Rock Slope Instability Zoning with Kinematic and Morphological Factors

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1. INTRODUCTION

In this paper, a natural rock slope is analyzed using a combination of geological and engineering approaches. The movement of the individual parts of the slope has been monitored since 1987. The objective of the work was to study the stability of the slope and the associated mechanisms utilizing this integrated approach. A particular feature was the kinematic and morphological zoning procedures, which further highlights the geological and geotechnical combination.

In the next two Sections, we describe the site conditions and the monitoring systems that we used. This is followed by a presentation of the movements that were detected and the consequential idea of kinematic and morphological instability zoning. Further work was conducted in modelling the blocks using FE-analyses to assist in understanding the fundamental mechanisms that are operating and the associated parameters.

Finally, as a result of the various factors that have been discussed, we summarize the crucial geotechnical parameters and make comments concerning the assessment of risk for a natural system.

2. SITE CONDITIONS

The research area, which is shown in fig. 1, is located in the Carinthian Alps in Austria in a region which has experienced several large scale landslides - which have had a deleterious effect on proximate roads.

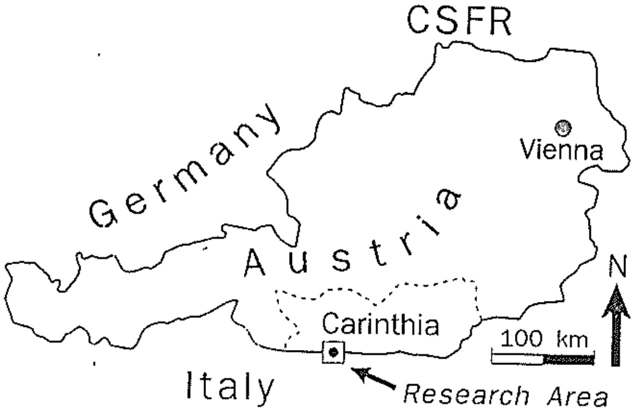

Fig. 1 Location of research area

In fig. 2, we present a schematic cross section of the "Tressdorfer Hoehe", a plateau-shaped mountain. It should be noted, that the surface topography and isolated limestone blocks are essentially the final stage of a disintegration process that has been operative since the last Ice Age, i.e. over the last ten thousand years.

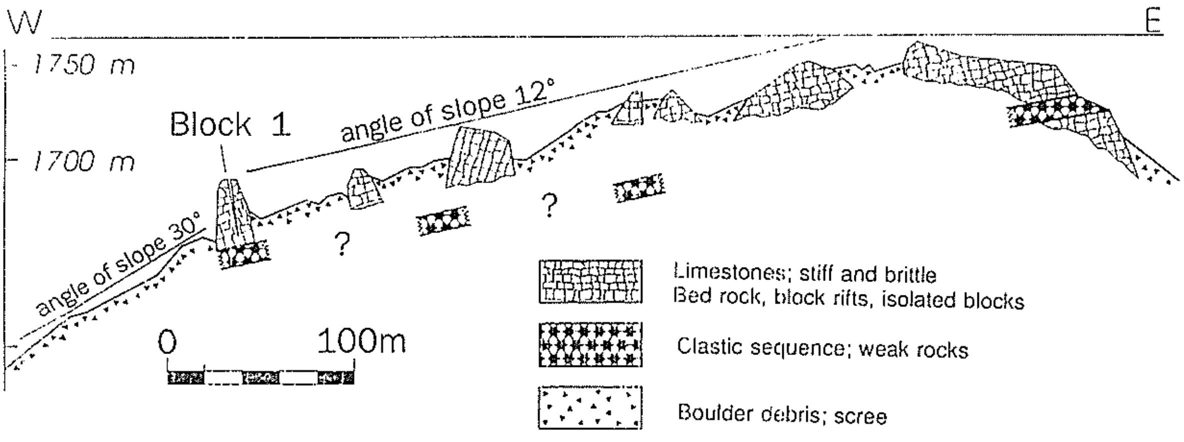

Fig. 2 Geological and morphological section through study area

The limestone slab at the mountain top disintegrated in a series of blocks, which are now moving and are potentially subject to sudden toppling. The stiffer cap-rock of which the blocks are composed overlies a stiff basement seperated by a weak foundation interlayer (fig. 3).

