Rock Engineering Risk Assessment through Critical Mechanism and Parameter Evaluation

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1. INTRODUCTION

There is currently a need in rock engineering for a coherent approach which allows the identification of the important parameters and mechanisms for any rock engineering activity - based on the project's objectives. A new methodology is being developed which enables, through a comprehensive listing of all major geotechnical parameters, the establishment of the interactive mechanisms associated with these parameters and also a method for prioritizing the mechanisms and parameters based on the 'cause' and 'effect' values and the assessment of instability scenarios (1,2). The appraisal is directed to the objective(s) of the project. This technique is demonstrated by use of rock interaction matrices where the cause and effect of parameter interactions can be used as an indication of the critical mechanisms and parameters before, during and after construction.

Essentially the 'cause' refers to the influence that a parameter has on the engineering system; whereas, the 'effect' refers to the influence that the system has on the parameter. The methodology is briefly referred to here and will be expanded in future papers. The principles of the technique are illustrated with repect to some of the rock treatment methods applied in the construction of the Fei-Tsui Dam in Taiwan (3).

2. USE OF THE INTERACTION MATRIX APPROACH

The interaction matrix is the running theme through a three-tier approach that is being developed to assist in the design, construction, and monitoring for all rock engineering. The three tiers are
a) REMIT - Rock Engineering Mechanisms Information Technology (in the language of systems, this component consists of morphological and cascading systems, ie the basic structure of the system with interlinking),
b) RESP - Rock Engineering System Performance (consisting of a process-response system with generic induced perturbations, ie studying the responses governed by the natural rock mass process and effects induced by engineering), and
c) ONSE - Objective-based Network Sequence Evaluation (consisting of the system pathways governed by the project engineering, ie the specific engineering work required to achieve the objective).

Within any engineered rock mass there will usually be a number of key parameters, from the rock mass, the site environment and the engineering project, which will dominate the performance of the engineered rock mass to the detriment of the engineering objectives. The key parameters can only be determined by identifying the mechanisms and the sequence of interactions which take place to create instability. We use the interaction matrix for this purpose.

Many interaction matrices have been developed by the senior author, and we can only demonstrate part of one here to give the general idea (see Figure 1). In this sub-matrix, of a larger slope stability assessment matrix, we show just three of the main parameters in the black boxes along the leading diagonal. The information in Box ij illustrates one example of the interaction of the parameter in Box ii on the parameter in Box jj.

We can now develop coding methods to enable this interaction matrix to be used for quantitative assessment of parameter significance, dominance, and indeed system risk. The general principle is shown in Figure 2. If the actual construction procedure is placed in the last box, ie Box nn, then the right hand column of the matrix illustrates the design factors, and the lower row of the matrix illustrates the effects of engineering.

As mentioned, the actual use of the total REMIT/RESPONSE system will be explained in future publications; here we simply illustrate how a key parameter can be identified in a complex sytem of parameters, interactions, inputs, outputs, and responses - all governed by mechanical and hydrological canonical ensembles.

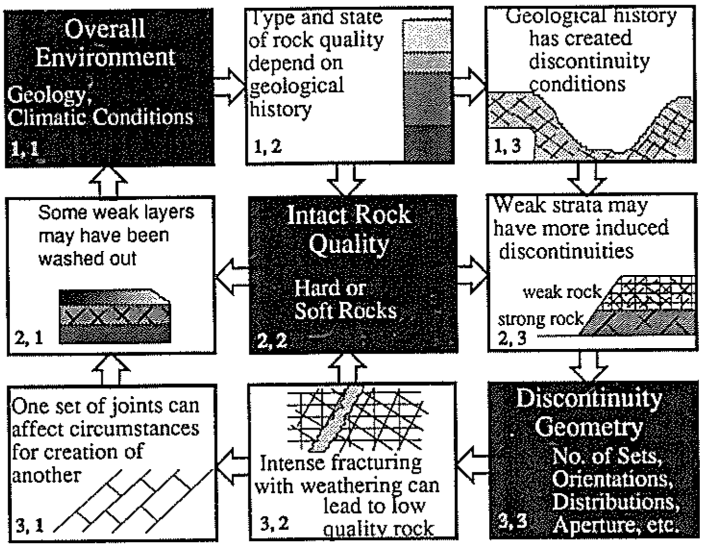

Figure 1 Interaction matrix for slope stability (this is a sub-matrix of a much larger array).

