A Goal Orientated Approach to Rock Slope Engineering

By Edward Button and Wulf Schubert

Rock slope engineering is rapidly becoming a key discipline in Civil Engineering as development increases throughout the mountainous regions of the world. The engineering requirements may vary considerably depending on when the engineer becomes involved. For example the requirements, available resources and information, and the ultimate solution are different if the project involved a preliminary risk assessment, temporary or permanent cut slope designs, or involved an actively failing slope. In all of these situations, the solutions are governed by risk and economics. The goal of the engineering works is to reduce both the project and public risks associated with a potential slope instability or failure to acceptable levels.

In order to asses a slope's potential instability a multi-disciplinary approach should be used. Engineers must work with geologists, hydrologists, geophysicists, and geodesists when evaluating a specific slope. The geotechnical engineer and the engineering geologist need to evaluate the available information and perform site reconnaissance to develop a site specific geologic model and determine what material parameters need to be evaluated and how to evaluate them. Hydrologists are necessary to evaluate the groundwater and hydrological system and assist the engineer in determining its importance to the slopes behavior. Geophysicists provide methods to evaluate a geologic features extent in the subsurface, as well as monitor active brittle failure with acoustic methods. The geodesists provide techniques for monitoring the surface and subsurface deformations with unprecedented accuracy. All of the information must be combined into a coherent model that can describe how the slope is behaving and what will happen over the course of time as environmental or engineering perturbations occur to the system. It is the goal of this paper to assist the geologist and engineer in identifying what is necessary, from a procedural point of view, to perform a robust evaluation of a slope's behavior. Several examples will be shown to highlight the principles discussed within this contribution.

Site investigations

The goal of the initial site investigation is to develop a site specific geologic model that allows the identification of active or potential failure modes. From this, additional investigations are designed that focus on acquiring the information necessary to perform a robust engineering analysis and design.

Zielorientierte Behandlung von Felsböschungsproblemen

Die ingenieurmäßige Behandlung von Felsböschungsproblemen erfordert eine intensive interdisziplinäre Zusammenarbeit. Ingenieure und Geologen müssen von Anfang an mit Geophysikern, Hydrologen und Geodäten eng zusammenarbeiten, um ein möglichst genaues geologisches Modell erstellen zu können. Zur Optimierung der Erkundung und der Planung ist eine zielorientierte Vorgangsweise zu wählen. Für jede Phase des Projektes sind die für die Analyse wesentlichen beziehungsweise notwendigen Informationen zu definieren, und entsprechende Methoden zur effizienten Erhebung von qualitativ hochwertigen Daten zu wählen. Die Aufgabe des Geologen ist es, die geologische Architektur zu erarbeiten und darzustellen. Das Modell soll die maßgebenden geologischen Strukturen, sowie Hinweise auf frühere aktuelle Instabilitätsphänomene, sowie Erhebungen von potenziellen oder aktiven Versagensmechanismen enthalten. In der Regel sind zusätzliche Erkundungen in einer zweiten Phase erforderlich, um das geologische Modell zu verifizieren und zu verfeinern, sowie die erforderlichen Parameter für Stabilitätsanalyse und eventuelle Sicherungsmaßnahmen zu erheben. Bei der Planung dieser Phase ist auf einen Zugewinn relevanter Information und die Sicherstellung von qualitativ hochwertigen Daten zu achten.

Rock slope engineering requires a multi-disciplinary approach. Engineers and geologists must work with geophysicists, hydrologists, and geodesists to develop accurate site geologic models. In order to optimize the investigation and design, a goal orientated approach should be taken. For each phase of the project the information necessary for the engineering evaluation should be defined and appropriate methods used to acquire quality data. The geologist needs to evaluate the sites geological architecture to develop an engineering geological map that documents what major geologic features exist at the site including any evidence of past or current instabilities. Potential or existing failure modes should be identified, and further field investigations planned to update and confirm the site geologic model and to acquire the necessary physical parameters for both stability evaluations and designing remedial measures. Throughout this process the quantity of information will increase and efforts need to be taken to ensure high levels of data quality.

Fig. 1 Small block failure in a road cut formed by a cross joint intersecting a major joint.

