Rock Anchorages and their Pull-Out Capacity in Mauthausen Granite

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with 10 figures und 5 tables

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Abstract

Due to lack of in-site measurement data, rock anchors often have to be dimensioned after the engineering geologist´s expertise. The determination of suitable anchor points and the appropriate anchor length for the foundation of a steel rope network is the scope of this article. The network should carry the membrane roof and the sound equipment for the „Mauthausen Memorial“ concert, dedicated to the victims of Nazism terror. The resulting displacements in the rock slope are calculated by numerical methods and confronted with empirical values.

1. „Mauthausen Memorial“ as a geological challenge

In the year 1998 in Austria the „Mauthausen Memorial“ concert took place. It was a public ceremony dedicated to the victims of Nazism terror. A three-dimensional steel rope construction was built at the granite quarry of Mauthausen (Upper Austria).

The rope construction should carry the sound equipment and the membrane roof in order to protect the orchestra against rainfall. 11 points in the quarry were chosen to attach the rope net to the rock (see Fig. 1).

The points to attach the steel ropes to the rock are situated at a height from 8 m to 41 m superior to the bottom plane of the quarry, partly on the rock wall, partly on the slope toe. From the start of the planning process to the concert event, there were only 5 weeks to fulfil this task. In order to keep the project in time, on-site pull-out tests on the rock anchors had to be cancelled. So the suitable locations for every single anchor had to be selected, according to the engineering geologist´s expertise. Then, the boreholes were drilled up to the appropriate length. The anchors were bonded to the rock with polyurethane foam. After the positive report concerning the rope system’s structural analysis, the load was applied to the construction. The steel ropes were connected to the anchor heads.

The resulting deformations in the rock mass could be monitored only by visual means, once resulting from the empty rope network, once resulting from the fully-loaded net. No significant displacements along the critical discontinuities could be monitored.

In the year 2000, a second memorial concert took place at the Mauthausen quarry. Visual control was conducted again, no resulting deformations could be found this time either.

Such a rough deformation control, however, is no serious way of planning, not only from the engineering geologist’s point of view, but also from other co-included engineer’s position.

Therefore it was decided to calculate to resulting stresses and deformations which occurred inside the rock slope by

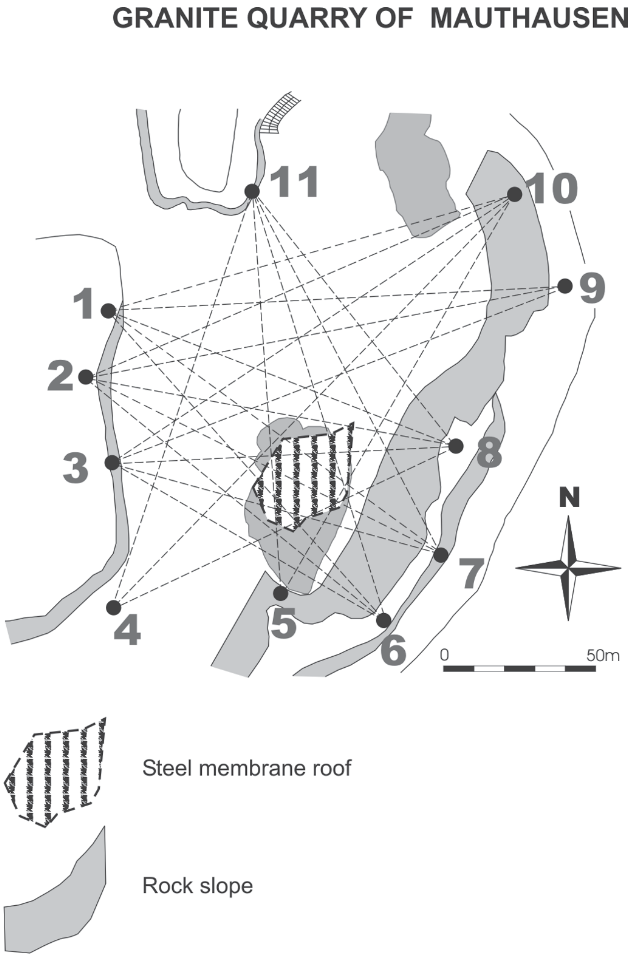

Fig.1: Location of the anchor points for the steel rope construction in the granite quarry of Mauthausen.

the means of UDEC 3.10 (Itasca Consultants). As the models are rather small-scale, including big granite blocks, the discontinuity system could be modelled in a realistic way. The results of the UDEC calculation will be confronted with the calculation method presented by LITTLEJOHN (1995). The estimation of the requested anchor length was found using the methods of HOBST & ZAJIC (1977) and LITTLEJOHN (1994).

