การออกแบบความลาดชันของหินโดยใช้ระบบความรู้ผู้เชี่ยวชาญ

นายสันทัศน์ กมุทชาติ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

สาขาวิชาเทคโนโลยีธรณี

มหาวิทยาลัยเทคโนโลยีสุรนารี

ปีการศึกษา 2547

ISBN 974-533-397-2

ROCK SLOPE DESIGN USING EXPERT SYSTEM

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A Thesis Submitted in Partial Fulfient of the Requirements for the

Degree of Master of Engineering in Geotechnology

Suranaree University of Technology

Academic Year 2004

ISBN 974-533-397-2

ROCK SLOPE DESIGN USING EXPERT SYSTEM

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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ระบบผู้เชี่ยวชาญได้ถูกพัฒนาขึ้นเพื่อใช้ในการประเมินเสถียรภาพและออกแบบการค้ำยันความลาดเอียงมวลหินภายใต้ลักษณะทางธรณีวิทยาและความต้องการทางด้านวิศวกรรมในรูปแบบต่าง ๆ ระบบนี้ไม่อยู่บนพื้นฐานของสูตรการคำนวณและทฤษฎีแบบดั้งเดิม แต่จะอาศัยความรู้ขบวนการการเชื่อมโยง และประสบการณ์ของผู้เชี่ยวชาญ ดังนั้น ปัจจัยต่าง ๆ ที่มีผลกระทบต่อเสถียรภาพ (ที่นอกเหนือไปจากความสามารถของสูตรดั้งเดิม) จึงสามารถนำมาใส่ในขบวนการวิเคราะห์ของระบบได้ เช่น ประวัติของความลาดเอียงมวลหิน วิธีที่ใช้ในการขุดเจาะ ขนาดของต้นไม้ การค้ำยันที่มีอยู่ในปัจจุบัน เป็นต้น ระบบผู้เชี่ยวชาญนี้ถูกสร้างขึ้นโดยเครือข่ายทางความคิดและขบวนการตัดสินใจที่ใช้คุณลักษณะความลาดเอียงมวลหินมาเป็นข้อมูลมีการประเมินข้อมูลและนำไปสู่ผลลัพธ์ในรูปของความน่าจะเป็นของการพังทลาย ชนิดของการพังทลายที่พิจารณาคือการไหลแบบระนาบและแบบรูปลิ่ม การพลิกคว่ำและการพังทลายแบบรูปโค้ง โครงสร้างของโปรแกรมถูกพัฒนาอยู่ใน Visual Basic ซอฟท์แวร์ ดังนั้น ระบบจึงสามารถโต้ตอบกับผู้ใช้ได้ และสามารถแก้ไขปรับปรุงได้ ปัจจัยที่เกี่ยวกับความลาดเอียงมวลหินสามารถจำแนกอย่างเป็นลำดับชั้นและแบ่งเป็นหลายกลุ่มโดยอาศัยเกณฑ์หลายประการ อาทิ ลักษณะของพื้นที่ ลักษณะทางด้านธรณีวิทยาและอุทกธรณีวิทยา คุณสมบัติเชิงกลศาสตร์ รูปทรงเรขาคณิตของความลาดเอียง การพังทลายในอดีต พืชปกคลุม แรงสั่นสะเทือน ความต้องการทางด้านวิศวกรรม ข้อจำกัดของการออกแบบจุดประสงค์ของโครงการ ฯลฯ ในขั้นแรกจะวิเคราะห์เชิงกลศาสตร์เพื่อกำหนดชนิดของการพังทลายที่จะเป็นไปได้ชุดของคะแนนจะกำหนดลงในปัจจัยเหล่านี้ เนื่องจากบทบาทของปัจจัยเหล่านี้จะต่างกันไปตามลักษณะมวลหิน ดังนั้น ชุดของค่าอิทธิพลจะถูกกำหนดขึ้นเพื่อเป็นตัวคูณ ความน่าจะเป็นของการพังทลายสามารถคำนวณได้โดย $P\{f\} = \Sigma\{R_n * I_n\}$ โดยที่ R_n คือ คะแนนของแต่ละปัจจัย I_n คือ ค่าอิทธิพล และ n เป็นจำนวนปัจจัยทั้งหมดที่นำมาพิจารณาสำหรับแต่ละความลาดเอียง (ผันแปรจาก 1, 2, 3, 4…ถึง n) ความสามารถในการคาดคะเนของระบบได้ถูกสอบทานกับความลาดเอียงมวลหินจริงในภาคสนาม 37 แห่ง ทั้งที่มีเสถียรภาพและไม่มีเสถียรภาพ ซึ่งผลออกมาเป็นที่น่าพอใจ สำหรับการออกแบบการค้ำยันระบบจะกำหนดหน้าที่เชิงวิศวกรรมสำหรับแต่ละชนิดการพังทลายและเลือกคำตอบของการออกแบบที่เหมาะสมโดยนำคุณลักษณะความลาดเอียงมวลหินมาพิจารณาผลของการออกแบบมี 9 กลุ่ม แต่ละกลุ่มมีองค์ประกอบหรือการรวมองค์ประกอบของการออกแบบที่ต่างกัน (เช่น หมุดยึดหิน ตาข่ายลวด ซีเมนต์ดาด ท่อระบายน้ำ ฯลฯ) รายละเอียด

ของององค์ประกอบเหล่านี้กำหนดจากคุณลักษณะของการพังทลายและค่าความปลอดภัยที่ต้องการ ข้อเสนอแนะในการออกแบบจะรวมไปถึงขบวนการติดตั้งอุปกรณ์สำหรับการค้ำยันแต่ละชนิด

สาขาวิชาเทคโนโลยีธรณี ลายมือชื่อนักศึกษา________________________

ปีการศึกษา 2547 ลายมือชื่ออาจารย์ที่ปรึกษา__________________

SAMTHAT KAMUTCHAT: ROCK SLOPE DESIGN EXPERT SYSTEM. THESIS ADVISOR : ASSOC. PROF. KITTITEP FUENKAJORN, Ph.D., P.E. 262 PP. ISBN 974-533-397-2

ROCK/SLOPE/EXPERT SYSTEM/STABILITY/FAILURE

An expert system has been developed for use in the stability evaluation and support design of rock slopes under various geological conditions and engineering requirements. The proposed system is not based on the known analytical solutions or theories, but is based on the heuristic knowledge, inference procedure and experience of a slope expert backed by the rationale and logic. As a result, other factors (beyond those considered in the classical methods), that may have an impact on the stability can be explicitly incorporated in the analysis, e.g., slope history, excavation methods, existing vegetation, current support, etc. This expert system is formed by neural network of paths and decision making procedures that use rock slope characteristics as input, evaluate the information, and lead to the output in form of the probability of failure. The modes of failure considered are plane and wedge sliding, toppling and circular failures. The program structure is developed on Visual Basic software, and hence makes it interactive, user-friendly and revisable. The input rock slope parameters are hierarchically characterized into several groups using various criteria, e.g., site characteristics, geological and hydrological conditions, mechanical properties, slope geometry, past failure, vegetation, ground vibration, engineering requirements, design constraints, and project goals, etc. The kinematics analysis is first performed to identify all potential modes of failure. A set of rating is assigned to these parameters for each failure mode considered. Recognizing that the role of these parameters can be different for different conditions of the rock mass, a set of influencing factors is also derived as a multiplying factor for the corresponding parameter. The probability of failure for each mode can be calculated by $P\{f\} = \Sigma\{R_n * I_n\}$, where R_n is the rate for each parameter, I_n is the influencing factor, and n represents type or number of the parameters considered for each slope (varying from 1, 2, 3, 4…n). The predictive capability of the proposed system has been verified by comparing with 32 actual rock slopes under a variety of stable and unstable conditions. The results are satisfactory. For the support design, the system first identifies the functional requirements for each mode of failure. Based on the slope characteristics, the system selects the most suitable design solution for the reinforcements. A total of 9 design solutions are available. They comprise different combinations of the design components (e.g., rock bolt, wire mesh, shotcrete, drained pipe, etc.). The specifications for each design component are determined by the failure characteristics and the safety requirements. The final design recommendations also include the construction process for each type of rock support.

School of Geotechnology　　Student's Signature____________________

Academic Year 2004　　Advisor' s Signature___________________

ACKNOWLEDGEMENTS

The author wishes to acknowledge the support from the Suranaree University of Technology (SUT) who has provided funding for this research.

Assoc. Prof. Dr. Kittitep Fuenkajorn is the thesis advisor, Asst. Prof. Thara Lekuthai and Asst. Prof. Dr. Suksan Horpibulsuk are the thesis committee.

Santhat Kamutchat

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LIST OF SYMBOLS AND ABBREVIATIONS

Acon	=	Average Joint Persistence
ASP	=	Average Joint Spacing
Bla	=	Blasting Method
DDA	=	Discrete Deformation Analysis
Em	=	Excavation Method
FDM	=	Finite Discrete Method
H_b	=	Bench height
JRC	=	Joint Roughness Coefficient
KBS	=	Knowledge Base System
Mcon	=	Maximum Joint Persistence
MiSp	=	Minimum Joint Spacing
W_b	=	Bench width

CHAPTER I

INTRODUCTION

1.1 Research Objectives

The primary objective of this research is to develop a computer software in form of expert system program for use in the design and analysis of rock slopes. The program, hereafter called ROSES (Rock Slope Analysis by Expert System), 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. Knowledge and experience of an expert on rock slope will be systematically extracted, compiled, analyzed, and recorded. Visual Basic will be applied for the program structure for data input and output. Such fundamental information as geology, hydrology, slope geometry, geological data, and other engineering limitation and requirements will be the input. The site-specific design recommendations are the output, which include support design and geometries of the slope problem.

1.2 Problem and Rationale

Expert system is 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 the computation and informs the user when a conclusion is reached. If more information is required to invoke additional rules, it prompts the user accordingly.

Even though numerous expert systems have been implemented in various engineering disciplines to assist in solving difficult tasks and operations, the application of the expert system in rock slope engineering remains extremely rare, particularly in Thailand. 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 (e.g., Hoek and Bray, 1981; Goodman, 1989; Jaeger and Cook, 1979) 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.

1.3 Scope and Limitation of Research

ROSES are 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. ROSES can evaluate and design six general geologic features, including 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 within one of these types, ROSES will immediately admit that it can not solve that problem. The slope geometry and orientation must be clearly identified. The system is applicable 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 supports. 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. The actual rock slope conditions existing in Thailand will be emphasized. Examples of the stability analysis and design by the system will be demonstrated and compared with the known analytical solutions.

1.4 Research Methodology

The research is divided into six tasks.

1) Literature review: Relevant information, current technology and literatures on rock slope design and expert systems will be searched, compiled, studied and summarized.
2) Interview and Information Collection: Questionnaires will be derived for use in the interview. They will include all relevant factors, considerations and guidelines specifically needed in the design of rock slopes. All questions will be systematically raised to the expert in the order of priority and significance. Design recommendations (answers) will be recorded.
3) Analysis: All design recommendations, performance requirements and design procedures obtained from the expert will be examined to ensure that all geological and engineering conditions posed will yield an answer, and that there is no dead-end for each path, and repetition on the input information. Flow charts will be developed to create the paths.
4) Software development: The information obtained from Task 3 will be used to construct an interactive computerized system. The design factors will be arranged in the order of significance and aimed at creating the fastest decision making. Visual Basic software will be used as inference engine.
5) Auditing and Verification: Internal review will be conducted to detect any apparent flaw in logic of the system. Code verification with actual cases will be performed. Comparison between expert's opinions and the results from analytical solutions will be made.
6) Thesis writing: A comprehensive document and software are prepared and presented in the thesis.

1.5 Thesis Contents

Chapter I states the objectives, rationale, and methodology of the research. Chapter II summarizes results of the literature review on expert systems as applied to rock and soil slopes. Chapter III describes field investigation and case history of rock slopes. Chapter IV describes the questionnaires given to the slope expert which includes criteria, parameter analysis, data classification, stability evaluation and support design. Chapter V gives ROSES flowcharts including 1) data acquisition phase, 2) data classification phase, 3) stability evaluation phase, and 4) support design and recommendation phase. Chapter VI describes the development of the expert system software. Verification of the system predictive capability is presented in Chapter VII. The design recommendations on slope stabilization are described in Chapter VIII. Chapter IX discusses the adequacy and performance of the ROSES software. Conclusions and recommendations for future research needs are given in Chapter X.

CHAPTER II

LITERATURE REVIEW

This chapter presents results of the literature review on the relevant methods of slope stability analysis, i.e., 1) mechanical method, 2) numerical method, 3) block theory, and 4) expert system.

2.1 Rock Slope Analysis

The problem of evaluating the stability of slopes in jointed and weathered rock masses remains as a major challenge in the practice of rock engineering. The stability of a structure depends on the strength and deformability of the rock masses. The rock masses are typically heterogeneous and anisotropic (unpredictable) because of the different rock types and properties. The most universally occurring anisotropic characteristic of all rock masses is the presence of distinct breaks, or discontinuities, in the physical continuity of the rock. These include bedding surfaces, joints, and faults, etc. The water can reduce rock strength from pervasive chemical weathering. The presence of discontinuities in rock mass is the primary controlling factor of rock mass strength and deformability. Discontinuities also have a dominant role in defining rock mass properties. The slope geometries have become important on stability evaluation. Hoek and Bray (1981) and Goodman (1989) have classified the modes of slope failure into four types; plane and wedge sliding, toppling and circular failure (Figure 2.1).

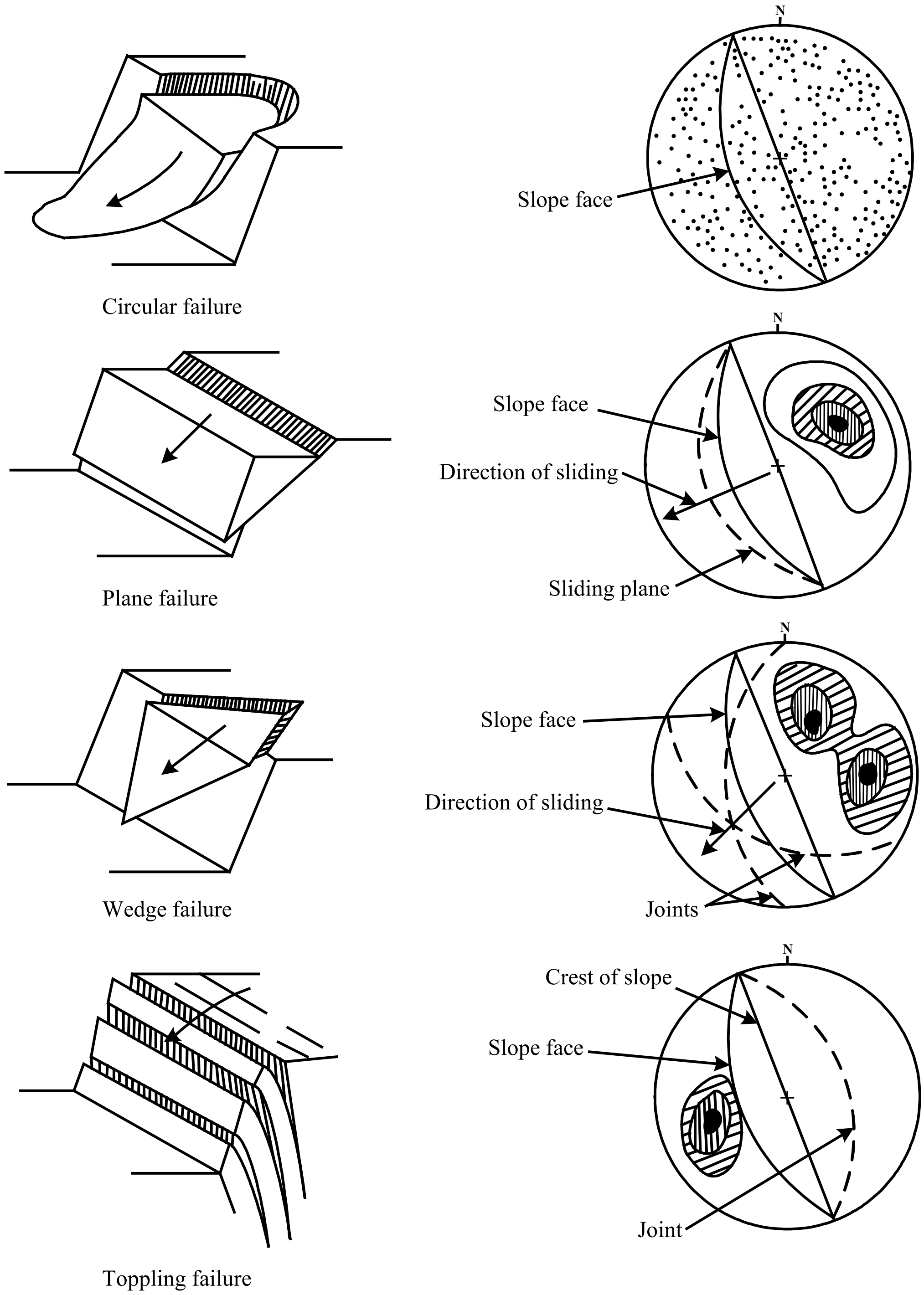

Figure 2.1 Modes of rock slope failure and comparison with dip direction and dip angle in form of stereoplots (after Hoek and Bray, 1981).

A plane slide forms under gravity alone when a rock block rests on an inclined weakness plane that “daylights” into free space. The inclination of the plane of slip must be greater than the friction angle of that plane. The conditions for failure reside dormantly in the slope until excavation or rock movement removes the barrier to block translation. Movement of a block like that shown in Figure 2.1 supposes that the restraint to sliding has been overcome not only along the surface of sliding but along the lateral margins of the slide as well. In soft rocks, like shale, the side restraint can be released by rupture of the rock itself if the base of sliding is inclined considerably steeper than the friction angle. In hard rocks, plane sliding can occur only if there are other discontinuities or valleys transverse to the crest of the slope releasing the sides of the block.

Wedge slides can occur when two planes of weakness intersect to define a tetrahedral block. Slip can occur without any topographic or structural release features if the line of intersection of two discontinuities daylights into the excavation.

Toppling failure involves overturning of rock layers like a series of cantilever beams in slates, schists, and thin-bedded sediments inclined steeply into the hillside. Each layer tending to bend downhill under its own weight transfers force downslope. If the toe of the slope is allowed to slide or overturn, flexural cracks will form in the layers above, liberating a large mass of rock. If there are frequent cross-joints, the layers can overturn as rigid columns rather than having to fail in flexure. In either event, destructive slope movements must be prefaced by interlayer slip of a normal fault type.

For a circular failure, rock body is divided into a discontinuous mass. The failure path is normally defined by one or more discontinuity. In case of soil slope, the individual particles are very small compared with the size of the slope, and a strongly defined structural no longer existed. Then the failure paths are in the circular form.

2.2 Mechanical Analysis

The mechanical method is a classical and simple method that uses for rock slope stability evaluation. It is the summation of the forces (forces balance) on the discrete block. There are two types for force summation, as 1) the summation of driving forces, such as rock weight, pore pressure and vibration, and 2) the summation of resisting forces, such as the friction force and existing support. The slope geometry and rock discontinuity are the parameters that use for calculation. This is the advantage of mechanical method.

There are very few cases in which the application of the mechanical analysis has been verified against actual observations of failure. The complexities of slope geometry, joints orientation and block volume are basic disadvantage of this method.

2.3 Numerical Analysis

Pande et al. (1990) describes the development of numerical method for stability analysis in medium. A number of numerical methods of analysis have been developed over the part three decades. They have become popular due to rapid advancements in computer technology and its availability to engineers. Before the advent of computers, the rock structures were designed largely based on rules of thumb, experience and trial and error procedure. Rules of thumb are invariably based on the past experience of the designer. They usually tend to be oversafe and are basically applicable to the situations similar to the ones for which they were developed. Engineers of today are, many times, faced with problems for which no past experience is available. It is also difficult to 'teach' past experience. The civil or mining engineering construction is usually a 'one off' situation every time. The increased consciousness amongst the public regarding safety and economy has led the engineers to seek more rational solutions to the problems in rock mechanics related to civil and mining engineering.

Analytical or closed form solutions are available for similar situations or can be developed. However, they can in most cases be developed assuming rock as a linear elastic material, which is a very drastic simplification. Numerical methods have, therefore, become very popular for solving problems in rock mechanics.

A number of numerical methods are available for solving problems of load deformation. By the term load-deformation problem, it means a problem in which a rock mass of arbitrary shape (this includes opening of arbitrary shape) is subjected to loads due to self weight, external forces, in-situ stresses, temperature changes, fluid pressure, prestressing, dynamic forces, etc. and we seek to find the deformation, strains and stresses throughout the rock mass.

Younger readers having a perhaps more rigorous background of theoretical mechanics will recognize the load-deformation problem as a general boundary value problem. The deformation or possibly collapse, of which we are interested in finding out when it is subjected to a general set of loads. A solution of this problem, i.e. deformations, strain, stresses throughout the rock mass must satisfy the following:

(a) Equilibrium

(b) Strain compatibility

(c) Stress-strain relations of the rock mass

(d) Boundary considerations of traction (forces) deformations (conditions of fixity).

All numerical methods satisfy the conditions (a), (b), and (d) in almost a routine manner. Stress-strain relations for rock masses (c) is a wide subject in itself and perhaps most crucial on which the usefulness of the solution depends.

There are mainly three numerical methods, which have been used in the problems of rock mechanics. They are (1) The Finite Element Method (FEM), (2) The Boundary Element Method (BEM) and 3) The Discrete Element Method (DEM).

All methods are approximate methods, i.e. we get an approximate solution to the problem. All methods have their advantages. FEM and BEM can be used for problems other than that of load-deformation, viz. seepage through rocks, consolidation due to pumping, heat condition, etc.

The three methods in an overall and general manner are summarized to show the essential differences in the various methods and their possible advantages and disadvantages.

(1) The Finite Element Method

This is the most popular method in engineering sciences. It has been applied to a large number of problems in widely different fields. Its popularity, particularly for load-deformation problems, largely depends on the fact that it is very appealing to engineers. They are able to relate it to a large extent to the background of structure mechanics as the physical meaning of the steps of calculations are relatively transparent. A large part of the finite element program can remain as a ‘black box’ to the user and even a beginner can obtain interesting results with minimal effort. It does not mean that the method is easy and no experience is required in solving engineering problems of practical importance. On the contrary, to make use of the full potential of the method and interpret the results of the calculation, considerable expertise is required.

The method essentially involves dividing the body in smaller ‘elements’ of various shapes (triangles or rectangular in two-dimensional cases and tetrahedrons or ‘bricks’ in three-dimensional cases) held together at the ‘nodes’ which are corners of elements. The more the number of elements used to model the problem, the better approximation to the solution is obtained. Displacements at the nodes are treated as unknowns and are calculated. Each element can have different material properties.
The major disadvantage of the method is that considerable effort is required in preparing data for a problem. This is particularly crucial in three-dimensional problems and has led to ‘mesh generation’ programs. These programs produce (to large extent) the input data required for the Finite Element program. Still considerable effort is needed in ‘starting up’ the problem. The method is also expensive in computer time.

A large set of simultaneous equations (several hundreds to several thousands) have to be solved to obtain solutions. The computer time goes up further if the problem is nonlinear, i.e. stress-strain relationship is not linear-which usually is the case. For a nonlinear problem, the sets of simultaneous equations are required to be solved a number of times.

Inspite of the above disadvantages, FEM has been extremely popular with geotechnical engineers. Its strength lies in its generality and flexibility to handle all types of loads, sequences of construction, installation of supports, etc.

(2) The Boundary Element Method

This method is increasingly popular. It lacks the generality and flexibility of the FEM. It is not so easily understandable and requires a higher level of understanding of mathematical complexities.

In this method only the surface of the rock mass to be analysed needs to be discretized, i.e. divided into smaller patches. Thus, for two-dimensional simulations line elements at the boundary represent the problem, while for fully three-dimensional problems, surface elements are required. The data preparation here is relatively simple. However, the computer program is not so transparent. Whenever there is a change of material properties, the surface defining the separation has to be discretized. Thus, if there are a number of layers of different materials, data preparation can still become complex. BEM appears to be a very efficient method for homogeneous, linear elastic problems, particularly in three dimensions. For complex nonlinear material laws with a number of sets of materials, advantages of the method are considerably diminished. The matrices of equations arising in this method are not banded and symmetric as for FEM but are fully populated. Thus, though the number of equations to be solved is considerably reduced, computation time does not reduce in the same proportion. The method makes use of certain closed from relations of what may be called ‘elementary’ problems. These solutions frequently contain trigonometric and logarithmic terms, which slow down the computations. Recognizing the advantages and disadvantages of the two methods, viz. FEM and BEM, many researchers have combined the two methods. This is coupled FEM/BEM method in which for a certain region (usually close to an opening or some other feature of interest) FE discretization is used, while for other regions BE discretization is adopted.

(3) The Discrete Element Method

This method is based on treating the rock mass as a discontinuum rather than continuum, as in the case of Finite Element and Boundary Element Methods. When loads are applied, the changes in contract forces are traced with time. In the earlier versions of the method rigid spherical balls or discs were used as elements. The equations of dynamic equilibrium for each element are repeatedly solved till the laws of contacts and boundary conditions are satisfied.

In the recent versions of the method, the elements can be of arbitrary shapes as in the Finite Element Method. They can also be deformable. Complex constitutive laws can also be used. The elements can split up based on the assumed fracture criterion during the calculation process without any external intervention. Thus, the method is extremely powerful.

There are, however, several drawbacks. Firstly, the parameters required for the description of material behavior are required to be chosen quite carefully in addition to certain additional parameters like the damping of the system. Computation time required to solve even simple problems can be excessive. At present, the method appears to be extremely useful in explaining the deformation and failure of rock masses qualitatively and provides a valuable insight into the failure mechanism. More experience is, however, required for it to be an acceptable tool of analysis in practice.

The numerical methods have long been in geotechnical engineering work. Ishida et al. (1987) used the DEM to evaluate the toppling failure of rock slope. Zhu and Zhang (1998) used the FEM to evaluate the stability and support design of heavily jointed rock of Three Gorges Dam foundation in China. Hu and Kempfert (1999) evaluated the model of bucking failure for bedded rock by using FEM. Fujjta (1999) evaluated the mass movement of soil slope by using the FEM. Nicot et al. (2001) used the DEM for wire mesh design of the rock fall protections. Forlati et al. (2001) used the FEM to analyze the deformation of rock mass in deep sea to prevent the large landslide. Lenart and Fifer-Bizjak (2002) used the FDM (FLAC program) to analyze and evaluate the effect of earthquake on stability of soil slope at Julian Alps, west of Slovenia. Ugai and Cai (2002) used FEM (3-D Elasto-plastic) to evaluate the soil stability to improve the soil strength by sheet plies. Cai and Ugai (2002) analyzed the effect of rainfall to explain the hydraulic gradient of pore pressure in a soil slope stability.

2.4 Block Theory

Goodman and Shi (1985) proposed a new method called block theory, for underground opening and rock slope analysis. The principle of block theory is that excavations cut into rock masses with several sets of discontinuities may liberate rock blocks of various sizes. The block of rock is isolated by the intersection of discontinuities and excavation surface. The potential movements of the most critically located block may then undermine neighbor blocks. The most critically located blocks are called “key blocks”. The theory establishes procedures for describing and locating key blocks and establishing their support requirements. The stereographic projection is used to define the location of key block. By using this procedure it is possible to plan an optimum reinforcement scheme, and to select excavation orientations and shapes that minimize or completely eliminate the need for artificial supports. The disadvantages of block theory are that 1) it is for the discrete block only (no displacement), 2) it can not be used for the intact stress analysis, and 3) the friction is not considered.

Hatzor (1995) used the block theory analyses to determine the behaviors of slope foundation of Pacoima dam as affected by earthquakes in California, USA. Hatzor (1999) used the block theory and DDA modeling to evaluate stability of slope at the Masada museum, western of Israel. Jeong-gi et al. (1996, 2001) used the block theory and stereographic projection to evaluate the maximum slope face angle of Three Gorges Dam foundation.

2.5 Expert System

The development of the Artificial Intelligence (or AI) and Expert System (or ES) software has begun about 20 years ago (Rich and Knight, 1991). AI and ES are the neural networks or the evaluation process for solving the complex problems, complex parameters and decision making. AI and ES use the decision network to solve the difficult problems. AI and ES are not database. Moula et al. (1995) compile the names of several expert systems and knowledge base systems that have been developed for the analysis and design in geotechnical engineering. Wharry and Ashley (1986) introduce one of the earliest KBSs to address the problem of determining the required level of geotechnical investigation. This is based on the requirements of proposed structure and the level of information known about the site.

The aim is to reduce the risk involved with the subsurface to an acceptable level. Smith and Oliphant (1991) develop a KBS to assist in the planning stages of a site investigation. The system provides suggestions as to the next stage of a site investigation (e.g. desk study, site reconnaissance, ground investigation etc.). The information obtained from the subsoil exploration stage is also used to create a 2-D visual representation of the soil layers. Alim and Munro (1987) present a very simple prototype KBS for soil identification that uses rather simplistic textbook knowledge. It provides judgment concerning the most likely foundation type under given soil and loading conditions, based on visual and physical observation of soil characteristics.

Rock mass classification systems make use of a set of reasonably defined well rules, therefore ideally suited for implementations as knowledge-based systems. A number of systems have been developed in geotechnical engineering, some of which have been reviewed by Zhang et al. (1988). Ghosh et al. (1987) describe an ES for deciding on rock bolt length and spacing for supporting coal mine roofs. Moon et al. (1995) have developed the software that is artificial neural-network integrated with expert system for preliminary design of tunnels and slopes.

There are some expert systems that have been developed for analysis and designs of the rock and soil slope. Grivas and Reagan (1988) describe a KBS (called STABCON) for evaluating slope instability and recommending appropriate types of treatment for soil slopes. It is similar to the analytical methods for calculating slope stability. Faure et al. (1991, 1995) develop the software called Expert System for Slope Stability for assisting in slope stability analysis. It assists in diagnosing the type of landslide on the basis of information about the geology, vegetation, geomorphology, and hydrogeology. Warakorn (1997) describes a KBS for soil slope stability existing in Thailand. Hao and Zhang (1994) describe a KBS for stability analysis of rock slopes. It uses fuzzy sets for representation of joint sets. Ozgenoglu and Ocal (1994) propose SEVDUR, a KBS for slope stability analysis relating to mining operations.

Adeli (1988) has described the advantages of expert system and the knowledge-based systems, for example the inference mechanism knowledge base is more explicit, accessible, and expandable. One can find a similarity between expert systems and the human reasoning process. It can be gradually and incrementally developed over an extended period of time. A general system with one inference mechanism can be developed for different types of applications simply by changing the knowledge base. The same knowledge may be used in different problems by possibly employing different inference mechanisms. An ES can explain its behavior through an explanation facility and can check the consistency of its knowledge entities or rules and point out the faulty ones through a debugging facility. ES does not make cursory or irrational decisions. It uses a systematic approach for finding the answer to the problem. The limitations of ES and KBS are that they do not learn, lack common sense and intuition. Their performance degenerates fast near the boundaries of their expertise. Most expert systems today lack a user-friendly natural language interface and are not easy to use by non-experts. Different experts often give more or less different design recommendations.