Bild 1 *Der Verschnitt von zwei Trennflächen führt zum Abgleiten eines kleinen Blocks.*

The engineer and geologist must communicate throughout this process to optimize the information gained from the available resources. The geologic mapping should foremost consider the scale of the project. For any slope the most important features will be discontinuities that are continuous at the scale of the slope or project. For example, in small road cuts individual joints can form blocks that are kinematically free to displace (Figure 1) while in a very large slope the same joint system may not lead to the same rock mass behavior. At the other extreme, intersecting major shears or faults can form very large blocks that require extensive support measures, while the similar features encountered in a small slope can lead to local failures associated with the local decrease in overall material strength (Figure 2).

Fig. 2 Examples of potential instabilities associated with faults or shears at different slope scales.

Bild 2 *Beispiele von potenziellen Versagensmechanismen in Zusammenhang mit Störungen oder Harnischen in verschiedenen Maßstäben.*

Failure mechanisms

Once the site geological model is established it is necessary to determine, given the specific geological and environmental conditions, what possible failure mechanisms may occur. Clues to previous or ongoing deformations can often be observed by careful evaluation of the sites geomorphic characteristics. By combining geomorphic evidence with the geological conditions primary and secondary failure modes should be determined. Goodman and Kieffer (1) and Goodman (2) present a review of slope failure modes and distinguish them by a kinematic hierarchy. This is a different approach than evaluating potential slope behavior through rigorous stress analysis, and is very practical during investigation stages as it helps to focus additional surveying and testing on the key parameters necessary for evaluating the identified failure mechanisms and potential remedial measures.

One of the most difficult engineering decisions is whether the rock slope can be treated as a continuum. Research work by many, including Kieffer (3) demonstrate that as the block size decreases relative to the scale of the slope, the overall behavior approaches that of a continuum. If major features (with weaker material properties) still exist within the slope or if one discontinuity set governs the failure mode then this assumption should be verified by performing additional analyses of discrete block systems and comparing the results to that of the continuum approach.

The evaluation of more complex failure mechanisms requires additional care as the mechanisms involved can be quite interdependent. Deformation of one zone or mode may create additional kinematic freedom for a more critical mode that leads to increased movements or slope failures. Many failure modes can often be observed in large deforming slopes, to properly analyze the slope the underlying mechanism needs to be determined. Then the secondary failures can be treated individually if they still pose a risk.

One must also consider if blocks are incompletely formed, rock bridges form a vital strength component in many rock slopes. Their behavior is very difficult to model and new approaches that base the overall strength on cohesion loss and friction mobilization with strain show some promising results (4, 5, 6) as do methods based on fracture mechanics and stress corrosion (7). The latter is still more in the research stage and is more difficult to apply as evaluating the correct material parameters is difficult and time consuming.

Triggering mechanisms

Once the potential failure modes are determined, the next goal is to identify possible triggering mechanisms. Triggering mechanisms can be either natural phenomenon or induced by man. The most critical triggering mechanisms usually involve changes in the slope geometry or the hydrological system. Other common factors include dynamic loading (most commonly from earthquakes), static loading, loss of material strength due to weathering, freeze-thaw cycles, etc. and a loss of lateral support through erosion or in some cases glacial retreat. Once the triggering mechanisms are identified and appropriate levels are determined which would result in slope instability, remedial measures can be developed to both prevent that level from being reached or to physically restrain the slope system.

Material parameters

In addition to having the correct system geometry, appropriate values for the strength and deformability are essential for any engineering evaluation. The evaluation of engineering material parameters should consider the identified failure modes and mechanisms, as well as potential remedial measures. This information should be used to determine where and how samples are acquired and to develop appropriate testing procedures that simulate the correct boundary conditions. Data quality should be the focus of the investigation, a few correct samples and appropriate tests are much more valuable then a huge number of tests that are not directly applicable to the engineering analyses. Laboratory results are very valuable if the tests are part of the overall evaluation but can be misleading if not directly related to the problem under investigation. Blümel and Semprich (8) discuss these concerns as well as how different boundary conditions can be simulated in the laboratory with modern testing equipment.