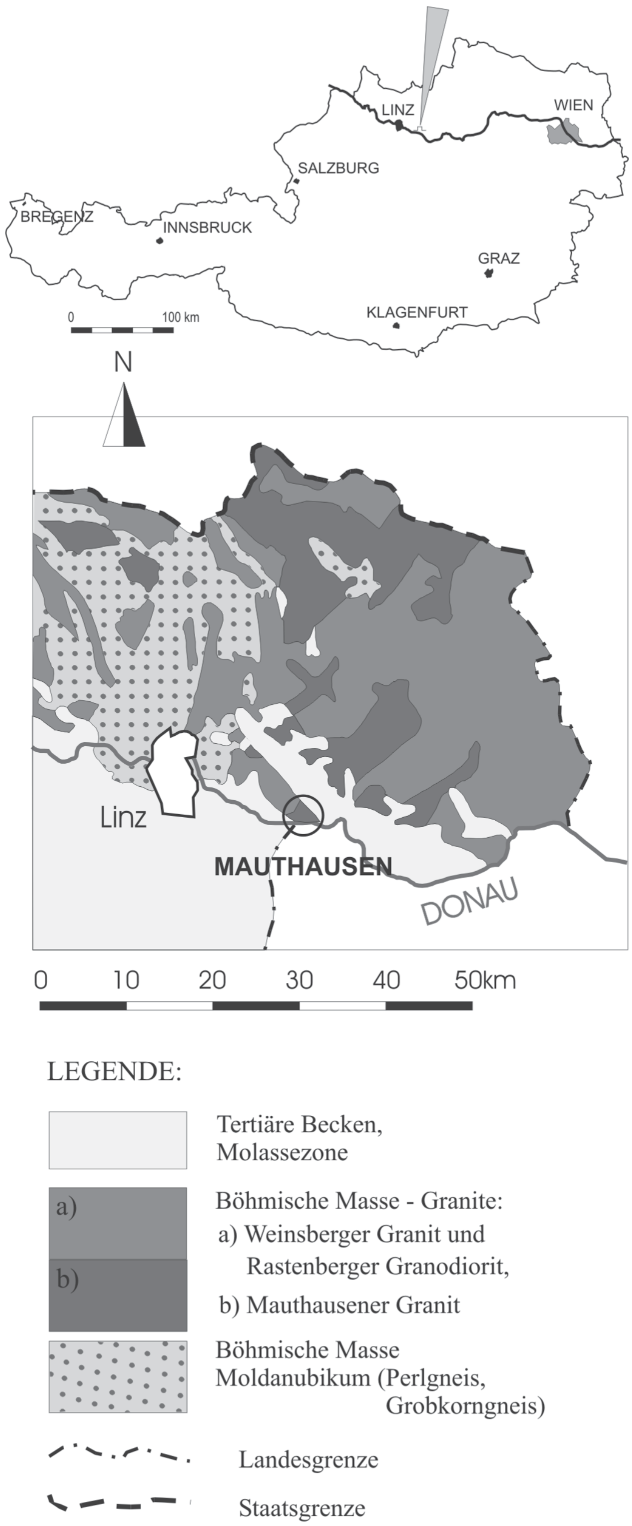

Fig. 2: Location of the granite quarry of Mauthausen in Austria.

2. Geological Setting

The granite quarry is situated in Austria, in the Bohemian Massif, about 15 km south-east of Linz (Upper Austria). Considering the Regional Geology, the area lies at the southern border of the „Moldanubicum", in the so-called „Southern Bohemian Pluton" (see Fig. 2).

2.1. Petrographic Characteristics

The base rock consists of „Mauthausener Granit". It is a fine to middle-grained, plutonic rock with a relatively high content of biotite. The hard minerals are feldspar with 25-35% and quartz with 23%. Caused by the content of biotite (10%) and due to its susceptibility to weathering and to transform itself into limonite, the granite is, along the discontinuities and often up to the centre of the blocks intensely brown coloured and sometimes disintegrated.