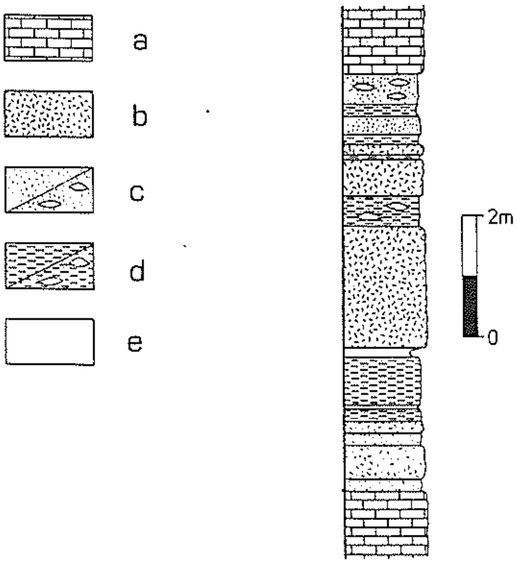

Fig. 3 Geological section of the weak interlayer. (a and b) limestone; (c) sandstone/with clay lenses; (d) siltstone/with clay lenses; (e) claystone

The geometry of the blocks in question is dominated by the main joint sets, which are shown in fig. 4. The NNE- and the ESE-dipping joint sets are opened during failure at the upper scarp (see fig. 2), whilst the SW-dipping sets are opened at the slope edge. The frequencies of the three joint vary from 0.1 to 1m: in some cases, the jointing can be widely spaced because of the existence of reef in the Lower Permian limestone.

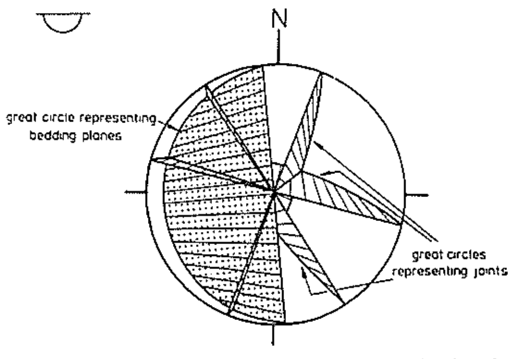

Fig. 4 Discontinuity pattern in study area bedrock

3. MONITORING SYSTEMS

A variety of monitoring devices were used for both the area of interest as a whole and for individual analyses of specific kinematic problems that were addressed. On the wider scale, a precise geodetical survey was undertaken starting in 1989 and is on-going. In Fig. 5, the vectors of absolute displacements and the error ellipses are shown. The geodetic net consists of two fixed pillars, from which 28 optical targets within the block field are monitored. To separate translational and rotational components of the displacements of individual blocks, at least three targets were positioned on the major blocks. The relative displacements between individual blocks were recorded using quasi-continuous readings of extensometers and other displacement indicators.

Some of these instruments were one electronic fixed clinometer, twelve location plinths for tiltmeters, four Moire-indicators, 120 locations for the tape extensometer measurements. Additionally, precipitation, rock and air temperatures are monitored continuously. An example of an instrumentation complex is shown in fig. 6. The pivot of a tilting block (1A) can be established from the configuration of the instrumentation set-up. In fact, the configuration of all the instrumentation was established for optimal interpretation of the slope's kinematics.

4. DETECTED MOVEMENTS

In fig. 7-10, we illustrate examples of the type of measurements that were made from the very large number of data recorded. In fig. 7, the within-crack temperature is shown over a three month period. I can be clearly seen that the variation is extremly smal - within one fifth of a degree - and hence will not affect the displacement readings significantly. In the same tension crack close to the upper scarp, precise extensometer measurements were conducted simultaneously . The results are shown in fig. 8. The dominant trend is a quasi-linear increase of crack aperture totalling one tenth of a millimeter over the same three month period.

Fig. 9 shows displacement readings over a much longer period from June 88 to July 90, taken in a crack close to the slope edge (see also fig. 2). These readings exhibit an almost linear trend over the 120mm recorded. The seasonal influences are detectable within these data. Finally, in fig. 10, we show a scaled up three month portion of the curve in fig. 9. On this curve, individual influences such as heavy rainfall are manifested. It is important to note that such detail is below the resolution of the geodetic survey; indeed, this was the motivation for the two phase displacement recording approach. Also, in anticipation of the need to detect such small displacements for zoning purposes the instrumentation was clearly necessary.

In the next section, we will be discussing the indicators for decoding the measured displacements.

