# Rock Slope Design using Expert System: ROSES Program

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## Abstract

A computerized expert system (called ROSES) has been developed to assist in the stability evaluation and support design of rock slopes. The system shell uses Visual Prolog to make it user-friendly, interactive and revisable. The system is designed for man-made and natural rock slopes under a variety of geological conditions and engineering requirements. The inference engine employs forward chaining strategy by collecting data, categorizing the slope to fit the preset conditions, evaluating the stability, and seeking the most appropriate design recommendations. The main input data include the general geological features, slope applications, water conditions, slope geometry, rock types, discontinuity characteristics, engineering constraints, geomechanics parameters, degrees of weathering, and vegetation. The considered modes of failure are plane sliding, wedge failure, toppling, and circular failure. The system has been subjected to tests using real mining situations and comparing with textbook solutions. The results are encouraging.

## 1. Introduction

Feigenbaum, a leading expert systems researcher has defined an expert system as [1,2]:

"...an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. Knowledge necessary to perform at such level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners of the field."

In an expert system, the rules or heuristics that are used to solve problems in a particular area are stored in the knowledge base. Problems are presented to the system in terms of certain information that is known about a particular problem. The expert system then tries to arrive at a conclusion from the known facts with the help of the knowledge base. The inference engine or the rule interpreter examines the existing facts in the working memory and the rules in the knowledge base. It adds new facts to the working memory when available. It also determines the order in which the rules will be used. The inference engine carries out consultation with the user and informs the user when a conclusion is reached. If more information is required to invoke additional rules, it prompts the user accordingly [3].

Even though numerous expert systems have been implemented in various engineering disciplines [4-21] to assist in solving difficult tasks and operations, the application of the expert system in rock slope engineering remains extremely rare, particularly in Thailand. Moula et al. [21] compile the names of several expert systems and knowledge base systems that have been developed for the analysis and design in geotechnical engineering.

Experts have designed over 50% of the rock slopes worldwide. These include the rock excavations in open pit mines and along roadcuts. Stability of many rock slopes can not be computed by analytical solutions given in the textbooks [22-24], due to their geological complexity, engineering requirements or time constraints. The slope experts can use their intuition, skills and experience to arrive at the final conclusion of the design. Through the course of their profession they have developed their own criteria and decision-making rules for the analysis and design process. Such expertise can be forever lost if the person leaves the organization. With the expert system such knowledge can be preserved indefinitely. The system is revisable and can be used to train new or inexperience engineers. It will never omit relevant factors and rules needed in the evaluation and design of rock slopes, and hence minimizes the damage caused by erroneous design.

The objective of the present research is to develop a computerized expert system for use in the analysis and design of rock slopes under various geological conditions and engineering requirements. The program, hereafter called ROSES, is not based on the known analytical solutions or theories, but is based on the experience and inference procedure of a slope expert supported by his rationale and logic. Described herein are the development and structures of the system, as well as the criteria, rules and geologic and engineering parameters used by the expert to classify, evaluate and design the slope problems. The actual rock slope conditions existing in Thailand have been emphasized. Examples of the stability analysis and design by the system are demonstrated and compared with the known analytical solutions [22-24].

## 2. Scope and Limitations of ROSES

ROSES is applicable to single benched rock slopes. It is not applicable to soil slope, landfill, and rock fill. The rock slope should not have thick soil cover. Each slope can have one or two different rock types. The geological features that are applicable to the system are described in section 4. The slope geometry and orientation must be clearly identified. It is desirable to design a bench slope in open pit mines or a slope along roadcut. For the existing slopes, the system can analyze the slope with or without artificial support. The system can analyze the existing conditions or suggests an alternative geometry to enhance the stability. The modes of failure considered here are plane sliding, wedge failure, circular failure, block toppling, and any combination of these modes. The recommended supports include rock bolt, wire mesh, drainage pipe and cement grout.

