trench.

4 METHODOLOGY

Several phases of technical assistance were required during the planification of the projects and the earthworks.

For each of these phases, the same methodology was applied for each intervention, planned according to the progress of the site:

1. Prior to the work, general geotechnical calculations were carried out to verify the stability of the walls, taking into account the various load cases depending on the locations concerned. Several scenarios (highly altered to decomposed rock, fractured rock and sound to slightly altered rock) were envisaged on the basis of the geotechnical studies and additional field observations, each corresponding to a type of support to be applied, which enabled to prepare several standard plans with the various types of securing.

2. During the works, an in-situ analysis of the state of the rock (geomechanical characterization and classification - RMR, Q, AFTES, GSI -, stereographic measurements) was carried out in order to be able to give initial recommendations as to the necessary securing measures. The input parameters for the classification were based on the following:
 - a. The RQD calculated from core drillings carried out for the pile study (10-100%)
 - b. Uniaxial compressive strength based on laboratory tests (22.3-73.7 MPa)
 - c. RockSchmidt hammer measurements taken in the field and compared with the uniaxial compressive strength results.
 - d. Geomorphological analysis of outcrops created by earthworks.

3. Regular monitoring made it possible to classify the rock in one of the predefined situations at each stage, enabling the contractor to secure the rock faces without losing time or stopping work. This works supervision principle also made it possible to optimise the stabilisation in particular cases or geometry.

4.1 Classification system used

In order to characterise the state of the rock mass, different classifications were used during each visit. These classifications make it possible to evaluate the rock face according to observational criteria or criteria derived from laboratory tests, in order to make an initial assessment of the appropriate support systems. Each system is assessed on the basis of a rating. These ratings are complementary and should, in theory, converge towards the same support recommendations.

4.1.1 Q-System Barton [Barton, 1974]

The value of the Q rating is between 0.001 and 1000. The quality of the rock mass according to Barton is represented by 9 classes (from exceptionally poor to exceptionally good). This classification provides a good characterisation of joints and spurs, and gives a numerical value to which a support is associated. The Q-system is also refined according to the size of the rock mass being excavated (NGI, 2015).

4.1.2 Rock Mass Rating (RMR) [Bieniawski, 1989]:

Rating of the massif from 0 to 100 according to 5 classes: massif of very poor quality to massif of very good quality. This classification was initially designed for underground works. It gives a numerical value to which is associated a duration and a stable length without support. The RMR is correlated with the Q-system ratings. Depending on the nature of the project, discounts are applied to the rating. This rating can therefore be applied to rock slopes (Bieniawski, 1989).

4.1.3 AFTES [AFTES, 1993]

This classification does not provide a rating but gives a detailed description of the massif, considering the state of continuity of the rock and the state of alteration. It is intended for use in underground workings and is based on a qualitative geological description of the rock mass. The AFTES classification takes into account the orientation of the fracturing in relation to the

orientation of the earthwork (AFTES, 2003 and 2020). Each parameter of the AFTES rating is weighted, which makes it possible to recommend an appropriate support in detail, and the variants that can be implemented. This classification also specifies the supports that are not applicable according to the score for each rating criterion.

4.1.4 Summary

The following table summarizes the input parameters for the different rating systems, and the rock classes obtained for each.

Table 1. Comparison of the quotation system

Raking parameters	Q-system	Rock Mass Rating (RMR)	AFTES
Unconfined compressive strength (UCS)		☑	☑
RQD	☑	☑	
Qualitative description of the alteration of the massif			☑
Description of discontinuities	☑	☑	
Spacing of discontinuities		☑	☑
Hydrogeological condition	☑	☑	☑
Permeability			☑
Stress state of the rock	☑		☑
Adjustment of the rating according to orientation		☑	☑
Output data of the rating			
Holding time of the wall without support		☑	
Mohr Coulomb parameters associated with rock class		☑	
Support according to rating	☑	☑	☑

4.1.5 Geological Strength Index GSI [Hoek & Brown, 2013]

In addition, the GSI index was also used. This index is a tool used to assess the quality of a rock mass. It is determined by visual observation of the rock mass structure. It ranges from 5 (very poor quality) to 85 (excellent quality). The GSI is a key parameter of the Hoek-Brown criterion and is used to define the parameters of the criterion based on the quality of the rock mass (structure and surface condition of discontinuities). The Hoek-Brown criterion uses the GSI to quantify the impact of discontinuities on rock strength, thereby enabling the behaviour of the rock mass to be modelled in various engineering situations.

5 DIMENSIONING OF THE SECURISATIONS

Several phases of technical assistance were required during the earthworks.