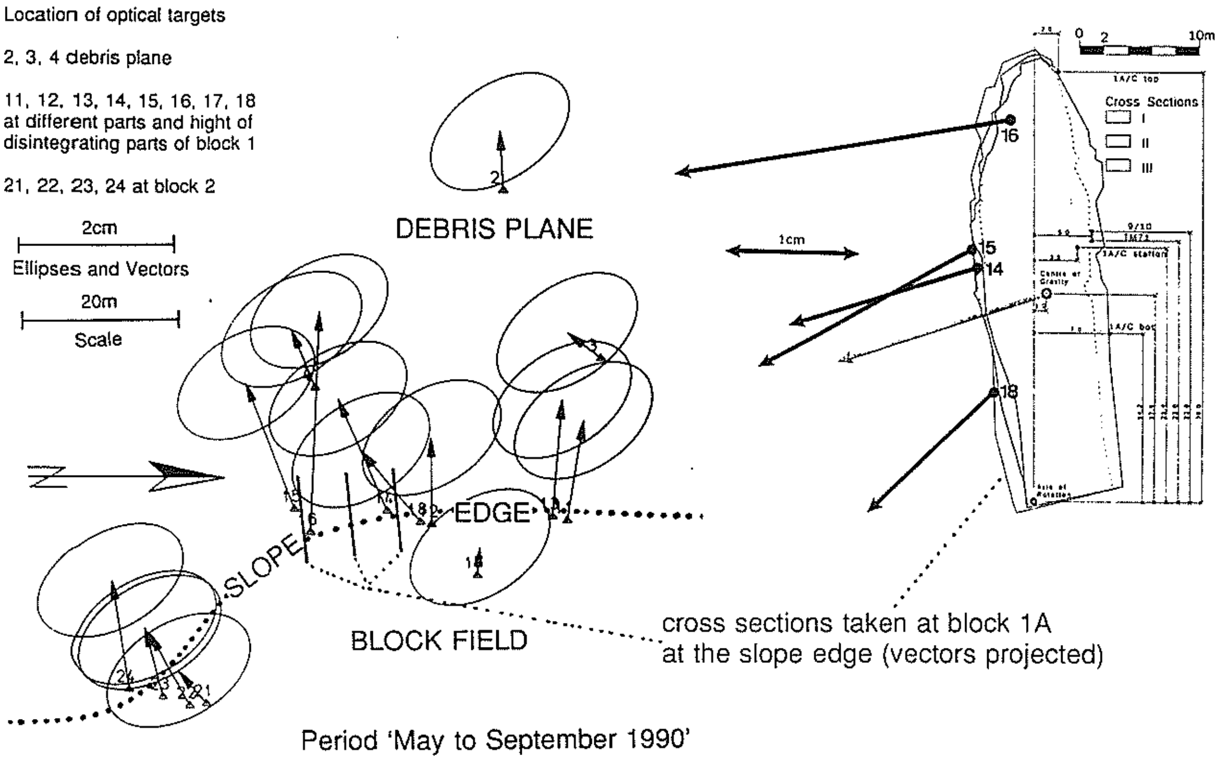

Fig. 5 Results of geodetic measurements in the area of the slope edge

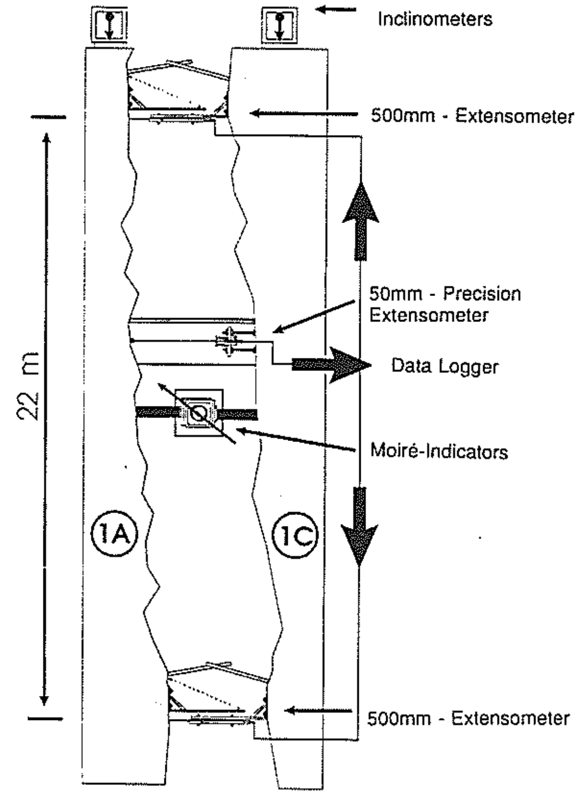

Fig. 6 Instrumentation complex used for continuous monitoring of the path of a block pivot