## 3. Program Development

A programmer who has background in rock slope engineering has interviewed a slope expert. The programmer uses questionnaires to obtain all steps, procedures, rules and design factors that the expert uses in the evaluation and design of rock slopes. The questions are classified and arranged from the most general to specific. The answers are organized into network linking the facts (data) to the rules or criteria (Figure 1). Flow diagrams for the main groups and subgroups are drawn to match the facts against the rules, and eventually reach the final conclusions. Each link is checked to ensure that there is no overlapping and no missing chain. Visual Prolog [25] is used as a system shell to create the links and paths that lead to the final conclusions. This results in an expert system. It is later audited by another slope engineer or by another expert. The auditor has used both assumed slope conditions and actual cases. Discrepancies and conflicts are resolved.

## 4. Program Structures

The program comprises three components: data acquisition, data evaluation, and design recommendations (Figure 2). These components sometimes work concurrently. The system uses forward chaining strategy. The data are compiled and subjected to rules and conditions to obtain specific answers. This approach is appropriate here because there are numerous different design recommendations at the end while a relatively narrow path of input data is derived. Even though the input data appear to reflect several slope types and characteristics, the problems are progressively defined as the new answer returns. The stability evaluation will yield a specific mode(s) of failure (if there is any) and will lead to a specialized support design (if needed).

### 4.1 Data Acquisition

The preliminary goal of ROSES is to know, as soon as possible, the general features of the rock slope that the user is dealing with. Such features include general geology, slope geometry, and engineering requirements. ROSES will quickly determine whether the slope problem is within the scope of its capability. If capable, ROSES will further define that slope and will try to match the input data with one of the preset conditions or slope types. This is achieved by posing a selected sequence of questions to the user. The questions in each set will be arranged into relevant categories, and from the most general to specific. The user can respond to each question by selecting one of the several prescribed answers. An option of unknown answer, e.g. "I do not know" is also available. The main categories whose questions belong to are as follows (Figure 3).

Geologic features. There are six types of rock slope that ROSES can evaluate and design based on their general geologic features (Figure 4): 1) massive rock, 2) blocky rock, 3) bedded rock, 4) heavily-jointed rock, 5) soft rock, and 6) hard-soft interbedded rock. The classification also reflects the scope of the system. If a slope problem can not fall into one of these types, ROSES will immediately admit that it can not solve that problem.

Slope applications. ROSES classifies the engineering applications of rock slope into four types. They represent the differences in degrees of safety and long-term stability. The criteria used here are the types of engineering structures (e.g., Railroad, home, major highway, spillway, dam abutment, mined road, etc.) and the distance between these structures and the slope toe.

Water conditions. ROSES classifies the water conditions in the slope in term of the water level as compared with the slope height. The options are from completely dry to water level up to 25%, 50%, 75%, or 100% of the slope height. If the user do not know the groundwater conditions, the system will further ask about the general climate where the slope is situated. Two options are available, tropical and arid climates.

Slope geometry. A crucial information that the system needs for stability evaluation is the slope geometry. This includes the existing slope orientation, slope height, slope angle, and slope curvature. The height should be given to the nearest 1 meter, the angle to the nearest 5 degrees. Three slope shapes are available, convex, concave and straight faces. Topography of the upper slope face and near the slope toe can be inserted as an option. ROSES can also design the optimum slope geometry, if requested.

Joint characteristics. The user must provide orientation, average spacing, continuity, aperture, filling, and roughness of all joint sets. Unless the slope is classified as heavily-jointed rock, the maximum joint set number of the slope problem is limited to four. The roughness is important because the system can use Barton strength criterion for the joints [26-28].

Geomechanics parameters. Rock density, uniaxial compressive strength, and shear strength of all joint sets must be provided. If the user does not know such information, the system will further ask about the types of rock forming the slope, and then will extract the missing information from its database. In this case, a conservative set of geomechanics parameters will be used in the stability evaluation.

Supplemental Information. For evaluating the stability of existing slope, some information can be of useful, but not necessary. These are available as input options which include the past failure, vegetation, methods of excavation, and current support. Such information may be used in the stability evaluation when applicable.

To gain trust and understanding from the user, instead of answering the question asked by ROSES, user may ask ROSES why it is asking a particular question. ROSES then gives the reasoning or basis for what the particular answer will be used, or the rule it is trying to satisfy. This makes ROSES user-friendly and helps the user to understand and rely on the system.