Even thought there are several design and field engineers who pose extensive skill and experience in rock slope analysis and design, the existing expert system in this discipline is extremely rare. The need in preservation of their knowledge and skill is increasingly important, as the relevant geological engineering projects become more complex in terms of geological conditions, engineering requirements, and economic constraints. It is however possible that many private firms in the developed countries could have developed and implemented some kind of intelligent systems for assisting in the analysis and design of rock slope. Application of such systems is normally for the internal use only. Such systems therefore have not been widely used, and hence have not been scrutinized by the public at large. In Thailand, in particular, no expert system on rock slope design publicly exists. The need in such systems becomes ever more crucial as the development of the infrastructures of the country must continue under the economic constraints.

CHAPTER III

FIELD INVESTIGATION AND CASE HISTORY COMPILATION

The main objectives of field investigation and case history review are to obtains data to develop criteria or rules for use in the stability analysis and design, and to use some of the field observation to verify the predictive capability of the developed software. This chapter summarizes the results of the field investigation routes and of the case history review. More details are given in Appendices A and B.

3.1 Field Investigation

The field investigation is divided into 7 routes. These routes and detailed locations are selected to obtain a variety of rock slope characteristics.

3.1.1 Kao Chow Lai Yai route

Kao Chow Lai Yai is located in Cha-Am district, Petchaburi province (Figure 3.1). The slope at this location is classified here as hard-soft interbedded rock mass. The bottom of the slope is shale, having a thickness of 80 meters. The upper slope is a massive limestone with a thickness of 120 meters. The rocks have three to four joint sets (Appendix A, slope nos.1 and 2). The mode of failure is secondary toppling on the vertical joint of limestone. The failure occurred due to the excessive excavation of the soft shale formation at the toe.

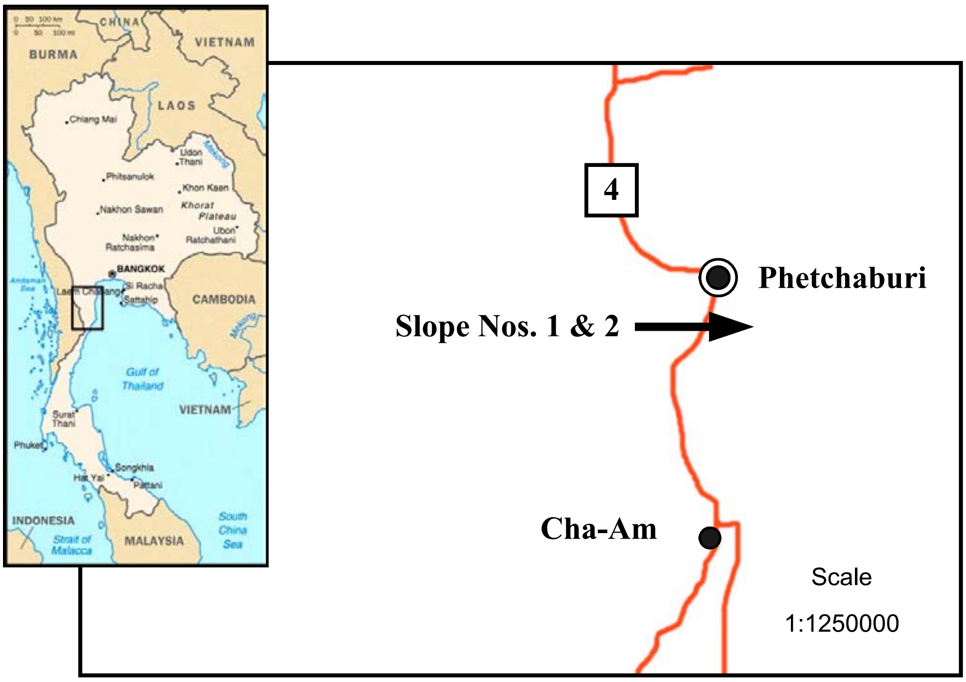

Figure 3.1 Slope locations along Khao Chow Lai Yai route, Cha–Am district Petchaburi province.

3.1.2 The Eastern route

The eastern route consists of eight slopes (slope nos.3 to 10 in Appendix A) located in the Nakhon Ratchasima, Prachinburi, Sa Kaeo, Chantaburi and Chon Buri provinces (Figure 3.2). Based on the rock mass characteristics, these slopes can be classified into three groups as follows.

1) The group of hard-soft interbedded rock mass is in Pak Thongchai district, Nakhon Ratchasima province, and in Sa Kaeo province (slope nos. 3 to 5 in Appendix A). The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft formation is shale. It is 0.2 to 1.0 meter thick. The slope heights are varied from 5 to 15 meters. The slope face angles are varied from 55 to 75 degrees. The rock has three joint sets. The failure is secondary toppling of the vertical joint in massive sandstone. The failure is initiated by the erosion of the lower soft shale bed which results in the collapse of the hard sandstone bed above.

2) The group of heavily jointed rock mass locates in Ban Pong Nam Ron district, Prachinburi province and in Chantaburi province (slope nos. 6 and 7 in Appendix A). The rock mass is shale having 5-25 MPa compressive strength (field-determined by ISRM method). The failure modes are the combination of plane sliding, toppling and circular failure. The failure is caused by the combination of water saturation, ground vibration (by heavy traffic) and angle slope face.

3) The group of blocky rock locates in Chon Buri province (slope nos. 8 to 10 in Appendix A). There are two types of rock; limestone and slaty-shale. The rock mass has three joint sets. The failure modes are plane sliding and block toppling. The failure is caused by the combination of water saturation and high angle slope face.

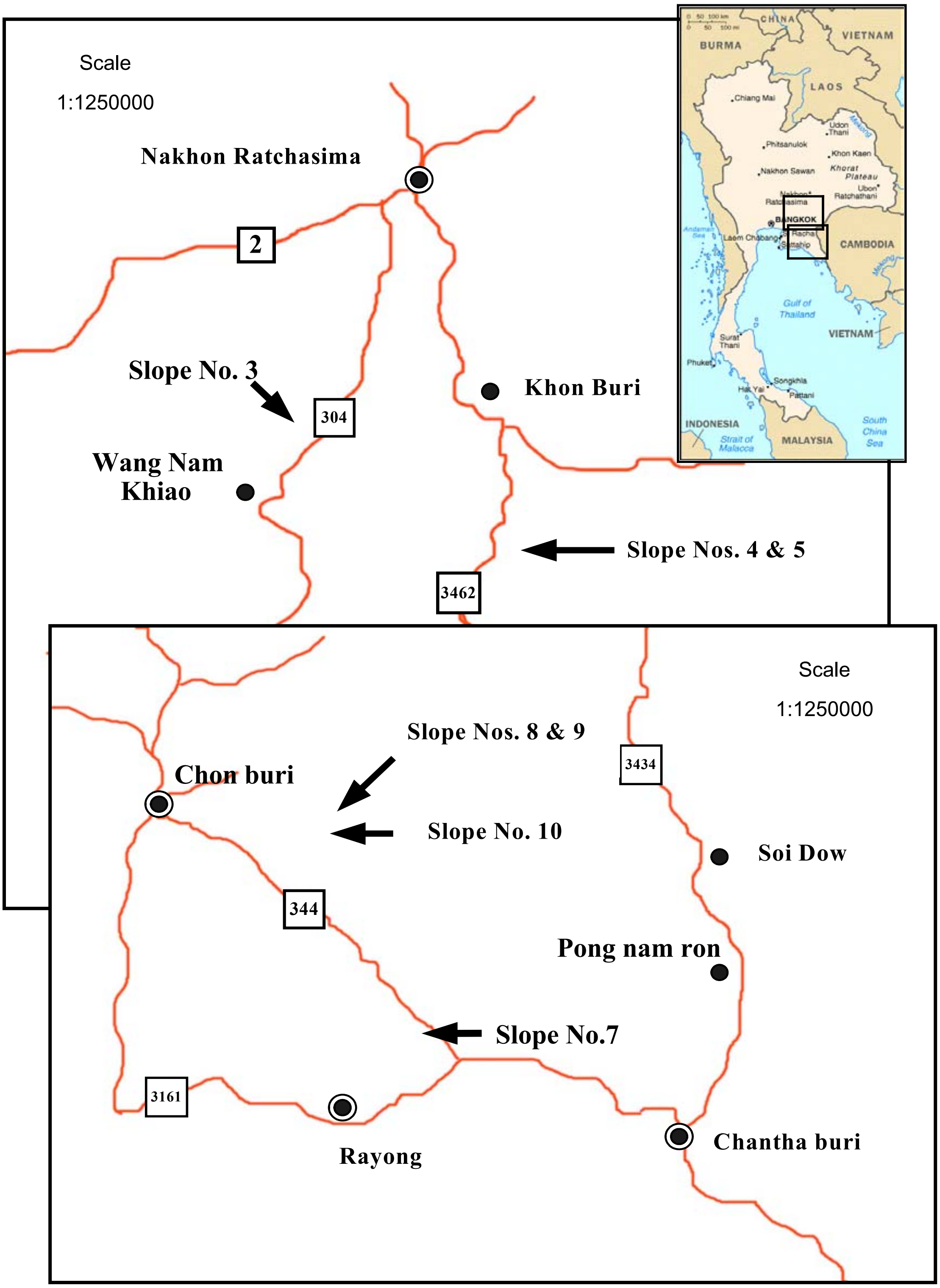

Figure 3.2 Slope locations along eastern route.

3.1.3 Khao Som Phot and Highway no. 2256 route

Khao Som Phot and Highway no. 2256 is located in Chai Badan district, Lop Buri province (Figure 3.3). There are two slope locations (slope nos. 11 and 12 in Appendix A), which can be classified into two groups as follows.

1) The group of blocky rock locates in Khao Som Phot quarry. The slope has (slope no.11) three joint sets. The joint spacing is about 0.5 to 0.8 meter. The slope heights are varied from 30 to 50 meters. The slope angles are varied from 60 to 80 degrees. The modes of failure are the combination of plane, wedge sliding and toppling of massive block (in form of rock fall). The failure is caused by blast vibration and steep slope face.

2) The group of hard-soft interbedded rock locates on highway no. 2256 (slope no. 12). The slope height is 50 meters. The slope angle is 70 degrees. The rock has three joint sets with 0.2 to 1.0 meter of spacing. The modes of failure are the combination of plane sliding and secondary toppling of hard blocks. The failure is caused by the erosion of the soft shale bed, water saturation, ground vibration (by heavy traffic) and the high angle slope face which results in the collapse of the hard sandstone bed.

3.1.4 Friendship Highway route

The Friendship highway route having 5 slope locations along the road cut between Nakhon Ratchasima and Sara-Buri provinces (Figure 3.4). The area is a part of Dong Phraya Fi Mountain range. The slope failures along the road cut have repeatedly occurred on some locations (slope nos. 13 to 17 in Appendix A). The slopes can be classified into three groups as follows.

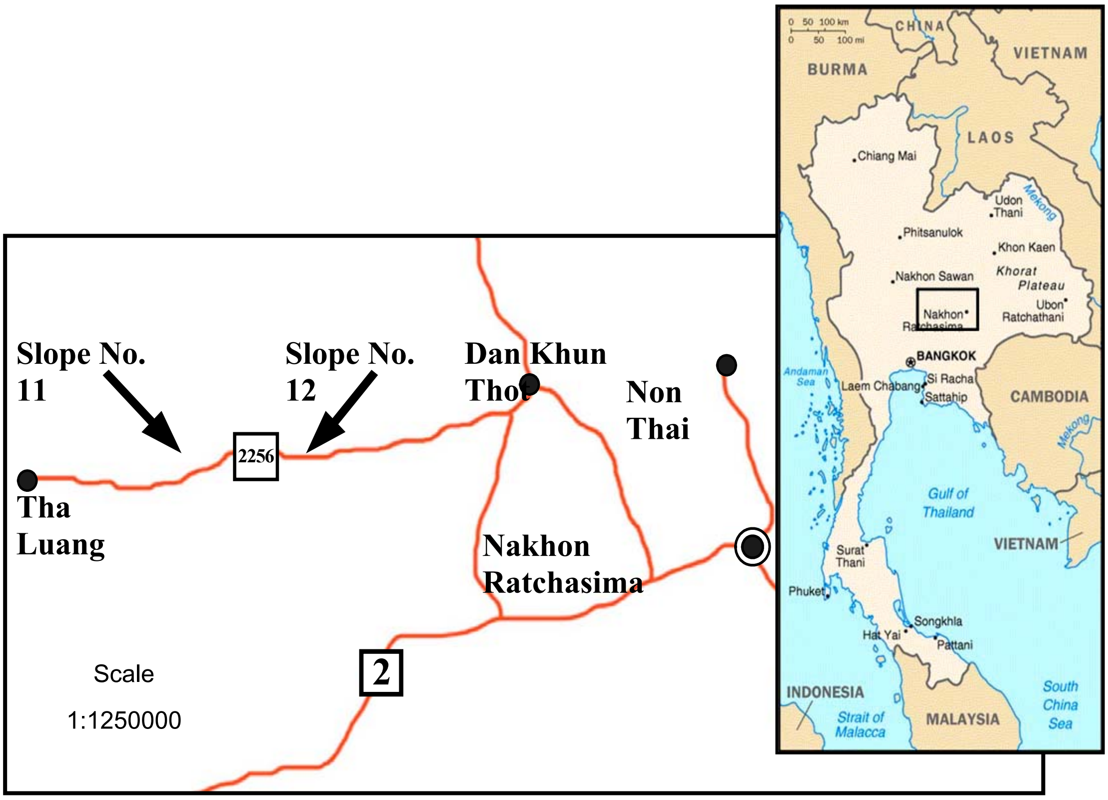

Figure 3.3 Slope locations along highway no. 2256 and Khao Som Phot route, Chai Badan, Lopburi province.

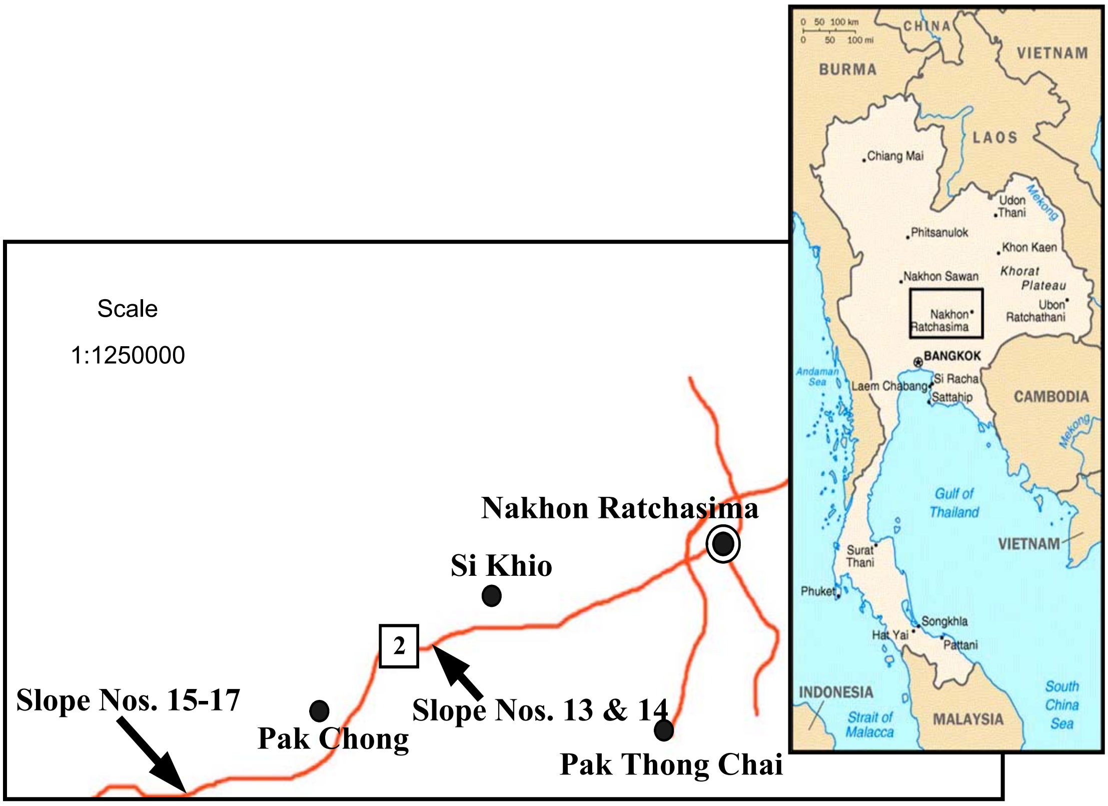

Figure 3.4 Slope locations along Friendship highway route, Saraburi to Nakhon Ratchsima provinces.

1) The group of hard-soft interbedded rock found on 194-196 km of the highway (slope nos. 13 and 14). The slope height is 40 meters. The slope face angle is 65 degrees. The hard formation is sandstone. It has 0.3 to 1.0 meter in thickness. The soft formation is shale. It has 0.2 to 0.7 meter in thickness. The rock has three joint sets. The failure mode is secondary toppling of the vertical joints in the massive sandstone. The failure is caused by the erosion of the soft shale bed, water saturation, ground vibration (by heavy traffic) which results in the collapse of the hard sandstone bed above.

2) The group of massive rock is found on 136 to 137 km of the Friendship highway (slope nos. 15 and 16). The rock is massive limestone. The slope height is varied from 10 to 15 meters. The slope face angles are varied from 50 to 80 degrees. The rock has three joint sets with 1.0 to 1.5 meters joint spacing. The joints have high roughness. Persistence of rock joints is low. The modes of failure are plane and wedge sliding of the hard block. The failure is caused by the water saturation and ground vibration which results in the sliding of the rock blocks.

3) The group of bedded rocks is found on 133 to 134 km of the Friendship highway (slope no. 17). The slope height is 12 meters. The slope face angles are varied from 40 to 45 degrees. The rock is slaty-shale. It has three joint sets, with smooth and high persistence. Clay filling is found. The slope is stable.

3.1.5 PANDS Barite mining route

PANDS barite mine is located in Chieng Kan district, Loei province (Figure 3.5). There are two groups for geologic features in the rock mass (slope nos. 18 and 19).

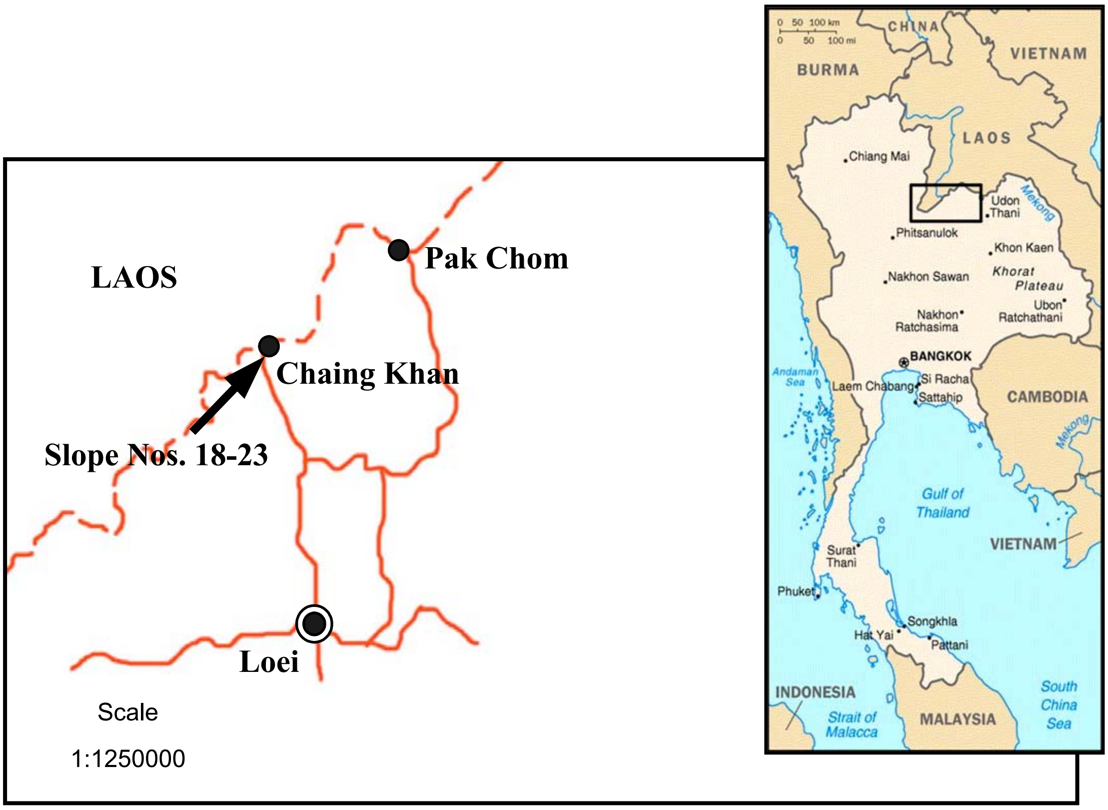

Figure 3.5 Slope locations at PANDs Barite mining route, Chieng-Kan Loei province.

1) The footwall slope has two types of rock; massive limestone and shale. The limestone has three joint sets. The joint spacing is large. The limestone joints have high roughness. Persistence of the rock joint is low. The joints are filled with ferrous oxides. There are three to four joint sets in shale with small spacing (less than 10 cm.), and with smooth and high persistence. Clay filling is found. The modes of failure are small plane and wedge sliding of the shale bedding plane. The failure is caused by the water saturation and ground vibration which results in the sliding of the rock blocks.

2) The hanging wall has two types of rock; massive limestone and shale. The limestone has three joint sets and large spacing. The limestone joints have high roughness. Persistence of the rock joint is low. Ferrous oxide filling is found. There are three to four joint sets in shale and small spacing (less than 10 cm), with smooth and high persistence. Clay filling is found. The failure modes are the combination of plane sliding, toppling and circular failure. The failure is caused by the combination of water saturation, ground vibration and high slope angle.

3.1.6 Highway no. 12

Lomsak-Chumpae highway was constructed over 20 years ago to shorten the distance from the north to the northeast of Thailand. It is 120 kilometers long, cutting across Phetchabun and Khon Kaen provinces (Figure 3.6). The slope failures along the road cuts have repeatedly occurred on some locations. The rock mass can be classified into three groups; bedded rock, heavily jointed rock and soft rock. The modes of failure are circular, plane, wedge and toppling failures.

The failure modes are the combination of plane, wedge sliding and toppling for slope nos. 24 to 26, 29 and 33 to 35. The failures are caused by the

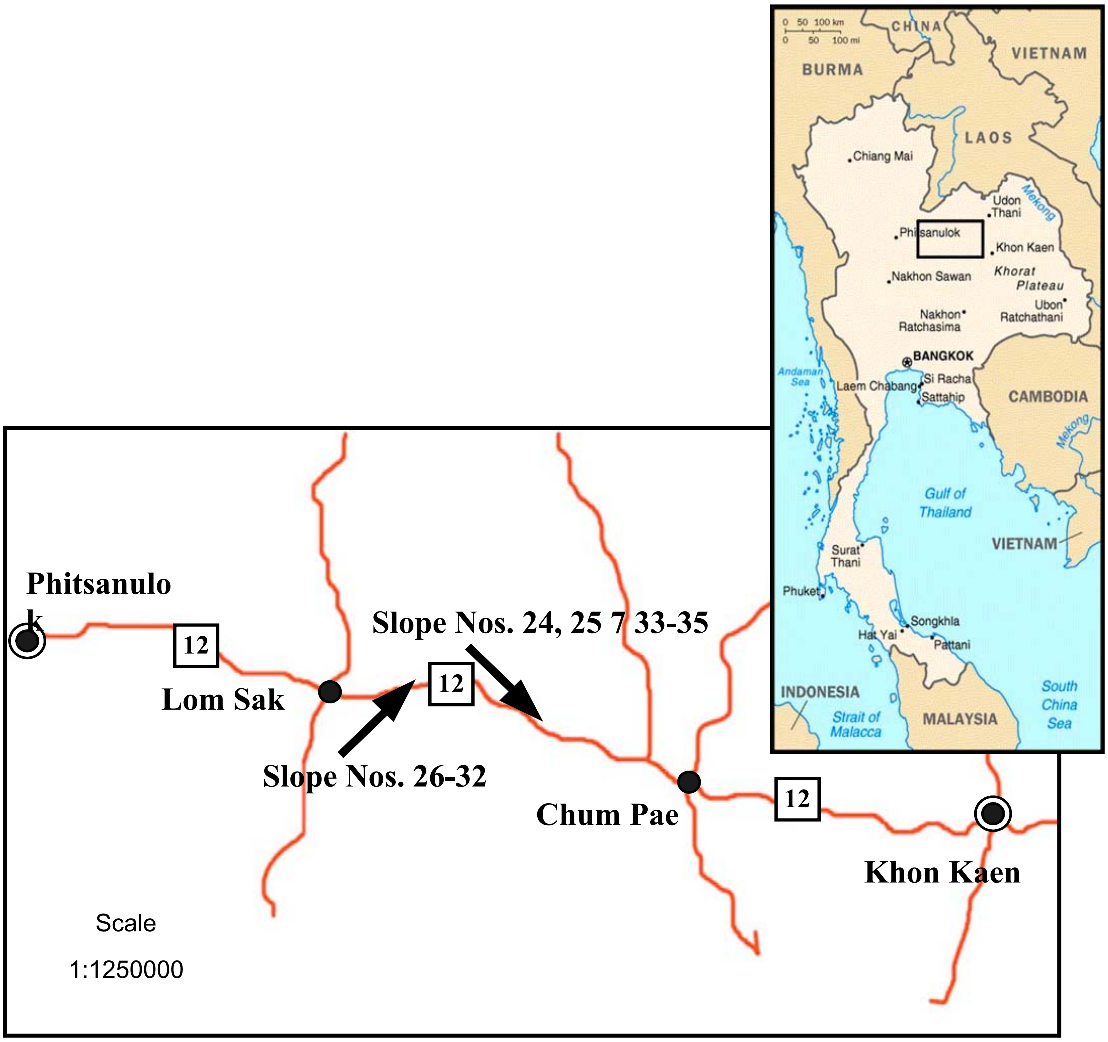

Figure 3.6 Slope locations along highway no.12 route, Chum Pae to Lom- Sak districts, Khon-Kaen to Petchabun provinces.

combination of water saturation, ground vibration (by heavy traffic) and steep slope face. The slope nos. 27 and 28 are classified here as heavily jointed rock. The mode of failure is circular. The slope nos. 30 to 32 is fairly stable.

3.1.7 Highway no. 105 and Ubonrat dam routes

The highway no.105 route shortens the distance between the central and the western parts of Thailand. It is 105 kilometers long, cutting across Tak province (Figures 3.7 and 3.8). The slope failures along the road cuts have repeatedly occurred on some locations, as follows.

The failure modes of slope nos. 36, 37, 40, and 42 to 44 are plane, wedge and toppling failures.

The circular failure has occurred on heavily jointed rock at slope nos. 38, 41 and 45 to 48. Slope nos. 39, 46, 49, 51 and 52 are highly stable.

The failure is caused by the water saturation, erosion, ground vibration (by heavy traffic) which results in the sliding.

3.2 Case History Reviews

The sources of data subjected to review are from journals and conference papers in geological and civil engineering fields, for examples journals in Rock Mechanics and Rock Engineering, Rock Mechanics and Mining Sciences, Geological Engineering and Geotechnical Engineering, Engineering Geology. The conferences papers are for example, “the Regional Symposium on Sedimentary Rock Engineering, International Symposium on Geotechnical Stability in Surface Mining and South Africa Mining, Latin America / Minerla Latinoamericana conference, and the US Symposium on Rock Mechanics.

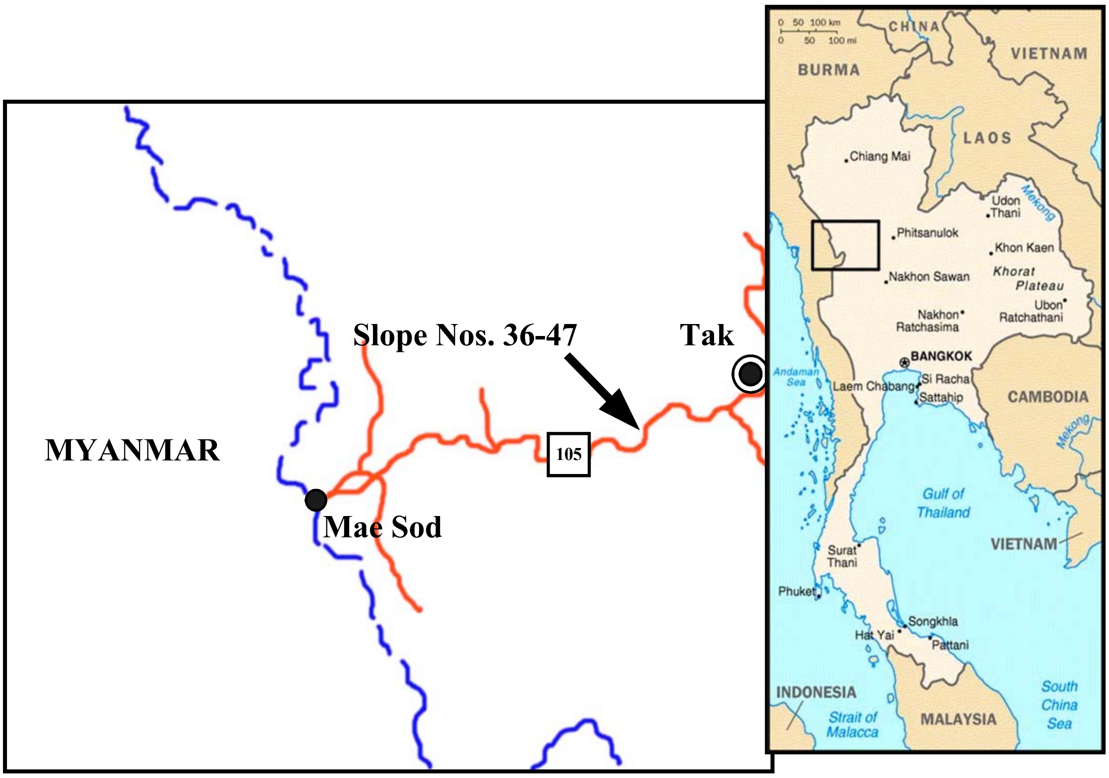

Figure 37 Slope locations along highway no.105 route, Mae Sod district, Tak province.

