Slope stabilization using anchored shafts

Stabilisation de pente à l'aide de puits ancrés

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ABSTRACT: In a river valley with extremely steep slopes a 160 m high and about 1.7 km long Motorway bridge is build. By the use of the observational method relevant downhill orientated slope displacements have been detected with inclinometers. To secure the overall stability of the bridge piers and of the slope challenging stabilization measures are necessary. Due to the extremely complicated local conditions a new technical method for slope stabilization has been developed. Therefore about 45 m deep shafts with a diameter of 6.6 m are constructed. For the load transfer the shafts are connected with a 4.2 m x 6.3 m thick and 32 m long strongly reinforced head board and tied back with up to 55 m long permanent anchors. Each anchor carries a design load of 3.0 MN. This new developed slope stabilization construction will be used in combination with permanent groundwater lowering.

To analyze the applicability of the construction a nonlinear 3D-Finite-Element-Model of the steep slope with the anchored shafts was developed and a parameter study has been conducted. In the paper this new developed slope stabilization scheme using the anchored shafts and the 3D-FE-Analysis will be described in detail.

RÉSUMÉ : Un pont autoroutier de 160 m de hauteur et d'environ 1,7 km de longueur est en cours de construction au-dessus d'une vallée fluviale avec des pentes extrêmement raides. La méthode observationnelle est appliquée pour contrôler les déplacements vers l'aval de la pente déterminés à l'aide d'inclinomètres. Des mesures sont nécessaires pour assurer la stabilité de l'ensemble des piles du pont et du talus. Etant données les conditions locales extrêmement compliquées, une nouvelle technique de stabilisation de pente a été développée. Des puits de 45 m de profondeur et 6,6 m de diamètre sont construits. Pour le transfert des charges, ces puits sont reliés à une poutre de couronnement fortement renforcée avec une section de 4,2 m x 6,3 m et une longueur de 32m et sont fixés à des ancrages permanents atteignant jusqu'à 55 m de longueur. Chaque ancrage peut supporter une charge de calcul de 3,0 MN. Cette construction qui vient d'être mise au point pour stabiliser la pente sera combinée à un rabattement de nappe permanent.

Un modèle éléments finis non linéaire 3D du talus et des éléments ancrés ainsi qu'une étude paramétrique ont permis d'analyser l'applicabilité de cette construction. Cet article présente ce nouveau concept de puits ancrés et décrit en détails l'analyse numérique 3D réalisée.

KEYWORDS: observational method, slope stabilization, 3D-Finite-Element-Model.

1 INTRODUCTION

In a river valley with extremely steep slopes a 160 m high and about 1.7 km long Motorway bridge is build (see Fig. 1). By the use of the observational method according to the Eurocode 7 (EC7) relevant downhill orientated slope displacements have been detected with inclinometers. To secure the overall stability of the bridge piers and of the slope challenging stabilization measures are necessary.

1.1 *Observational Method*

If the identification of the mechanical behavior of soil is difficult, it is necessary to apply the observational method to review the design during the construction time and (if necessary) during service time. For example in the European Standard Eurocode 7 (EC 7) the effect and the boundary conditions of the observational method are defined.

Figure 1. Visualization of the 160 m high and 1.7 km long Motorway bridge.

The application of the observational method is recommended for the following types of construction projects (Katzenbach et al. 2013):

- very complicated/complex projects,
- projects with a distinctive soil-structure interaction, e.g. mixed shallow and deep foundations, retaining walls for deep excavations, Combined Pile-Raft-Foundations (CPRFs),
- projects with a high and variable water pressure,
- complex interaction situations consisting of ground, excavation and neighbouring buildings and structures,
- projects with pore-water pressures reducing the stability,
- projects on slopes.

The observational method is always a combination of the common geotechnical investigations before and during construction together with the theoretical modelling and a plan of contingency actions (Figure 2). Only monitoring to ensure the stability and the serviceability of the structure is not sufficient and, according to the standardization, not permitted for this purpose.

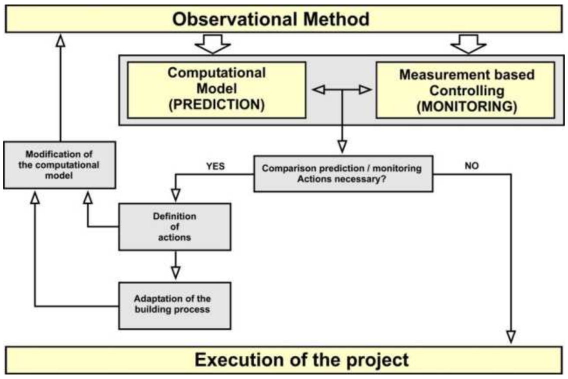

Figure 2. Principle of the observational method.