5.1 Knuedler car park

The 19.50m-deep excavation pit beneath the Place Guillaume II was secured by various types of retaining wall, depending on the constraints and terrain of the site. Tensioned micropile walls

made of tubular sections were used on the north and east sides, between the surface (304.50mNN) and the 295.00mNN level. A wall of Ø68 'Lutetian' type piles spaced 1.50m apart with tie rods was recommended to support the umbrella vault (located at level 299.92 mNN) and to support the southern side of the excavation up to level 292.70mNN. The base of the piles and micropiles was planned at the level of the more or less weathered rock. Between the base of the walls and the bottom of the excavation located at level 285.00mNN, a 90° excavation in the more or less fractured sandstone was planned, with general stabilisation consisting of a layer of C30/37 shotcrete at least 15cm thick and a regular mesh of Ø25 'Gewi' nails of the passive type 2.0m vertically and 1.50 m horizontally, with an inclination of between 10° and 15°.

In order to prove the stability of the rock slopes below the retaining walls, calculations were carried out using GGU-Stability, a two-dimensional computer-aided design software programme that allows the verification of slopes using equilibrium-limit methods in accordance with Eurocode 7. Stability was analyzed using the vertical slice method. This method assumes polygonal fracture surfaces, and inter-slice vertical forces are taken into account in the calculation.

The calculation model has been simplified and certain assumptions have been made. The retaining walls and the ground formed by soils and fractured sandstone were treated as a surcharge on the bedrock. The retaining walls transfer vertical forces (between 126kN/m and 367kN/m) to the bedrock. The horizontal loads acting on the walls are taken up by the tie rods, which have been modelled as horizontal loads distributed at the level of the sealing bulb. Fracture mechanisms in the compact, slightly fractured Luxembourg sandstone were defined as a priori, based on a polygonal profile. Following the observations made during the previous earthworks phases, the fracture surfaces were modelled with maximum inclinations of 5° to the horizontal (stratifications) and 10° to the vertical (joints) in slightly altered rock.

Particular attention was paid to stability at the foot of the walls, especially during the earthworks phase directly beneath the piles supporting the umbrella vault. The nailing was phased along the length of the wall to avoid the risk of landslides. In addition, the vertical elements of the wall were connected by steel ties or reinforced concrete headers to ensure overall behaviour in the event of a localized problem.

After securing the foot of the walls, a series of standard cases was calculated in advance to cover a wide combination of rock that was more or less weathered at certain pre-established levels, in order to reduce intervention times during the worksite.

A particular feature of the large-scale earthworks phase was the need to maintain the column of rock measuring 5.30m x 7.20m beneath the monument on Place Guillaume II. In this case, the rock pillar was chained together with a reinforced concrete sill connected by sub-horizontal tie rods. Underneath, a shotcrete skin and nails were used to secure the pillar. The nails passing through the rock pillar were injected and anchor heads were fitted at both ends of the nails to achieve a containment effect.

Once the earthworks phase was complete, work began on the underpinning of the existing car park. This work involved adding 2 basement levels under part of the existing building (approximately 9m in length) at an average height of 6m. The work was carried out in several phases, taking into account the loads and constraints imposed on the site, including the very limited working space. Our role was to monitor the work to check the assumptions about the strength of the rock, and to validate the phasing recommended by the design engineer.

The partial excavation of the two reinforced concrete columns of the existing structure was identified as the most

critical phase. The load under the foundation of the most heavily loaded column was quantified at 4,538kN at the serviceability limit state (SLS). A series of preliminary measures were recommended by the design office to reduce the load during construction of the reinforced concrete base: the foundation was connected to the existing structure by a reinforced concrete beam, and temporary steel supports fitted with a hydraulic jack were installed on the three floors of the existing car park. This reduced the load to 2,538kN at SLS. We carried out a series of calculations to verify the underpinning phases of the column. Based on our on-site observations, we assumed that the fracture surfaces would be inclined between 0 and 15° from the vertical (joints). Given the good condition of the rock observed in situ as the excavation phases progressed, no additional stabilization was required to complete the work.

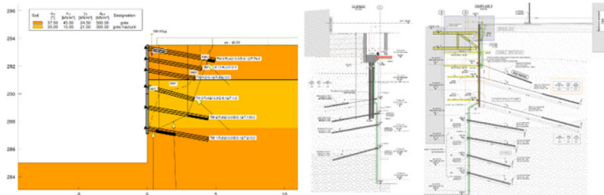


Figure 6. Example of calculations and typical support cases

5.2 Hosingen

As mentioned before, the methodology adopted envisaged several foreseeable geological cases, each corresponding to a type of slope securing that could be applied.

In total, 9 cases were predefined (6 cases for the eastern slope, considered to be the most unfavourable on the basis of the unfavourable dip orientation of the discontinuities affecting the rock highlighted during the study, and 3 cases on the western side considered to be more favourable) depending on the state of alteration and fracturing of the rock, as well as the presence or absence of clayey fillings along the main discontinuity planes. In addition, these cases have been declined into the 3 typical heights likely to be encountered along the length of the cut-and-cover section (15m, 20m and 25m).