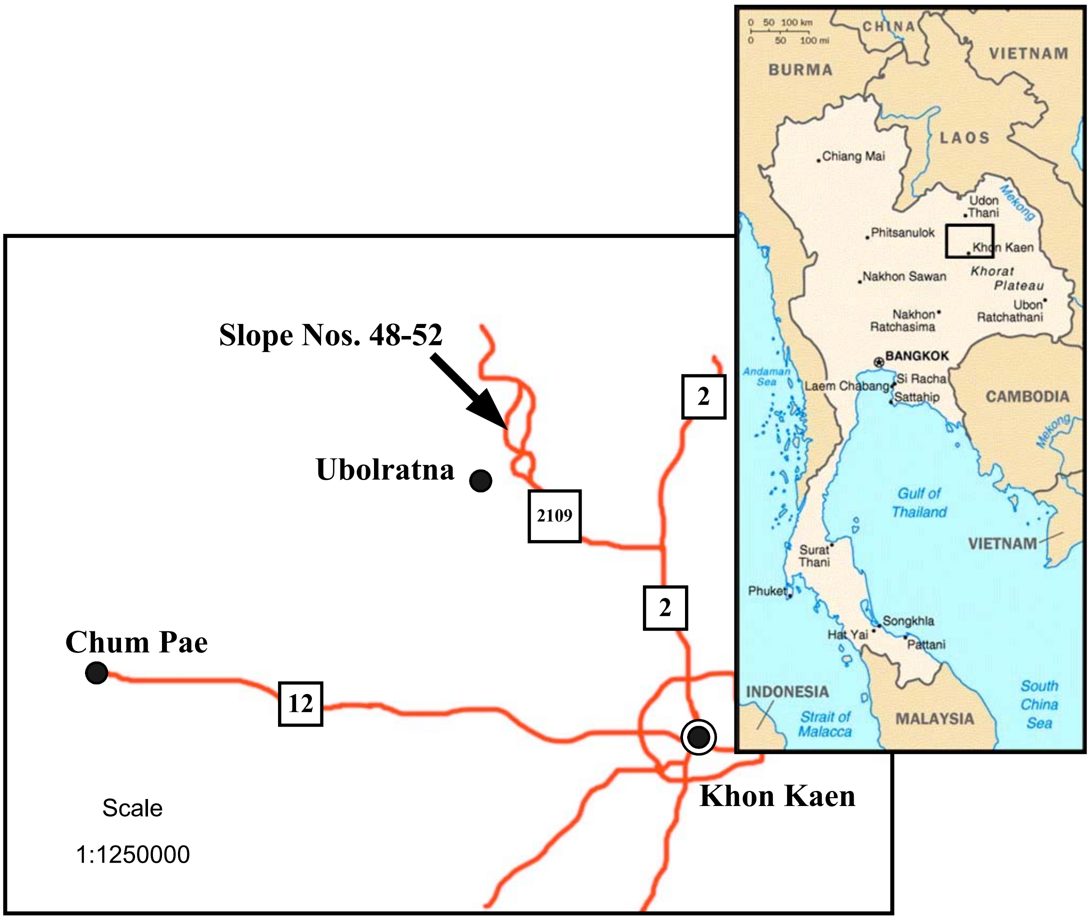

Figure 3.8 Slope locations along Ubonrat dam route, Khon Kaen province.

Over 80% of the articles are the symposium conferences. Only 55 out of 200 papers give complete information on the slope parameters and stability conditions. Most of the missing parameters are slope height, slope face angle, slope application, failure modes, number of joint sets, joint orientation, joint spacing, joint aperture, material infilling, joint roughness, joint persistence and groundwater table.

CHAPTER IV

DEVELOPMENT OF PROGRAM STRUCTURE

This chapter explains the concept used in the development of the proposed expert system for the rock slope stability analysis and support design, hereafter called ROSES.

4.1 Program Structures

The program comprises three components: data acquisition, data evaluation, and design recommendations (Figure 4.1). 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).

4.2 Considered Parameters

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

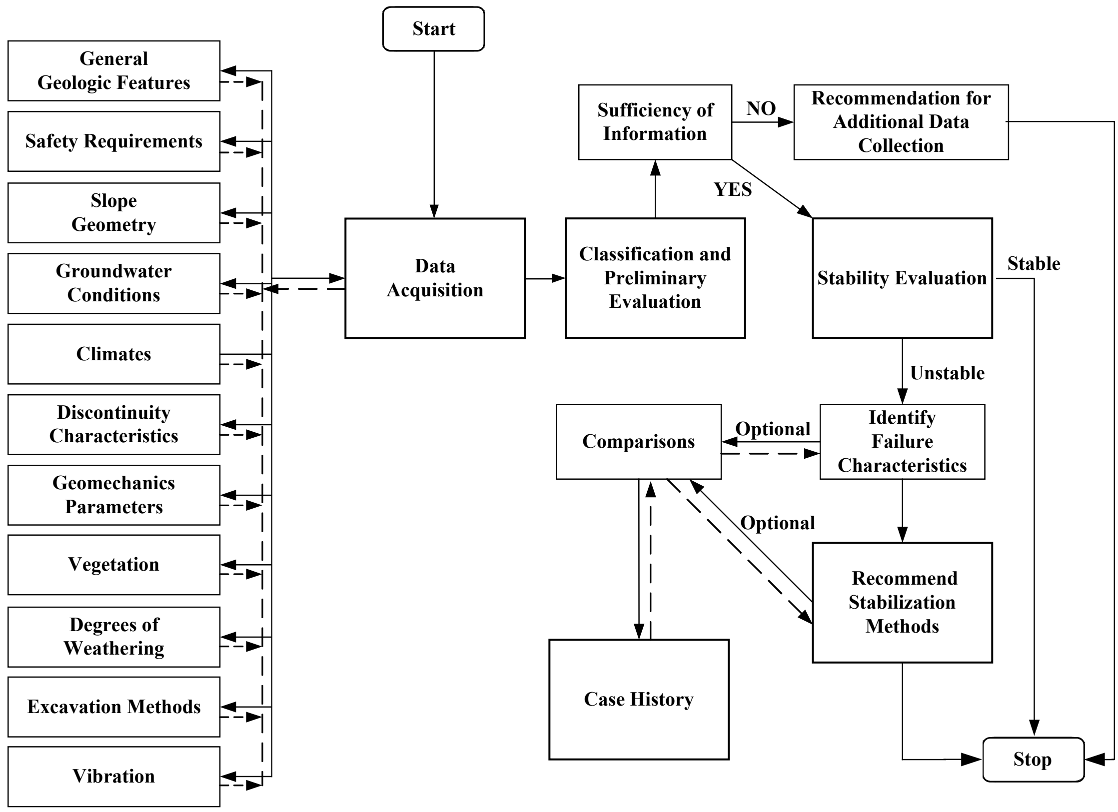

Figure 4.1 Main network of ROSES.

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. "Unknown" is also available. The main categories whose questions belong to are as follows.

4.2.1 Geologic features: There are six types of rock slope that ROSES can evaluate and design based on their general geologic features 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.

4.2.2 Slope applications: ROSES classify 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.

4.2.3 Water conditions: ROSES classifies the water conditions in the slope in terms of the water levels 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 does 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.

4.2.4 Slope geometry: 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.

4.2.5 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 number of joint sets of the slope problem is limited to four. The roughness is important because the system can use Barton strength criterion for the joints.

4.2.6 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.

4.2.7 Supplementary 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. A ROSE 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.

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 a progress, ROSES evaluates the incoming information and tries to classify the slope to narrow down the types of problem, and hence makes them 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 Stability Evaluation

The system classifies each factors considered in the stability evaluation into small ranges or sub-divisions mainly to convert the input slope characteristics into quantitative form. The classification follows as much as practical the suggested methods by the International Society of Rock Mechanics (ISRM-Brown, 1981). A set of rating is then assigned to these parameters for each failure mode considered. Recognizing that the significance of these parameters can be at different degrees for different conditions of rock mass, a set of influencing factors is also defined as multiplying factors for the corresponding parameter. The probability of failure P{f} in percent for each mode can then be calculated by equations:

$$P\{f\} = \Sigma\ \{R_n * I_n\} \qquad (1)$$

where R_n is the rating for each parameter, In is the influencing factor for the corresponding parameter, and “n” represents type or number of the parameters considered for each slope (varying from 1, 2, 3, 4 …n). Table 4.1 and 4.2 list the rates and influencing factors to calculate the probability of the circular failure. In this case, the value n equals to 8. The calculations of the probability of failure for plane and wedge sliding use 12 parameters, hence n = 12 and toppling use 10 parameters. Detailed classifications, rating, and influencing factors for the plane and wedge sliding and toppling failure evaluation are given in Tables 4.1 through 4.8.

To correlate the probability of failure to the factor of safety, the system defines that the factor of safety is 1.0 when P{f} equals to 50%. The system recommendations also compare the calculated P{f} against the degrees of safety required for four types of engineering application. For Type A where the slope toe is nearby the residential structures or power plant facilities, P{f} should be less than 10% . Type B is for the

Table 4.1 Rating factors for evaluation of circular failure.

Slope height		**Slope face angle**		**Groundwater**		**Degree of weathering**	
(m)	**Rate**	**Degrees**	**Rate**	**(%)**	**Rate**	**Conditions**	**Rate**
5-7	1	20-25	0	0	0	Fresh	2
7-10	5	25-30	1	25	5	Slightly	4
10-15	8	30-35	2	50	10	Moderately	6
15-20	10	35-40	3	75	10	Highly	8
>20	10	40-45	5	100	10	Completely	10
		45-50	6	Unknown	*5 or 10	Unknown	5
		50-55	8				
		55-60	9				
		60-65	9				
		65-70	10				
		>70	10				

Vegetation		**Number of discontinuity**		**Vibration**		**Average discontinuity spacing**	
Conditions	**Rate**	**(Sets)**	**Rate**	**Conditions**	**Rate**	**(mm)**	**Rate**
No vegetation	10	≤ 2	1	Near Blasting sites, earthquake	10	< 20	10
Only grass	7	3	8	Near main highway	5	20-60	7
Grass with small trees	5	≥ 4	10	No vibration	0	60-200	5
Full grown trees	0	Unknown	5	Unknown	5	>200	0
Unknown	5					Unknown	5

* 5 for arid climate, 10 for tropical climate

Table 4.2 Influencing factors for evaluation on circular failure.

Rock grade	Slope height	Slope face angle	Groundwater	Degree of weathering
R0	2.0	2.0	3.1	0
R1	1.7	1.8	2.2	0.2
R2	0.1	0.1	1.2	0.4
Rock grade	**Vegetation**	**Number of discontinuity**	**Vibration**	**Average discontinuity spacing**
R0	0.5	0	2.4	0
R1	1.1	0.4	0.5	2.1
R2	2.0	1.2	0.1	4.9

Table 4.3 Rating factors for evaluation of plane and wedge slide.

Number of other discontinuity		Slope height		Apertures of the analyzed set		Infilling of the analyzed set	
Sets	**Rate**	**(m)**	**Rate**	**(mm)**	**Rate**	**Type**	**Rate**
1	2	5-7	1	<0.1	1	Calcite	0
2	6	7-10	2	0.1-0.25	2	Nothing	5
3	10	10-30	4	0.25-0.5	3	Sand, Silt	10
4	10	30-50	8	0.5-2.5	5	Clay	10
Unknown	8	>50	10	2.5-10	8	Unknown	5
				>10	10		
				Unknown	5		
Persistence		**JRC first set**		**$(\psi_p - \phi)^*$**		**Degree of weathering**	
%	**Rate**		**Rate**	**Degrees**	**Rate**	**Conditions**	**Rate**
0-50	0	0-2	10	70-80	10	Fresh	2
50-80	2	2-4	10	60-70	10	Slightly	5
80-100	10	4-6	9	50-60	8	Moderately	8
Unknown	5	6-8	7	40-50	5	Highly	10
		8-10	6	30-40	3	Completely	10
		10-12	4	20-30	2	Unknown	8
		12-14	2	10-20	1		
		14-16	0	0-10	1		
		16-18	0	-10-0	0.5		
		18-20	0	<-10	0		
		Unknown	5				
Groundwater		**Slope shape**		**Vegetation**		**Excavation methods**	
(%)	**Rate**	**Shape**	**Rate**	**Conditions**	**Rate**	**Methods**	**Rate**
0	1	Concave	5	No vegetation	10	Blasting with pre-splitting	5
25	5	Straight	7	Only grass	7	Blasting without pre-splitting	10
50	10	Convex	10	Grass & small tree	5	Backhoe	0
75	10			Full grown tree	0	Unknown	5
100	10			Unknown	5		
Unknown	** 5 or 10						

* ψ_p = sliding plane angle; ϕ = friction angle of joint ** 5 for arid, 10 for tropical

Table 4.4 Influencing factors for evaluation of plane and wedge slide.

Rock grade	**Other discontinuity**	**Slope height**	**Aperture**	**Infilling**	**Persistence**	**JRC first set**
R2	0	2.1	0	0	0	0
R3	0.4	1.8	0.3	0.9	0.5	0.5
R4	1.3	0.8	0.5	1.3	1.8	1.0
R5	1.3	0	1.0	1.8	2.4	2.0
Rock grade	**ψ_p - ϕ**	**Degree of weathering**	**Groundwater**	**Slope shape**	**Vegetation**	**Excavation methods**
R2	3.0	1.0	2.1	0.5	0.7	0.6
R3	2.5	0.6	1.2	0.3	0.5	0.5
R4	1.8	0.3	0.5	0.2	0.3	0.2
R5	1.5	0	0	0	0	0

Table 4.5 Rating factors for evaluation of toppling failure.

Number of other discontinuity		**Average persistence of the set 2^{nd} & 3^{rd}**		**Average of apertures**		**Infilling set 3^{rd}**	
Sets	**Rate**	**%**	**Rate**	**(mm)**	**Rate**	**Type**	**Rate**
1-2	0	0-20	2	<0.1	1	Calcite	0
3	8	20-40	2	0.1-0.25	5	Nothing	10
4	10	40-60	6	0.25-0.5	10	Sand, Silt	10
Unknown	5	60-80	8	0.5-2.5	10	Clay	10
		80-100	10	2.5-10	10	Unknown	10
		Unknown	6	6	10		
				Unknown	10		
Persistence of the set 1^{st}		**JRC of the set 3^{rd}**		**Dip of set 1^{st}**		**Degrees of weathering**	
%	**Rate**		**Rate**	**Degrees**	**Rate**	**Conditions**	**Rate**
0-20	2	0-2	10	80-90	3	Fresh	2
20-40	2	2-4	10	20-80	10	Slightly	5
40-60	6	4-6	9	0-20	10	Moderately	8
60-80	8	6-8	5			Highly	10
80-100	10	8-10	5			Completely	10
Unknown	6	10-12	5			Unknown	8
		12-20	2				
		Unknown	5				
Groundwater table		**Vegetation**		**Excavation methods**		**Vibration**	
(%)	**Rate**	**Conditions**	**Rate**	**Methods**	**Rate**	**Conditions**	**Rate**
0	1	No vegetation	10	Blasting with pre-splitting	5	Near Blasting sites, earthquake	10
25	5	Only grass	7	Blasting without pre-splitting	10	Near main highway	5
50	5	Grass & small tree	5	Backhoe	0	No vibration	0
75	5	Full grown tree	0	Unknown	5		
100	10	Unknown	5				
Unknown	** 5 or 10						
** 5 for arid climate, 10 for tropical climate							

Table 4.6 Influencing factors for evaluation of toppling failure.

Rock grade	Other discontinuity	Average persistence set 2nd & 3 rd	Average of apertures	Infilling set 3 rd	Average persistence of the set 1st	JRC of the set 3 rd
R2	0.8	0.5	0.9	0.1	0.5	0.2
R3	1.0	0.6	0.8	0.2	0.6	0.3
R4	1.2	0.7	0.7	0.2	0.7	0.4
R5	1.3	0.8	0.6	0.3	0.9	0.5
R6	1.4	1.0	0.5	0.4	1.0	0.7

Rock grade	Dip of set 1st	Degree of weathering	Groundwater table	Vegetation	Excavation methods	Vibration
R2	3	1.1	0.6	1.0	0.6	0.7
R3	3	0.9	0.4	1.0	0.4	0.8
R4	3	0.7	0.3	0.9	0.3	0.9
R5	3	0.4	0.2	0.8	0.2	1.0
R6	3	0.0	0.2	0.5	0.1	1.2

Table 4.7 Rating factors for evaluation of hard / soft interbedded rock (rock fall).

Slope height		Slope face angle		Number of joint		Soft thickness	
(m)	**Rate**	**Degrees**	**Rate**	**Set**	**Rate**	**(m)**	**Rate**
5-7	2	20-25	2	1	2	0.3-0.6	3
7-10	5	25-30	3	2	5	0.6-0.9	3
10-15	8	30-35	4	3	7	0.9-1.2	4
15-20	8	35-40	6	4	10	1.2-1.5	5
>20	10	40-45	7	Unknown	5	1.5-1.7	6
		45-50	8			1.7-2.0	7
		50-55	8			> 2.0	10
		55-60	9				
		60-65	10				
		65-70	10				
		>70	10				

Average joint spacing		δ_q		Ψ_{ap}	
(mm)	**Rate**	**Degrees**	**Rate**	**Degrees**	**Rate**
<20	10	0-10	10	0-10	0
20-60	8	10-20	9	10-30	2
60-200	6	20-30	8	30-50	5
200-600	5	30-40	7	>50	10
600-2000	4	40-50	6		
2000-6000	3	50-60	5		
>6000	2	60-70	4		
Unknown	5	70-110	3		
		110-120	4		
		120-130	5		
		130-140	6		
		140-150	7		
		150-160	8		
		160-170	9		
		170-180	10		

Groundwater		Vegetation		Vibration	
(%)	**Rate**	**Conditions**	**Rate**	**Conditions**	**Rate**
Completely dry	3	No vegetation	10	Near blasting sites / Earthquake	10
25	5	Only grass	7	Near main highway	5
50	7	Grass & small tree	6	No vibration	0
75	8	Full grown tree	5	Unknown	5
100	10	Unknown	*5 or 10		
Unknown	10				

* 5 for arid climate, 10 for tropical climate

Table 4.8 Influencing factors for evaluation of hard / soft interbedded rock (rock fall).

Soft rock & Hard rock	**Slope height**	**Slope face angle**	**Number of discontinuity**	**Average discontinuity spacing of hard rock**
R1&R4	1.8	2.1	0	0.2
R1&R3	1.8	2.0	0.7	0.5
R2&R5	1.2	2.0	1.3	1.3
R2&R4	1.0	1.5	2.0	1.9
R3&R5	0.9	1.3	2.5	2.5

Soft rock & Hard rock	δ_q	Ψ_{ap}	**Groundwater**	**Vegetation**	**Vibration**
R1&R4	1.0	1.2	1.3	0.4	1.0
R1&R3	0.8	1.2	1.2	0.4	0.6
R2&R5	0.7	1.0	1.0	0.3	0.5
R2&R4	0.7	0.9	0.8	0.2	0.4
R3&R5	0.6	0.8	0.7	0.2	0

δ_q = Oblique angle between dip direction of slope face and dip direction of hard formations

Ψ_{ap} = Apparent dip angle of hard formations along dip direction of slope face slopes along he main highways, railroads, and large bridges, which requires the P{f} less than 30%. Type C is for the slopes along the small roads and reservoirs, which requires the P{f} less than 50%. Type D requires P{f} less than 70% which is defined for the temporary access or small roads in open pit mines.

4.4 Support Design and 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 length of the drained pipes (Hoek and Bray, 1981).

Based on the slope characteristics, the system selects the most suitable design solution for the reinforcements. A total of 9 design solutions are available. They comprise different combinations of the design components (Figure 4.2). The

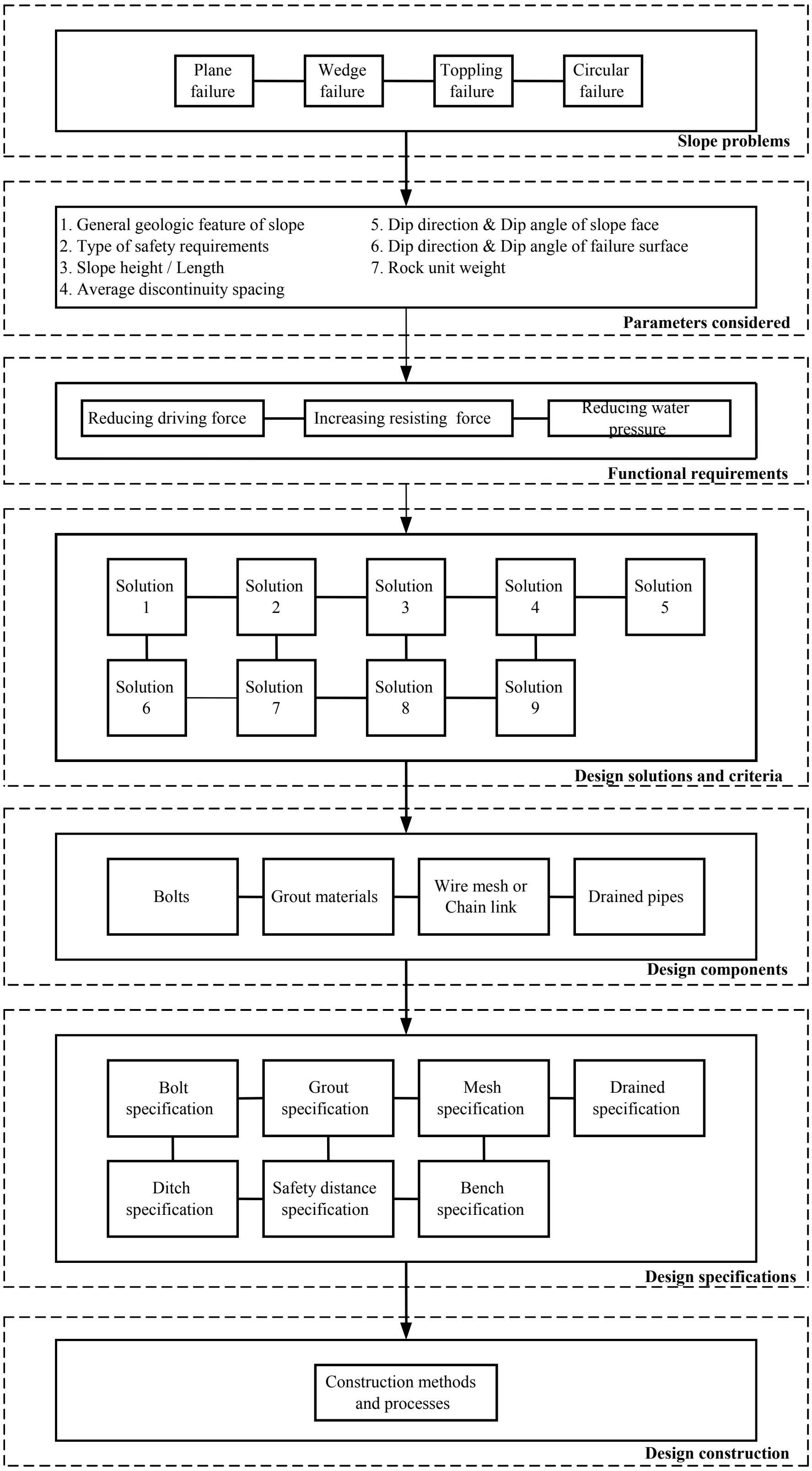

Figure 4.2 Stabilization methods of ROSES diagram.

specifications for each design component are determined by the slope characteristics and by the safety requirements (Table 4.9). Comparing with the actual rock slopes under a variety of stable and unstable conditions has assessed the predictive capability of the proposed expert system.

Table 4.9 Design process for slope stabilization.

Parameters Considered	Functional Requirements	Design Solutions	Design Components	Constraints	Design Specifications:
σ_c = 0.25-1 & 1-5 MPa	Reduce driving force	Solution : 5 Modify slope shape	1. Slope height 2. Slope face angle	None	1. 5-7 m / 35° * 2. 7-10 m / 30° 3. > 10 m / bench width ≥ 4 m & working face = 30°
σ_c = 5-25 MPa				A & B	1. 5-10m / 50° 2. 10-15m / 45° 3. 15-20m / 40° 4. > 20m / bench width ≥ 4 m & working face = 40°
σ_c = 5-25 MPa				C & D	1. 5-10 m/ 60° 2. 10-15m / 55° 3. 15-20m / 50° 4. > 20m / bench width ≥ 4 m & working face = 50°
σ_c = 25-50 MPa				A & B	1. 5-7m / 65° 2. 7-10m / 60° 3. 10-15m / 50° 4. 15-20m / 45° 5. > 20m / bench width ≥ 4 m & working face = 45°
σ_c = 25-50 MPa				C & D	1. 5-7m / 75° 2. 7-10m / 70° 3. 10-15m / 60° 4. 15-20m / 55° 5. > 20m / bench width ≥ 4 m & working face = 55°
1. Dip direction of failure plane 2. Average joints spacing 3. Slope height 4. Slope length 5. Slope dip direction 6. Slope dip angle 7. Rock unit weight 8. Groundwater level 9. Intact strength	1. Increase resisting force 2. Reduce driving force	Solution : 1	Rock bolts	(A, B, C or D)	**Rock bolts*** Fully grout steel rebar (A &B) Rock anchored (C & D) **Grout materials** Resin (A) Cement (B) **Wire mesh** Galvanize (A) **Drained pipe** PVC or Steel pipe
		Solution : 2	Rock bolts Wire mesh		
		Solution : 3	Rock bolts Wire mesh Drained pipe		
		Solution : 4	Drained pipe		
		Solution : 6	Rock bolts Bench design		Same as solution : 1 to 5 but If Intact strength = R3 to R4 and Slope height > 30 m (A & B) or > 40 m (C & D) Then Bench width ≥ 4 m and Slope face angle < 60°
		Solution : 7	Rock bolts Wire mesh Bench design		
		Solution : 8	Rock bolts Wire mesh Drained pipe Bench design		
		Solution : 9	Drained pipe Bench design		

σ_c = Uniaxial Compressive Strength, * Slope Height / Slope Face Angle,
** Williams Form Engineering Corp (2002), A, B, C and D = Slope Types (Safety Requirements)

CHAPTER V

FLOWCHART

This chapter shows all flowcharts describing the development of ROSES program. The program comprises 4 parts; 1) data acquisition, 2) classifications and preliminary evaluation, 3) stability evaluation, and 4) recommended stabilization methods.

5.1 Flowchart of ROSES

There are 4 main phases in ROSES as follows (Figure 4.1).

1) Data acquisition phase
2) Classifications and preliminary evaluation phase
3) Stability evaluation phase
4) Recommended stabilization methods phase

Figures 5.1 through 5.8 give flowcharts showing the paths and decision-making for the process of data collection or data acquisition representing the first phase. Such information is memorized and forwarded to the second phase. The second phase is dealing with the classification and evaluation of the collected data. These processes are shown by the flowcharts given in Figure 5.9. If it is proved that the input information is sufficient for the stability evaluation, ROSES will forward the input slope problem to the third phase. This third phase will perform the stability evaluation as shown in details in Figures 5.10 through 5.13. If the slope problem shows the possibility of failure, the program will offer the design for stabilization schemes. Figures 5.14 through 5.17 show how the program recommends the appropriate methods to stabilize the slope.

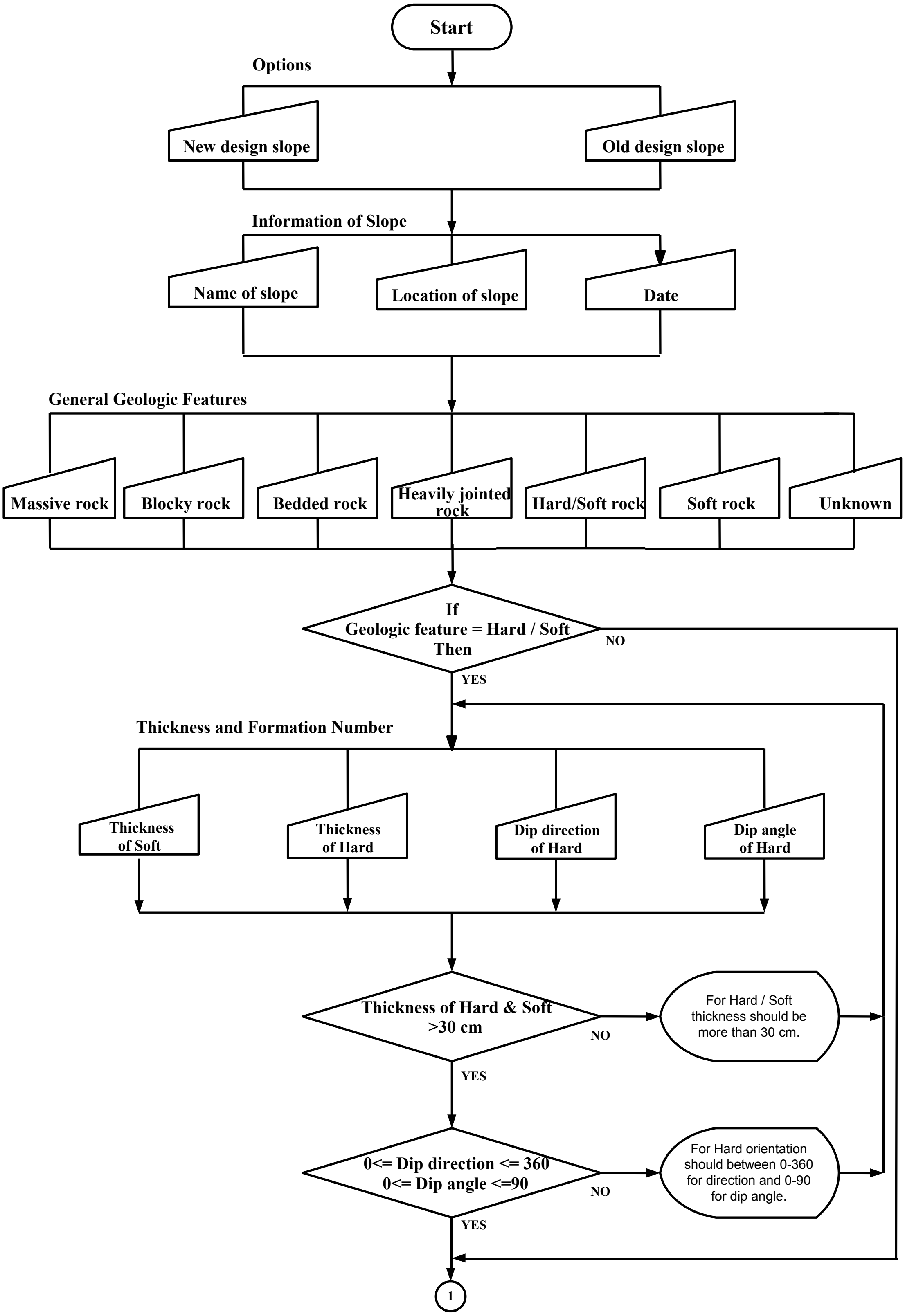

Figure 5.1 Data acquisition flowchart.

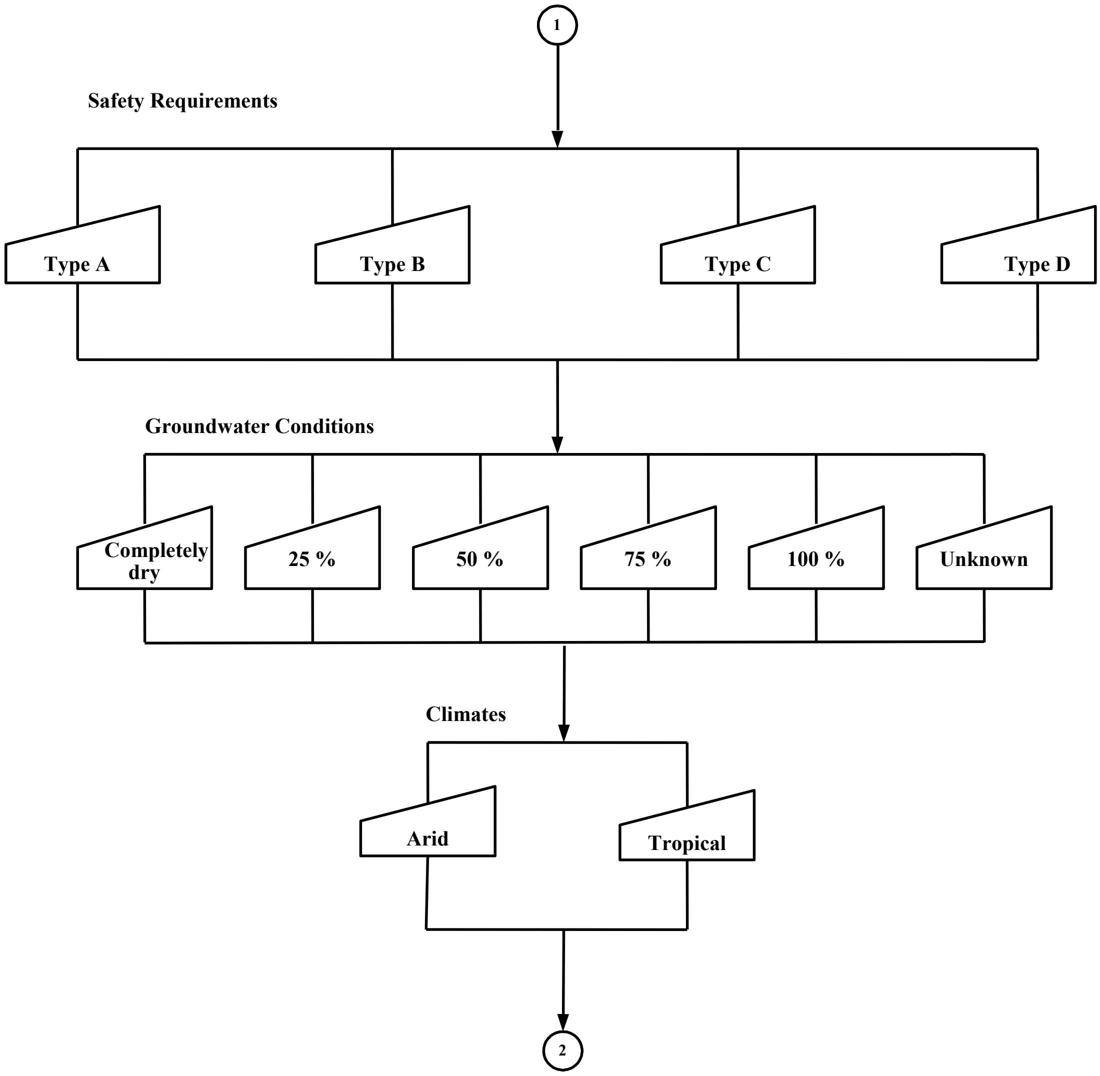

Figure 5.2 Data acquisition flowchart (cont.).