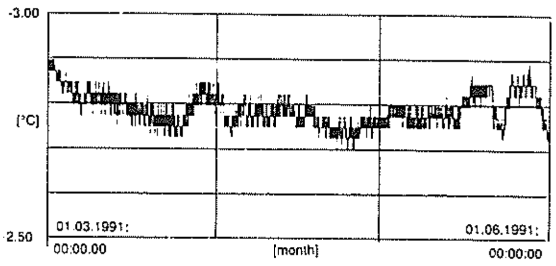

Fig. 7 Within-tension crack temperature measurements close to the upper scarp

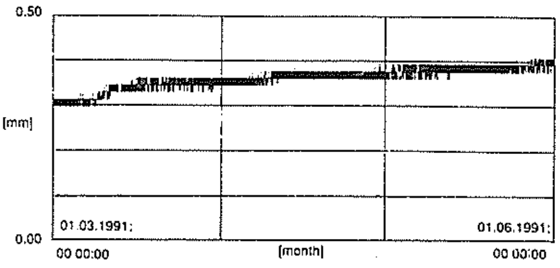

Fig. 8 Precision extensometer measurements in the tension crack close to the upper scarp (see Fig. 7)

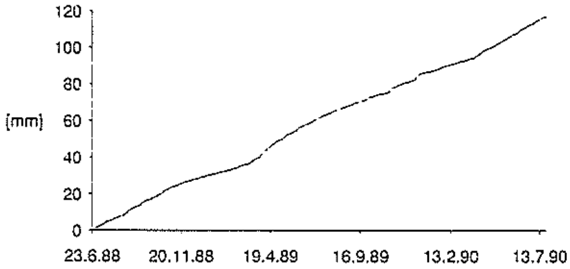

Fig. 9 Precision extensometer measurements in a tension crack close to the slope edge

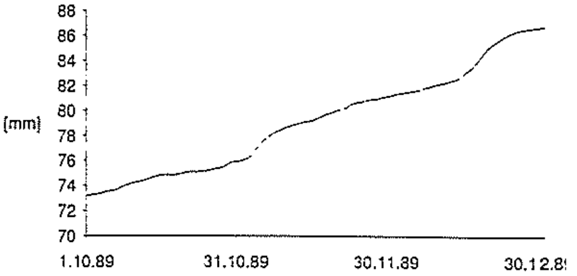

Fig. 10 Scaled-up portion of curve in Fig. 9

A crucial contribution to this interpretation was the use of tiltmeters, indicating the degree to which each block is rotating. This information is an essential pre-cursor to mechanism interpretation.

5. KINEMATIC AND MORPHOLOGICAL INSTABILITY ZONING

Utilizing this procedure for interpreting the displacements, we found that the movements could be conveniently characterized by the factors listed in the table in fig. 11. These can be classified as 'kinematic' characteristics and 'morphological' characteristics, as they apply to the various rock regions from the bed rock right through the completly disintegrated rock mass of the debris plane. We have also provided some guidance on the approximate block sizes in the centra column of the table.

This procedure was implemented to produce the instability zone plane shown in fig. 12. This is clearly leading to the possibility of a risk assessment map for the area. Of course, a total mechanical analysis is not possible because of the complexity of the circumstances: this is why the observational and interpretative approach was used. However, we can gain great advantage by modelling some basic mechanisms of individual parts of the slope, especially being able to take into account the relatively soft foundation layer beneath the blocks. Some of this research is presented in the next Section.

	KINEMATIC CHARACTERISTICS (results of monitoring)	CUBE OF BLOCKS	MORPHOLOGICAL CHARACTERISTICS
BED ROCK	No movement detectable	not defined	insignificant changes in slope angles at the top region; three joint sets and bedding planes; no open cracks or other instability criteria, Karst
BLOCK RIFTS	creep with low rate (<mm/a); toppling and external influences on the kinematics not detectable	< 150.000m^3	trench and ridge structures; lateral disintegration of block rifts (tension cracks), local depressions; opening of two joint sets
BLOCK FIELD	creep with significant rate (cm/a); toppling and seasonal external influences detectable	< 50.000m^3	isolated blocks and pinnacles, different amount of rotation indicated by dip of bedding planes, block shapes controlled by the two opened joint sets
SLOPE EDGE	creep with high rate (<dm/a); seasonal and transient external influence significant; sudden toppling failure; rock falls	< 25.000m^3	convex slope edge; opening of the third joint set; significant amount of rotation indicated by dip of bedding planes
DEBRIS PLANE	differing amounts of displacement (mm/a to cm/a), no seasonal or transient external influences detectable	< 100m^3	uniform dip of slope, individual boulders of intact rock