Examples

Figure 3 shows a wedge failure in a foliated rock mass created by the intersection of a cross joint and a slickensided foliation plane. To evaluate this failure mechanism the joint and foliation planes orientations and dip (as well as their variability) are necessary as are the strength properties of the surfaces. In this case deformability is not necessary as elastic deformations are not really of concern. What is important, and often impossible to measure in space is the curvature It should be noted that the cross joint is not planar (evident by the

Fig. 3 Wedge failure in a foliated rock mass. Note the curved line of intersection indicating non-planar joint surfaces.

Bild 3 *Keilversagen in geschiefertem Gebirge. Der gekrümmte Verschnitt zeigt, dass die Trennflächen nicht eben sind.*

curved intersection line) and therefore predicting the safe excavation depth given the location of the intersection above the slope would have conveyed false security. In many

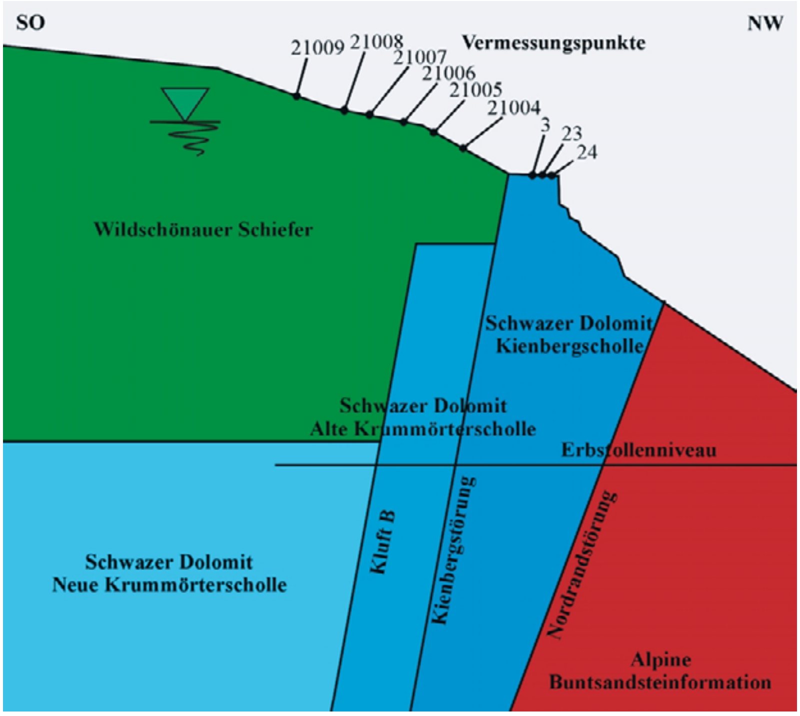

Fig. 4 Simplified geologic cross section of the Eiblschrofen.
Bild 4 *Vereinfachter geologischer Schnitt durch den Eiblschrofen.*

Fig. 5 The first major block fall at Eiblschrofen on the 10th of July.
Bild 5 *Der erste Felssturz am Eiblschrofen vom 10. Juli.*

Fig. 6 Photo on the 12th of July.
Bild 6 *Foto vom 12. Juli.*

cases joints or faults associated with complex deformations are curved. This characteristic often results in increased stability if the block movement is restricted due to dilation. In other cases where dilation does not restrict block movement the difficulty in projecting the features in space can lead to errors in the analysis. This case demonstrates several difficulties associated with a relatively simple failure mode. These problems are not restricted to this example but are encountered in many projects associated with complexly fractured and or folded rock masses where joints and faults are often curved.

The next example focuses on the difficulty in determining triggering mechanisms when multiple mechanisms may be acting on the system. In this example a dolomitic rock mass experienced several large block failures over a period of several months. A major fault zone separates the failing dolomite rock mass and phyllites that extend towards the mountain peak. A simplified geological section is shown in Figure 4. Figures 5, 6 and 7 show the progressive initial failure of the dolomite over a period of four days.