### 4.2 Evaluation

After the data have been systematically stored ROSES first determines 1) whether the information is sufficient to evaluate the stability, 2) whether there is any conflict between the answers, and 3) whether the input parameters are valid. If it decides that the information is insufficient, it will skip the design process. In this case it will recommend the user to acquire the missing information, and to repeat the answering process from the top with the additional information.

In the evaluation, ROSES will resolve the conflicts and will check the validity of the input data. For example, if the user assigns unrealistic friction angles, or if two joint sets have identical attitudes, ROSES will prompt the user to recheck or correct his input data.

It should be noted that the data collection and data evaluation are sometimes carried out concurrently. As the data collection progresses, ROSES evaluates the incoming information and tries to classify the slope to narrow down the types of problem, and hence makes it more and more specific. The next question to the user will therefore be partly dictated by the previous answers. This strategy is adopted to make the neural network efficient and to reach the final conclusions quickly. For example, if it has been defined that the slope comprises relatively massive rock where no joint is daylight, ROSES will concentrate effort on getting more information on the existing slope height, slope angle, rock strength and degree of weathering, etc. It will not request the information on joint roughness, joint friction, or joint spacing, etc. because in this case the joints will have no impact on the stability.

### 4.3 Design Recommendations

The stability evaluation of ROSES may yield two groups of outcome; 1) the slope is stable as it is, and no rock support is required; or 2) the slope is unstable under the existing geometry, and geometry modification or rock support is necessary. Even though the slope problem is determined to be stable, the user may continue to request the system to give an alternative designed geometry with or without the rock support. If requested, ROSES will optimize the slope geometry, and redesign that slope under the site-specific conditions and requirements.

If the system determines that the slope problem is unstable, it will identify and inform the most likely modes of failure that may occur. The user may further request the system to design the new slope geometry (e.g., slope face angle or slope height) or to design the rock support or drainage system that can enhance the stability under the existing geometry.

The artificial supports considered by ROSES are rock bolts (mechanical and fully-grouted), wire mesh, and cement grout. The design recommendations for rock bolt will be in terms of type, strength, length, spacing or pattern, and installed angles. For the drainage system, ROSES will recommend the minimum diameter, pattern, and length of the drained pipes.

## 5. Examples

Two examples of the actual rock slopes are presented here to briefly demenstrate the predictive capability of the system. The actual slope behavior (stability conditions) is compared with the results from analytical solutions and with the prediction from ROSES program. The comparisons are made under the actual slope height (H) and slope angle ($\psi_f$) and under the assumed geometry.

The first example is the case of a limestone quarry located at Khoa Som Poat, Lopburi province. The slope orientation is (strike/dip angle) 150/70 with an average height of 30 meters. The rock density is 2.70 g/cc, and the uniaxial compressive strenght is 125 MPa. There are four discontinuity sets as follows (strike/dip) 295/15, 250/90, 320/85 and 180/75. The average spacing is 50 cm. The basic friction angle is assumed as 30 degrees. The joint roughness coefficient (JRC) is measured as three. ROSES clasifies the slope as blocky rock. Table 1 compares the results.

The second example is the slope of a shale quarry in Chonburi province (Table 2). The slope orientation is 110/80 with the measured height ranging between 8 and 10 meters. There are fout discontinuity sets: 340/85, 285/10, 085/70 and 195/90. The friction angle is assumed as 25 degrees. The average joint spacing is 15 cm. ROSES classifies this slope as heavily-jointed rock to soft rock.

Comparison of the results suggests that the system predictions agree well with the actual slope behavior. It however tends to be conservative as compared with the results from analytical solutions and with the database compiled by Hoek and Bray [22].

## 6. Discussions

The design recommended by the expert may be similar to or may be different from those obtained from the analytical solutions or from textbooks. This does not mean that the expert opinions are correct or incorrect. The measure should be made in terms of the appropriateness of the design as compared with the actual slope behavior. The system explicitly includes other observed factors and conditions beyond the variables identified in the analytical solutions.