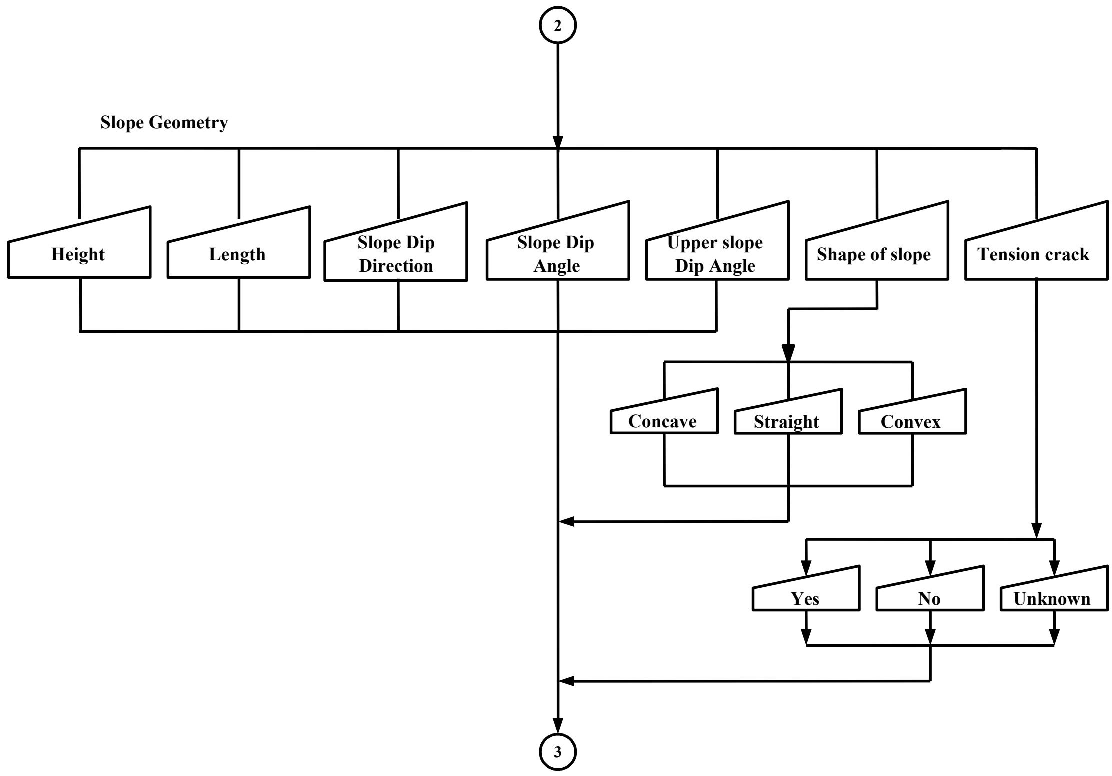

Figure 5.3 Data acquisition flowchart (cont.).

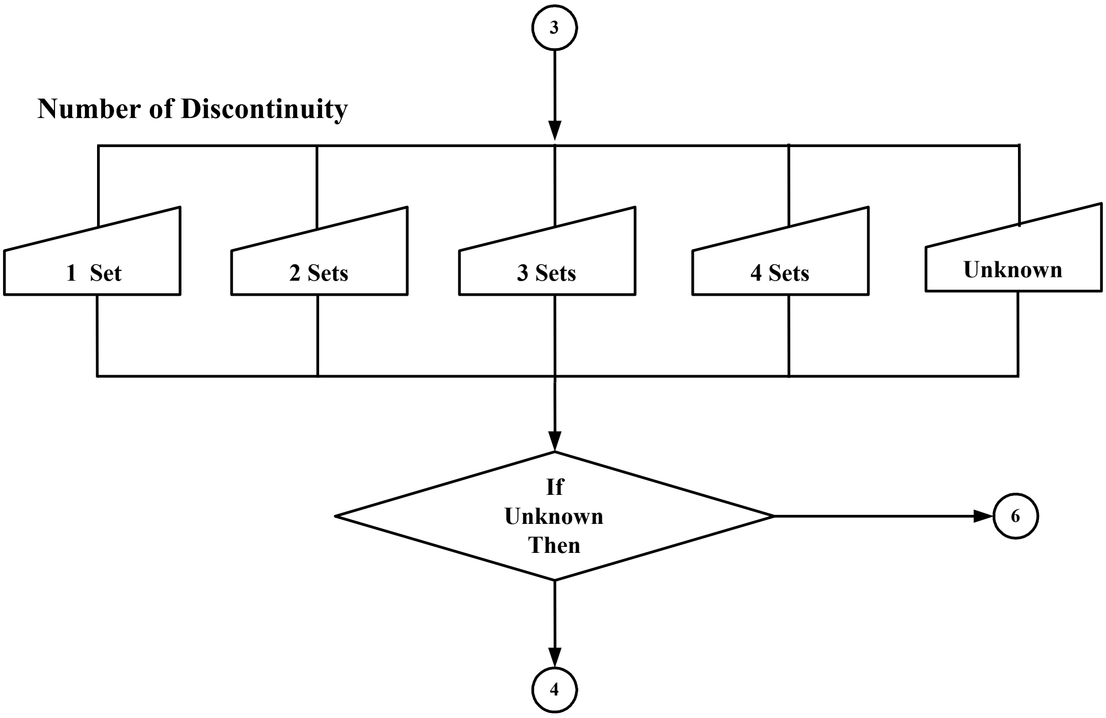

Figure 5.4 Data acquisition flowchart (cont.).

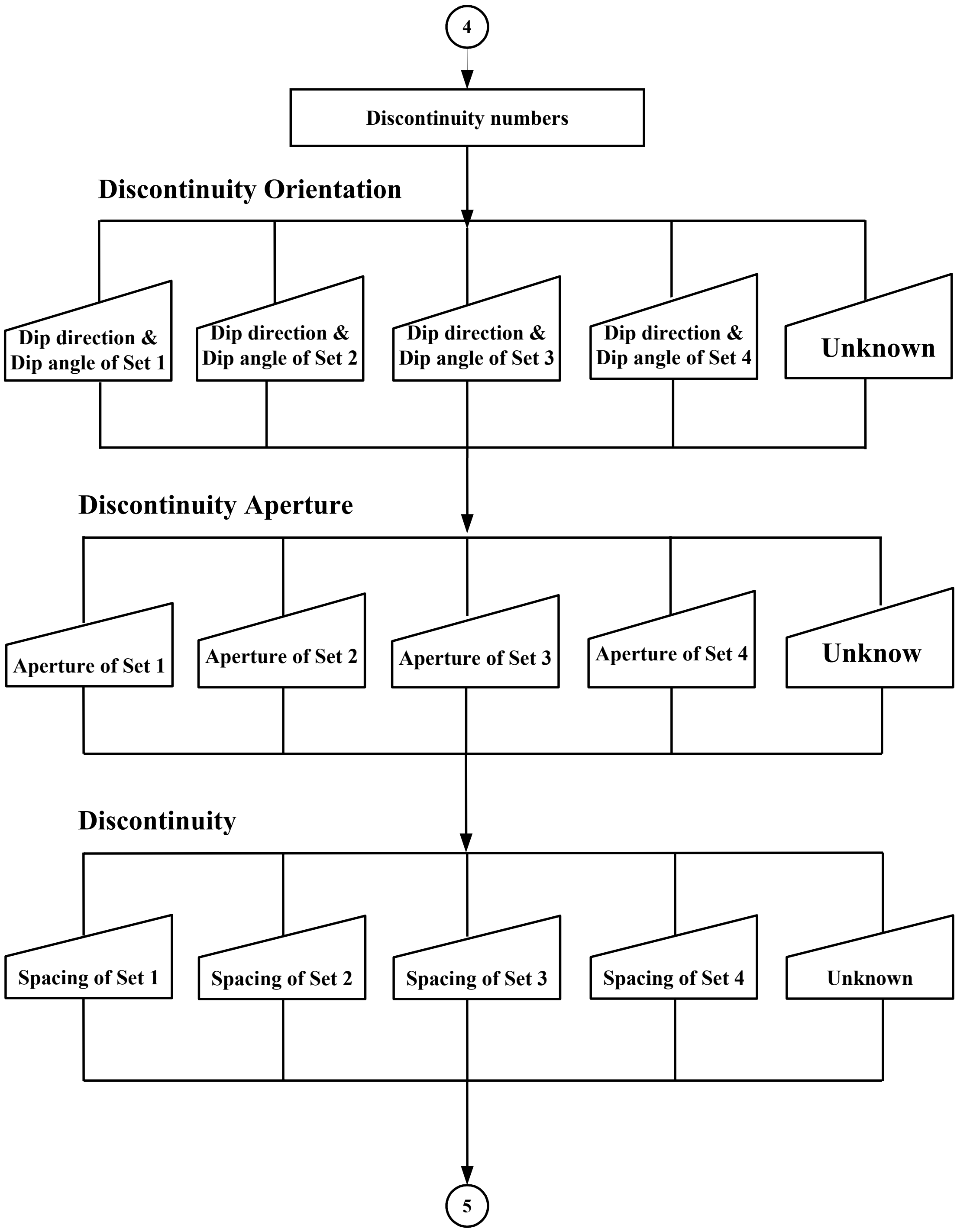

Figure 5.5 Data acquisition flowchart (cont.).

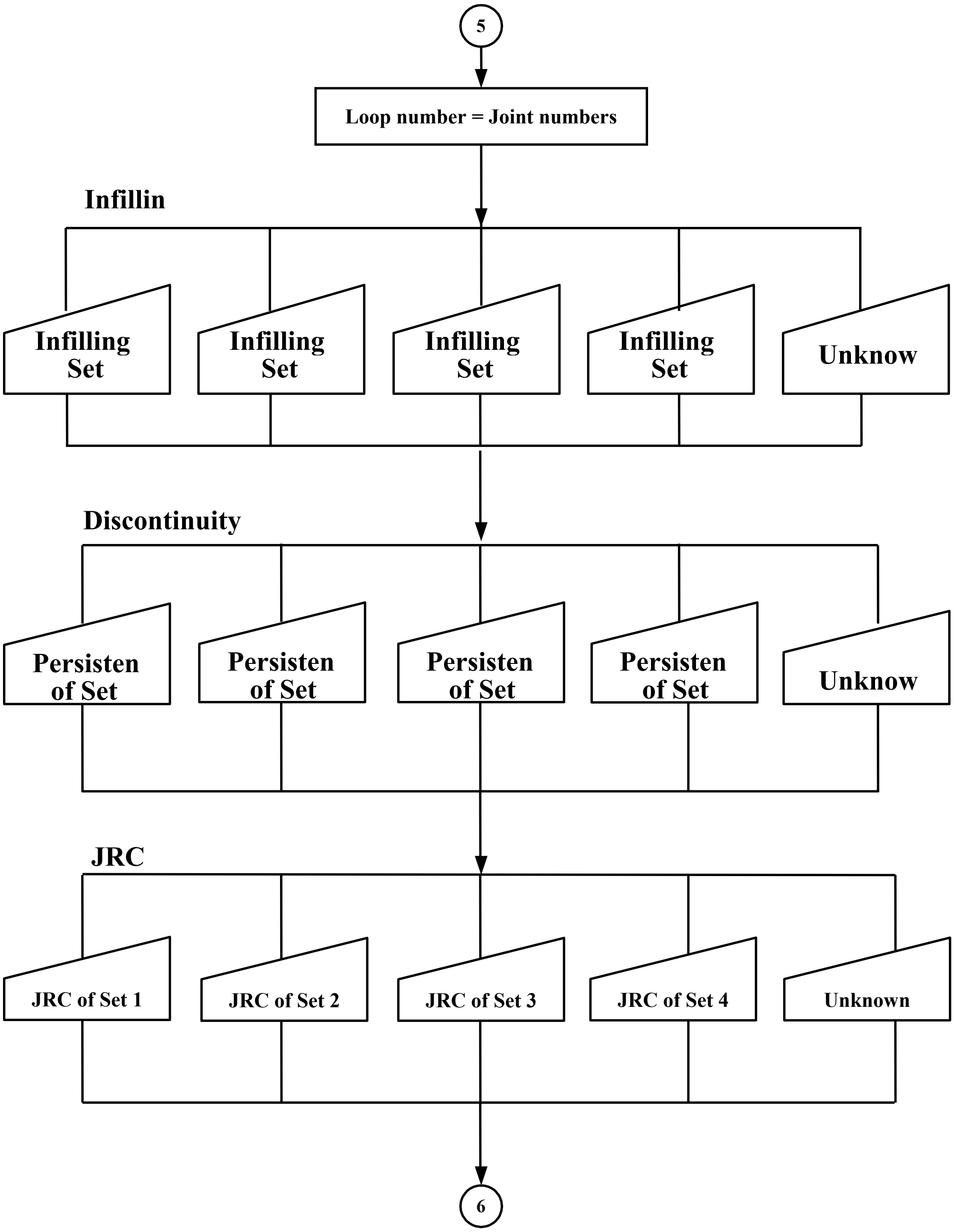

Figure 5.6 Data acquisition flowchart (cont.).

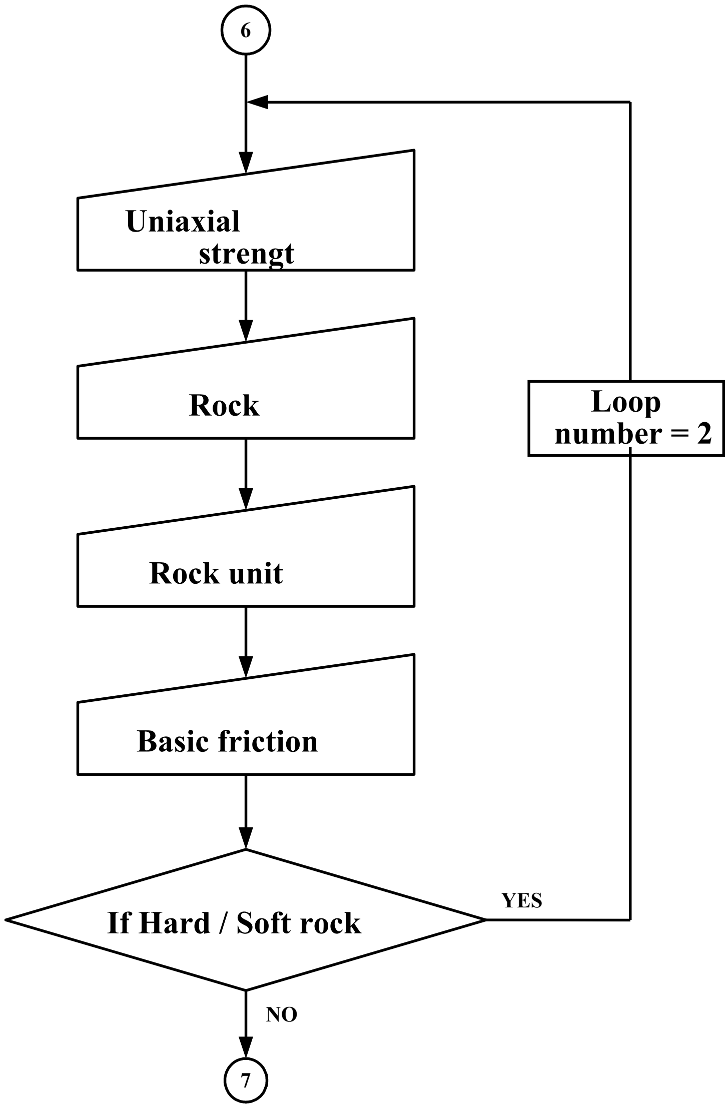

Figure 5.7 Data acquisition flowchart (cont.).

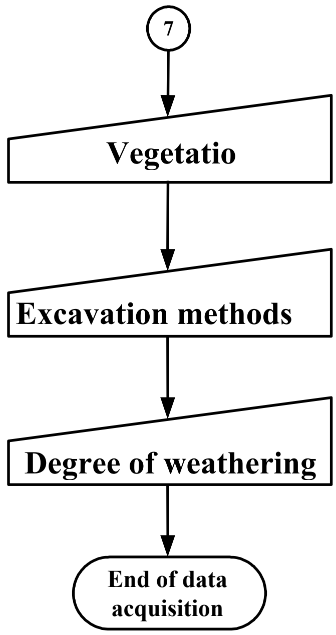

Figure 5.8 Data acquisition flowchart (cont.).

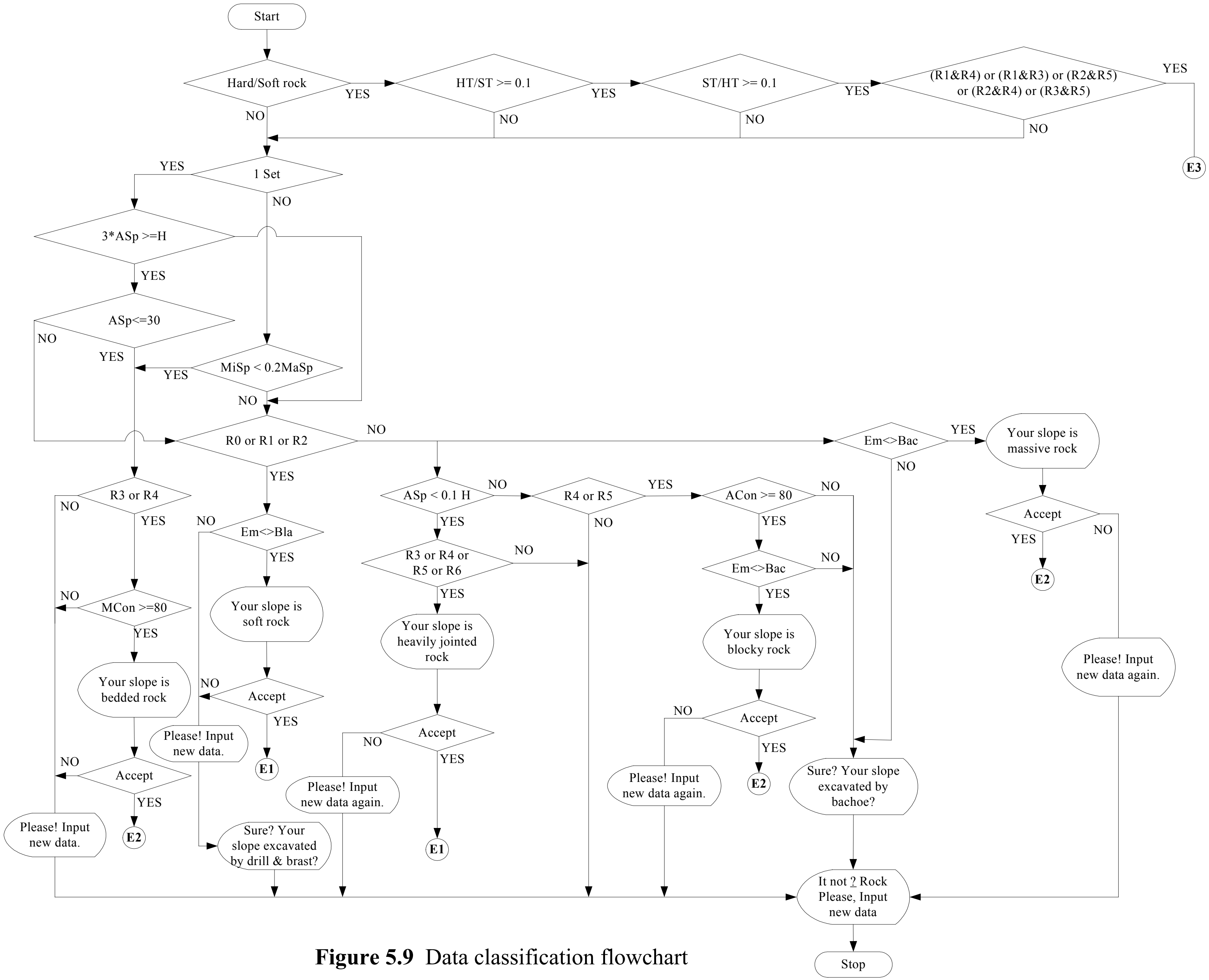

Figure 5.9 Data classification flowchart

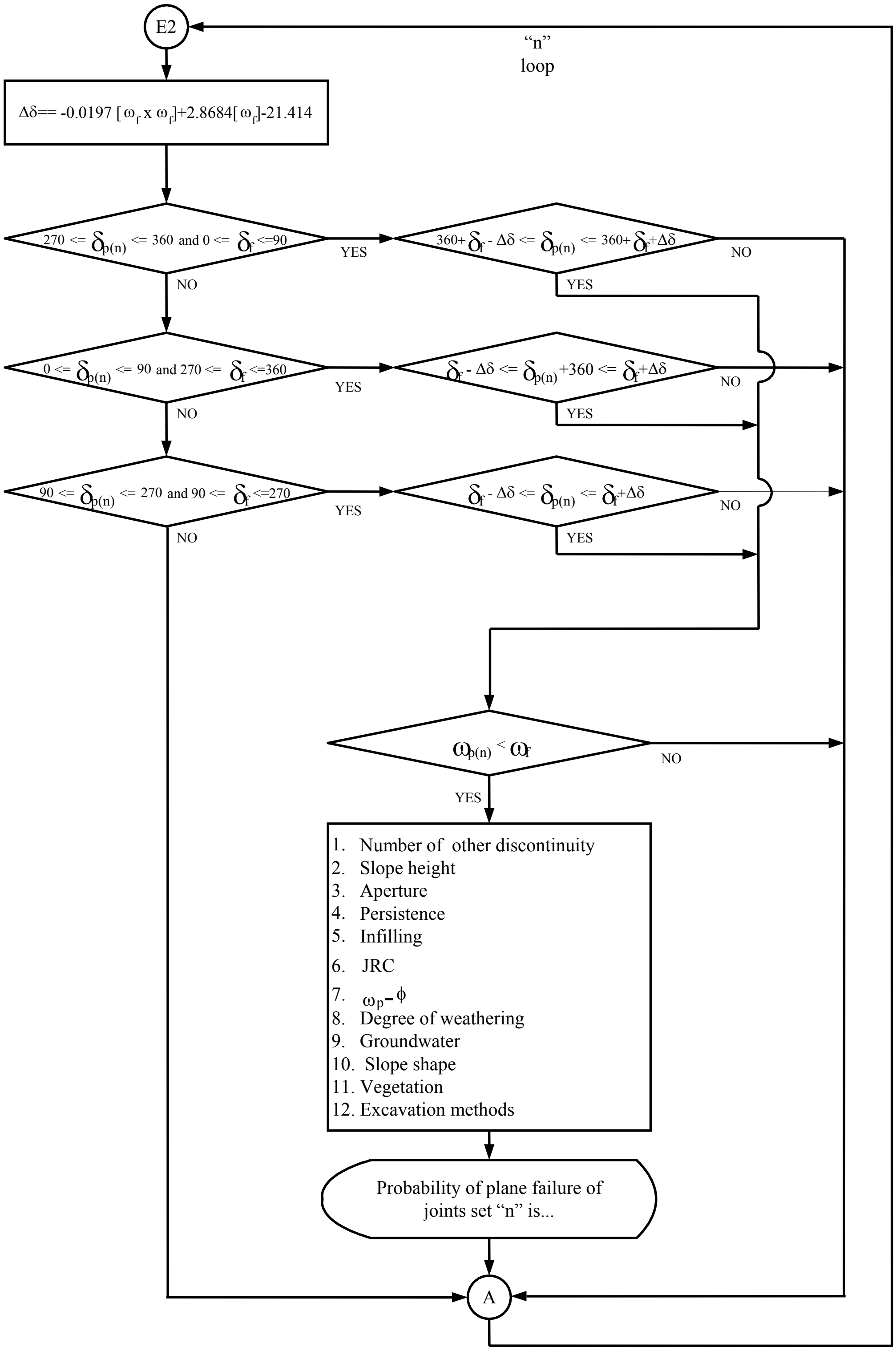

Figure 5.10 Stability evaluation flowcharts

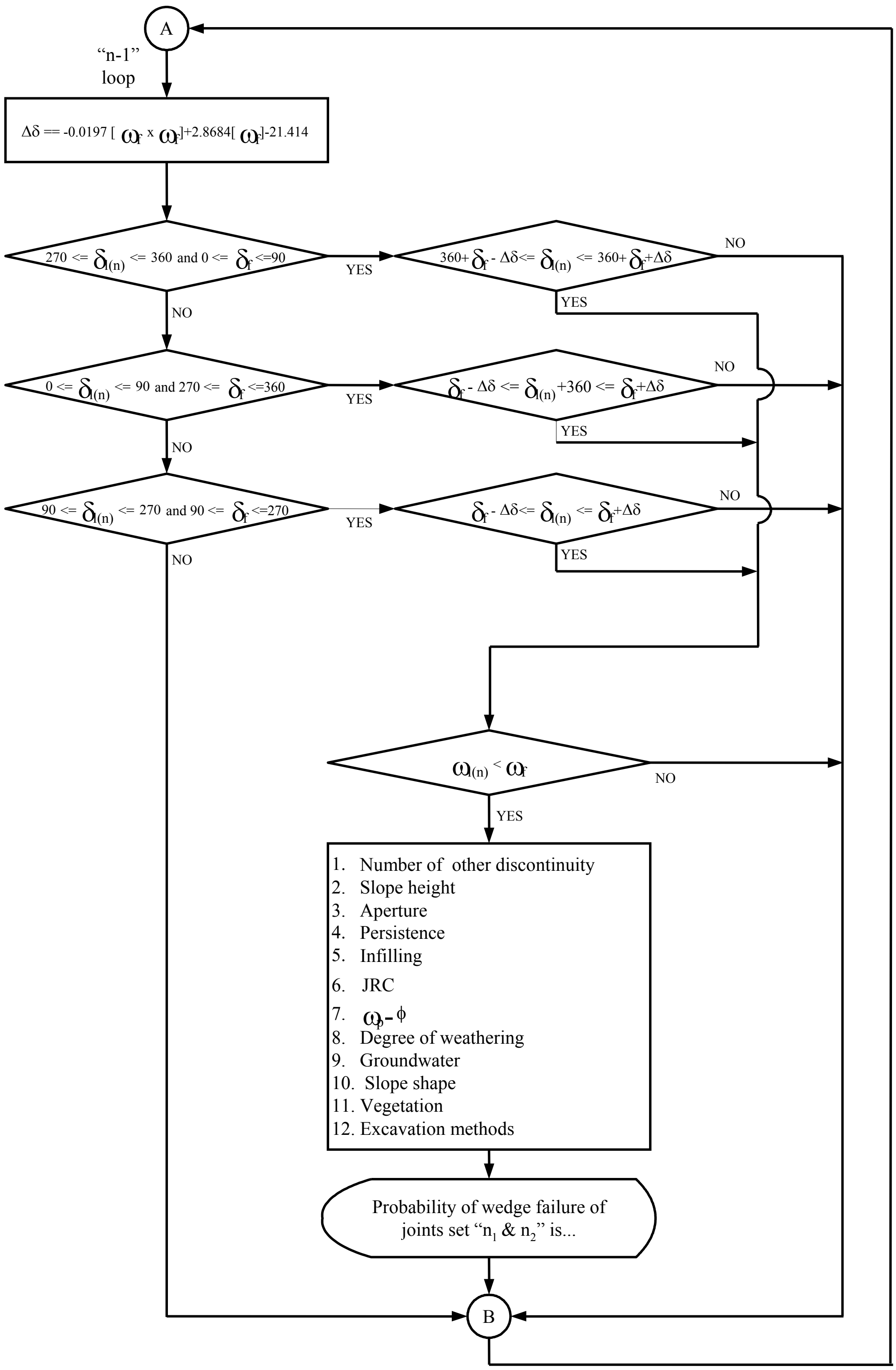

Figure 5.11 Stability evaluation flowcharts (cont.)

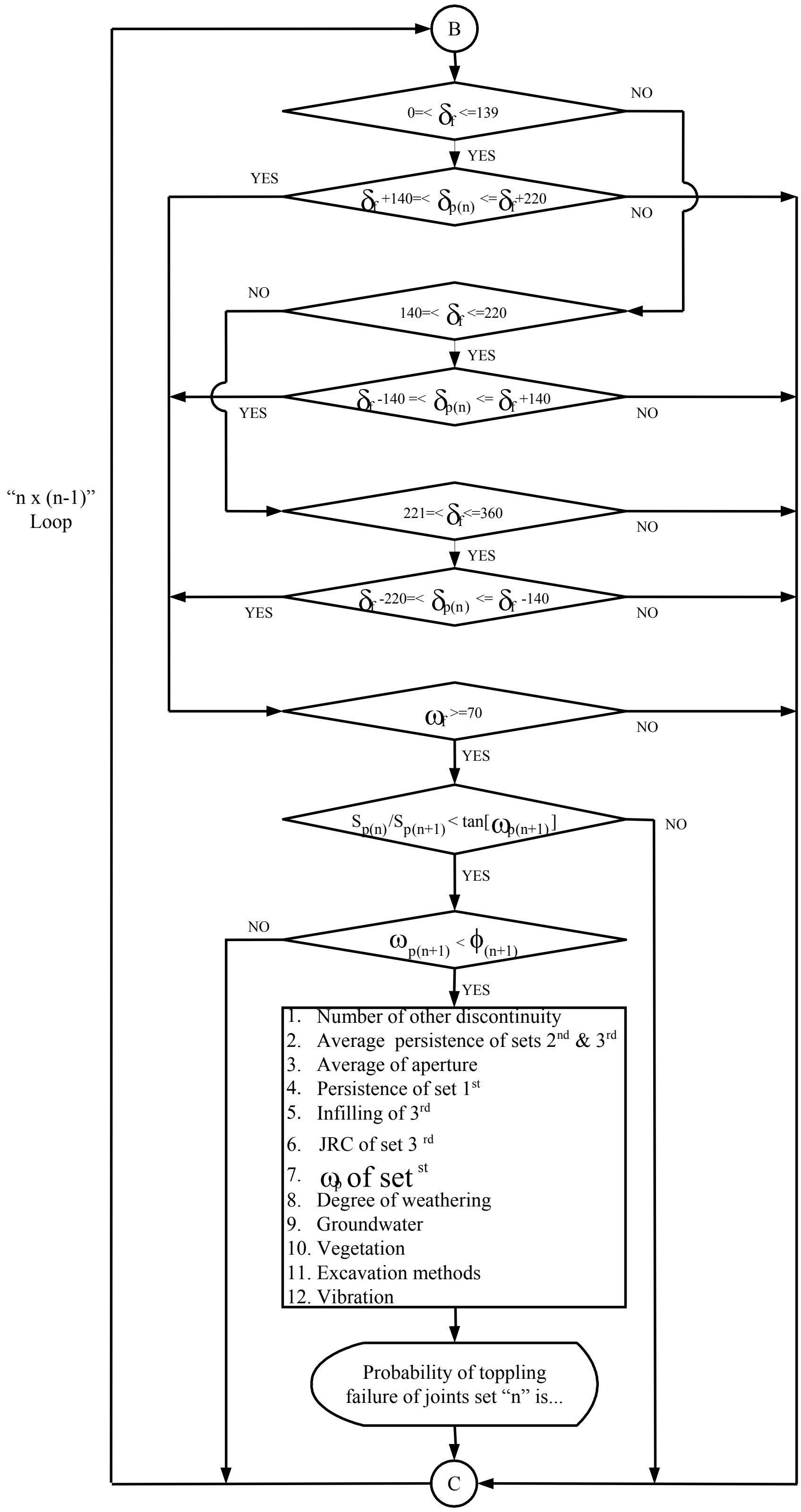

Figure 5.12 Stability evaluation flowcharts (cont.)