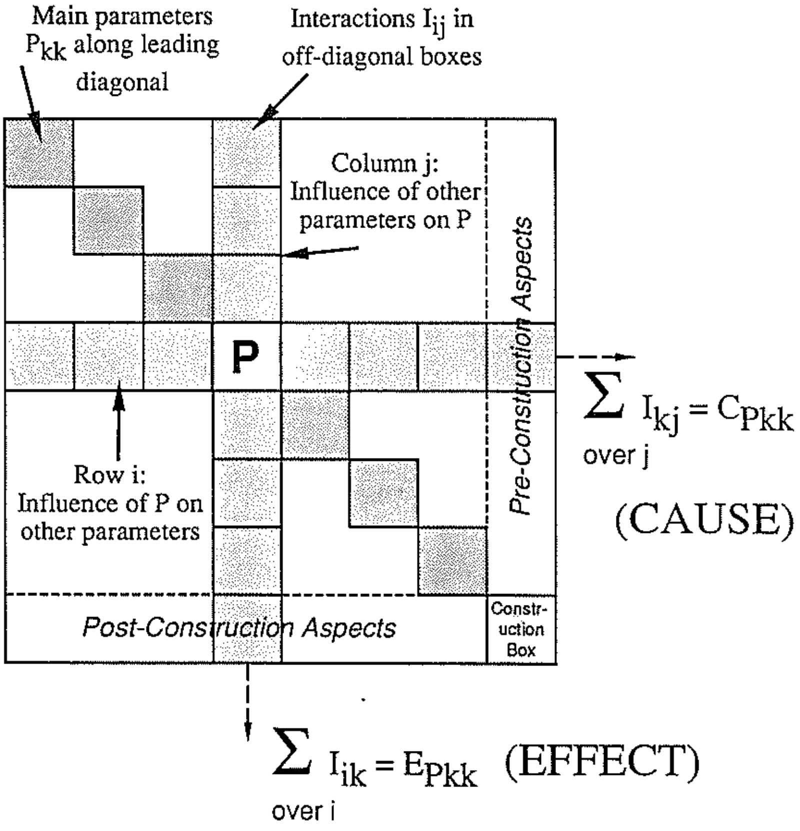

Figure 2 Generic interaction matrix.

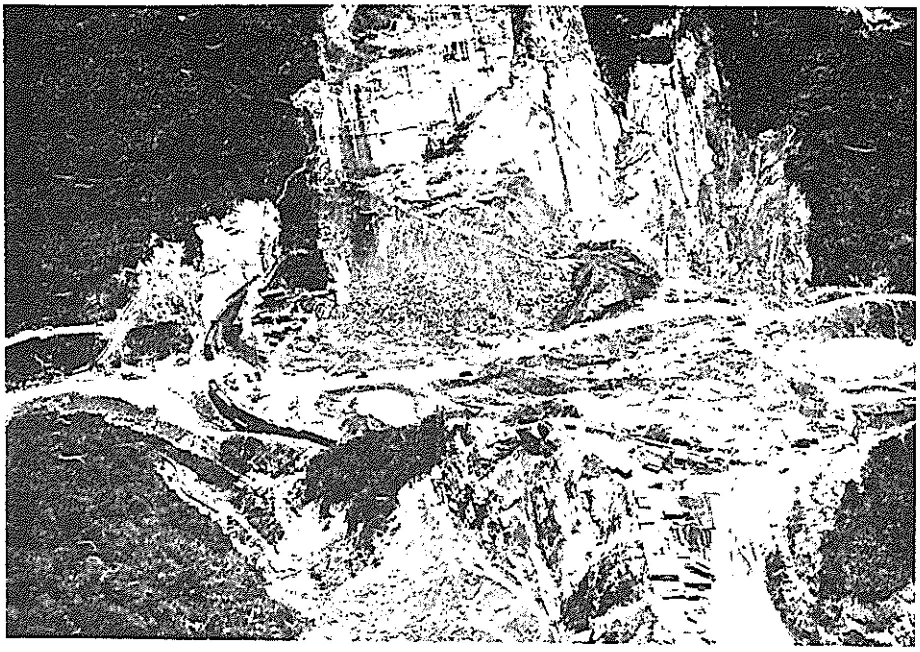

Figure 3 Excavation of the Fei-Tsui Dam.