2.2. Rock and Rock Mass Parameters

The material parameters were taken from prior field surveys, being conducted in the course of the project. The last measurement campaign took place two years after the first concert event. The field survey included measurements with the Schmidt Hammer and the Point Load Test tool. By the help of the classification systems like the RMR (BIENIAWSKI 1989) , the SMR (ROMANA 1985) and the GSI (HOEK 1999) the input parameters for the numerical model could be evaluated.

3. Discontinuities and Sphere Diagrams

Anchor Point 03

In order to guarantee an optimal distribution of loads, the

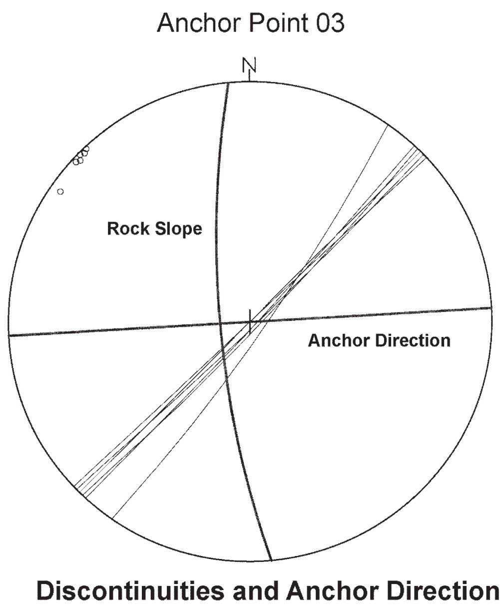

Fig. 3: Sphere diagram of Anchor Point 3.

	Material Parameters	Value
Mass density	ρ	2700 kg/m³
Bulk modulus	$\boldsymbol{K}$	$22{,}5 \cdot 10^9$ Pa
Shear modulus	$\boldsymbol{G}$	$11{,}25 \cdot 10^9$ Pa
Young´s modulus (rock mass)	$\boldsymbol{E_{mass}}$	$27 \cdot 10^9$ Pa
Young´s modulus (rock)	$\boldsymbol{E_{rock}}$	$54 \cdot 10^9$ Pa
Poisson ratio	ν	0,2
Material friction angle	φ	43°
Friction angle in discontinuity	φ	26°
Material Cohesion	$\boldsymbol{c}$	$7{,}4 \cdot 10^6$ Pa
Cohesion in discontinuity	$\boldsymbol{c}$	$1 \cdot 10^6$ Pa
Joint normal strength	***jkn***	$27 \cdot 10^9$ Pa/m
Joint shear strength	***jks***	$11{,}25 \cdot 10^9$ Pa/m

Tab. 1: Material Parameters of „Mauthausener Granit“.

anchor direction was chosen 270° to 090°. As the existing discontinuities in the granite include an angle of more than 40° with the anchor direction, which is bigger than the friction angle of the discontinuity set, hardly any movement will be initiated.
Also, the orientation of the anchor to the rock slope, which is nearly orthogonal to the slope face, contributes to an optimal distribution of loads, which are as high as 1091kN! Considering the profile geometry of Anchor Point 03, the anchor direction encloses a dip angle of 5 degrees with the flat lying discontinuity set which is falling in ENE direction (see also Fig. 7).

Fig. 4: Anchor point 7.

Anchor Point 06

The anchor direction encloses an angle between 30 and 50 degrees to the main discontinuity set. The angle enclosed between anchor and slope direction has a value of about 80 degrees.
Both angles are favourable for an optimal pull out resistance, besides some discontinuities which enclose an infavourable angle. All discontinuities in the area have mostly rough surfaces and are tightly closed, no significant displacements should take place.
As the mean block side-length is about 0.8 m, the granite can be categorized as a blocky, relatively undisturbed rock mass. Only the flat lying joints show apertures of up to 10 mm. They are filled with weathered granite particles.