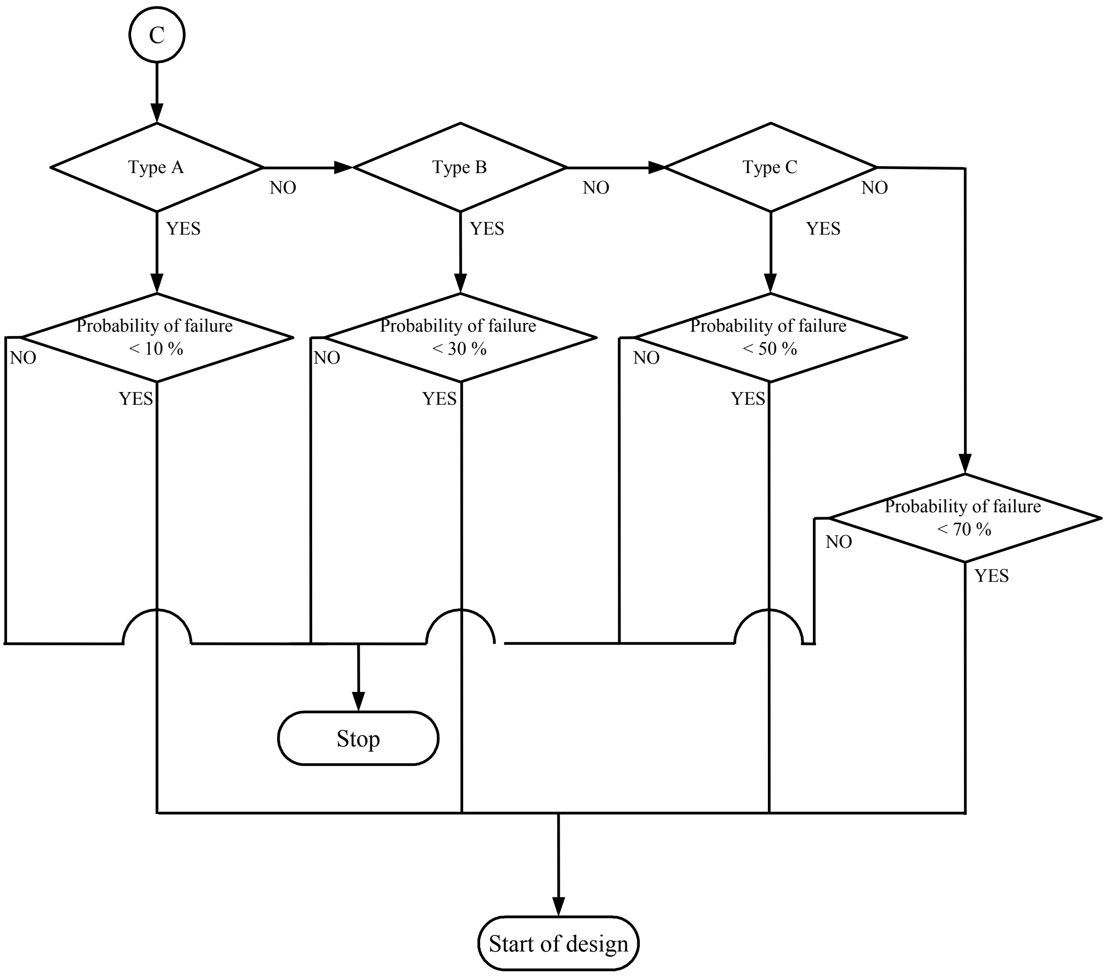

Figure 5.13 Stability evaluation flowcharts (cont.)

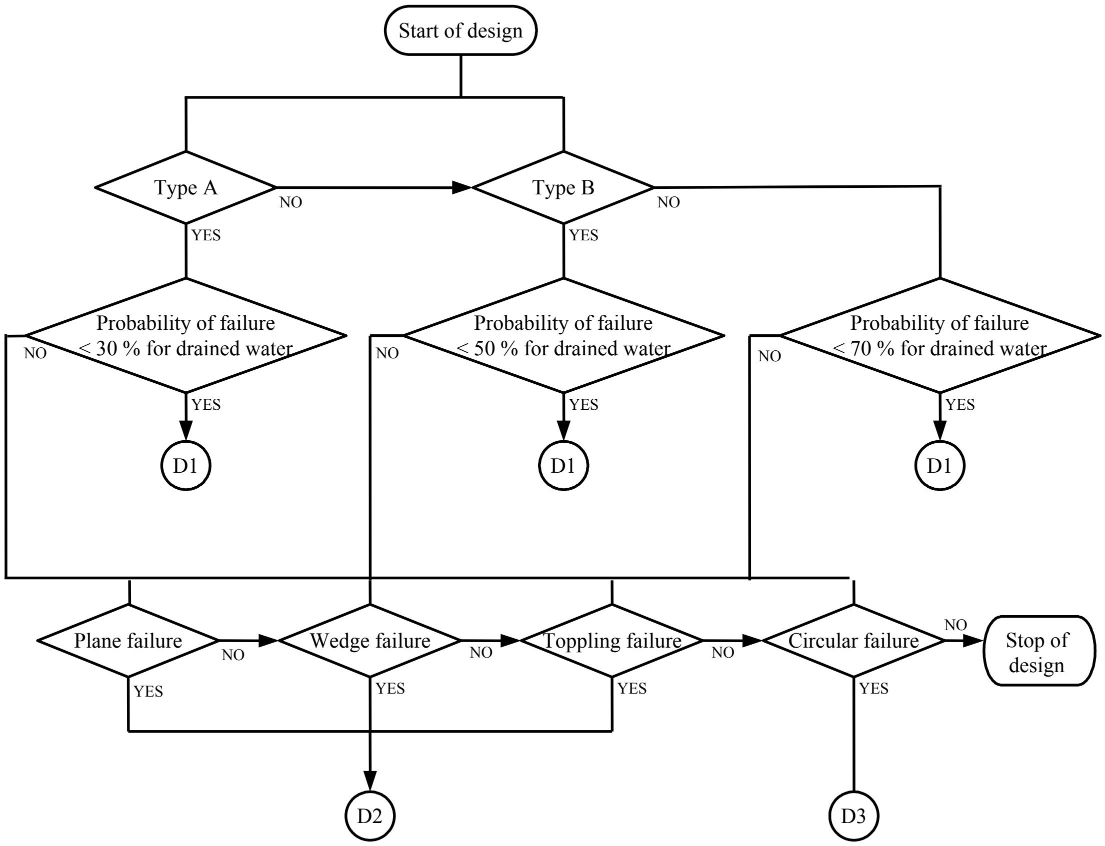

Figure 5.14 Design supports and recommendations flowchart

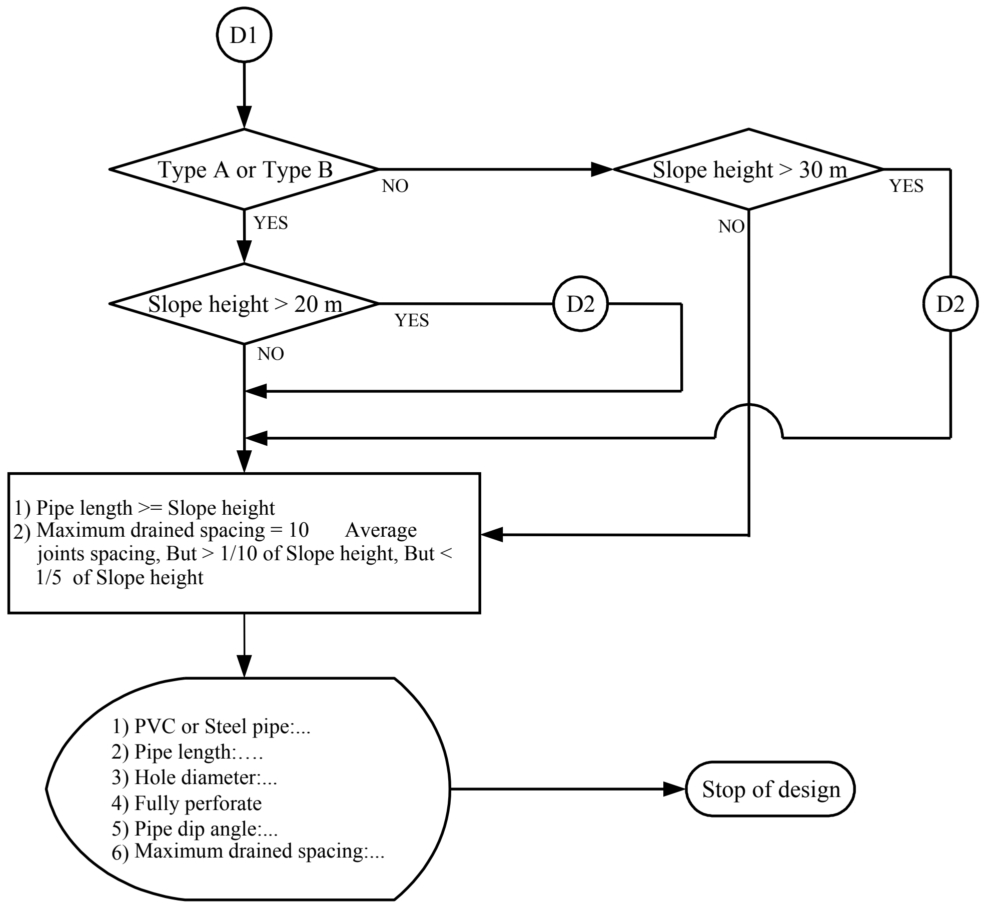

Figure 5.15 Design supports and recommendations flowchart (cont.)

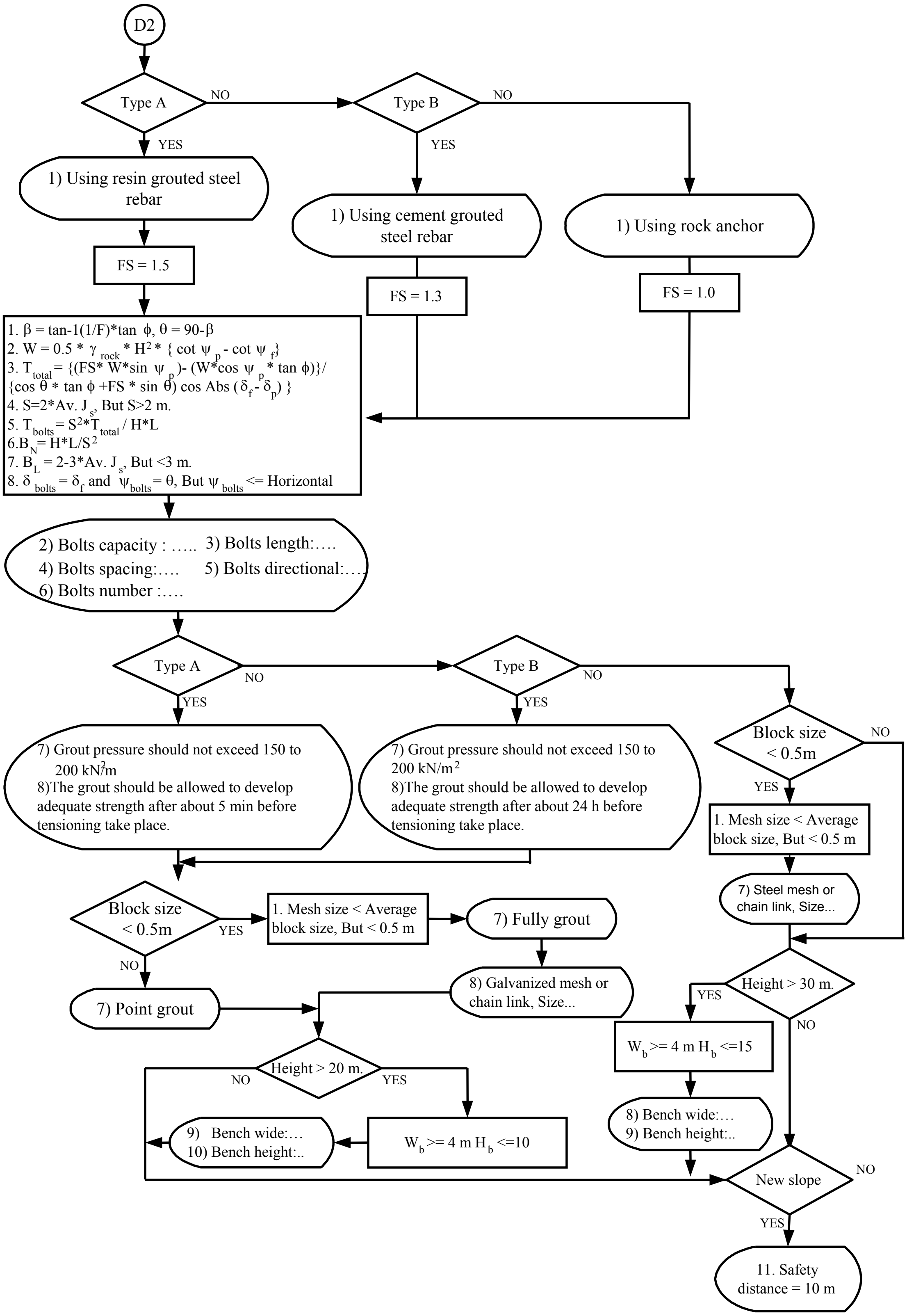

Figure 5.16 Design supports and recommendations flowchart (cont.)

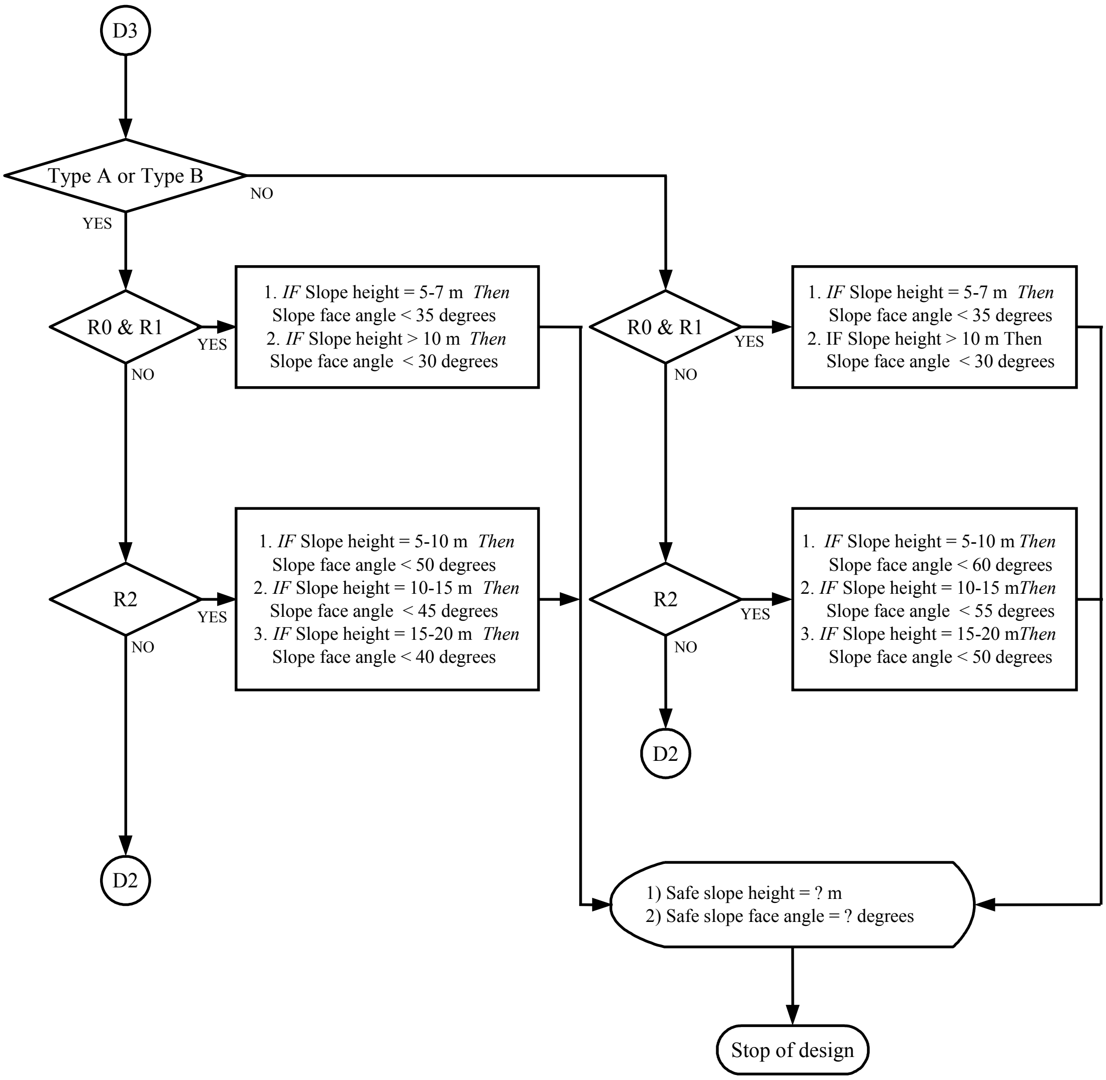

Figure 5.17 Design supports and recommendations flowchart (End)

CHAPTER VI

DEVELOPMENT OF SOFTWARE

This chapter explains how the program is developed. The program can be divided to into three phases, including (1) system shell, (2) system control, and (3) database system. The system shell is used as program structure. The system control directs the paths and flows of the program. The database stores the rules and case studies of the rock slopes.

6.1 System Shell

The computer software that used for ROSES development is the Visual Basic. The advantages of Visual Basic are 1) equipped with the GUI–Graphical User Interface, 2) ease of application, 3) quick construction, and 5) supporting the management database system, such as Microsoft Access, FoxPro, SQL Sever of Microsoft or dBase, Oracle and Sybase, etc. The Visual Basic can not be applied to the complex calculation. The system shell is divided into two parts; data acquisition and data presentation.

The data acquisition is the interface part linking the program systems with the user to make the system easy to understand. The main data acquisition parts are described as follows.

1) General geologic features

2) Thickness and orientation of hard formations:

3) Safety requirements:

4) Groundwater conditions

5) Climates

6) Slope geometry: including slope height, slope length, slope orientation, slope face angle, upper slope face angle, and slope shapes.

7) Joint characteristics: including joint number, joint orientation, joint aperture, joint spacing, joint in-filling, joint persistence, and Joint Roughness Coefficient (JRC)

8) Geomechanics parameters: including intact strength of rock, rock unit weight, and basic friction angle

9) Vegetation, excavation methods, degree of weathering and vibration

10) Case history

The data presentation can be divided into five parts: 1) data as input, 2) data classification and primary evaluation, 3) stability evaluation, 4) design and recommendations, and 5) database presentations.

1) Data as input: When, the user finishes data input, the system will show all of data in form of application "Text Box" of Visual Basic.

2) The results of data classification and preliminary evaluations are presented in form of "Massage Box". The massage box explains general geologic features of rock slope, or some conflict, or insufficient data input, and preliminary evaluation. The system shows these problems in form of application "Text Box", if needed.

3) Stability evaluation: The probability of failure for each mode is presented in form of application "Text Box"

4) Design and recommendations; The program shows the results of design recommendations in form of application "Text Box"

5) The results of data search are presented in form of “Data Grid” and the details of relevant case history which can be shown in form of “Text Box”.

6.2 System Control

The main processes for control functions are the decision making, iteration, array and procedure. The main structures of program developments are as follows.

1) Decision structures

   (i) two-way decision making ; “ If …Then…Else”

   (ii) more than two-way decisions making ; “Select…Case”

2) Iteration structures

   (i) known number of iteration ; “ For….Next”

   (ii) unknown number of iteration ; “While…When”

   (iii)unknown number of iteration and go out from iteration ; “Do/While…Until/Loop”

3) Array and Dynamic. Array structures are parts of permanent and non-permanent storage data that are used for calculation.

4) Procedure structures ; include

   (i) sub programs (sub routine)

   (ii) function (sub function)

6.3 Data Base System

The data extracted from case histories have been compiled and stored in form of Microsoft Access. They can be searched by Data Query Language (SQL) and Data Control contained in Visual Basic software.

CHAPTER VII

VERIFICATION OF ROSES PREDICTION

The predictive capability of ROSES software has been assessed by comparing the calculated probability of failure with the actual slope conditions obtained from 32 field sites and 5 slopes from literatures. Table 7.1 shows the details of actual slope conditions and the parameters used in the computation by ROSES. Figure 7.1 shows the results of comparison. The results of ROSES prediction show that five slopes are highly stable and two slopes are stable. There are 12 slopes having fair condition. A total of 15 slopes are highly unstable. ROSES divides the slope stability conditions into five levels as follows.

1) highly stable (P{f}= 0 to 20%)
2) stable (P{f}= 20 to 40%)
3) fair (P{f}= 40 to 60%)
4) unstable: (P{f}= 60 to 80%)
5) highly unstable: (P{f}= 80 to 100%)

The results from the verification by comparing with the actual stability conditions of rock slope indicate that ROSES can predict the stability conditions close to the actual slope behavior. The prediction from the program tends to be conservative. This means that the system will give probability of failure higher than the actual in most cases. Nevertheless the predictability of ROSES is satisfactory.

Table 7.1 Comparisons between expert system predictions and actual conditions.

Case No. (Slope No.)	Slope Characteristics	Actual Conditions	Expert System Prediction
Case 1 (Slope No.24)	H = 18 m δ_f = 205° ψ_f = 76° J1 = 168°/32° J2 = 345°/63° J3 = 233°/67° Saturated	1) plane failure along J1 & J3 2) wedge failure between J1 & J2, J1 & J3 3) toppling failure : J2 & J3	1) plane failure along J1 & J3 : P_f = 34% 2) wedge failure between J1 & J2, J1 & J3 : P_f = 34% 3) toppling failure: J2 & J3 : P_f = 68%
Case 2 (Slope No.25)	H = 19 m, δ_f = 20° ψ_f = 76°, J1 = 168°/32° J2 = 345°/63°; J3 = 233°/67°, Saturated	1) plane failure along J2 2) toppling failure J1 & J2, J1 & J3 & J2 & J3	1) plane failure along J2 : P_f = 34% 2) toppling failure J1 & J2, J1 & J3 & J2 & J3 : P_f = 71%
Case 3 (Slope No.26)	H = 50 m δ_f = 286° ψ_f = 45° J1 = 276°/45° J2 = 200°/81° J3 = 91°/37° Saturated	stable	P_f = 0%
Case 4 (Slope No.27)	H = 30 m δ_f = 314° ψ_f = 62° J1 = 80°/40° J2 = 291°/50° J3 = 164°/62° Saturated	1) circular failure 2) plane failure along : J2 3) wedge failure between J1 & J2, J2 & J3	1) circular failure : P_f = 65% 2) plane failure along : J2 : P_f = 68% 3) wedge failure between J1 & J2, J2 & J3 : P_f = 71%
Case 5 (Slope No.28)	H = 16 m δ_f = 30° ψ_f = 48° J1 = 309°/42° J2 = 182°/72° J3 = 47°/78° Saturated	1) circular failure 2) wedge failure between J1 & J3	1) circular failure : P_f= 70% 2) wedge failure between J1 & J3 : P_f = 60%
Case 6 (Slope No.28)	H = 18 m δ_f = 145° ψ_f = 54° J1 = 309°/42° J2 = 182°/72° J3 = 47°/78° Saturated	1) circular failure	1) circular failure : P_f = 70%
Case 7 (Slope No.33)	H = 20 m δ_f = 51° ψ_f = 52° J1 = 21°/55° J2 = 114°/70° J3 = 294°/89° Saturated	1) wedge failure between J1 & J2, J2 & J3	1) wedge failure between J1 & J2, J2 & J3 : P_f = 75%

Table 7.1 Comparisons between expert system predictions and actual conditions (cont.).

Case No. (Slope No.)	Slope Characteristics	Actual Conditions	Expert System Prediction
Case 8 (Slope No.34)	H = 15 m $\delta_f = 30^\circ$ $\psi_f = 55^\circ$ J1 = 21°/55° J2 = 114°/70° J3 = 294°/89° Saturated	1) wedge failure between J1 & J2, J2 & J3	1) wedge failure between J1 & J2, J2 & J3 : P_f = 75%
Case 9 (Slope No.7)	H = 13 m $\delta_f = 30^\circ$ $\psi_f = 60^\circ$ J1 ; J2 J3 = N/A σ_c = 5-25 MPa Saturated	1) circular failure	1) circular failure : P_f = 48%
Case 10 (Slope No.11)	H = 50 m $\delta_f = 161^\circ$ $\psi_f = 71^\circ$ J1 = 27°/24° J2 = 138°/77° J3 = 78°/84° J4 = 211/78 Saturated	1) wedge failure between J3 & J4	1) wedge failure between J3 & J4 : P_f = 53%
Case 11 (Slope No.11)	H = 30 m $\delta_f = 240^\circ$ $\psi_f = 70^\circ$ J1 = 27°/24° J2 = 138°/77° J3 = 78°/84° J4 = 211/78 Saturated	1) wedge failure between J1 & J4 2) toppling failure : J1 & J2, J1 & J3	1) wedge failure between J1 & J4 : P_f = 48 % 2) toppling failure: J1 & J2, J1 & J3 : P_f= 78%
Case 12 (Slope No.11)	H = 30 m $\delta_f = 84^\circ$ $\psi_f = 80^\circ$ J1 = 27°/24° J2 = 138°/77° J3 = 78°/84° J4 = 211/78 Saturated	1) plane failure along : J1 & J2 2) wedge failure between J1 & J2, J2 & J3, J3 & J4	1) plane failure along : J1 & J2 : P_f= 56% 2) wedge failure between J1 & J2, J2 & J3, J3 & J4 : P_f= 56%
Case 13 (Slope No.36)	H = 16 m $\delta_f = 215^\circ$ $\psi_f = 79^\circ$ J1 = 54°/33° J2 = 154°/80° J3 = 241°/75° Saturated	1) plane failure along : J3 2) wedge failure between J2 & J3	1) plane failure along : J3 : P_f= 54% 2) wedge failure between J2 & J3 : P_f= 54%

Table 7.1 Comparisons between expert system predictions and actual conditions (cont.).

Case No. (Slope No.)	Slope Characteristics	Actual Conditions	Expert System Prediction
Case 14 (Slope No.37)	H = 12 m δ_f = 280° ψ_f = 45° J1 = 47°/34° J2 = 240°/60° J3 = 177°/51° Saturated	1) wedge failure between J1 & J2	1) wedge failure between J1 & J2 : P_f= 46%
Case 15 (Slope No.38)	H = 10 m δ_f = 80° ψ_f = 75° UCS = 5-25 MPa Saturated	1) circular failure	1) circular failure : P_f = 48%
Case 16 (Slope No.41)	H = 40 m δ_f = 220° ψ_f = 60° J1 = 344°/03° J2 = 224°/81° J3 = 190°/70° Saturated	1) circular failure 2) wedge failure between J1 & J3	1) circular failure: P_f = 78% 2) wedge failure between J1 & J3 : P_f= 62%
Case 17 (Slope No.42)	H = 15 m δ_f = 105° ψ_f = 70° J1 = 107°/87° J2 = 273°/78° J3 = 48°/66° Saturated	1) plane failure along : J3 2) wedge failure between J1 & J3	1) plane failure along : J3: P_f = 53% 2) wedge failure between J1 & J3 : P_f = 59%
Case 18 (Slope No.43)	H = 30 m δ_f = 150° ψ_f = 70° J1 = 107°/87° J2 = 273°/78° J3 = 48°/66° Saturated	1) wedge failure between J1 & J2	1) wedge failure between J1 & J2 : P_f = 62%
Case 19 (Slope No.44)	H = 50 m δ_f = 150° ψ_f = 68° J1 = 55°/36° J2 = 76°/79° J3 = 330°/07° J4 = 324/76 Saturated	stable	P_f = 0%
Case 20 (Slope No.45)	H = 18 m δ_f = 115° ψ_f = 70° J1 = 55°/36° J2 = 76°/79° J3 = 330°/07° J4 = 324/76 Saturated	1) plane failure along : J1 2) wedge failure between J1 & J4, J3 & J4	1) plane failure along : J1 : P_f = 50% 2) wedge failure between J1 & J4, J3 & J4 : P_f = 51%

Table 7.1 Comparisons between expert system predictions and actual conditions (cont.).

Case No. (Slope No.)	Slope Characteristics	Actual Conditions	Expert System Prediction
Case 21 (Slope No.47)	H = 25 m δ_f = 102° ψ_f = 70° J1 = 59°/49° J2 = 149°/80° J3 = 240°/58° Saturated	1) plane failure along : J1 2) wedge failure between J1 & J2	1) plane failure along : J1 : P_f = 50% 2) wedge failure between J1 & J2 : P_f = 58%
Case 22 (Slope No.48)	H = 20 m δ_f = 260° ψ_f = 80° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	1) plane failure along : J3 2) wedge failure between J1 & J3, J2 & J3 3) toppling failure J1 & J2, J1 & J3	1) plane failure along : J3 : P_f = 61% 2) wedge failure between J1 & J3, J2 & J3 : P_f = 79% 3) toppling failure J1 & J2, J1 & J3 : P_f = 76 %
Case 23 (Slope No.49)	H = 20 m δ_f = 150° ψ_f = 75° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	1) wedge failure between J1 & J2, J1 & J3 2) toppling failure J2 & J1, J2 & J3	1) wedge failure between J1 & J2, J1 & J3 : P_f = 79% 2) toppling failure J2 & J1, J2 & J3 : P_f = 44%
Case 24 (Slope No.50)	H = 16 m δ_f = 110° ψ_f = 72° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	1) wedge failure between J1 & J2 2) toppling failure J3 & J1, J3 & J2	1) wedge failure between J1 & J2 : P_f = 79% 2) toppling failure J3 & J1, J3 & J2 : P_f = 72%
Case 25 (Slope No.51)	H = 18 m δ_f = 300° ψ_f = 60° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	stable	P_f = 0%
Case 26 (Slope No.52)	H = 20 m δ_f = 350° ψ_f = 60° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	stable	P_f = 0%
Case 27 (Slope No.15)	H = 10 m δ_f = 190° ψ_f = 50° J1 = 197°/51° J2 = 318°/65° J3 = 73°/71° Saturated	1) wedge failure between J1 & J2, J1 & J3	1) wedge failure between J1 & J2, J1 & J3 : P_f = 60%

Table 7.1 Comparisons between expert system predictions and actual conditions (cont.).