The first figure shows the initial slope failure which involved a wedge, created by a major shear plane (open fracture right side of the failure) and a highly weathered filled joint (evident by the coloring). The additional kinematic freedoms introduced by the first failure coupled with continued movement of the entire slope induced several additional wedge failures over the next several days and weeks. There are two possible triggering mechanisms for this case. High precipitation amounts throughout the winter and spring increased the ground water levels in the phyllites behind the dolomite. This increased the load on the dolomite, which acts like a buttress for the phyllites, gradually toppling the slope. The toppling caused previously stable blocks to fail (9). Indeed throughout the Alps large landslides were reactivated in the spring-summer of 1999 consistent with the climatic influence as a probable mechanism (10). The other potential influencing factor is a mine located some 400 to 450 m beneath the slope (11). A previous mine cavity failure propagated to the surface, resulting in a typical sink hole type depression at the surface, however the stability of the dolomite was not compromised in this event. A failure in another section of the mine has not been proved or disproved due to lack of access. So this influence is still debatable.

Information necessary to analyze this failure includes orientation data of major features, especially noting which joints have opened, where, in which direction, and how deep if possible. Strength data for the dolomite including both, discontinuities and intact rock, the intact rock is necessary to evaluate the strength of rock bridges that gradually fail as the load conditions change. Ground water levels in the phyllites, the orientation and strength data, as well as the geometry and failure characteristics of the potential mine collapse need to be known. This is an important consideration for evaluating the triggering mechanisms. A slope monitoring program was initiated after the failure. This data assists in modeling the post failure behavior, however no monitoring data was available before the failure. So the magnitude and style of the failures development are not available for calibrating the model.

By examining the joint orientation data, potential failure modes can be distinguished, including toppling, sliding, and multiple wedges. Figure 8 shows a summary of the joint and fault orientations provided in a geological report (12). When displayed in this manner individual modes are difficult to distinguish, ideally in a geologic report accompanying the summary would be individual plots showing which discontinuities result in which failure mechanism. In addition to this, the spatial characteristics and relationships of these discontinuities are important for evaluating the slope behavior.

Figures 9 and 10 show a slope excavated in a sequence of sandstone and claystone. The thickness of the claystone layers ranged between 10 to 30 cm. The initial slope was cut at angles between 50° and 56° taking advantage of the sandstones strength. Immediately after the excavation the slope began to deform. The deformation in the weak claystone resulted in brittle fracturing of the thicker sandstone layers forming blocks which were then able to detach, slide and fall into the excavation. This process continued until the slope approached the original slope angle. No additional support was implemented and it was necessary to acquire more land to accommodate the final stable slope.

One must consider how the components of a complex system will interact if and when deformation begins. Even though a component or individual feature may make up only a small portion of the rock mass if it is considerably weaker and continuous it may control the entire slope response. Overlooking these features and their importance can potentially lead to problems as demonstrated with this example.

Conclusion

Rock slope engineering is a complex field that requires engineers and geologists to work together towards a common goal. The engineer requires specific information to solve the problem at hand and must be aware of how the geology influences the slope behavior. The geologist must approach the project from a perspective of the engineer, what is necessary to describe the engineering behavior of the rock mass while supplying accurate information about the sites geologic architecture. It is tempting to provide a complete description of the geologic develop-

Fig. 7 Photo on the 14th of July.

Bild 7 *Foto vom 14. Juli.*

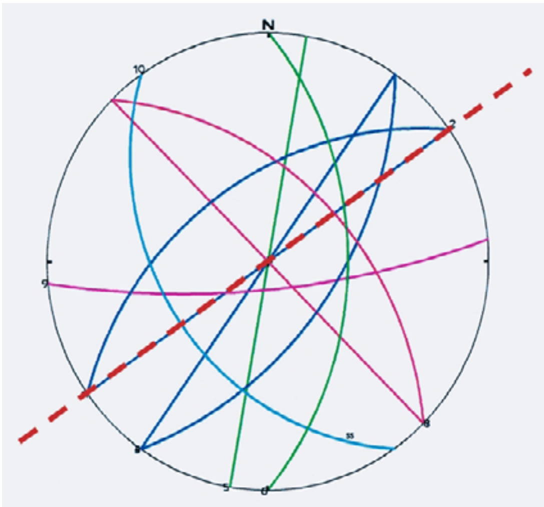

Fig. 8 Measured joint orientations (lower hemisphere) at the western part of the Eiblschrofen The dashed line represents the slope orientation.