Anchor Point 07

For this point, the anchor direction is also favourable to the

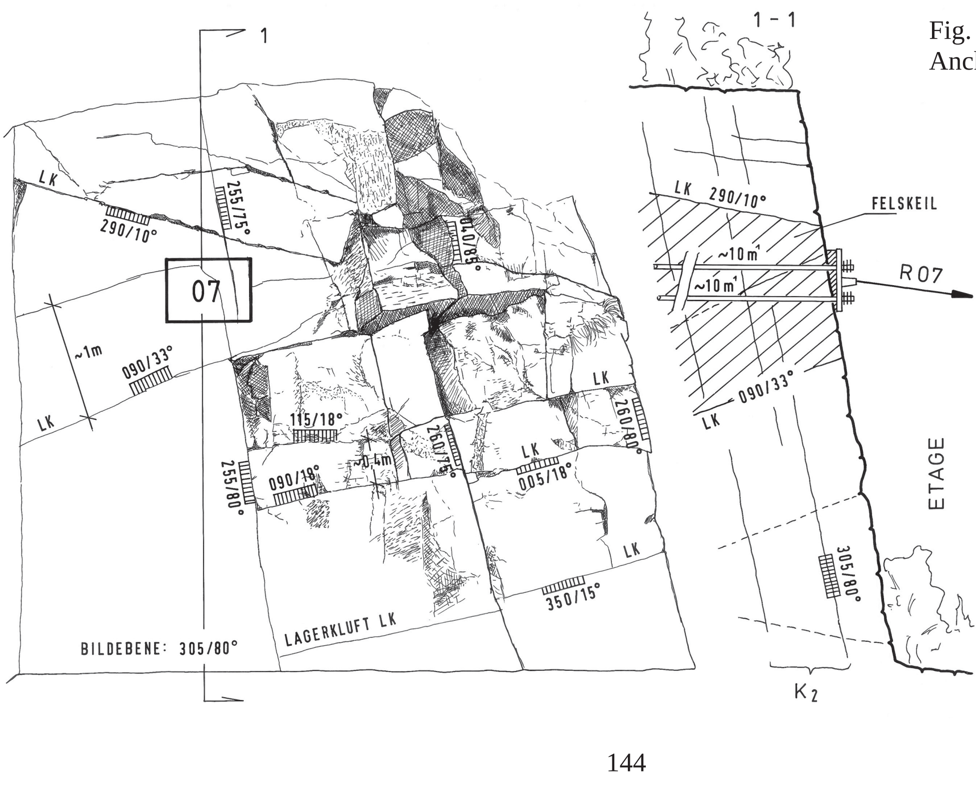

Fig. 5: Discontinuity sketch of Anchor Point 7.

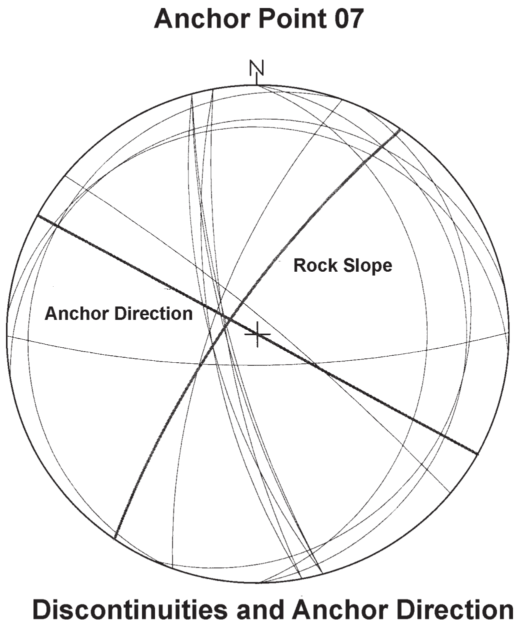

Fig. 6: Sphere diagram of Anchor Point 7.

stability of the slope – it encloses an angle of 90 degrees to the slope.
It consists of 2 main discontinuity sets, one flat and one rather steep, running in direction N-S. These two appearing discontinuity sets form large granite blocks. The side length of the blocks is 1.5 m × 0.9 m × 1.5 m. Therefore, the anchor rod is placed inside one block with a weight of about 5.5 tons. These parts form, together with 2 single joints, a wedge which is nearly impossible to pull out of the block system (see Fig. 5).

Anchor Point 11
Here, the anchor direction is forming a rather small angle with the appearing discontinuity sets. These joint sets dip to the west, consisting of slightly rough to smooth joint surfaces. Together with steep, NW dipping joint sets and the flat lying joints, they form segments of 5-7 tons of total weight.
Although the anchor direction is infavourable, no displacements appear. This can be explained on the one hand because of the weight of the overburden and on the other hand because of the joint surfaces' individual properties.