Case No. (Slope No.)	Slope Characteristics	Actual Conditions	Expert System Prediction
Case 28 (Slope No.16)	H = 15 m δ_f/ ψ_f = 185°/80° J1 = 356°/22° J2 = 40°/87° J3 = 115°/89° Saturated	1) toppling failure J1 & J2, J1 & J3	1) toppling failure J1 & J2, J1 & J3 : P_f = 73%
Case 29 (Slope No.17)	H = 10 m δ_f = 180° ψ_f = 50° J1 = 170°/80° J2 = 300°/75° J3 = 92°/83° Saturated	stable	P_f = 0%
Case 30 (Slope No.12)	H = 50 m δ_f = 170° ψ_f = 60° J1,J2 & J3 = N/A Saturated Hard-Soft rock	1) rock fall	1) rock fall : P_f = 74%
Case 31 (Slope No.13)	H = 20 m δ_f = 300° ψ_f = 54° J1 = 86°/06° J2 = 104°/89° J3 = 310°/72° Saturated Hard-Soft rock	1) rock fall	1) rock fall : P_f = 64%
Case 32 (Slope No.14)	H = 40 m δ_f = 296° ψ_f = 55° J1 = 103°/06° J2 = 18°/89° J3 = 293°/83° Saturated Hard-Soft rock	1) rock fall	1) rock fall : P_f = 66%
Case 33 Dolomite, Theodore Roosevelt Dam, USA (Scott, 1995)	H = 34 m δ_f = 360° ψ_f = 84° J1 = 50 /25 J2 =180/70 J3 = 318/83 J4:58 /31 ϕ = 35° Saturated	1) plane failure along J3 2) toppling failure between J2 & J4	1) plane failure along J3 : P_f = 52% 2) toppling failure between J2 & J1 and J2&J4: P_f = 64%
Case 34 Marl, Eskihisar (Yatagan-Mugla), Turkey / (Sonmez and Ulusay, 1999)	H = 25 m δ_f = N/A ψ_f = 78° σ_c= 1.14-6.41MPa Slightly weathered Dry conditions	1) circular failure	1) circular failure: P_f = 60%

Table 7.1 Comparisons between expert system predictions and actual conditions (cont.).

Case No. (Slope No.)	**Slope Characteristics**	**Actual Conditions**	**Expert System Prediction**
Case 35 Jointed Marly, Kisrakdere Lignite, Turkey / (Sonmez and Ulusay, 1999)	H = 100 m δ_f = N/A $\psi_f = 40^{\circ}$ S1=1.2 ft S2 = 2.25 ft S3 = 3.21 ft S4 = 0.39 ft $\phi = 21^{\circ}$ σ_c = 40.2 MPa c = 340 psf Slightly weathered Dry conditions	1) circular failure 2) toppling failure	1) circular failure: P_f = 45% 2) Undetermined
Case 36 Norite, Western High Wall, South Africa/ (Bye and Bell, 2001)	H = 20 m $\delta_f = 85^{\circ}$ $\psi_f = 75^{\circ}$ J1 = 73 /55 J2 = 73 /55 J3 = 340/80 $\phi = 31^{\circ}$ γ = 172 pcf Saturated	1) plane failure 2) wedge failure	1) plane failure along J1: P_f = 54% 2) wedge failure between J1&J2: P_f = 74% and J1&J3: P_f = 58%
Case 37 Highly weathered Granite, The Muak pass, Seoul city, Korea / (Lee., Suh., Chang, & Shin, 1992)	H = 23 m $\delta_f = 236^{\circ}$ $\psi_f = 72^{\circ}$ J1 = 290 /65 J2 = 240 /80 J3 = 195 /80 J4 = 55 /75 $\phi = 35^{\circ}$ Saturated	1) Not identify 2) Not identify	1) plane failure along J1: P_f = 52% 2) wedge failure between J1 & J2, J1 & J3, J1 & J4 : P_f = 56%

H = Slope Height ψ_f = Dip Angle of Slope Face δ_f = Dip Direction of Slope Face σ_c = Uniaxial Compressive Strength c = Cohesion ϕ = Friction angle	P_f = Probability of Failure J1, J2, J3 and J4 = Joint Set Number (dip direction / dip angle) S1, S2, S3 and S4 = Joint Spacing for set 1, 2, 3 and 4 Slope number designation as indicated in Appendix

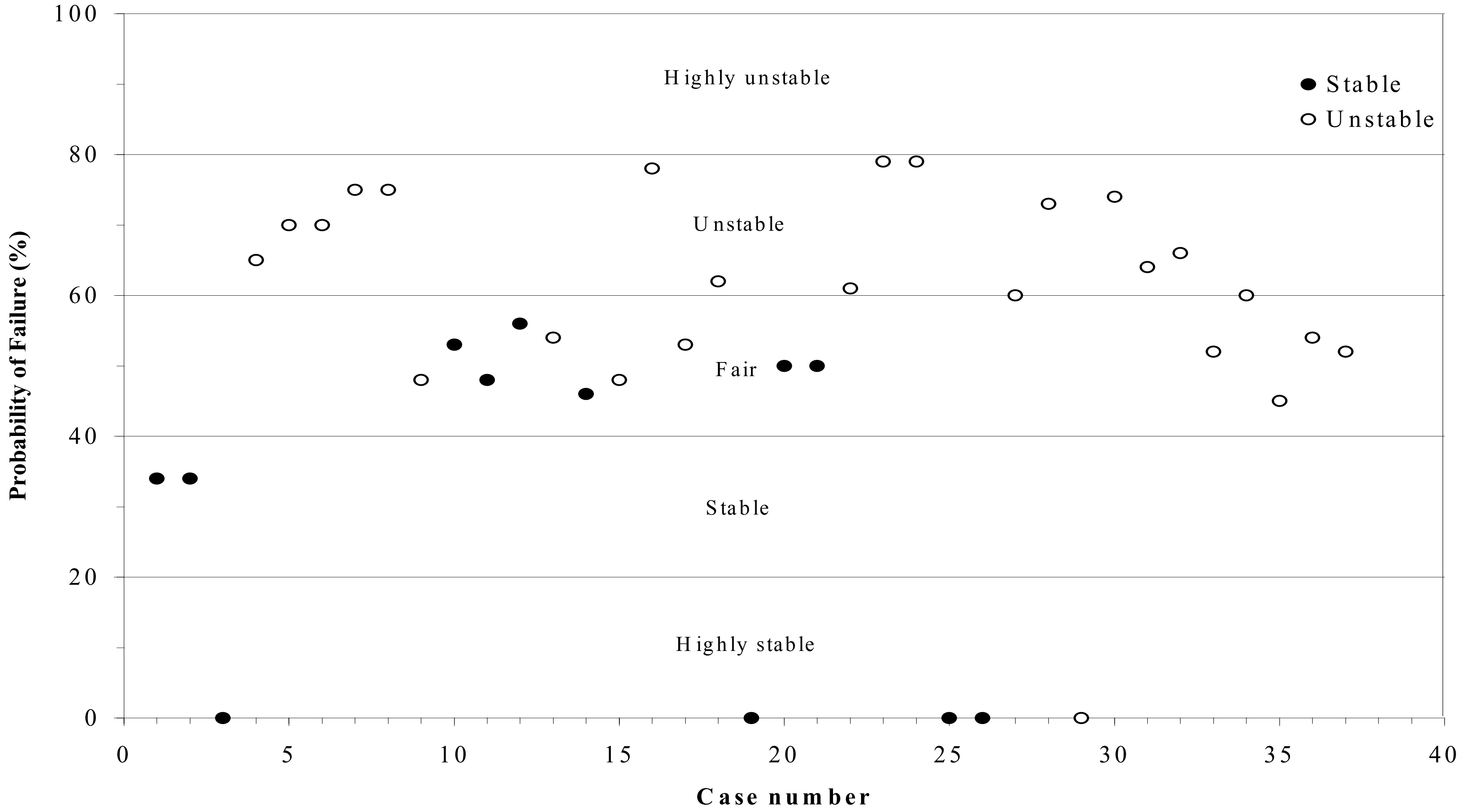

Figure 7.1 Comparisons between expert system predictions and actual condition.

CHAPTER VIII

SUPPORT DESIGN EXAMPLES

This chapter shows examples of the support design for 32 slopes actually observed in the field and 5 slopes from the case studies. A total of nine methods are proposed here for slope stabilizations.

Table 8.1 shows the results of stabilization methods for the 37 slopes by using ROSES program. The first column shows the number of slope (same as the slope number in Appendices A and B), the second column shows the general geologic features of rock, and the third column shows the details of stabilization methods.

1) Rock bolts (or cable bolts) are recommended for slope nos. 15, 16, 42, 43, 45 and 47 to 50, because the slopes are classified as massive rock and the rocks have high strength (R3 to R6). The joint spacing is large (more than 50 cm).

2) Rock bolts (or cable bolts) and wire mesh are recommended for slope nos.11 and 24 to 26, because the slopes are blocky rock and the rocks have high strength (R3 to R6). The joint spacing is small (less than 50 cm).

3) Rock bolts (or cable bolt), wire mesh and drained pipe are recommended for slope nos.17, 28, 33, 34, 36, 37 and case study no.5, because the slopes are blocky rock and the rocks have medium strength (R2 to R4). The joint spacing is small (less than 50 cm), and groundwater level is high.

Table 8.1 Some examples of support design by ROSES program.

Slope No.	Slope Characteristics	Support Design
Slope No.24	H = 18 m $\delta_f = 205^\circ$ $\psi_f = 76^\circ$ J1 = $168^\circ/32^\circ$ J2 = $345^\circ/63^\circ$ J3 = $233^\circ/67^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 6 kN Recommended applied load at 30% of ultimate pressure Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 205 degrees. Bolts angle : 54 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 40×40 cm^2 Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.25	H = 19 m $\delta_f = 20^\circ$ $\psi_f = 76^\circ$ J1 = $168^\circ/32^\circ$ J2 = $345^\circ/63^\circ$ J3 = $233^\circ/67^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 6 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts square spacing : 3 m Bolts direction: 20 degrees. Bolts angle : 54 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 40×40 cm^2 Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.26	H = 50 m $\delta_f = 286^\circ$ $\psi_f = 45^\circ$ J1 = $276^\circ/45^\circ$ J2 = $200^\circ/81^\circ$ J3 = $91^\circ/37^\circ$ Saturated	No support required

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.27	H = 30 m $\delta_f = 314^\circ$ $\psi_f = 62^\circ$ J1 = $80^\circ/40^\circ$ J2 = $291^\circ/50^\circ$ J3 = $164^\circ/62^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 314 degrees. Bolts angle : 68 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 31×31 cm^2 Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.28	H = 16 m $\delta_f = 30^\circ$ $\psi_f = 48^\circ$ J1 = $309^\circ/42^\circ$ J2 = $182^\circ/72^\circ$ J3 = $47^\circ/78^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate strength : not less than 14 kN Recommended applied load at 30% of ultimate pressure Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction: 30 degrees. Bolts angle : 82 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 16 m Hole diameter of drained pipe : not less than 10 cm Drained pipe spacing : 2 m Dip direction of drained pipe : 30 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.28	H = 18 m δ_f = 145° ψ_f = 54° J1 = 309°/42° J2 = 182°/72° J3 = 47°/78° Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 12 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than 6×100×100 mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 145 degrees. Bolts angle : 76 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 18 m Hole diameter of drained pipe : not less than 10 cm Drained pipe spacing : 4 m Dip direction of drained pipe : 145 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal.
Slope No.33	H = 20 m δ_f = 51° ψ_f = 52° J1 = 21°/55° J2 = 114°/70° J3 = 294°/89° Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than 6×100×100 mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 51 degrees. Bolts angle: 65 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 31×31 cm^2 Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 20 m Hole diameter of drained pipe : not less than 10 cm Drained pipe spacing : 3 m Dip direction of drained pipe : 51 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.34	$H = 15$ m $\delta_f = 30^\circ$ $\psi_f = 55^\circ$ $J1 = 21^\circ/55^\circ$ $J2 = 114^\circ/70^\circ$ $J3 = 294^\circ/89^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 8 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 30 degrees. Bolts angle: 60 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 31×31 cm^2 Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 15 m Hole diameter of drained pipe : not less than 10 cm Drained pipe spacing : 3 m Dip direction of drained pipe : 30 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal.
Slope No.7	$H = 13$ m $\delta_f = 30^\circ$ $\psi_f = 60^\circ$ J1; J2; J3 = N/A $\sigma_c = 5\text{-}25$ MPa Saturated	Slope height is : 13 m Slope face angle is : 45 degrees
Slope No.11 Face 1	$H = 50$ m $\delta_f/\psi_f = 161^\circ/71^\circ$ $J1 = 27^\circ/24^\circ$ $J2 = 138^\circ/77^\circ$ $J3 = 78^\circ/84^\circ$ J4 = 211/78 Saturated	The result of stability evaluation for your slope can be acceptable
Slope No.11 Face 2	$H = 30$ m $\delta_f = 240^\circ$ $\psi_f = 70^\circ$ $J1 = 27^\circ/24^\circ$ $J2 = 138^\circ/77^\circ$ $J3 = 78^\circ/84^\circ$ J4 = 211/78 Saturated	Rock anchor or mechanical bolts Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 7 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 240 degrees. Bolts angle : 35 degrees from horizontal. Hole diameters : not less than 41 mm Steel mesh or steel chain link size : less than 40×40 cm^2

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
SlopeNo.11 Face 3	H = 30 m $\delta_f/\psi_f = 84^\circ/80^\circ$ J1 = $27^\circ/24^\circ$ J2 = $138^\circ/77^\circ$ J3 = $78^\circ/84^\circ$ J4 = 211/78 Saturated	The result of stability evaluation for your slope can be acceptable
Slope No.36	H = 16 m $\delta_f = 215^\circ$ $\psi_f = 79^\circ$ J1 = $54^\circ/33^\circ$ J2 = $154^\circ/80^\circ$ J3 = $241^\circ/75^\circ$ Saturated	Fully grouted steel rebar with cement Steel produced 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 215 degrees. Bolts angle: 60 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 16 m Holes diameter of drained pipe : not less than 10 cm Drained pipe spacing : 3 m Dip direction of drained pipe : 215 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal
Slope No.37	H = 12 m $\delta_f = 280^\circ$ $\psi_f = 45^\circ$ J1 = $47^\circ/34^\circ$ J2 = $240^\circ/60^\circ$ J3 = $177^\circ/51^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 8 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 280 degrees. Bolts angle : 25 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 13×13 cm^2 Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 12 m Holes diameter of drained pipe : not less than 10 cm Drained pipe spacing : 1 m, Dip direction of drained pipe : 280 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.38	H = 12 m $\delta_f = 80^\circ$ $\psi_f = 75$ UCS = 5-25 MPa Saturated	Slope height : 12 m. Slope face angle is : 45 degrees
SlopeNo.41	H = 40 m $\delta_f = 220^\circ$ $\psi_f = 60^\circ$ J1 = $344^\circ/03^\circ$ J2 = $224^\circ/81^\circ$ J3 = $190^\circ/70^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 11 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 220 degrees. Bolts angle: 51 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 4×4 cm^2 Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 40 m Hole diameter of drained pipe : not less than 10 cm Drained pipe spacing : 4 m Dip direction of drained pipe : 220 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal Design bench height : 8 m Design bench wide : 10 m Working safe of slope face angle : 55 degrees
Slope No.42	H = 15 m, $\delta_f = 105^\circ$ $\psi_f = 70^\circ$ J1 = $107^\circ/87^\circ$ J2 = $273^\circ/78^\circ$ J3 = $48^\circ/66^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 105 degrees. Bolts angle: 47 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.43	H = 30 m $\delta_f = 150^\circ$ $\psi_f = 70^\circ$ J1 = $107^\circ/87^\circ$ J2 = $273^\circ/78^\circ$ J3 = $48^\circ/66^\circ$ Saturated	Fully grouted steel rebar with cement Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 10 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 150 degrees. Bolts angle : 47 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.44	H = 50 m $\delta_f/\psi_f = 150^\circ/68^\circ$ J1 = $55^\circ/36^\circ$ J2 = $76^\circ/79^\circ$ J3 = $330^\circ/07^\circ$ J4 = 324/76 Saturated	Stable
Slope No.45	H = 18 m $\delta_f = 115^\circ$ $\psi_f = 70^\circ$ J1 = $55^\circ/36^\circ$ J2 = $76^\circ/79^\circ$ J3 = $330^\circ/07^\circ$ J4 = 324/76 Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 12 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 115 degrees. Bolts angle : 47 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.47	H = 25 m $\delta_f = 102^\circ$ $\psi_f = 70^\circ$ J1 = $59^\circ/49^\circ$ J2 = $149^\circ/80^\circ$ J3 = $240^\circ/58^\circ$ Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 7 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 102 degrees. Bolts angle: 47 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.48	H = 20 m $\delta_f = 260^\circ$ $\psi_f = 80^\circ$ J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	Fully grouted cable bolts with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 13 kN Recommended applied load at 30% of ultimate pressure. Cable bolts diameters : not less than 12.7 mm Steel plates size : not less than $6 \times 100 \times 100$ mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Cable bolts length : not less than 7 m Cable bolts spacing : 4 m (Square pattern) Cable bolts direction : 260 degrees. Cable bolts angle : 61 degrees from horizontal. Hole diameters : not less than 41 mm Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.49	H = 20 m $\delta_f = 150^\circ$ $\psi_f = 75^\circ$ J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	Fully grouted cable bolts with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Cable bolts diameters : not less than 12.7 mm Steel plates size : not less than $6 \times 100 \times 100$ mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Cable bolts length / spacing : not less than 7 m / 4 m (Square pattern) Cable bolts direction : 150 degrees. Cable bolts angle : 66 degrees from horizontal. Hole diameters : not less than 41 mm Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.50	H = 16 m $\delta_f = 110^\circ$ $\psi_f = 72^\circ$ J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	Fully grouted cable bolts with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 6 kN Recommended applied load at 30% of ultimate pressure. Cable bolts diameters : not less than 12.7 mm Steel plates size : not less than $6 \times 100 \times 100$ mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Cable bolts length : not less than 7 m Cable bolts spacing : 4 m (Square pattern) Cable bolts direction : 110 degrees. Cable bolts angle : 69 degrees from horizontal. Hole diameters : not less than 41 mm Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Slope No.51	H = 18 m δ_f = 300° ψ_f = 60° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	No support required
Slope No.52	H = 20 m δ_f = 350° ψ_f = 60° J1 = 116°/76° J2 = 360°/83° J3 = 279°/76° Saturated	No support required
Slope No.15	H = 10 m δ_f = 190° ψ_f = 50° J1 = 197°/51° J2 = 318°/65° J3 = 73°/71° Saturated	Fully grouted cable bolts with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 8 kN Recommended applied load at 30% of ultimate pressure. Cable bolts diameters : not less than 12.7 mm Steel plates size : not less than 6×100×100 mm^3 Cable bolts length : not less than 9 m Cable bolts spacing : 6 m (Square pattern) Cable bolts direction : 190 degrees. Cable bolts angle: 37 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.
Slope No.16	H = 15 m, δ_f = 185° ψ_f = 80° J1 = 356°/22° J2 = 40°/87° J3 = 115°/89° Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than 6×100×100 mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 185 degrees. Bolts angle : 7 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	**Slope Characteristics**	**Support Design**
Slope No.17	H = 10 m δ_f = 180° ψ_f = 50° J1 = 170°/80° J2 = 300°/75° J3 = 92°/83° Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 5 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than 6×100×100 mm^3 Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction: 180 degrees. Bolts angle : 63 degrees from horizontal. Hole diameters : not less than 41 mm Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 10 m Holes diameter of drained pipe : not less than 10 cm Drained pipe spacing : 2 m Dip direction of drained pipe : 180 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal
Slope No.12	H = 50 m, δ_f = 170° ψ_f = 60° J1, J2 & J3 = N/A Saturated Hard-Soft rock	Your slope face angle : should be less than 40 degrees
Slope No.13	H = 20 m δ_f = 300° ψ_f = 54° J1 = 86°/06° J2 = 104°/89° J3 = 310°/72° Saturated, Hard-Soft rock	Your slope face angle : should be less than 40 degrees
Slope No.14	H = 40 m δ_f = 296° ψ_f = 55° J1 = 103°/06° J2 = 18°/89° J3 = 293°/83° Saturated Hard-Soft rock	Design bench height : 8 m Design bench wide : 10 m Working safe of slope face angle : 40 degrees

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Dolomite, Theodore Roosevelt Dam, USA / (Scott, 1995)	H = 34 m δ_f = 360° ψ_f = 84° J1 = 50 /25 J2 = 180/70 J3 = 318/83 J4 = 58/31 ϕ = 35° Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 45 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Bolts length : not less than 4 m Bolts spacing : 3 m (Square pattern) Bolts direction : 90 degrees. Bolts angle : 56 degrees from horizontal. Hole diameters : not less than 41 mm Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 34 m Holes diameter of drained pipe : not less than 10 cm Drained pipe spacing : 7 m Dip direction of drained pipe : 90 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal Design bench height : 10 m Design bench wide : 12 m Working safe of slope face angle : 60 degrees
Marl, Eskihisar (Yatagan-Mugla), Turkey / (Sonmez and Ulusay, 1999)	H = 25 m δ_f = N/A ψ_f = 78° σ_c = 1.14-6.41 MPa Slightly weathered Dry conditions	The result of stability evaluation is acceptable without any support.
Jointed Marly, Kisrakdere Lignite, Turkey / (Sonmez and Ulusay, 1999)	H = 100 m δ_f = N/A ψ_f = 40° S1=1.2 ft S2 = 2.25 ft S3 = 3.21 ft S4 = 0.39 ft ϕ = 21° σ_c = 40.2 MPa c = 340 psf Slightly weathered Dry conditions	The result of stability evaluation is acceptable without any support.

Table 8.1 Some examples of support design by ROSES program (cont.).

Slope No.	Slope Characteristics	Support Design
Norite, Western High Wall, South Africa/ (Bye and Bell, 2001)	H = 20 m δ_f = 85° ψ_f = 75° J1 = 73 /55 J2 = 73 /55 J3 = 340/80 ϕ = 31° γ = 172 pcf Saturated	The result of stability evaluation is acceptable without any support.
Highly weathered Granite, The Muak pass, Seoul city, Korea / (Lee., Suh., Chang, & Shin, 1992)	H = 23 m δ_f = 236° ψ_f = 72° J1 = 290 /65 J2 = 240 /80 J3 = 195 /80 J4 = 55 /75 ϕ = 35° Saturated	Fully grouted steel rebar with cement. Steel produced of 0.2% carbon and Hot rolled Ultimate pressure : not less than 11 kN Recommended applied load at 30% of ultimate pressure. Bolts diameters : not less than 12 mm Steel plates size : not less than $6\times100\times100$ mm^3 Using plastic grout tube : Out-size and In-size diameters should not less than 10 and 6 mm Bolts length : not less than 3 m Bolts spacing : 3 m (Square pattern) Bolts direction : 326 degrees. Bolts angle: 39 degrees from horizontal. Hole diameters : not less than 41 mm Galvanized mesh or galvanized chain link size : less than 33.25×33.25 cm^2 Grout pressure should not exceed 150 to 200 kPa. Use corrosion protection, for example epoxy coated or galvanized coated. The grout should be allowed to develop adequate strength after about 24 hrs before tension takes place. Using PVC or Steel drained pipe Fully perforated drained pipe Length of drained pipe : not less than 23 m Holes diameter of drained pipe : not less than 10 cm Drained pipe spacing : 3 m Dip direction of drained pipe : 326 degrees Dip angle of drained pipe : 5 to 10 degrees from horizontal
H = Slope Height ψ_f = Dip Angle of Slope Face δ_f = Dip Direction of Slope Face σ_c = Uniaxial Compressive Strength c = Cohesion ϕ = Friction angle		J1, J2, J3 and J4 = Joint Set Number (dip direction/dip angle) S1, S2, S3 and S4 = Joint Spacing for set 1, 2, 3 and 4

4) Modification of slope shape with rock bolts (or cable bolts) installed are recommended for slope no.41 and case study no.1, because the slope is high with medium rock strength (R0 to R3). The joint spacing is large.

5) Slope shape is modified for slope nos.7 and 12 to 14, because the slope is high with low rock strength (R0 to R2).

6) No stabilization is required for slope nos. 26, 41, 51 and 52. Slope no.11 and case study nos. 2 to 4 show low probability of failure. This is because the joint of rock does not daylight and the potential failure plane is highly stable.

CHAPTER IX

DISSCUSSTIONS

9.1 Concept for Slope Stability Evaluation

There are very few research papers in the areas of rock slope stability evaluation and support design, comparing with other engineering studies, such as soil slopes, tunnel, building, bridge, testing and survey, etc. The Fuzzy Set Theory is an available computer software program for rock slopes which is widely used but there are some complications and difficulties dealing with the program. This concerns the users, especially new graduates and inexperienced engineers. Moreover, this computer software is not suitable for slope support design under instability conditions. This research yields a more practical computer software for users. It provides easy techniques for the stability evaluation. The analysis is based on rules of physics and mechanics. The computer software uses the design methodology for slope support. Conclusively, ROSES program is the new concept which contains a combination of stability evaluation and engineering design.

9.2 Scope and Limitation

The computer software developed here has classified rock mass into 6 geologic features. The research covered more than 80 % of rock slopes for both natural and manmade. These 6 features represent the major features of the rock slope worldwide. In regard to the effects of groundwater, the software has divided the groundwater conditions into 5 levels. Therefore, this software has provided sufficient solutions for most actual conditions. The software is however not applicable to soil slopes and rock-fill slope or land-fill due to the differences in the mechanisms and processes of failure.

9.3 Rating and Influencing Factors of Stability Evaluation

The important advantage of this computer software is the ability to obtain all available factors which covers most rock slopes problems. The classical methods of calculation and mechanics analysis cannot solve the problems because the several factors cannot be set in form of the calculable numbers. Even though users are unable to know these factors, the computer software can infer these values from the other information e.g., geology, hydrology which are required by the system.

The system uses the effects from each individual factor by using influencing coefficient which is the multiplier that makes variations on the effects for each set of factors under different situations. From the experts and research experience, the main factors that make significant changes on each individual factor is the rock strength. Therefore, this value is considered for the variation of each individual factor numerically. For instance, the effect from groundwater will decrease if the rock strength increased. The effect of slope height on the stability will reduce if the rock strength increases.

9.4 Field Data and Case Studies

The objectives of collecting field data are to calibrate the rating and influencing factors under various features of rock slopes, geological characteristics and safety requirements. The survey covered all various features required, though, it was managed under restricted time and budget. The developed computer software is calibrated and verified from more than 90% of the features of rock slopes in Thailand. Comparing this system with foreign rock slopes, it covers more than 70% of the features of foreign rock slopes (estimated from literary research papers). However, this computer software cannot estimate or include two features of instabilities; freezing conditions and wind erosion.

The results from researches and studies in Thailand and overseas on the relevant articles suggest that from 200 articles on rock slope case studies, there are only 55 articles that contain important information needed for this research. These factors are mostly used in verifying the rating, influencing factors and techniques for stability evaluation of the expert system. It can be concluded that the majority of the articles do not provide significant information usable for the application of the system. The missing information includes, joint direction, slope height and shape (curvature). Most articles do not offer these significant data due to the differences in the analysis and the method of development. However, from verifying the stability evaluation for rock slopes that retrieved from the actual 55 articles, the results can be satisfactorily confirmed the accuracy of the concept and the techniques of stability evaluation of the system.

9.5 Stability evaluation

For stability evaluation, the computer software in this research uses rating method to define factors that have effects on the stability of rock slopes and determining influence factors in each set parameters. The set of influencing factors also varies with rock strength evaluated from the field data. Each mode of failure obtained from the evaluation had different rating sets. Rating and influence factors from individual factors depend on each other and the range of rating which they are related. In some cases, the rating of two factors may be the same, and in some cases the rating from individual factors is significantly different depending on the types of failure. The influence factors given in the system will be logically different related to the features of rock slopes. There are more than 10,000 different cases from the features of rock slopes which are possible for in the system output. Therefore, this technique will cover wide range of actual rock slopes. Fundamentals and structures of the stability evaluation in this feature allow the rating and influence factors to be adjusted and developed conveniently and efficiently when new information is obtained.

9.6 Accuracy of Computer Software

From the software verification, "The predicted probability of failure" was compared with "the actual event" surveyed from the field data and derived from international case studies. The software can closely estimate the levels of stability and instability of actual rock slopes.

9.7 Support Design by ROSES Program

The concept of support design uses the theories and methodologies from engineering design. It starts by identifying the type of failure of each individual slopes (problem statements) and clarifying the particular objectives of the design. Then the functional requirements are defined in the support system. Each function will offer the answer that supports the design solutions. Each set of answers will consist of design components as engineering principle applied. The related components are rock bolt, wire mesh, cement grout, etc. After that the system will select the most appropriate answer using optimization procedures. All relevant factors and results from evaluating stability will help in decision-making process. When obtaining the answer, the system will give explanations and suggestions regard to the design specifications (size and shape of engineering materials). Eventually the system will provide the design construction. Therefore, such design is entirely operated under the rules of rock sloped engineering and it is quite conservative. The system will strictly follow the design process without omitting the important factors which are considered in the design.

CHAPTER X

CONCLUSITIONS AND RECOMMENDATIONS

10.1 Conclusions

The objective of this research is to develop a computer software for the stability evaluation and support design of rock slopes. The research consists of 7 main task: 1) literature review, 2) concept formulation, 3) data collection, 4) neural network construction, 5) software development 6) system verification and 7) documentation.

A simple form of neural network for an expert system has been developed for evaluating the mechanical stability of rock slopes. The input parameters are hierarchically characterized into several groups and sub-groups, using various criteria, i.e., site characteristics, geological and hydrological conditions, mechanical properties, slope geometry, past failure, vegetation, ground vibration, engineering requirements, design constraints, and project goals. The kinematic analysis is first performed to identify the possibility of all potential modes of failure. Specific sets of rating and influencing factors are assigned to these parameters for each rock condition and each failure mode considered. The probability of failure is the summation of the multiplied products between the rating and the corresponding influencing factor. The predicted results agree reasonably well with the actual slopes under a range of stability conditions.

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.

The conceptual network of computer software using considered factor related stability system and rating each factor and influencing factor that each factor has effect on the instability level. The results from evaluating stability are in form of probability of failure which varies from 0-100%. The greater value in probability means that the more opportunities that failure can occur. Besides, the system also considers the required engineering safety of each slope, which leads to a proper recommendation on support design at each level. In the part of support design, involved factors and features of failure are considered in order to select materials and support methods. These paths and decision-making processes are contained in the Visual Basic program, which make it easy and convenient for data input and display.

The results from the verification by comparing with the actual stability conditions of rock slopes indicate that ROSES can predict the stability conditions close to the actual slope behavior. The prediction from the program tends to be conservative. This means that the system will give probability of failure higher than the actual in most cases. Nevertheless the predictability of ROSES is satisfactory. For support design, ROSES follows the theories and principles of engineering design process.