It should be recognized that the analytical solutions can not solve the slope problem that contains missing key parameters or containing parameters with high uncertainties in terms of geologic and geomechanics conditions. Textbook solutions only provide a rough guideline through the calculation of forces and friction for rock slope stability. The governing equations are also derived under rigorous assumptions that the rock is homogeneous, the discontinuities are uniformly distributed with consistent frequency and orientation, and that the mechanical properties of the discontinuities are identical throughout the slope, etc. No actual rock slope anywhere can provide such ideal conditions. In addition, statistical analysis on the parameters with such high intrinsic variability may not truly represent the actual field conditions. As a result, expert opinion or an expert system, such as ROSES, remains useful for the practical design of rock slopes.

Different experts often give more or less different design recommendations. An expert system therefore should be developed from one expert. Each expert has his own way to classify the rock slopes, to evaluate their stability, and to assign the confidence level to the information he receives. Even though two different experts may provide an identical design recommendation, their inference procedures and rules could be totally different.

## 7. Conclusions

ROSES is a computerized expert system that has been developed to assist in the stability analysis and support design of rock slopes. It is developed by compiling the answers to a series of questionnaires that are posed to an expert. These questionnaires evolve the slope characterization, geological and engineering factors, and design schemes. The answers from the expert are systematically organized to form a neural network of paths and decision making. The results in form of the rules and conditions are written onto Visual Prolog which are used as the inference interpretator. To put ROSES into use, a sequence of questions is posed to the user interactively to define the geological conditions and engineering requirements for the slope problems. The system evaluates the input information and offers recommendations with respect to the data sufficiency and engineering designs. ROSES is subject to tests using actual slope examples and comparing the expert's recommendations with those obtained from the analytical solutions. The results are encouraging.

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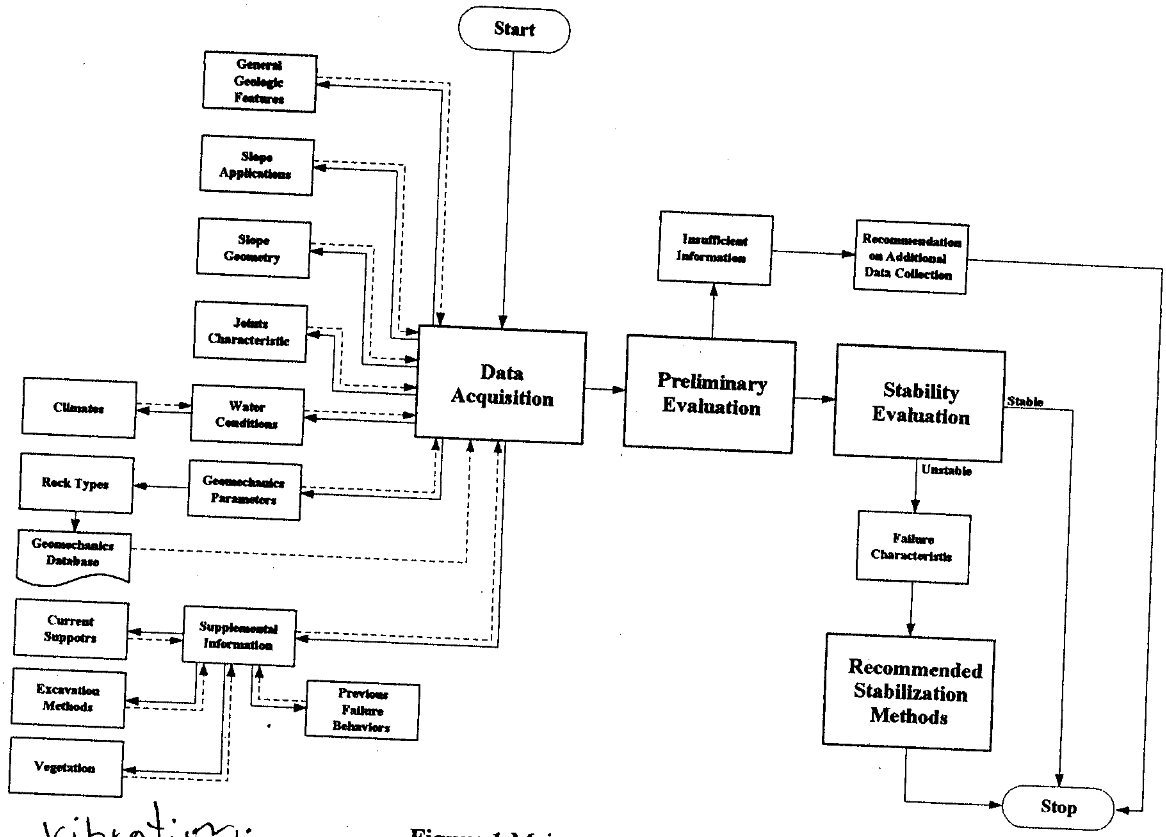


vibration.