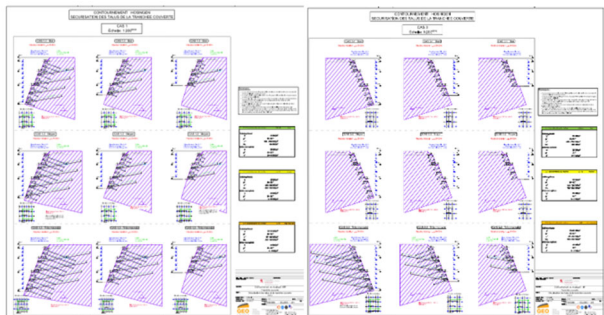


Figure 7. Some of the typical cases

These typical cases have been designed with the software “GGU Stabiliti”, with the option “wire mesh slope”. The water level assumption was playing a huge part in this design, thus the clay joints characterization. All the initial cases where design with the same wire mesh protection system, provided in the tender.

Geological and geotechnical observations were subsequently used to characterize more complex security systems, where the situations were more critical. For these areas we replaced the wire mesh with a shotcrete shell. The typical cases have been also optimized if the field observations showed a main dip different from the angles of stratification taken into account during the case study.

6 RESULTS OF THE OBSERVATIONAL SUPERVISION

This chapter illustrates some of the difficulties and special cases encountered during site monitoring. It should be remembered that the influence of earthworks on fracturing meant that all the other parameters of the classification systems used had to be analyzed carefully to ensure that the classification was as accurate as possible. In fact, the fracturing visible during our work not only corresponded to the discontinuities naturally affecting the rocks but was also largely caused by earthworks.

6.1 Knuedler car park

The following table describes several specific cases encountered, together with the corresponding safety measures, rating systems, and the rock classes obtained for each.

Table 2. Peculiarity area with Q and RMR results

Difficulties encountered	Q	RMR	Case of securing considered
Presence of a joint altered in sand	6,67 - 12	53 - 67	Weathered rock
Highly fractured and altered zone	7,5 - 12	19 - 31	Weathered rock
Dissolution pocket around a joint	1,67 - 6,67	28 - 35	Heavily weathered to decomposed rock
Rock to be secured under the base of the piles	4 - 10	58 - 63	Weathered rock
Rock under secured zone at the base of the piles	10 - 12	76 - 89	Sound rock, no additional securing
Highly altered zone along axis 1	0,556 - 6,67	28 - 35	Heavily weathered to decomposed rock
Highly fractured zone with clay fill axis 9	0,067 - 0,42	5 - 23	Heavily weathered to decomposed rock
Highly resistant rock axis 1 but with carbonaceous fills and more locally altered zone	10 - 213	46 - 67	Good rock with nailing in weak areas

For the large-scale earthworks, the following decisions were taken on the basis of the findings: earthwork embankments in phases, lay the embankments down, shotcrete them or leave the rock as it was. For the 3 side walls, minimal gunning was still planned to enable the waterproofing to be applied, but with simple pinning used solely to hold the trellises in place, as the gunning had no static role in this case. Depending on the findings, it was decided either to maintain the simple pinning, or to add nails according to a mesh and length predefined by the calculations explained in Chapter 5.

Finally, for the underpinning, the state of fracturing and the strength of the rock were checked at each phase of the earthworks to validate in-situ the calculation hypotheses.

Figure 7 shows some specific cases encountered during the project.



Figure 8. Some specific cases encountered during the excavation

6.2 Hosingen

The observational method on the Hosingen bypass allows us to discover some geological features such as unexpected folding, faults, and atypical clay filling material.

As the project progressed, it became clear that the situation initially anticipated did not totally correspond to what was encountered in situ. And clay joints were systematically encountered. At the end of the securing, around 70% of the rock slopes have been secured by using the typical cases.

During excavation work, an unfavourable 50° dip with clay fillings was identified over a length of approximately 50m on the south-east side of the covered trench. The area required specific securing and additional calculation. The safety of this area was ensured using shotcrete and thicker plates than planned. As the sliding planes were very active during the works, the width of the excavation was limited to 5 meters with a tamping system. This meant that one over two section was excavated and secured before moving on to the remaining sections.

On the West part, a fault zone has been discovered across a width of approximately 10m. This fault moved southward at depth, which requires to secure the area with shotcrete shell.

In addition, the earthworks also created instability, often characterized by overhangs. Due to the height of the earthworks, these overhangs had to be secured using concrete

reinforcement and steel tie beams, or with cables system working in shear to hold the block in place.



Figure 9. Specific situation requiring an adaptation of the securing

7 CONCLUSIONS

The methodology presented in this article, based on rock classification systems and recommendations, and applied to the extension of the Knuedler underground car park in Luxembourg, and the Hosingen bypass, shows how the application of the observational method, by giving the opportunity both to check the exact geological conditions of the rock as the site progresses and to adapt the necessary safety measures to the situation encountered in situ, makes it possible to optimize the supports while limiting site stoppages. Ultimately, this means better control of costs while guaranteeing completion deadlines

8 ACKNOWLEDGEMENTS

The authors would like to thank Mr. Claude Peschon of the City of Luxembourg and Mr. Marc Ries and Mr. Michel Simon of the Diekirch Roads Division of the “Administration des Ponts & Chaussées” for their trust, as well as Dr Romain Meyer, formerly of the Geological Survey of Luxembourg, now of the Geological Survey of Greenland for his opinions and advice.

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