4. Calculation of pull-out capacity of the rock anchor

Because of lack of time during the construction phase and due to financial decisions, no in-site pull-out tests were conducted. Therefore another method had to be found to determine if the bond length was chosen correctly, in order to absorb the tensile forces.
An empirical formula, presented by (LITTLEJOHN 1995) allows to calculate the required tensile strength of the rock anchor.

$$T_f = \pi \cdot D \cdot L \cdot t_{ult}$$

T_f	anchor capacity
D	diameter of the anchor rod
L	bond length
t_{ult}	ultimate bond or skin friction at the rock/grout interface

These 4 tables present the rough calculation of the anchor capacity, the calculated safety factors and the determination of the required bond length for Anchor Point 01 to 11.
For Anchor Point 03 and 07 an additional numerical calculation is performed.

4.1. Numerical Simulation with UDEC

Four UDEC–models were created to investigate the applied forces which act on the rock and to monitor the resulting displacements. The version 3.10 of the mentioned code

Anchor point	Anchor length [m]	Anchor number	D_{total} Ø [mm]	[N/mm] $t = 0,5.t_{ult}$	(MN) T_{fmax}	(MN) $T_{fmax}.2$	(MN) T_{fexist}	$S_{(exist)}$	$S_{(req)}$
01	2,0	2	114	0,25	0,179	0,358	1,079	5,9	2
	12,0			0,7	3,008	6,017			
02	5,5	2	114	0,25	0,492	0,985	1,062	~4,0	2
	6,5			0,7	1,630	0,259			
03	10,0	2	92	0,7	2,023	4,046	1,111	3,6	2
04	5,0	2	114	0,25	0,448	0,895	0,828	7,6	2
	15,0			0,5	2,686	5,372			
05	10,0	2	92	0,7	2,023	4,046	0,418	9,7	2
06	10,0	2	92	0,7	2,023	4,046	1,036	3,9	2
07	7,0	2	92	0,25	0,506	1,012	0,759	2,9	2
	3,0			0,7	0,607	1,214			
08	2,0	2	92	0,25	0,145	0,289	0,916	5,6	2
	12,0			0,7	2,427	4,856			
09	25,0	2	114	0,10	0,895	1,791	0,480	3,7	2
10	10,0	2	92	0,7	2,023	4,046	1,066	3,8	2
11	10,0	2	92	0,7	2,023	4,046	1,031	3,9	2

anchor capacity
$T_{fmax} = \pi \cdot D \cdot L \cdot t$

t.....working bond strength
T....working load
S....factor of safety
L....anchor length
D....diameter of the fixed anchor

Tab. 2: Anchor capacities and the calculated safety factors considering anchor failure for chosen anchor rod diameters and length.

	Grade of weathering	t (N/mm^2)	Grades
Granite	W 1	0,7	fresh
	W 2-3	0,5	slightly weathered
	W 3-4	0,25	highly weathered
	W 4	0,10	disintegrated

Tab. 3: Grades of weathering for granite and the corresponding working bond strength.

developed by the Itasca Consulting Group was used for the calculation. These points are

Anchor point	Anchor load [KN]	Anchor length [m]	e [m]	$L_{req.}$ [m] (n. S. LITTLEJOHN)	$S_{(req)}$	W [1-4]
01	1079/2	14	2	4,5	2	1
02	1062/2	12	2	4,5	2	1
03	1111/2	10	0,5	9,0	2	1
04	828/2	20	0,5	9,0	2	3-4
05	418/2	10	0,5	5,5	2	1
06	1036/2	10	3	3,4	2	1
07	759/2	10	0,5	7,5	2	1
08	916/2	14	10	1,8	2	1
09	480/2	25	4	2,7	2	4
10	1066/2	10	0,5	8,9	2	1
11	1031/2	10	0,5	8,7	2	1

$$L_{req} = \left(\frac{T \cdot S}{\rho \cdot e}\right)^{\frac{1}{2}}$$

T........working load
S........factor of safety
L_{req}....bond length
e........anchor spacing
ρ........rock density

$\rho_{granite} = 27\ KN/m^3$ ($\hat{=}$ W1)

$\rho_{granite\ blockmaterial} = 20\ KN/m^3$ ($\hat{=}$ W3-4)

$\rho_{granite\ detritus} = 17\ KN/m^3$ ($\hat{=}$ W4)

Tab.4: Determination of the required bond length (L_{req}) at a given tensile load at the anchor points 01-11 (after the formula of LITTLEJOHN (1994) considered as row of anchors in jointed rock!).