3. FEI-TSUI DAM IN TAIWAN

Thus, in order to illustrate the way in which such a system may operate, we have chosen to consider some key aspects of the Fei-Tsui dam in Taiwan. Naturally, in this limited presentation, we cannot consider the dam construction comprehensively, but we can illustrate our methodology with reference to certain key aspects that were encountered.

3.1 Overall Site Conditions

The Fei-Tsui dam is a wide V-shaped concrete dam 122.5m in height and 510m in length along the top of the dam. Massive sandstone and siltstone of Oligocene age form the foundation of the dam site. The strike of bedding is generally parallel to the river with a dip of 40 degrees towards the right bank. This leaves the left abutment dip -slope and the right scarp slope. Although the sandstone and siltstone are strong, clay bedding seams vary from less than 1cm to about 15cm in thickness and form unfavourable weak planes. Additionally, moderately developed joints are detected in the area and stress relief may complicate the situation. The excavation is illustrated in Figure 3 and the completed dam is shown in Figure 4.

Typhoons and earthquakes are two natural factors in the area. Although other factors such as north-east monsoons, south-west monsoons and extra topical storms affect the rainfall over the reservoir area, typhoons produce the maximum rainfall every year. The maximum precipitated water of 2.5gm/cm2 was recorded in 1963 and 1969. Earthquakes in northern Taiwan are mainly caused by the subduction of the Philippine sea plate beneath the Eurasia plate. Magnitudes of 4 are common and could exceed 7 on the Reichter scale; a peak ground accelleration of 0.25g horizontal and 0.15g vertical is used for the basic earthquake design criteria.

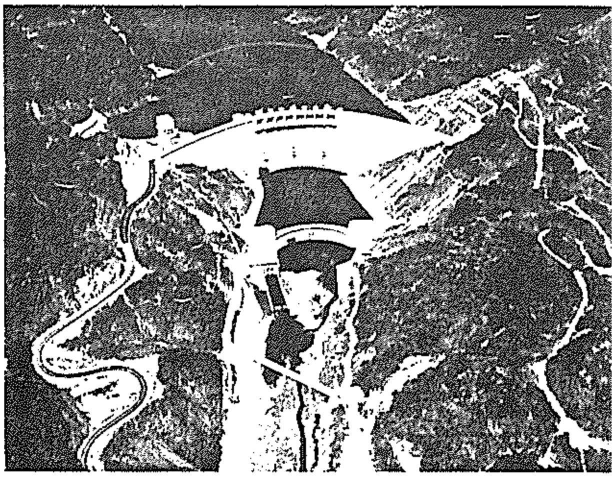

Figure 4 The completed Fei-Tsui Dam.

3.2 Major Concerns Relating Fei-Tsui Dam

Since the dam is located only 30km south of the densely populated Taipei City, the perception of dam stability is important to the public as well as the project engineers. From the rock mechanics point of view, the rock mass shear strength at the dam site plays an important role as far as the stability problem is concerned. In practice, there is little that the engineers can do to improve the quality of the intact rock, and that leaves the engineering effort directed towards the improvement of the discontinuity mechanical properties. Also, the discontinuity geometry, which includes factors such as number of sets, orientation, distributions, aperture etc, demands a thorough investigation.

3.3 Leading Diagonal Terms for Interaction Matrix

Various aspects of the dam design will require consideration of different parameters. However, if we concentrate on the stability of the abutments, we can list out twelve leading diagonal terms for the interaction matrix which represent the main aspects used in the compilation of a 12x12 interaction matrix for this part of the dam. These are given below with illustrative components of the terms.

These are

1,1 - **Overall Environment**
Geology, climate, seismic risk, previous instability

2,2 - **Intact Rock Quality**
Strong, weak, weathering susceptibility.

3,3 - **Discontinuity Geometry**
Sets, orientations, apertures, roughnesses.

4,4 - **Discontinuity Mechanical Properties**
Stiffness, cohesion, friction.

5,5 - **Rock Mass Properties**
Deformability, strength, failure.

6,6 - ***In Situ* Rock Stress**
Principal stress magnitudes and directions.

7,7 - **Hydraulic Conditions**
Permeability.

8,8 - **Slope Orientation and Locations**
Dip, dip direction, position.

9,9 - **Slope Dimensions**
Height, width, local and overall.

10,10 - **Proximate Engineering Disturbances**
Adjacent blasting.

11,11 - **Support/ Maintenance**
Bolts, cables, grouting, pre/post construction.

12,12 - **Construction**
Excavation method, sequencing.