Overall the observational method is an institutionalised controlling instrument to verify the soil and rock mechanical modelling (Abel 2003, Blume, Glötzl 2003, Brandl 1999, Herten 2010, Katzenbach et al. 1999, Nagel et al. 2012, Rodatz et al. 1999).

The identification of all potential failure mechanisms is essential for defining the measure concept. The concept has to be designed in that way that all these mechanisms can be observed. The measurements need to be reliable and should be done in a direct and defined way. The measurement devices need to be of an adequate accuracy to allow the identification of critical tendencies. The required accuracy as well as the boundary values need to be identified within the design phase of the observational method.

Contingency actions need to be planned in the design phase of the observational method. The construction method or design method depends on the ductility of the system. It is essential that contingency action can be applied.

The observational method must not be seen as a potential alternative for a comprehensive soil investigation campaign. A comprehensive soil investigation campaign is in any way of essential importance.

To establish the above mentioned boundary values before the construction has started is a challenging task and requires powerful calculation tools which reply on suitable constitutive laws for the soil.

As a secondary effect the observational method is a tool of quality assurance and allows the verification of the parameters and calculations applied in the design phase. The observational method helps to achieve an economic and save construction.

2 SLOPE STABILIZATION

In the depth of about 22 m a sliding zone of the steep slope has been detected during the consequent use of the observational method according to the Eurocode EC 7 with inclinometers. Since May 2000 to September 2016 a head deformation of 2.5 cm has been measured by the exemplary inclinometer shown in Figure 3.

The shear band is between the axis 2 and 3 of the bridge at a steep slope with an inclination of about $\beta = 25°$. The geometry is shown in Figure 4

The shear band is overlaid with deposits/hillside loam and exterior weathering argillaceous schist. Below the shear zone the soil consists of decomposed argillaceous schist till a depth of about 80 m. With the depth of 80 m argillaceous schist as a rock was determined. The groundwater level is illustrated in Figure 4.

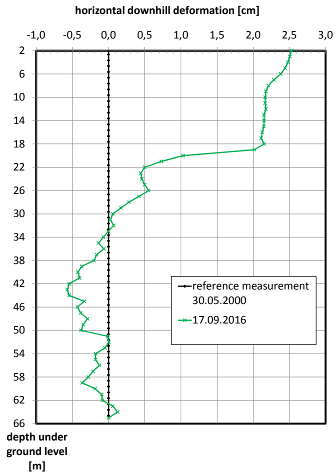

Figure 3. Inclinometer measuring since May 2000.

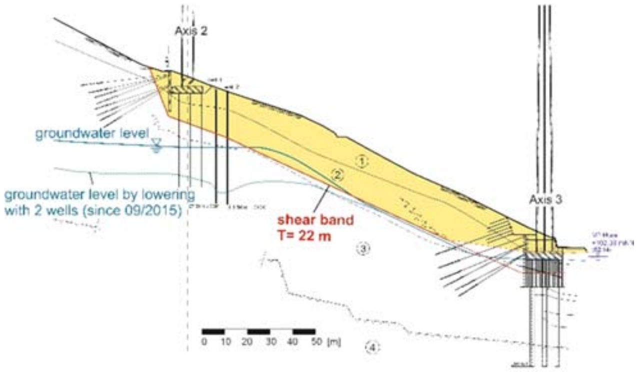

Figure 4. Subsoil layers with the shear band at depth of 22 m.

The soil parameters of the different layers illustrated in Figure 4 are given in Table 1.

Table 1. Soil Parameters

No.	Layer	γ/γ_r [kN/m³]	φ' [°]	c' [kN/m²]
1	deposits/hillside loam	22/11	30.0	15.0
2	exterior weathering argillaceous schist	22/11	30.0	15.0
	shear band	-	22.0	7.0
3	decomposed argillaceous schist	22/11	30.0	33.0
4	argillaceous schist	26/16	$\geq$ 40.0	0.0

2.1 *Detection of the necessary stabilization force*

For the dimension of the slope stabilization the necessary stabilization force had to be calculated. Due to the fact, that the piers will be a fix point it has to be assumed for the worst case scenario when the slope will fail that the force of the moving body of the landslide will be transferred by side friction to the soil body between the piers. The principle is shown in Figure 5.