The type of failure of each individual slopes is identified. (problem statements) The specific objectives of the design are declared. The functional requirements are defined for the support system. Each function will offer the answer that supports the design solutions. Each set of answers will consist of design components as engineering principle applied. The related components are rock bolt, wire mesh, cement grout, etc. After that the system will select the most appropriate answer using optimization procedures. All relevant factors and results from evaluating stability will help in decision-making process. When obtaining the answer, the system will give explanations and suggestions regard to the design specifications (size and shape of engineering materials applied). Eventually the system will provide the design construction. Therefore, such design is entirely operated under the rules of rock sloped engineering and it is quite conservative. The system will strictly follow the design process without omitting the important factors which are considered in the design.

10.2 Recommendations

The computer software in this research can be improved to increase the accuracy by using proven and new fields data. Users can adjust rating and influencing factors in order to improve the predictability of the software. The users can add more variables into the system, if appropriate. The experience users should however be familiar with the system functions before improving the system. Original codes should be maintained to ensure that the modified version shows some improvement. Frequent verifications of the system with the actual field condition should be performed.

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APPENDIX A

FIELDS INVESTIGATION

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A-1 Khao Chow Lai Yai Route

Khao Chow Lai Yai is located in Cha-Am district, Petchaburi province (Figure A.1). Slope nos.1 and 2 are classified here as hard-soft interbedded rock mass (Figures A.2 and A.3). The bottom of the slope is shale and having a thickness of 80 meters. The upper slope is a massive limestone with a thickness of 120 meters.

A-1.1 Slope No.1

The height of slope no.1 is 200 meters. The strikes of the slope face are from 160 to 200 degrees. The dip angles are varied from 35 to 90 degrees. The uniaxial compressive strength (here as UCS) of the intact rock is about 5-25 MPa for shale and about 40-50 MPa for limestone. Shale has three joint sets, as follows (Figures A.4 and A.5).

Joint No.1 (bedding plane) has a strike between 140 and 160 degrees, with 30 degrees dip angle. The joint spacing is 10-20 cm. The joint aperture is 0.3-0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike between 55 and 65 degrees, with 60 and 70 degrees dip angle. The joint spacing is 10-15 cm. The joint aperture is 0.3 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 1. The joints are filled with clay.

Joint No.3 has a strike between 245 and 260 degrees, with 75 degrees dip angle. The joint spacing is 15 cm. The joint aperture is 0.1 cm. Persistence of the rock joint is about 40-60%. The JRC is estimated as 2. The joints are filled with clay.

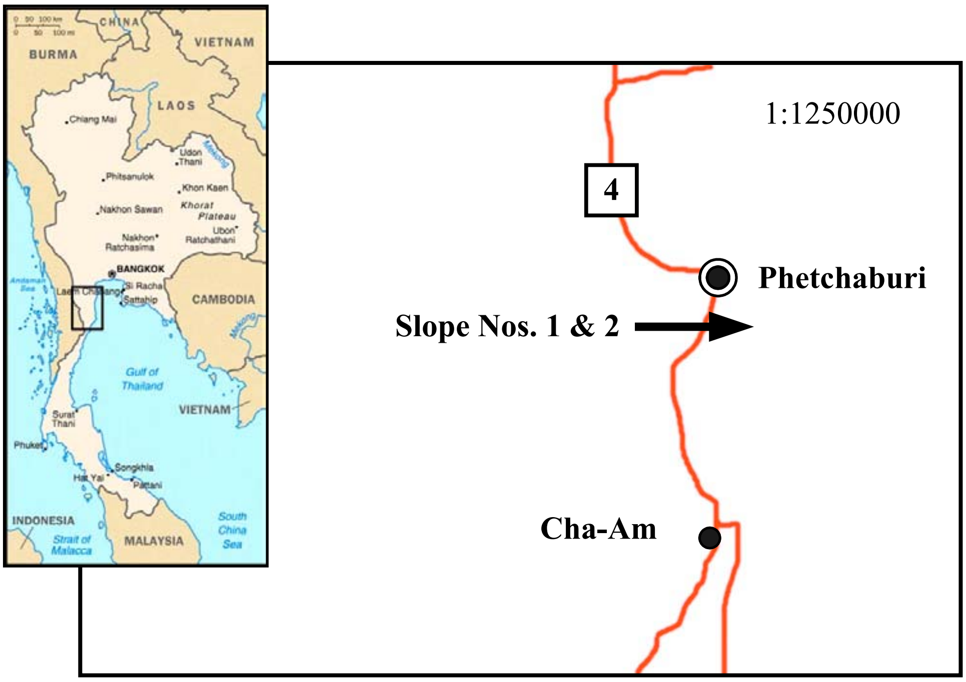

Figure A.1 Slope locations along Khao Chow Lai Yai route, Cha–Am district Petchaburi province.

Figure A.2 The secondary toppling of Khao Chow Lai Yai, Cha-Am district, Phetchaburi province (slope no.1).

Figure A.3 The vertical joint of limestone is located in Khod Nang Panturat of Khao Chow Lai Yai (slope no.1).

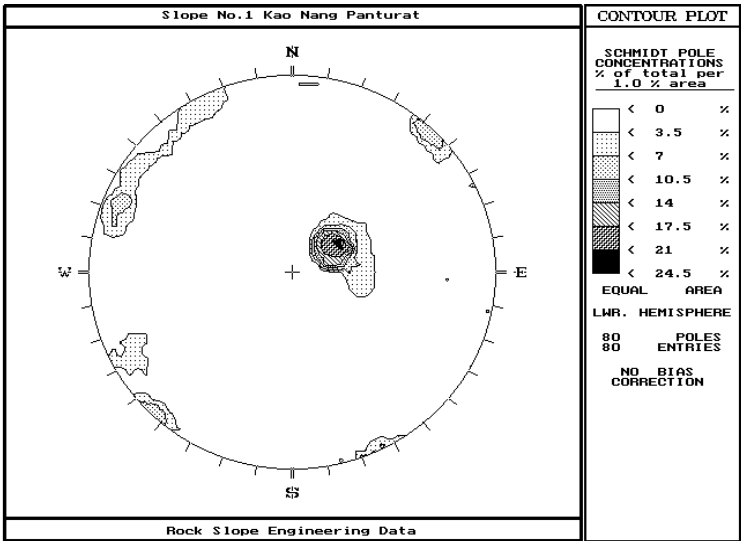

Figure A.4 The contour plots for shale discontinuity of Khao Chow Lai Yai slope (slope no.1).

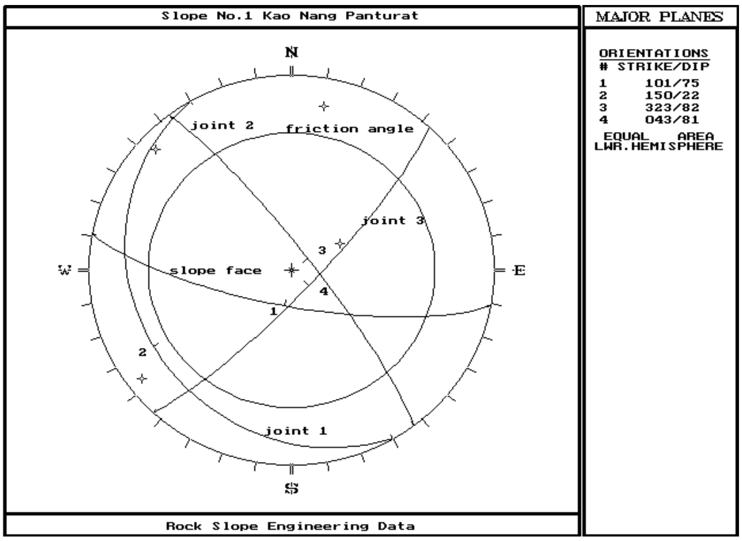

Figure A.5 The representative plane, slope orientation and friction angle of shale of Khao Chow Lai Yai slope (slope no.1).

The limestone has three joint sets. Give more joint detail of limestone as follow (Figure A.6 and A.7).

Joint No.1 (bedding plane) has a strike between 170 and 180 degrees, with 25 degrees dip angle. The joint spacing is 1-3 m. No joint aperture. The rock joint is low persistence (40-50%).

Joint No.2 has a strike of 270 degrees, with 70 degrees dip angle. The joint spacing is 2 m. The joint aperture is 1-2 m. Persistence of the rock joint is about 80%. The JRC is estimated as 15. No filling material.

Joint No.3 has a strike between 65 and 80 degrees, with 85 degrees dip angle. The joint spacing is 3-10 m. The joint aperture is 0.5-1 m. Persistence of the rock joint is about 60-80%. The JRC is estimated as 15. No filling material.

The mode of failure is secondary toppling on the vertical joint of limestone. The failure occurred due to the excessive excavation of soft shale formation at the toe.

A-1.2 Slope No.2

The height of slope no.2 is 200 meters (Figures A.8 and A.9). The strike of the slope face is 009 degrees. The dip angles are varied from 35 to 90 degrees. Shale has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike between 140 and 160 degrees, with 30 degrees dip angle. The joint spacing is 10-20 cm. The joint aperture is 0.3-0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike between 55 and 65 degrees, with 65 degrees dip angle. The joint spacing is 10-15 cm. The joint aperture is 0.3 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 1-2. The joints are filled with clay.

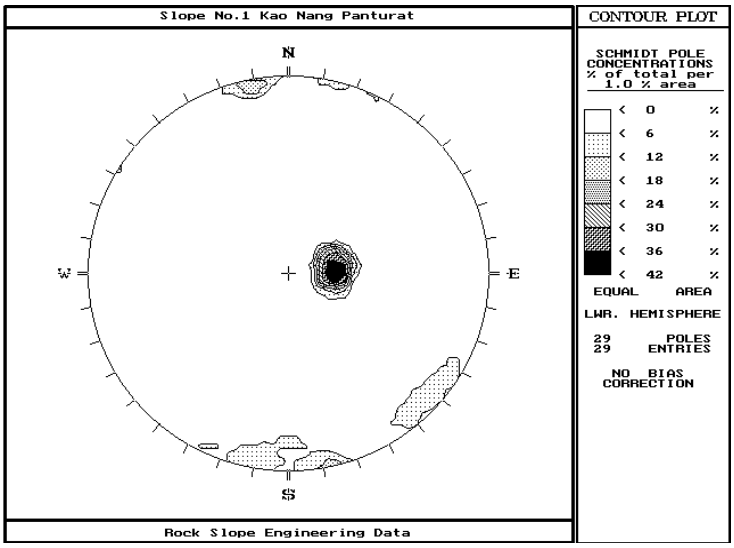

Figure A.6 The contour plots for limestone discontinuity of Khao Chow Lai Yai slope (slope no.1).

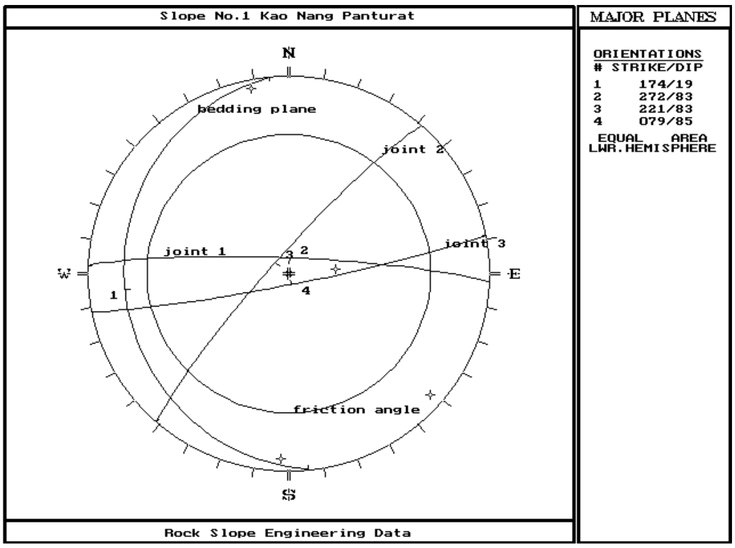

Figure A.7 The representative plane, slope orientation and friction angle of limestone of Khao Chow Lai Yai slope (slope no.1).

Figure A.8 The excessive excavation of the soft shale formation at the toe of Khao Chow Lai Yai (slope no.2).

Figure A.9 The excessive excavation of the soft shale formation at the toe of Khao Chow Lai Yai (slope no.2).

Joint No.3 has a strike between 245 and 260 degrees, with 75 degrees dip angle. The joint spacing is 15 cm. The joint aperture is 0.1 cm. Persistence of the rock joint is about 40-60%. The JRC is estimated as 2. The joints are filled with clay.

The limestone has three joint sets. Give more joint details of limestone as follows (Figures A.10 and A.11).

Joint No.1 (bedding plane) has a strike between 170 and 180 degrees, with 25 degrees dip angle. The joint spacing is 1-3 m. No joint aperture. The rock joint is low persistence (40 -50%).

Joint No.2 has a strike of 270 degrees, with 70 degrees dip angle. The joint spacing is 2 m. The joint aperture is 1-2 m. Persistence of the rock joint is about 80%. The JRC is estimated as 15.

Joint No.3 has a strike between 65 and 80 degrees, with 85 degrees dip angle. The joint spacing is 3-10 m. The joint aperture is 0.5-1 m. Persistence of the rock joint is about 60-80%. The JRC is estimated as 15.

A-2 The Eastern Route

The eastern route consists of eight slopes (slope nos.3 to 10) located in the Nakorn Ratchasima, Prachinburi, Sa Kaeo, Chantaburi and Chon Buri provinces (Figure A.12).

A-2.1 Slope No.3

The slope no.3 is located in Pak Thong Chai district, Nakhon Ratchasima province. The slope location is 47 P 0813538 and UTM 1600267 of GPS system (Figures A.13 and A.14). The slope is classified here as hard-soft interbedded rock mass. The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft

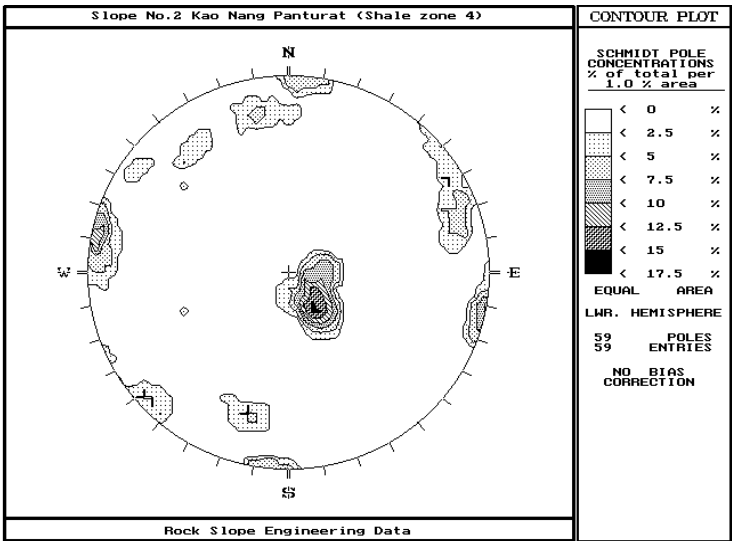

Figure A.10 The contour plots for shale discontinuity of Khao Chow Lai Yai slope (slope no.2).

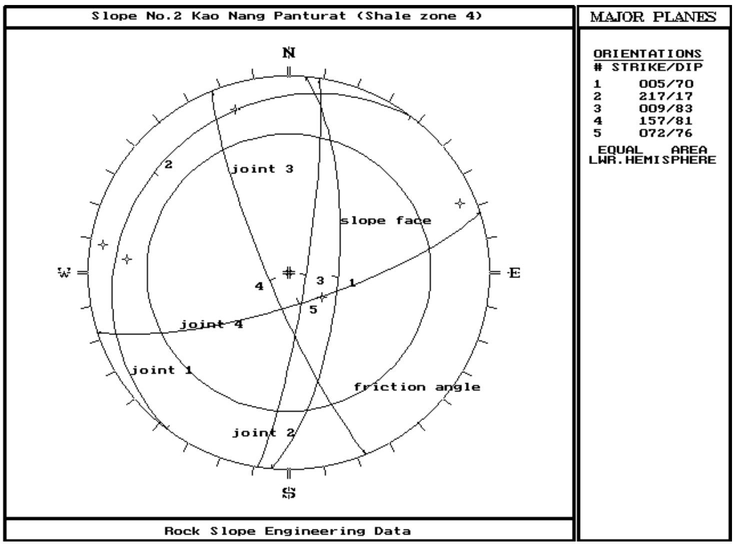

Figure A.11 The representative plane, slope orientation and friction angle of shale of Khao Chow Lai Yai slope (Slope No.2).

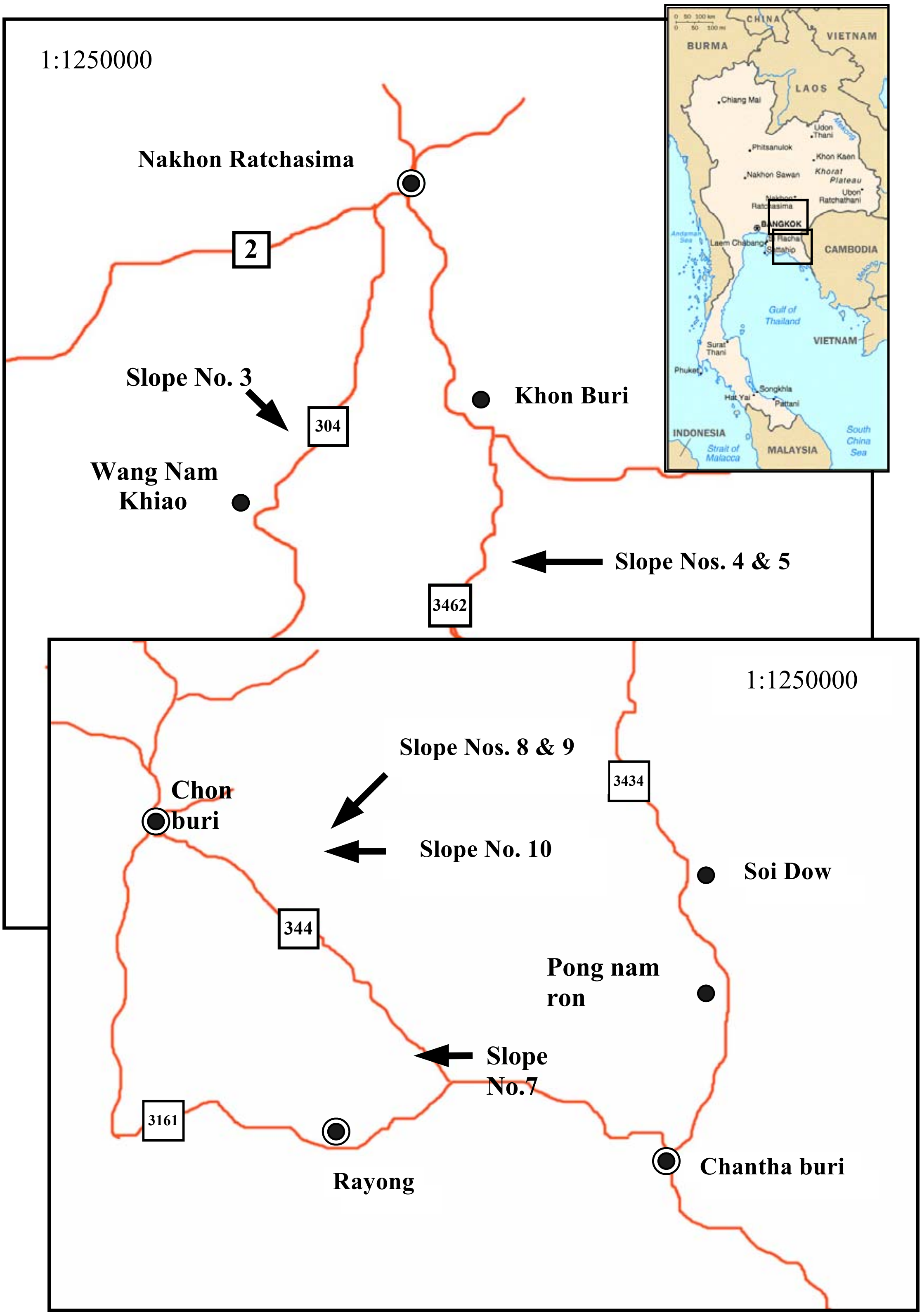

Figure A.12 Slope locations along eastern route.

Figure A.13 The secondary toppling of hard-soft interbedded rock is located at km 70 of highway No. 304 (slope no.3).

Figure A.14 The block sizes of sandstone are $0.7\times0.8\times0.5$ m^3 at the toe of slope (slope no.3).

formation is shale. It has 0.2 to 1.0 meter thickness. The slope height is 13 meters. The strike of the slope face is 300 degrees. The dip angles are varied from 55 to 75 degrees. The UCS of the intact rock is about 5- 25 MPa for shale and about 40-50 MPa for sandstone. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 136 degrees, with 21 degrees dip angle. The joint spacing is 0.7 m. The joint aperture is 0.5-1.0 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike of 240 degrees, with 80 degrees dip angle. The joint spacing is 0.8 m. The joint aperture is 5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 335 degrees, with 60 degrees dip angle. The joint spacing is 0.5 m. The joint aperture is 2-10 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

The mode of failure is secondary toppling of the vertical joint in massive sandstone (size is $0.7\times0.8\times0.5$ m^3). The failure is caused by the erosion of the soft shale bed which results in the collapse of the hard sandstone bed above.

A-2.2 Slope No.4

The slope no.4 is located on highway no.3462, Pak Thong Chai district, Nakhon Ratchasima province. The slope location is 48 P 0811068 and UTM 1582341 of GPS system (Figure A.15). The slope is classified here as hard-soft interbedded rock mass. The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft formation is shale. It has 0.2 to 1.0 meter thickness. The slope height is 15 meters. The slope face angle is 30 degrees. The existing supports include rock bolts,

Figure A.15 Slope stabilization by shortcrete method is located on highway no. 3462, Sa Kaeo province (slope no.4).

and wire mesh. Wire mesh is 6 x 7 cm in opening. Shotcrete is between 2 and 8 cm in thickness. The length of drained pipes is between 30 and 50 cm. The inner diameter of drained pipes is 6.5 cm and the outer diameter of drained pipes is 6.8 cm. The slope is stable.

A-2.3 Slope No.5

The slope no.5 is located on highway no.3462, Pak Thong Chai district, Nakhon Ratchasima province. The slope location is 48 P 0198523 and UTM 1548638 of GPS system. The slope is classified as hard-soft interbedded rock. The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft formation is shale. It has 0.2 to 1.0 meter thickness. The slope height is 5 meters. The slope face angle is 80 degrees. The slope is stable. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 330 degrees, with 20 degrees dip angle. The joint spacing is 1.0 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike of 225 degrees, with 85 degrees dip angle. The joint spacing is 0.5-1.2 m. The joint aperture is 5 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 340 degrees, with 80 degrees dip angle. The joint spacing is 1.0 m. The joint aperture is 2-5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

A-2.4 Slope No.6

The slope no.6 is located in Pong Nam Ron district, Chanthaburi province. The slope location is 48 P 0203877 and UTM 1427846 of GPS system (Figures A.16 and A.17). The slope is classified as heavily jointed rock. The slope height is 8-10

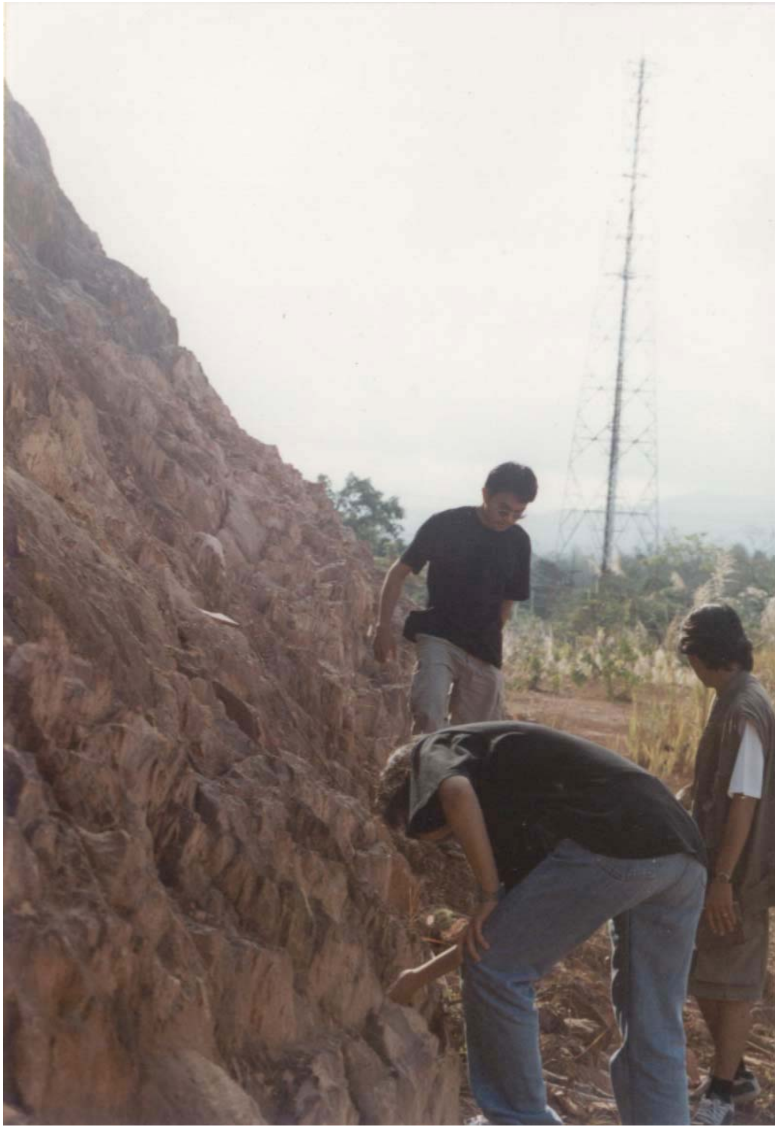

Figure A.16 Shale quarry is located in Pong Nam Ron district, Prachin Buri province (slope no.6).

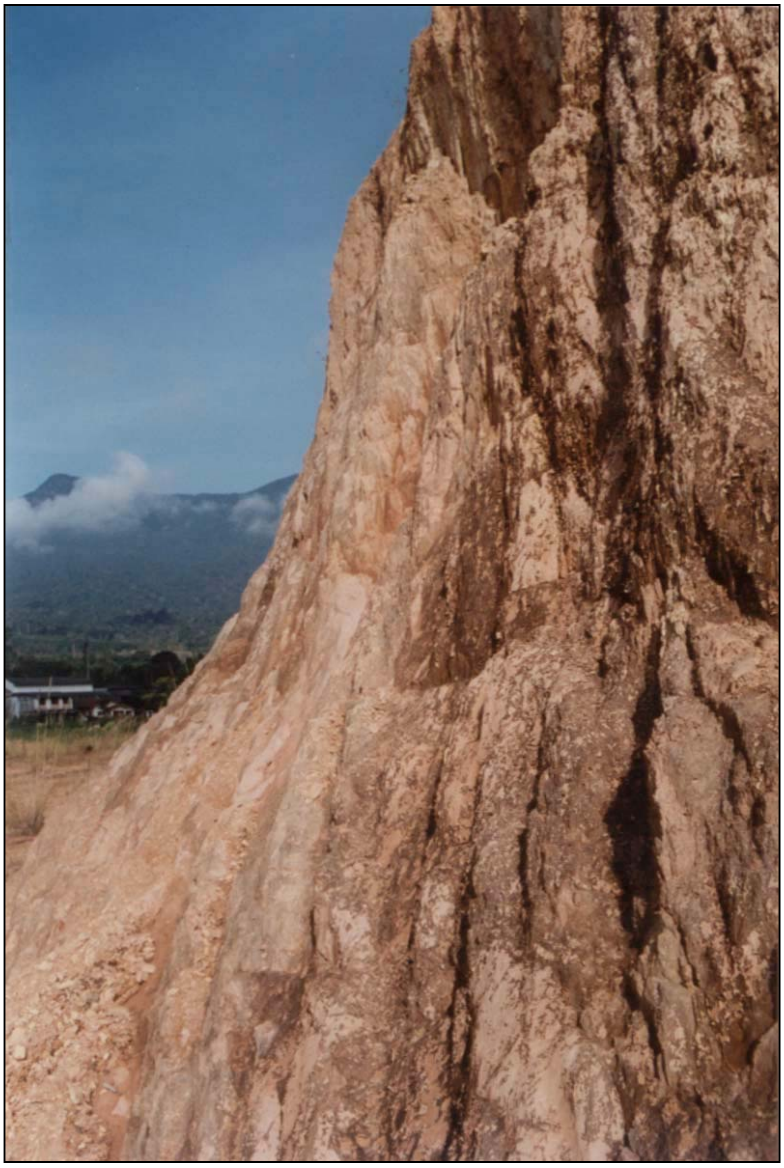

Figure A.17 Heavily jointed rock of shale quarry is located in Pong Nam Ron district, Chathaburi province (slope no.6).

meters. The strike of the slope face is 150 degrees. The dip angles are varied from 70 to 80 degrees. The UCS of the intact rock is 5-25 MPa. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 340 degrees, with 85 degrees dip angle. The joint spacing is 0.1-0.2 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with clay.

Joint No.2 has a strike of 015 degrees, with 85 degrees dip angle. The joint spacing is 0.5-1.2 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 50%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 175 degrees, with 60 degrees dip angle. The joint spacing is 1.0 m. The joint aperture is 0.2-0.5 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 1-3. The joints are filled with clay.

The failure modes are the combination of plane sliding, toppling and circular failure. The failure is caused by the combination of water saturation, ground vibration (by heavy traffic) and the high angle slope face.

A-2.5 Slope No.7

The slope no.7 at km 92-93 of highway no.344 is located in Chanthaburi province. The slope location is 47 P 0784101 and UTM 1421792 of GPS system (Figures A.18 and A.19). The slope is classified as heavily jointed rock. The slope height is 13 meters. The strike of the slope face is 300 degrees. The dip angle is 60 degrees. The UCS of the intact rock is 5-25 MPa. The rock has two joint sets, as follows.

Figure A.18 Heavily jointed rock slope is located at km 92-93 of highway no.344 (slope no.7).

Figure A.19 The circular failure of heavily jointed rock slope on highway no. 344, Chon Buri province (slope no.7).

Joint No.1 (bedding plane) has a strike between 190 and 205 degrees, with 40 and 45 degrees dip angle. The joint spacing is 0.5-1.0 cm. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with clay.

Joint No.2 has a strike between 270 and 305 degrees, with 60 and 85 degrees dip angle. The joint spacing is 0.5-1.0 cm. The joint aperture is 0.5 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 3. The joints are filled with clay.

The failure modes are the combination of plane sliding, toppling and circular failure. The failure is caused by the combination of water saturation, ground vibration (by heavy traffic) and the high angle slope face.

A-2.6 Slope No.8

The slope no.8 is located in Wat Khao Shee Chan Park, Sattahip district, Chon Buri province. The slope location is 47 P 0712817 and UTM 11411742 of GPS system (Figure A.20). The rock type is limestone. The slope is classified as blocky rock. The slope height is 170 meters. The strike of the slope face is 275 degrees. The dip angle is 75 degrees. The UCS of the intact rock is 50-60 MPa. The existing supports include rock bolt and drained pipe.