· Anchor Point 3
· Anchor Point 6
· Anchor Point 7
· Anchor Point 11

During the project, these 4 points were stated to be the most critical, regarding the safety of the steel network construction. Therefore 4 vertical profiles were created. On order to simplify the problem, the two anchors were considered as one, loaded with the double tensile load. Two of the calculated profiles are presented below.

4.2. The Model

The tensile test is modelled according to the proposals taken from the UDEC manual. The anchor head is embedded into a very stiff block, which is successively moved outwards. This is done with a certain velocity for a number of timesteps in order to control the displacement. Consecutively the anchor is subject to an increasing tensile load. By the help of a monitoring function, the resulting tensile force is measured.

Anchor Point 03:
Point 3 is according to the maximum tensile load of 1091kN the most critical for the survey. The discontinuity system is favourable to the direction of the tensile force, the surrounding rock´s UCS is 130MPa, accounted for the whole length of the rock anchor.
In the course of the simulation the parameters were varied.

Anchor point	Anchor load [KN]	Anchor length [m]		τ_b [KN/m^2]	$\varnothing_d$ [mm]	$L_{req.}$ [m] (n. HOBST & ZAJIC, 1977)	$S_{(req)}$	W [1-4]
01	1079/2	14		700	114	4,3	2	1
02	1062/2	12	2 10	250 700	114	11,9 4,3	2	1
03	1111/2	10		700	92	5,5	2	1
04	828/2	20	5 15	250 500	114	9,2 4,6	2	3-4 2-3
05	418/2	10		700	92	2,1	2	1
06	1036/2	10		700	92	5,1	2	1
07	759/2	10	7 3	250 700	92	10,5 3,8	2	2-3
08	916/2	14	2 12	250 700	92	12,7 4,5	2	1
09	480/2	25		100	114	13,4	2	4
10	1066/2	10		700	92	5,3	2	1
11	1031/2	10		700	92	5,1	2	1

$$L_{req} = \frac{S \cdot P}{\pi \cdot d \cdot \tau_b}$$

S......factor of safety
P.......working load
d.......bore hole diameter
τ_b.....working bond strength
W.....weathering grade
L_{req}...bond length

Tab. 5: Determination of the required bond length (L_{req}) at a given tensile load at the anchor points 01-11 (after the formula of HOBST & ZAJIC 1977).

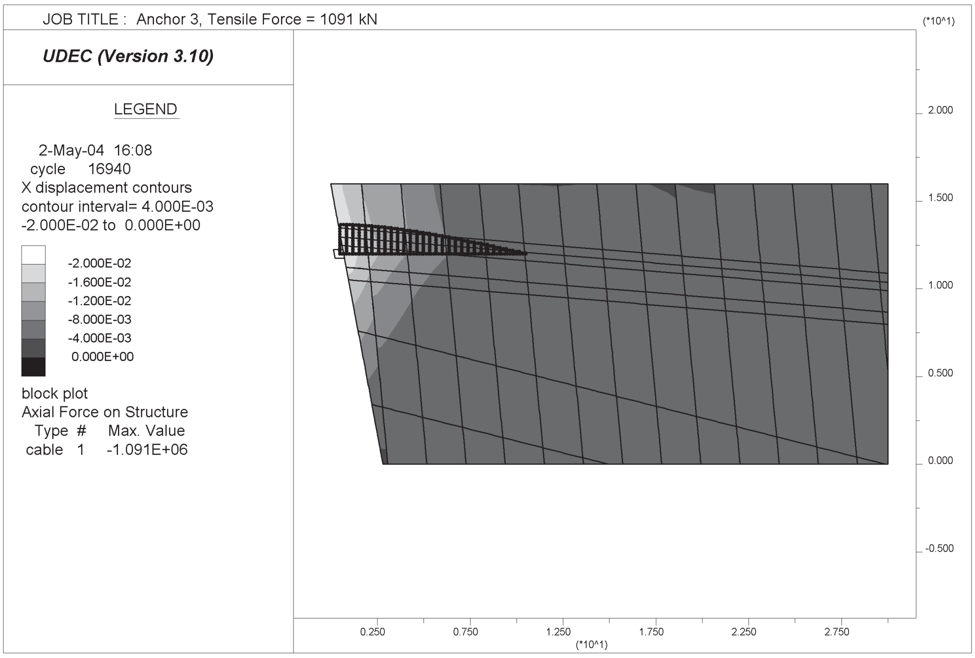

Fig. 7: Profile geometry of Anchor Point 3, x-displacement contours and axial force distribution along the anchor.