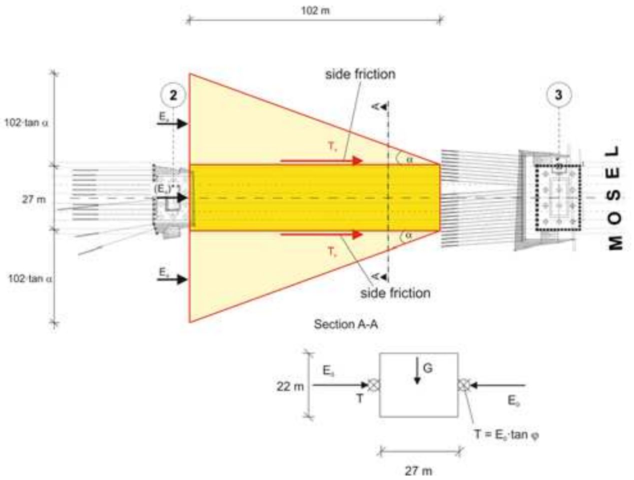

Figure 5. Model to dimension the side force.

The calculation of the side friction was conducted by the approach of the maximum of the transferable force with the earth pressure at rest as follows for each side:

$$K_{0g} = 1 - sin\varphi = 1 - sin30° = 0.500 \quad (1)$$

$$E_0 = \frac{1}{2} \cdot (22m)^2 \cdot 102m \cdot 22\ kN/m^3 \cdot 0.500 \quad (2)$$

$$E_0 = 271{,}524\ kN = \ 271{,}5\ MN \quad (3)$$

$$C = 22m \cdot 102m \cdot 0.015\ MN/m^2 = 33.7\ MN \quad (4)$$

$$T_{\varphi} = E_0 \cdot tan30° = 157{,}7\ MN\ (c\ =\ 0) \quad (5)$$

$$T_{\varphi+c} = 156.7\ MN\ + 33.7MN\ =\ 190{,}4\ MN \quad (6)$$

To reach a stable and according to the Eurocode 7 (EC 7), section 11 proved overall stability of the slope a slope stabilization construction had to be dimensioned to a force of about 540 MN. A special challenge thereby was that the construction has to be built with small machines due to the steep slope and the risk that big load introduction could initiate the slope failure.

2.2 *Slope stabilization construction*

For the slope stabilization to guarantee the Overall Stability according to the Eurocode 7 (EC 7), section 11 a new construction has been developed.

Therefor overall 6 shafts will be constructed with a diameter of 6.6 m and a depth of 45 m. The shafts will be protected with a 30 cm thick shotcrete lining during the construction. The reinforced concrete ring of the shaft will be about 1.0 m thick (see Figure 6 and Figure 7).

The shafts will be spread into two rows with 3 shafts between the pier 2 and pier 3. Each row will be connected with a 4.2 m x 6.3 m thick and 32 m long strongly reinforced head board for the load transfer. The head boards are going to be tied back with up to 55 m long permanent anchors. These anchors have to carry a design load of 3.0 MN.

Additional a groundwater lowering is necessary to prove the Overall Stability according to the Eurocode 7 (EC 7). For the groundwater lowering one shaft will be built as a drainage shaft. On this drainage shaft 10 horizontal drainages in two layers with 5 horizontal drainages with a length up to 50 m are connected (see Figure 6 and Figure 7).

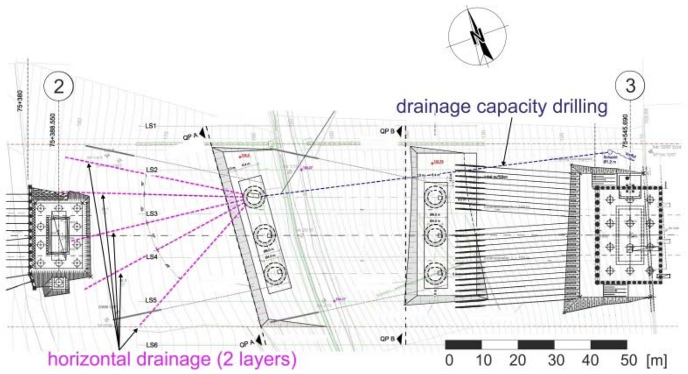

Figure 6. Location plan of the slope stabilization construction.

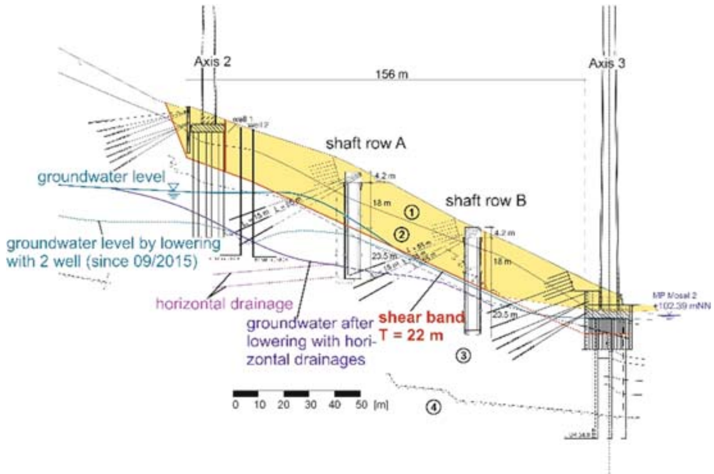

Figure 7. Cross section of the slope stabilization construction.