Fig. 11 Table of kinematic and morphological characteristics

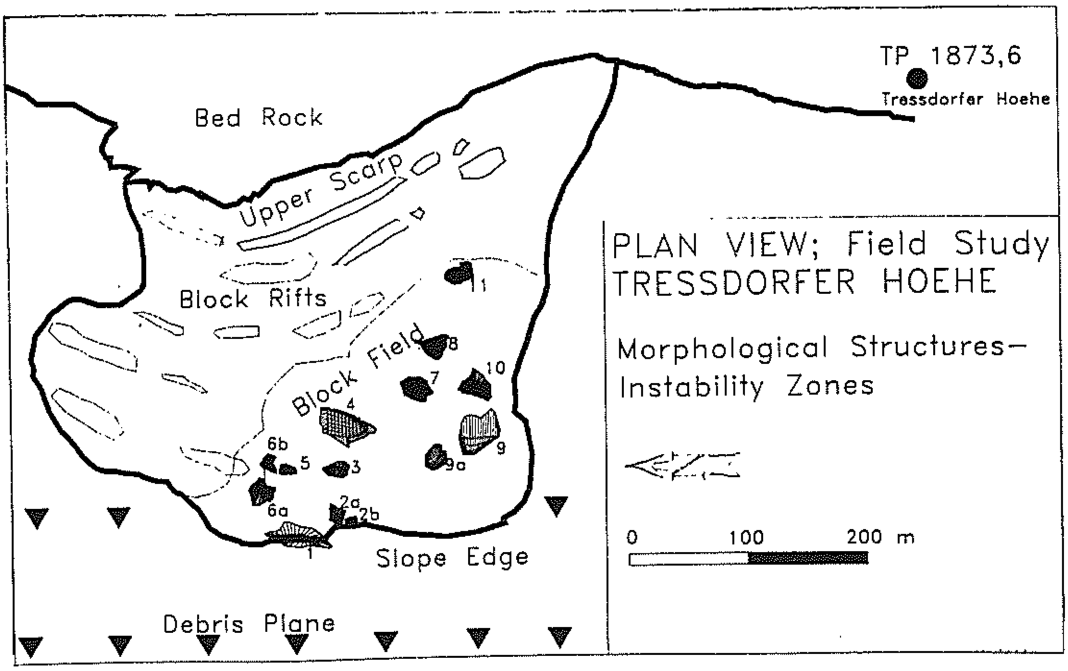

Fig. 12

6. RESULTING POTENTIAL FAILURE MECHANISMS

The field conditions for block 1A and for the presently developed upper scarp were idealized as shown in fig. 13, the dip of the overall slope being 12 degrees. The thickness of the weak strata and the stiff cap-rock are eight metres and fourty metres, respectively.

Results from the FE-analyses are shown in fig. 14: these include the horizontal stresses at the slab margin and the deformed mesh resulting from gravitational loading. It is realized that the rock disintegrated earlier while gravity was acting, but these results are useful to indicate the likely areas of high stress and displacement and hence failure mechanisms.

The failure criterion allowed for post-yield plasticity. The analysis indicated that increasing plasticity of the weak layer led to the development of a tensile zone within the lower parts of the cap-rock behind the free face, which possibly initiated the disintegration of the