These twelve leading diagonal terms can be used to create a total 12x12 matrix which will have 144-12=132 interaction terms (4). To illustrate the type of information that this produces, in Figure 1 we illustrated a 3x3 part of the 12x12 main matrix.

3.4 Important Aspects of the Fei-Tsui Dam

In a short paper we cannot discuss the significance of all the 132 potential interactions, and indeed the matrix might need to be enlarged. We can, however, point to some of the interesting interactions to illustrate our methodology.

Some of the leading diagonal parameters are fixed and some are not. Essentially parameters 1,1 to 7,7 are functions of the rock mass and site, whereas parameters 8,8 to 12,12 are functions of the engineering. In fact, the slope orientation, location and dimensions are more or less fixed because of the dam considerations. However, we do have the opportunity to vary some of the parameters as follows.

1,1 Overall Environment - cannot be altered
2,2 Intact Rock Quality - cannot be altered
3,3 Discontinuity Geometry - cannot be altered
4,4 Discontinuity Mechanical Properties - can be altered.
5,5 Rock Mass Properties - can be altered
6,6 *In Situ* Rock Stress - cannot be altered
7,7 Hydraulic Conditions - can be altered
8,8 Slope Orientation/location - essentially fixed
9,9 Slope Dimensions - essentially fixed
10,10 Proximate Engineering Disturbances - can be modified
11,11 Support / Maintenance - can be modified
12,12 Construction - can be modified.

Because of the perception that the dam should be safe and also because of the real geotechnical importance of the discontinuities and given the constraints listed above, one finds that many of the potential instability mechanisms can be avoided if attention is placed on the discontinuity mechanical properties, leading diagonal term 4,4.

3.5 Alteration of Discontinuity Mechanical Properties

A very elegant method was used on site to essentially eliminate all of the mechanisms associated with the row and column interactions for the leading diagonal term 4,4 - in fact, this amounts to 22 separate mechanisms associated with the mechanical properties associated with the discontinuities. In other words, if it is possible to enhance the mechanical properties of the discontinuities so they are commensurate with the proximate rock, then they will be effectively mechanically inert.

On site, this was achieved by use of a water jet and water knife to wash out the discontinuity fill which was mainly clay, rock fragments and weathered rock. When the aperture of the discontinuity was larger than 10mm, a water jet was used between two parallel adits approximately 12m apart. When the aperture of the discontinuity was smaller than 10mm, a water knife and water drill were used with the water drill hole spacing at about 200mm. The water jet operated at a pressure of 200kg/cm2; the water knife and water drill operated at a pressure of 2400kg/cm2.

Naturally, this discontinuity treatment programme required the initial excavation of a series of access tunnels and working adits in the dam-loaded zone. A typical discontinuity is shown in Figure 5; a 'halfway stage in the washing-out is shown in Figure 6; and the cleaned, open discontinuity shown in Figure 7.

This programme was extensively planned to allow for the idiosyncrasies of the left and right abutment and the below river bed zone. The washed and cleaned discontinuities were then backfilled with non-shrinking cement mortar and paste grouted under pressure, with checks to ensure that the discontinuity had been completely filled. Tests on the shear strength showed that the treated discontinuities had good average strengths with a cohesion value of above 3.1MN/m2 and a friction value of 38 degrees. The grouting access tunnels and boreholes were also backfilled with concrete.

3.6 Effect of Treating the Discontinuities

If now, we consider the deleterious mechanisms that have been minimised or eliminated by this treatment, we have the following by consideration of row 4 and column 4 in the total 12x12 matrix.

Matrix row 4 interactions

4,1 Treated discontinuities lead to better overall environment.
4,2 Joint movement inhibited, less effect on intact rock.
4,3 Strong joints inhibit formation of new joints.
4,4 Discontinuity mechanical properties - enhanced by treatment described.
4,5 Stiffer discontinuities give better rock mass properties.
4,6 Treated discontinuities have less effect on the *in situ* stress.
4,7 Filled discontinuities inhibit water flow.
4,8 Stronger discontinuities give safer slopes.
4,9 Increased cohesion allows higher slopes
4,10 Stronger joints allow closer proximate disturbance.
4,11 Treated joints require less support and maintenance.
4,12 Stronger joints allow greater flexibility during construction.