2.3 *3-D-Finite-Element Model of the slope stabilization construction*

To prove the approach of the transferable force and the function of the slope stabilization construction a 3D-Finite-Element-Analysis has been conducted.

The 3D-Finite-Element-Model has a width of 200 m and a length of 320 m (see Figure 8). The ground surface of the steep slope has been modelled with an average inclination of β = 25° according to the true conditions at the slope.

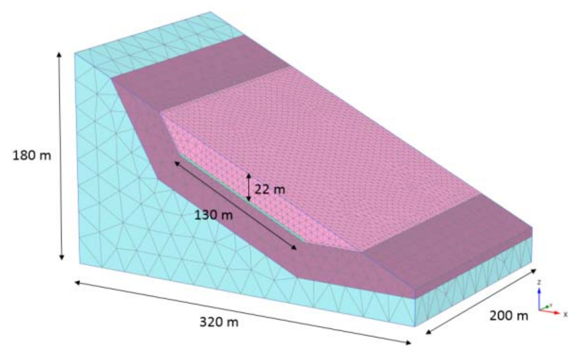

Figure 8. Dimensions of the 3D-Finite Element Model.

The material behavior of the layers has been modelled with linear elastic - ideal plastic material law. As the friction condition according to the Mohr-Coulomb friction condition, which is described with the shear parameters φ' and c', was conducted. The soil parameters can be obtained in Table 1.

The modelling of the shafts and the head board have been carried out in Plaxis 3D with plate elements. The interaction between the soil and the shafts was modelled with Interface-Elements.

For the reproduction of the anchors beam elements has been used. The grout body was built with Embedded Piles (see Figure 9).

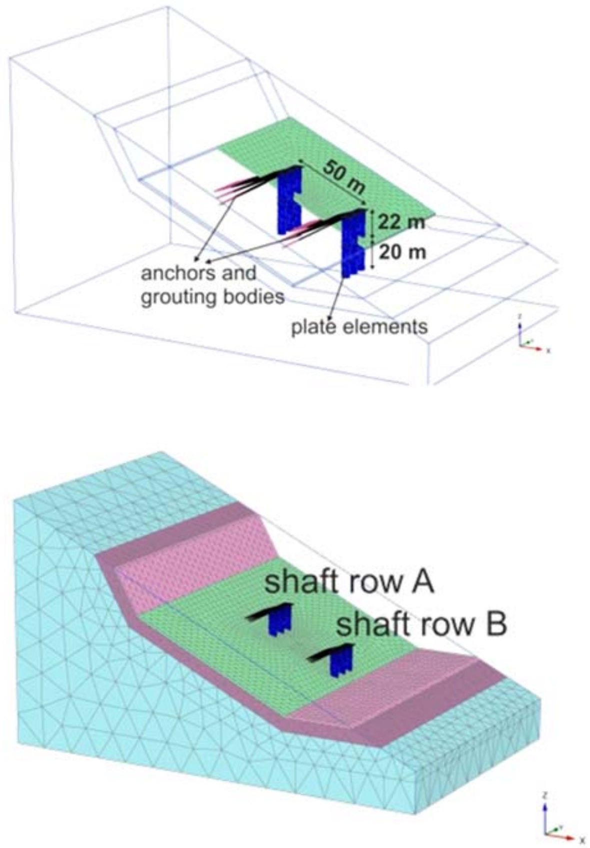

Figure 9. 3D-Finite Element Model.

The shafts were modeled linear elastic with a modulus of elasticity of 30,000 MN/m² and a Poission's ration of 0.2. The anchors were also modelled linear elastic, the maximum surface friction of the grout body was defined with $q_{s,k}$ = 250 kN/m².

For the numerical calculation the incremental sequences of the calculation steps were elected to be able to analyze the changes from the actual situation with activated sliding joint to the situation after the installation of the shafts.

With the help of the 3D-Finite-Element-Modell it was possible to prove and confirm the necessary stabilization load that has been calculated by a simple model with the transferable force. Further it could be verified, that the planned slope stabilization construction is able to absorb the load, which will occur by the slope failure. Therefor it could be proven that the bedding of the piers will be conserved.

Further it was possible to prove with the 3D-Finite-Element Modell that the forces will spread equally over the anchors of each shaft row. Due to the high account of anchors and the distribution all over the panel a sliding between the shafts will be prevented.

3 CONCLUSION

With the help of the 3D-Finite-Element Model it was possible to show that the developed slope stabilization construction with six anchored shafts will work to absorb the occurring forces of the worst case scenario and the proof of Overall Stability according to the Eurocode 7 (EC 7), section 11 is given.

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