A model run with parameters corresponding to the measured values was carried out. In a first step the tensile load of 1091kN was applied to the anchor. It resulted in displacements of up to two centimetres on the rock surface. Afterwards the anchor was unloaded by moving the block embedding the anchor head back the its original position, letting the anchor relax. Resulting plastic deformations remained in the order of 1.9 cm shear displacement along the involved joints.
In another simulation run, the rock was set very stiff (bulk and shear modulus set to $1\cdot10^{12}$Pa/m), while the joint properties remained as before. Resulting displacements after a complete load / unload cycle were now in the order of 1 mm.

Anchor Point 07:
Regarding the local strength of the rock, anchor point 7 seems critical. Two thirds of the anchor length consist of weathered rock with a UCS of 50MPa and a low coverage. At the slope's surface, the rock is less weathered due to its higher strength and resistance. The discontinuity system seems favourable to the system, but the effect on the overall stability cannot be estimated. Therefore the point was chosen for modelling.

The anchor was loaded up to 1.2 times the required load. The required load was with a value of 759kN the lowest of the 4 points. During the simulation, resulting displacement on joints remained at 4 mm. The overall displacement relati-

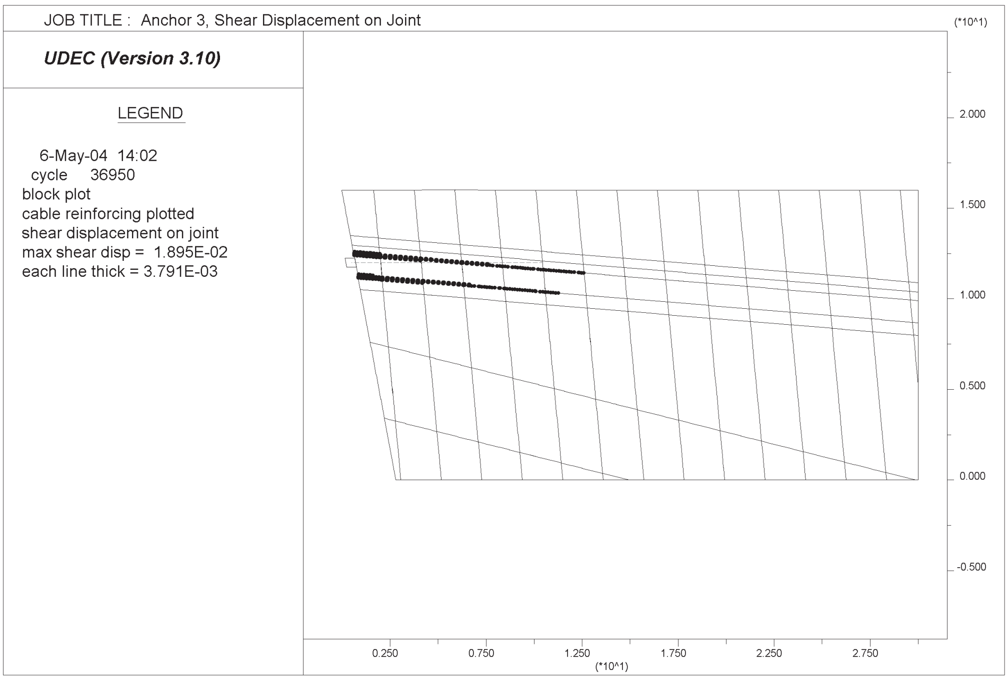

Fig. 8: Anchor Point 3 – Shear displacement along the joints remain in the order of 1.9 cm!

ve to a fixed point was 6mm.