Bild 8 *Kluftdiagramm des westlichen Bereichs des Eiblschrofens. Die strichlierte Linie zeigt die Orientierung der Böschung.*

Fig. 9 Photo of a failing rock cut showing the original slope height and approximate angle. Note the shallow dipping claystone beds forming the breaks in the slope.

Bild 9 *Flach einfallende Tonsteinlagen führen zu Böschungsversagen.*

Fig. 10 Close up of one claystone layer and fracturing of the overlying sandstone.

Bild 10 *Detailansicht einer Tonsteinlage mit darüber liegendem Sandsteinblock.*

ment of a site. Much of this information has purpose in developing relationships between different materials, discontinuity sets, their distributions and material properties. It is up to the engineering geologist to interpret these relationships and communicate to the engineer the locations, relationships, and conditions of important features. Together they must develop a geologic model with appropriate material properties that can be evaluated using today's techniques. The investigation phase of a project lays the groundwork for all further engineering work. Focusing the investigation on acquiring quality information about the key geologic structures, their material properties, and confirming the geologic conditions that influence the slopes behavior optimizes resource utilization. An accurate geologic model is essential for meaningful rock engineering analyses.

References

1. Goodman, R.E. ; Kieffer, D.S.: *Behavior of Rock in Slopes*. Journal of Geotechnical and Geoenvironmental Engineering 126 (2000), No. 8. pp. 675-684.
2. Goodman, R.E.: *A Hierarchy or Rock Failure Modes*. Felsbau 21 (2003), No. 2, pp. 8-12.
3. Kieffer, D.S.: *Rotational Instability of Hard Rock Slopes*. Felsbau 21 (2003), No. 2, pp. 31-38.
4. Hajiabdolmajid, V. ; Kaiser, P.K. ; Martin, C.D.: *Mobilization of Strength in Brittle Failure of Rock – In Laboratory vs. In Situ*. Proceedings of the 5th North American Rock Mechanics Symposium, Toronto, Canada, Vol. 1. pp. 227-234. University Toronto Press, 2002.
5. Hajiabdolmajid, V. ; Kaiser, P.K.: *Modelling slopes in brittle rock*. Proceedings of the 5th North American Rock Mechaniscs Symposium, Toronto, Canada, Vol. 1. pp. 331-338. University Toronto Press, 2002.
6. Eberhardt, E. ; Kaiser, P.K. ; Stead, D.: *Numerical Analysis of Progressive Failure in Natural Rock Slopes*. Proceedings International Symposium on Rock Engineering for Mountainous Regions, EUROCK 2002, Funchal, Portugal, pp. 145-153. Sociedade Portuguesa de Geotecnia, 2002.
7. Kemeny, J.: *The Time-Dependent Reduction of Sliding Cohesion due to Rock Bridges Along Discontinuities: A Fracture Mechanics Approach*. Rock Mechanics and Rock Engineering 36 (2003), No. 1 pp. 27-38.
8. Blümel, M. ; Semprich, S.: *Slope Instability – Laboratory and In-Situ Testing*. Felsbau 21 (2003), No. 2, pp. 39-45.
9. Volkman, G.: *Einfluss von Gebirgsstruktur und Reibungseigenschaften auf Hangbewegungen am Beispiel des Eiblschrofens*. Diplomarbeit. Institut für Felsmechanik und Tunnelbau, Technische Universität Graz, 2000.
10. Latelin, O. ; Bollinger, D. ; Hegg, C. ; Kreusen, H.R.: *The Analysis of the 1999 Landslides in Switzerland*. Proceedings International Conference on Landslides – Causes, Impacts, and Countermeasures. Davos, Switzerland, pp. 159-167. Essen: Verlag Glückauf, 2001.
11. Pöttler, R.: *Landslides and Mining: Collect – Calculate – Compare – Concept at the Eiblschrofen Rockfall*. Proceedings International Conference on Landslides – Causes, Impacts, and Countermeasures. Davos, Switzerland, pp. 351-364. Essen: Verlag Glückauf, 2001.
12. ILF: *Bericht zur Georisikokartierung Eiblschrofen und Mehrerkopf*. 1996.

Authors

Edward Button and Professor Dipl.-Ing. Dr. Wulf Schubert, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstrasse 12, A-8010 Graz, Austria, E-Mail tunnel@tugraz.at