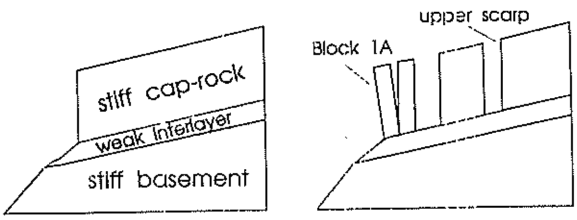

Fig. 13 Idealized field conditions for FE modelling

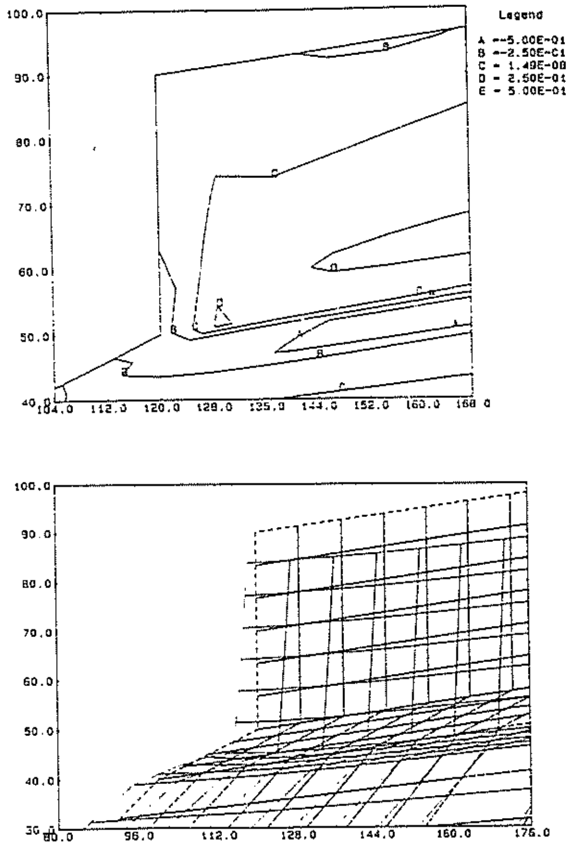

Fig. 14 Illustrative FE modelling results for stress and displacement

stiff slab into single blocks. This failure mechanism appears to exist at the present upper face.

These analyses also indicated, via the stress distribution of individual blocks, that 'shear outs' at the blocks are appear to be highly unlikely - because the deviatoric stresses do not exceed 2.0MPa. This is another indication of the value of such analyses in indicating likely and unlikely failure mechanisms - within the context of the types of instabilities being discussed here.

Because of the restriction on the length of this presentation, we cannot demonstrate all the analyses and results, but we hope that the limited presentation here will have highlighted our basic philosophy and methodology in approaching this very complex natural instability.

7. CRUCIAL GEOTECHNICAL PARAMETERS

As a result of the work described here, we have been able to identify the important geotechnical parameters and mechanisms associated with this specific problem. In this table we have included such factors as block geometry and the various types of displacement indicators. Thus, our interpretation of geotechnical parameters includes all those factors which are necessary to solve the geotechnical problem - whether these be mechanical, geometrical or geological.

In fig 15, we include a table of these parameters as they relate to the toppling mechanisms discussed earlier. These can be used directly as we have demonstrated in this paper to monitor potential instability. They could also be used in a tailored risk assessment methodology, via a semi-quantitative classification scheme, especially to indicate relative block instability risk priority.

8. CONCLUSIONS

In this paper, we have described the study of a particular natural instability. The techniques were specifically directed towards analyzing the potential risk of slope instability at the case study location "Tressdorfer Hoehe", and were tailored accordingly. However, we would like to emphasize that the methodology has a very general applicability in assessing geotechnical risk. In the complex circumstances encounted, simple models are inadequate and complex models are not viable because the input is insufficient. Thus, an intermediate approach has to be adopted, which integrates the observational techniques with trend interpretation and identification of the critical geotechnical parameters. As we have mentioned, a series of blocks such as those analyzed could be classified according to their relative risk - which is often what is required in remedial measures when constraints are imposed by limited financial resources.

	GEOTECHNICAL PARAMETERS AND INSTABILITY INDICATORS	CONSEQUENTIAL RISK	GEOTECHNICAL APPROACH
WEAK SEQUENCE	mechanical properties of rock mass and intact rock	bearing capacity failure, development of shear zone results in secondary block toppling	laboratory testing, continuous monitoring of pivot (tiltmeters, extensometers), geodetic monitoring
	geometry (dip, thickness)		
CAP-ROCK AND INDIVIDUAL BLOCKS	block (pinnacle) geometry	single block toppling	field study and monitoring of path (depth) of pivot
	strength of rock mass	disintegration of bed-rock, shear off at block toe, sudden failure	laboratory testing, FE- and DE-analyses
	discontinuity orientation, spacing and shear strength	secondary failure (plane, block) in toppling blocks, decrease of block toppling factor of safety	field study, monitoring of block tilting
	rate of tilting	indicator only	
	degree of external influences	sudden toppling failure induced by joint water pressure (for potential toppling blocks $F \sim 1/z_w^3$)	continuous, precise monitoring of external factors, block tilting and tension crack aperture

Fig. 15 Table of significant parameters for block instability zoning and block instability risk assessment