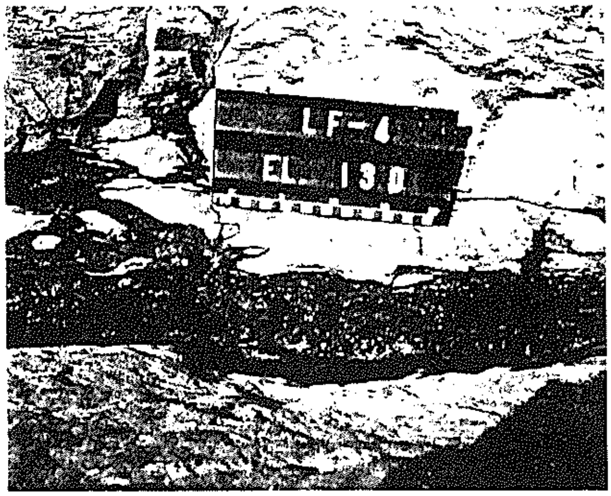

Figure 5 Typical clay filled discontinuities in the rock mass

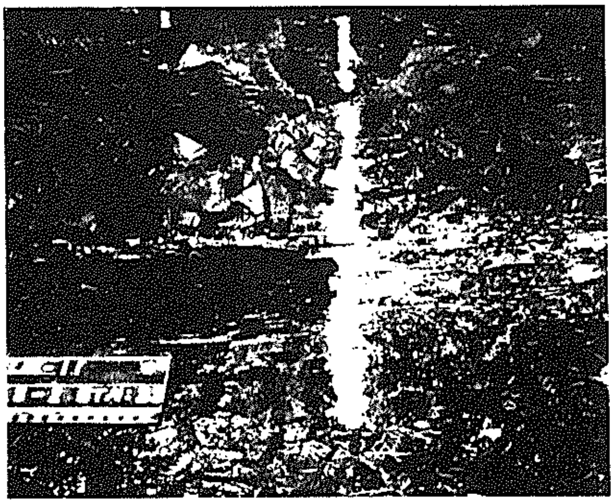

Figure 6 Washing out the clay in the discontinuity

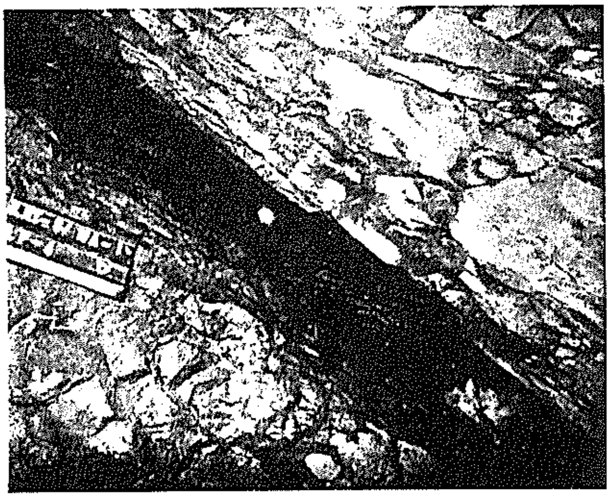

Figure 7 The 'cleaned' discontinuity

Matrix column 4 interactions

1,4	The overall environment has less effect on the discontinuities.
2,4	Weak intact rock has less effect on discontinuities.
3,4	Number of effective discontinuities reduced.
4,4	Discontinuity mechanical properties enhanced
5,4	Discontinuities less affected by mass behaviour.
6,4	Discontinuities less affected by *in situ* stress.
7,4	Discontinuities less affected by water flow.
8,4	Position of slope will not affect discontinuities
9,4	Discontinuities not susceptible to high slope effects.
10,4	Discontinuities less affected by blasting.
11,4	Less support required.
12,4	Many construction problems minimised.

We have discussed the interaction matrix row and column associated with just one parameter. Naturally, in a full application of this system, we would consider all the possibilities, and indeed the significance of both the parameters and the interactive mechanisms in the context of geotechnical risk. Moreover, this would be a continuing process, from the start of site investigation right through to the monitoring and remedial action phase.

4. CONCLUSIONS

In this paper, we have had the opportunity to briefly present the results of an on-going, long-term, research programme aimed at developing a structured approach to all rock engineering. This methodology has the acronym REMIT/RESPONSE. *Inter alia*, this allows direct identification of geotechnical parameter significance, the assessment of sub-system risk, and the consequential overall system risk - as linked to critical parameters and mechanisms by using the interaction matrix described. We illustrated how this methodology can operate via one specific case example. The research will continue to make the evaluation of risk more explicit.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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