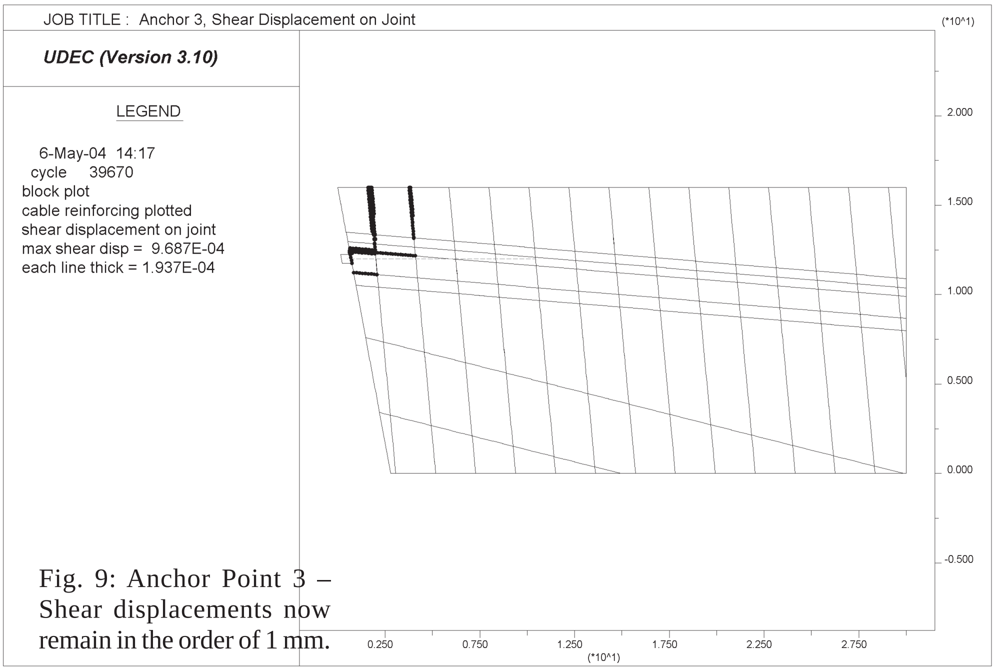

Fig. 9: Anchor Point 3 – Shear displacements now remain in the order of 1 mm.

5. Conclusion

This example shows a typical problem in the subject of engineering geology. Due to missing time or exploration data, important decisions have to be taken in insufficient time. It is, however, a question of responsibility to find the optimal balance between necessities of economy and safety by overdimensioning.
By the means of numerical simulation, a tool is presented, which permits to verify the own assumptions. These assumptions however, due to missing measurement data, do not increase the reliability of the result! In the end, it is still the engineering geologist who has to decide whether to implement certain precautions or not.
It would be wise, to establish a longer period for exploration prior to the construction process.

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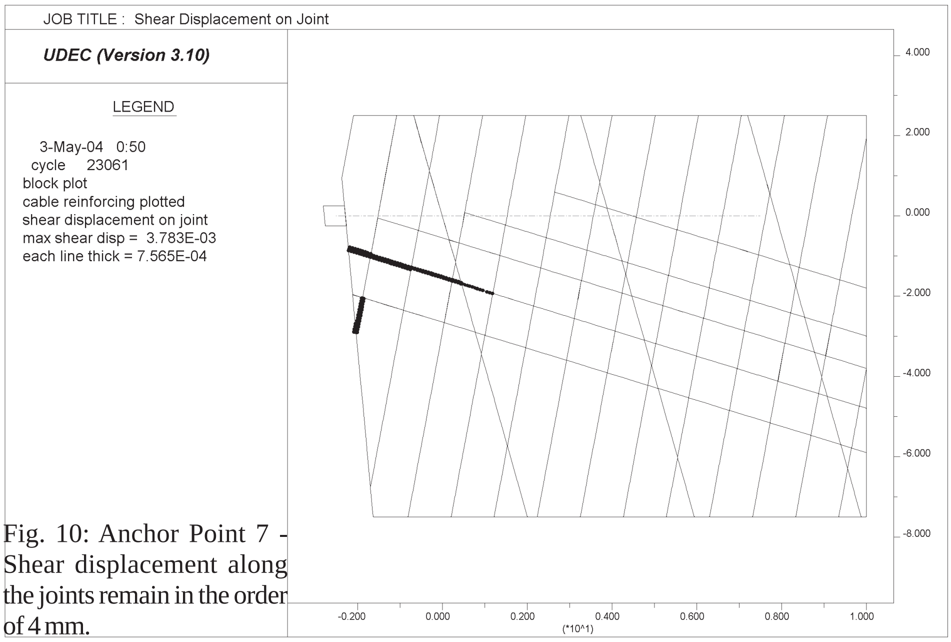

Fig. 10: Anchor Point 7 - Shear displacement along the joints remain in the order of 4 mm.