**Figure 1** Main network of ROSES.

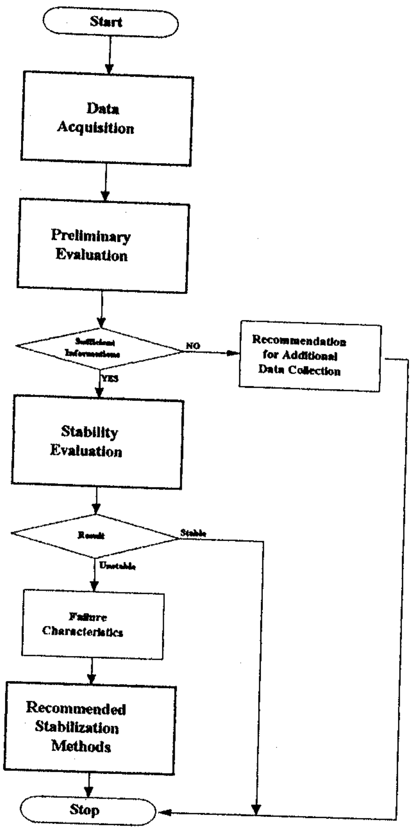


**Figure 2** Main flow chart.

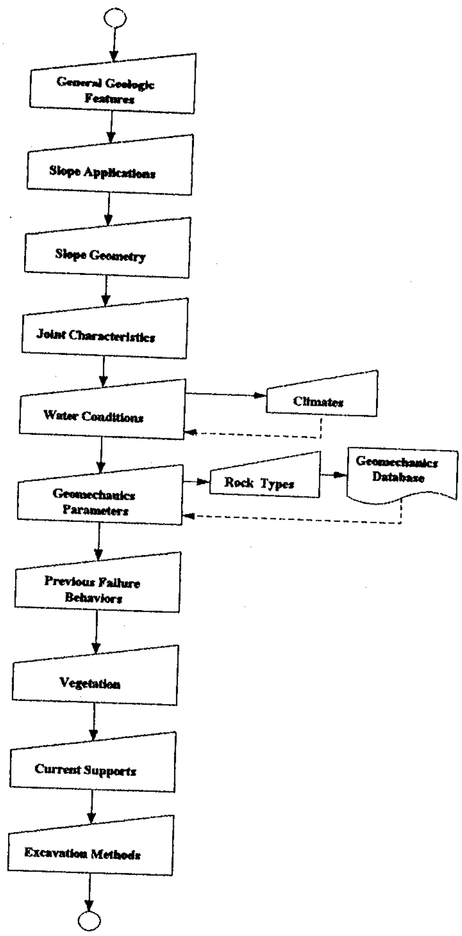


**Figure 3** Flow chart in data acquisition component.

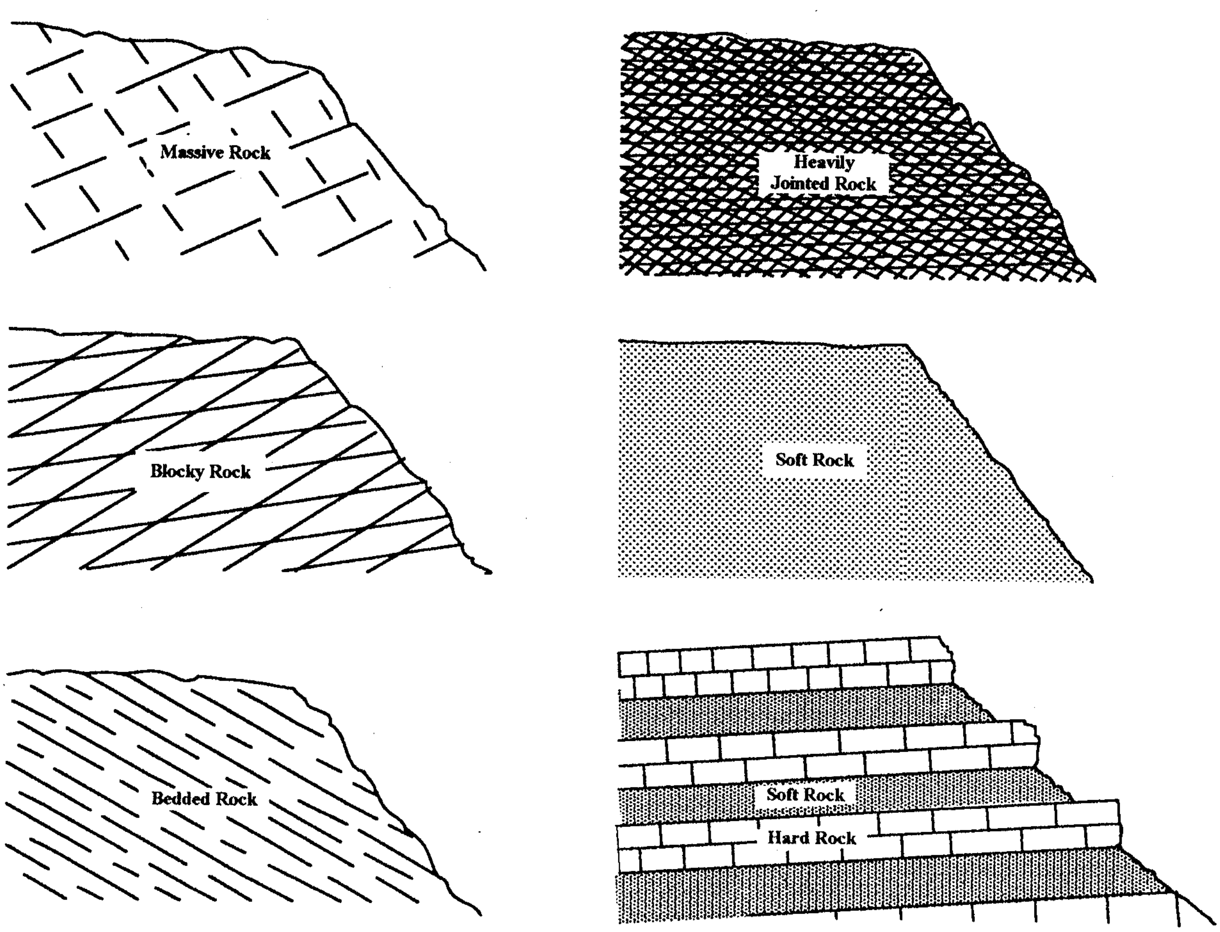


**Figure 4** Six general geological features allowed by ROSES.

**Table 1** Comparison of the results from expert system (ROSES), analytical solution (Barton) [27], and kinematic analysis [23] with the actual slope of Khao Som Poat, Lopburi province.

| Case | ROSES | Barton | Kinematic analysis | Actual Behavior |
|---|---|---|---|---|
| **Actual**<br>H = 100 ft<br>$\psi_f = 70^\circ$ | unstable | unstable | unstable | Fail by plane sliding and toppling |
| **Assumed**<br>H = 70 ft<br>$\psi_f = 70^\circ$ | unstable | unstable | unstable | N/A |
| **Assumed**<br>H = 70 ft<br>$\psi_f = 55^\circ$ | stable | stable | stable | N/A |
| **Assumed**<br>H = 100 ft<br>$\psi_f = 55^\circ$ | unstable | stable | stable | N/A |

**Table 2** Comparison of the results from expert system (ROSES), Hoek and Bray's database [22], and kinematic analysis [23] with the actual slope of Ban Pong Nam Ron quarry at Chantaburi province.

| Case | ROSES | Hoek and Bray's database | Kinematic analysis | Actual Behavior |
|---|---|---|---|---|
| **Actual**<br>H = 10 ft<br>$\psi_f = 80^\circ$ | unstable | Stable | unstable | Fail by plane sliding and toppling |
| **Assumed**<br>H = 10 ft<br>$\psi_f = 60^\circ$ | stable | Stable | stable | N/A |