A-2.7 Slope No.9

The slope no.9 is located near with Wat Khao Shee Chan Park, Sattahip district, Chon Buri province. The slope location is 47 P 0713246 and UTM 1409209 of GPS system (Figures A.21 and A.22). The rock type is limestone. The slope is classified as blocky rock. The slope height is 50 meters. The strike of the slope face is 030 degrees. The dip angle is 75 degrees. The UCS of the intact rock is 50-60 MPa. The slope is stable. The rock has three joint sets, as follows.

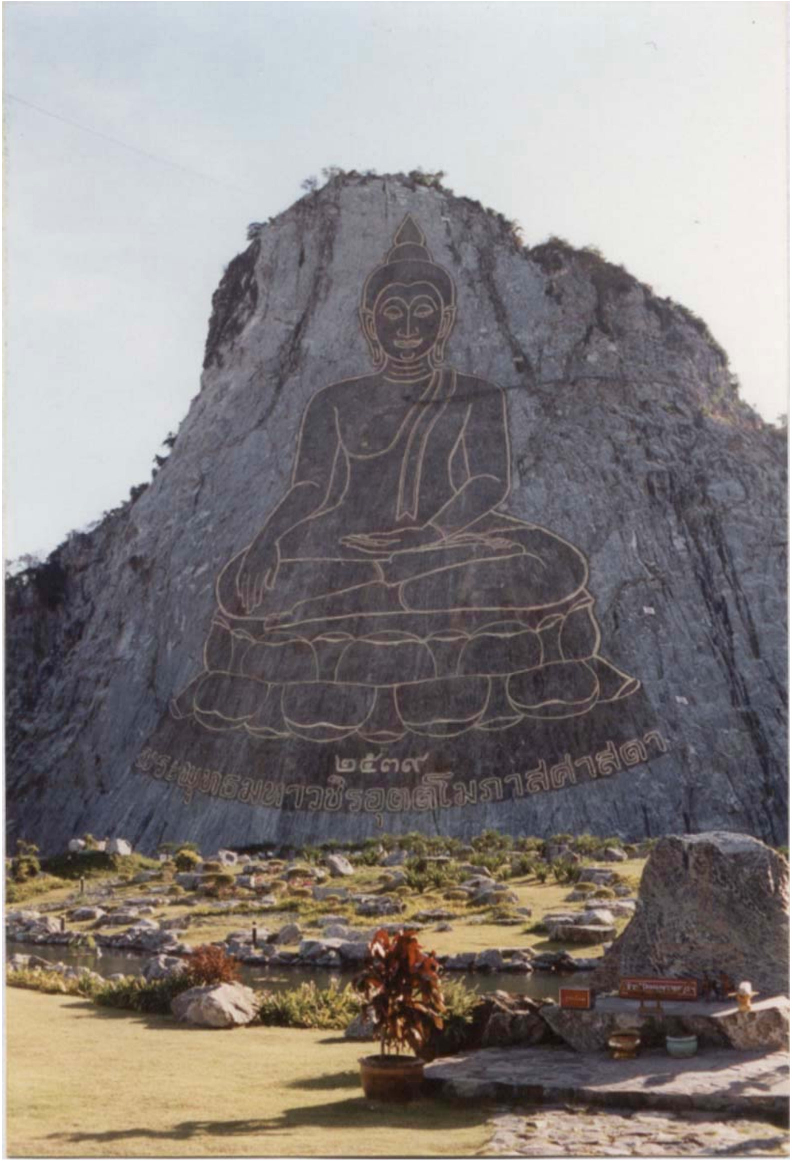

Figure A.20 Kao Shee Chan slope is located in Sattahip district, Chon Buri province (slope no.8).

Figure A.21 Blocky rock slope of limestone quarry is located near with Khao Shee Chan, Chon Buri province (slope no.9).

Figure A.22 Blocky rock slope of limestone quarry is located near with Khao Shee Chan, Chon Buri province (slope no.9).

Joint No.1 (bedding plane) has a strike of 120 degrees, with 40 degrees dip angle. The joint spacing is 0.2-0.3 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike of 225 degrees, with 60 degrees dip angle. The joint spacing is 0.2-0.5 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 3-5. The joints are filled with calcite.

Joint No.3 has a strike of 320 degrees, with 55 degrees dip angle. The joint spacing is 0.7 m. The joint aperture is 0.2-0.5 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 3-5. The joints are filled with calcite.

A-2.8 Slope No.10

The slope no.10 is located in Sattahip district, Chon Buri province. The slope location is 47 P 0714024 and UTM 1405059 of GPS system (Figures A.23 and A.24). The rock type is shale. The slope is classified as heavily jointed rock. The slope height is 13 meters. The strike of the slope face is 080 degrees. The dip angle is 72 degrees. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 250 degrees, with 75 degrees dip angle. The joint spacing is 0.02-0.1 m. The joint aperture is 0.5-1.0 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike of 160 degrees, with 80 degrees dip angle. The joint spacing is 0.03-0.05 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 3. The joints are filled with clay.

Figure A.23 Folding of shale is located in slaty-shale quarry, Chon Buri province (slope no.10).

Figure A.24 Circular failure of blocky rock slope of slaty-shale quarry, Chon Buri province (slope no.10).

Joint No.3 has a strike of 100 degrees, with 80 degrees dip angle. The joint spacing is 0.1 m. Thee joint aperture is 0.5-1.0 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 3. The joints are filled with clay.

The failure modes are toppling and surface circular failure. The failure is caused by the combination of water saturation, ground vibration and the high angle slope face.

A-3 Khao Som Phot Quarry and Highway No. 2256 Route

Khao Som Phot quarry and highway no.2256 is located in Chai-Badan district, Lop Buri province (Figure A.25). The route having 2 locations is slope no.11 and no.12, as follows.

A-3.1 Slope No.11

The slope location is 47 P 0748946 and UTM 1672234 of GPS system (Figures A.26 and A.27). The rock type is limestone. The slope is classified as heavily jointed rock. The slope height is 60 meters. There are three of slopes faces. The strikes of the slope face are 354, 070 and 150 degrees. The dip angles are 72, 65 and 70 degrees. The UCS of the intact rock is about 50-100 MPa. The rock has four joint sets (Figures A.28 and A.29), as follows.

Joint No.1 (bedding plane) has a strike of 280 degrees, with 25 degrees dip angle. The joint spacing is 0.3-0.5 m. The joint aperture is 0.5-1.0 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with calcite.

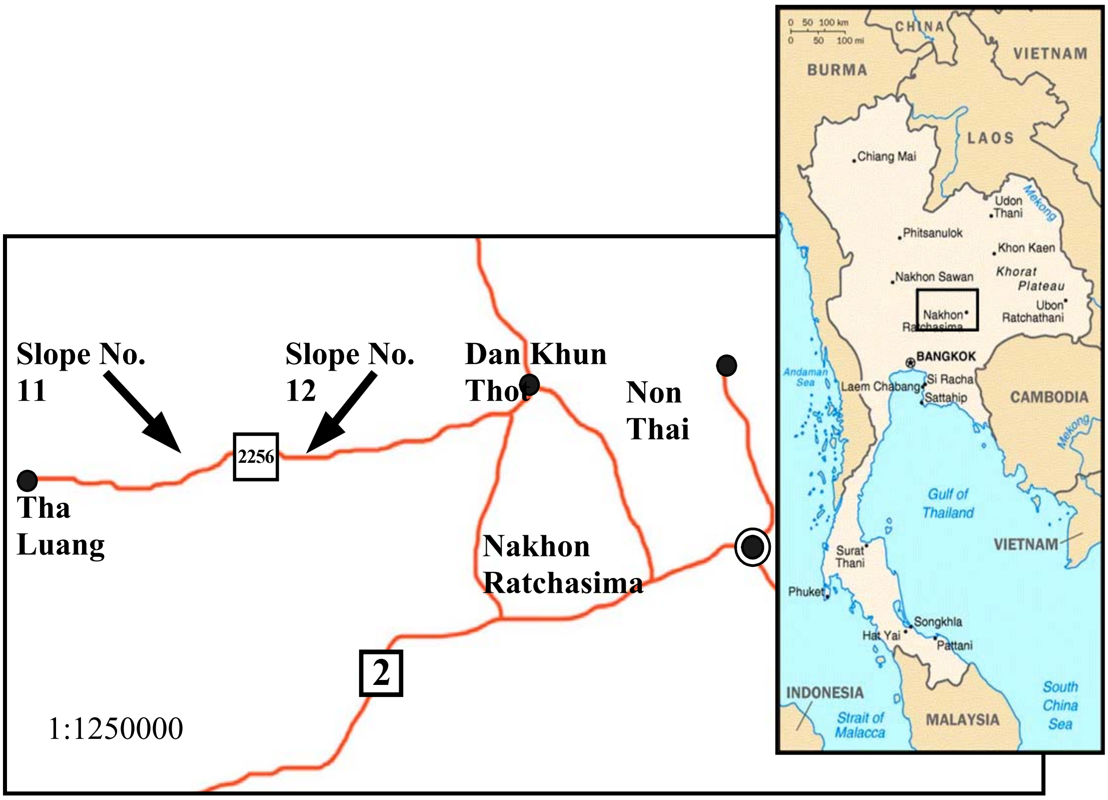

Figure A.25 Slope locations along 2256 and Khao Som Phot route, Chai Badan Lopburi province.

Figure A.26 Khao Som Phot limestone quarry, Chai Badan district, Lop Buri province (slope no.11).

Figure A.27 Khao Som Phot limestone quarry, Chai Badan district, Lop Buri province (slope no.11).

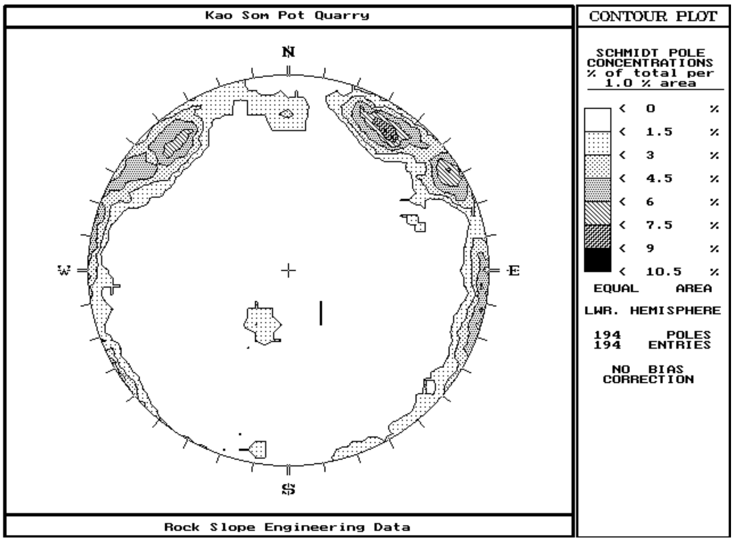

Figure A.28 The contour plot of discontinuity of Khao Som Phot limestone, Chai Badan district, Lop Buri province (slope no.11).

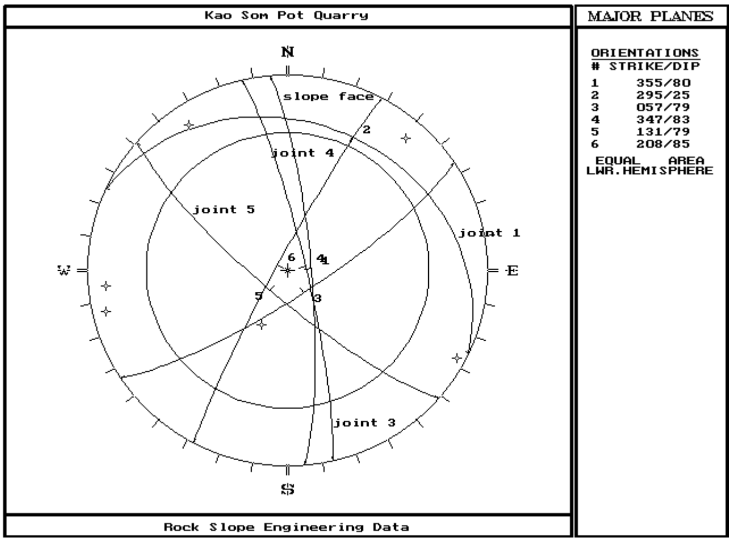

Figure A.29 Representative plane, slope orientation and friction angle of discontinuity of Khao Som Phot limestone, Chai Badan district, Lop Buri province (slope no.11).

Joint No.2 has a strike of 025 degrees, with 90 degrees dip angle. The joint spacing is 0.2-0.3 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 5. The joints are filled with calcite.

Joint No.3 has a strike of 315 degrees, with 80 degrees dip angle. The joint spacing is 0.4-0.5 m. The joint aperture is 1-5 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 5-7. The joints are filled with calcite.

Joint No.4 has a strike of 142 degrees, with 80 degrees dip angle. The joint spacing is 0.3 m. The joint aperture is 1-5 cm. Persistence of the rock joint is about 60%. The JRC is estimated as 5. The joint is not filling.

The failure modes are plane, wedge and toppling failure. The plane and wedge failures are on the face of 354 / 86 and toppling on 150 / 70 degrees. There are limestone block size of $0.5 \times 0.5 \times 0.7\ m^3$ on toe of slope. The failure is caused by the blast vibration and the high angle slope face.

A-3.2 Slope No.12

The slope no.12 is located on highway no.2256. The slope location is 47 P 0759028 and UTM 1670703 of GPS system (Figures A.30 and A.31). The slope is classified as hard-soft interbedded rock mass. The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft formation is shale. It has 0.2 to 1.0 meter thickness. The slope height is 50 meters. The strike of the slope face is 080 degrees. The dip angle is 60 degrees. The UCS of the intact rock is about 5-25 MPa for shale and about 50-100 MPa for sandstone. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 320 degrees, with 25 degrees dip angle. The joint spacing is 0.8 m. The joint aperture is 0.5-1.0 cm. Persistence of the

Figure A.30 The rock slope on highway no.2256, Chai Badan district, Lop Buri province (slope no.12).

Figure A.31 The sandstone block size is $0.8{\times}0.7{\times}0.7$ m^3 on the toe of slope (slope no.12).

rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike of 105 degrees, with 80 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-2 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.3 has a strike of 175 degrees, with 70 degrees dip angle. The joint spacing is 0.2-0.7 m. The joint aperture is 0.5-5 cm. Persistence of the rock joint is about 80 %. The JRC is estimated as 3-5. The joints are filled with clay.

The failure is secondary toppling of the vertical joint in massive sandstone (size is $0.5 \times 0.5 \times 0.7$ m^3). The failure is caused by the erosion of the soft shale bed which results in the collapse of the hard sandstone bed. The existing supports include shotcrete, drained holes and ditch.

A-4 Friendship Highway Route

The Friendship highway route having 5 slope locations along the road cut in Nakorn Ratchasima and Sara-Buri provinces (Figure A.32). The area is a part of Dong Phraya Fi Mountain range. The slope failures along the road cuts have repeatedly occurred on some locations (slope nos.13 to 17).

A-4.1 Slope No.13

The slope no.13 at km 195-196 is located on Friendship highway. The slope location is 47 P 0776496 and UTM 1842789 of GPS system (Figures A.33 and A.34). The slope is classified as hard-soft interbedded rock. The hard formation is sandstone. It has 0.6-1.0 meter in thickness. The soft formation is shale. It has 0.5-1.5 meter thickness. The slope height is 20 meters. The strike of the slope face is 210 degrees.

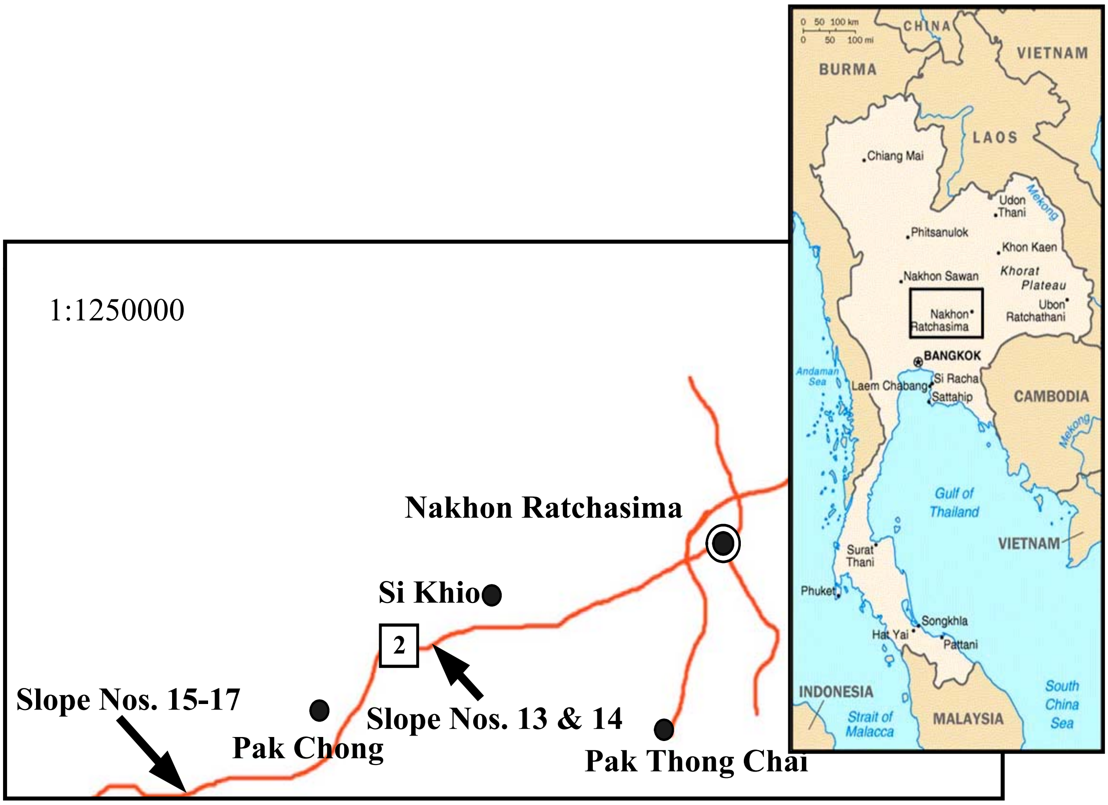

Figure A.32 Slope locations along Friendship highway route, Saraburi to Nakhon Ratchsima provinces.

Figure A.33 The slope location at km 195-196 of Friendship highway, Lam Takong dam, Nakhon Ratchasima province (slope no.13).

Figure A.34 Sandstone block size is 2×1×1 m^3 on the toe of slope (slope no.13).

The dip angle is 54 degrees. The UCS of the intact rock is about 5-25 MPa for shale and about 50-100 MPa for sandstone. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 356 degrees, with 06 degrees dip angle. The joint spacing is 0.6-0.8 m. The joint aperture is 0.5-1.0 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike of 014 degrees, with 89 degrees dip angle. The joint spacing is 0.2-0.8 m. The joint aperture is 2-5 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.3 has a strike of 220 degrees, with 70 degrees dip angle. The joint spacing is 1.2 m. The joint aperture is 1-5 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 3-5. The joints are filled with clay.

The failure is secondary toppling of the vertical joint in massive sandstone (size is $0.5 \times 0.5 \times 0.7$ to $2.0 \times 1.0 \times 1.0$ m^3). The failure is caused by the erosion of the soft shale bed which results in the collapse of the hard sandstone bed.

A-4.2 Slope No.14

The slope no.14 at km 194-195 is located on Friendship highway. The slope location is 47 P 0775301 and UTM 1641908 of GPS system (Figures A.35 to A.37). The slope is classified as hard-soft interbedded rock. The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft formation is shale. It has 0.5 to 1.5 meter thickness. The slope height is 40 meters. The strike of the slope face is 206 degrees. The dip angle is 55 degrees. The UCS of the intact rock is about 5-25 MPa for shale and about 50-100 MPa for sandstone. The rock has three joint sets (Figures A.38 and A.39). Give more joint detail as follows.

Figure A.35 The slope location at km 193-194 of Friendship highway, Lam Takong dam, Nakhon Ratchasima province (slope no.14).

Figure A.36 The slope location at km 193-194 of Friendship highway, Lam Takong dam, Nakhon Ratchasima province (slope no.14).

Figure A.37 The failure is caused by the erosion of the soft shale bed which results in the collapse of the hard sandstone bed (slope no.14).

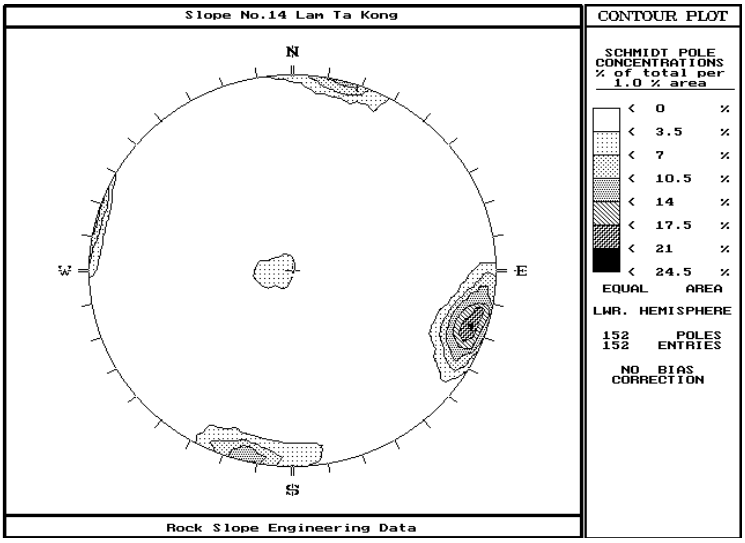

Figure A.38 The contour plot of sandstone discontinuity set of slope is located at km 193 -194 of Friendship highway (slope no.14).

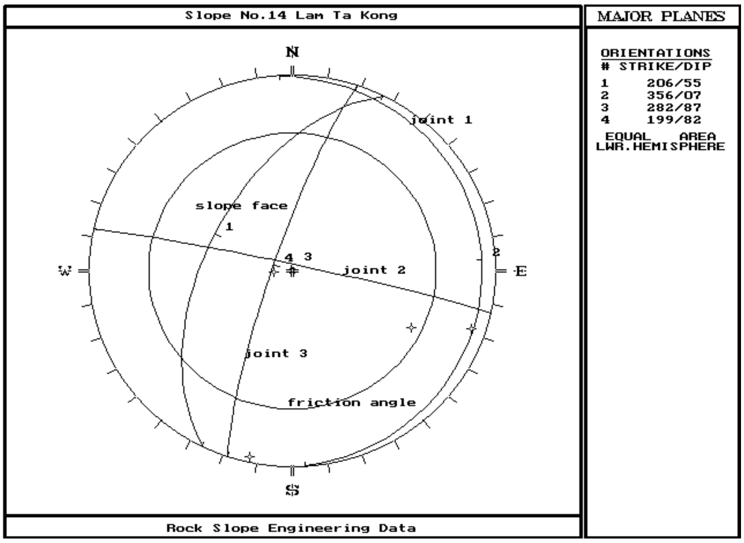

Figure A.39 Representative plane, slope orientation and friction angle sandstone discontinuity set of slope is located at km 193 -194 of Friendship highway (slope no.14).

Joint No.1 (bedding plane) has a strike of 013 degrees, with 06 degrees dip angle. The joint spacing is 0.3-1.0 m. The joint aperture is 1-5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike of 288 degrees, with 89 degrees dip angle. The joint spacing is 0.3-2 m. The joint aperture is 1-4 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 5-7. The joints are filled with clay.

Joint No.3 has a strike of 202 degrees, with 83 degrees dip angle. The joint spacing is 0.6 m. The joint aperture is 2-3 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 5-7. The joints are filled with clay.

The failure is secondary toppling of the vertical joint in massive sandstone (size is $0.2 \times 0.3 \times 0.5$ to $0.6 \times 0.8 \times 1.0$ m^3). The failure is caused by the erosion of the soft shale bed which results in the collapse of the hard sandstone bed.

A-4.3 Slope No.15

The slope no.15 at km 135-136 is located on Friendship highway. The slope location is 47 P 0732026 and UTM 1619048 of GPS system (Figures A.40 to A.41). The slope is classified as massive rock. The slope height is 15 meters. The strike of the slope face is 100 degrees. The dip angle is 50 degrees. The rock type is limestone. The UCS of the intact rock is about 50-100 MPa. The slope is stable. The rock has three joint sets (Figures A.42 and A.43), as follows.

Joint No.1 (bedding plane) has a strike of 107 degrees, with 51 degrees dip angle. The joint spacing is 0.3-1.0 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 15. The joints are filled with calcite.

Figure A.40 The limestone slope is located at km 136-137 of Friendship highway, Muak Lek district, Sara Buri province (slope no.15).

Figure A.41 The limestone slope is located at km 136 -137 of Friendship highway, Muak Lek district, Sara Buri province (slope no.15).

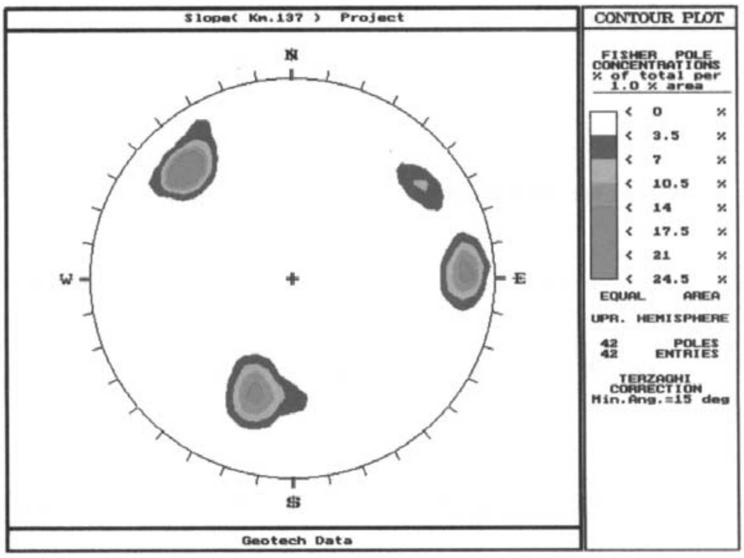

Figure A.42 The contour plot of limestone discontinuity set is located at km 136-137 of Friendship highway (slope no.15).

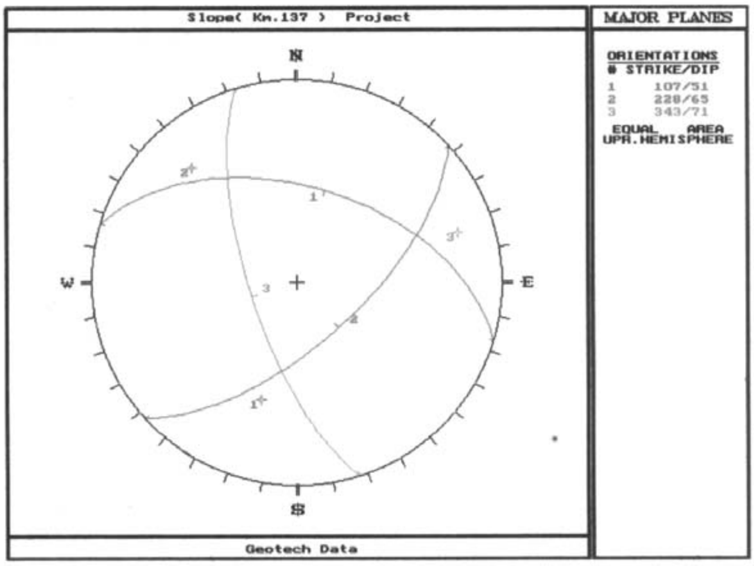

Figure A.43 Representative plane of limestone discontinuity set is located at km 136-137 of Friendship highway (slope no.15).

Joint No.2 has a strike of 228 degrees, with 65 degrees dip angle. The joint spacing is 0.5-2 m. The joint aperture is 5-20 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 5-7. The joints are filled with calcite.

Joint No.3 has a strike of 343 degrees, with 71 degrees dip angle. The joint spacing is 1-2 m. The joint aperture is 5-20 cm. Persistence of the rock joint is about 40-60%. The JRC is estimated as 11. The joints are filled with calcite.

A-4.4 Slope No.16

The slope no.16 at km 134-135 is located on Friendship highway. The slope location is 47 P 0731404 and UTM 1619159 of GPS system (Figures A.44 to A.45). The slope is classified as massive rock. The slope height is 15 m and the length is 40 m. The strike of the slope face is 100 degrees. The dip angle is 50 degrees. The rock type is massive limestone. The UCS of the intact rock is about 50-100 MPa. The slope is stable. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike of 266 degrees, with 22 degrees dip angle. The joint spacing is 0.3-0.8 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 20-30%. The JRC is estimated as 9-13. The joints are filled with calcite.

Joint No.2 has a strike of 310 degrees, with 87 degrees dip angle. The joint spacing is 0.3 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 20-40%. The JRC is estimated as 11. The joints are filled with calcite.

Joint No.3 has a strike of 025 degrees, with 89 degrees dip angle. The joint spacing is 0.3 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 30-50%. The JRC is estimated as 11-17. The joints are filled with calcite.

Figure A.44 The limestone slope is located on 135-136-km of Friendship highway, Muak Lek district, Sara Buri province (slope no.16).

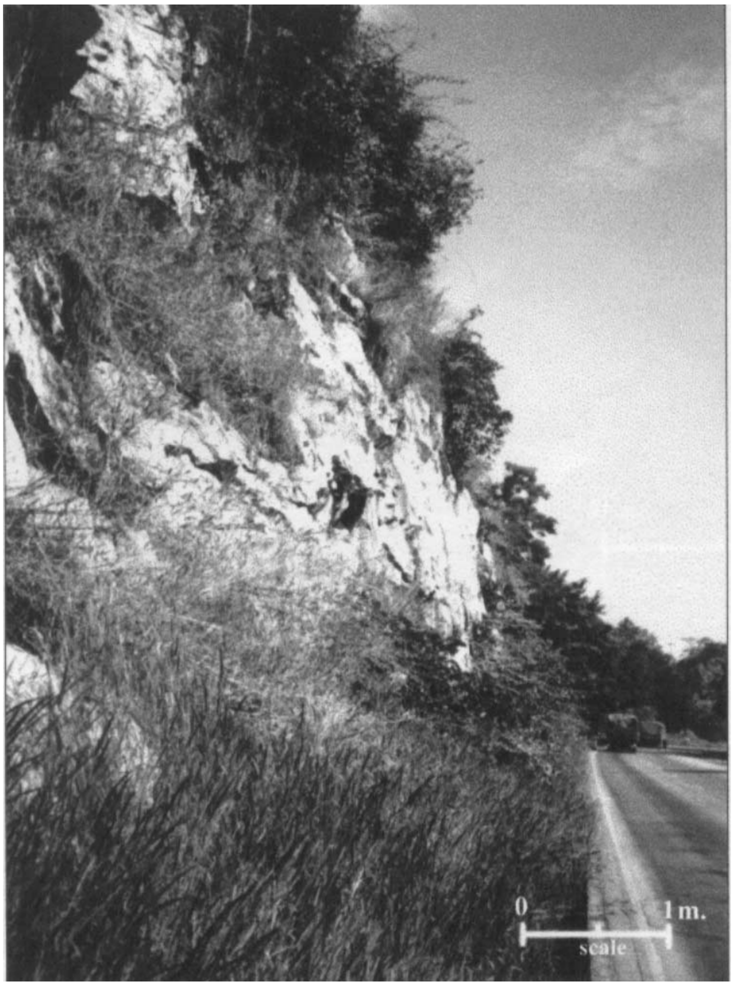

Figure A.45 The limestone slope is located on 135-136-km of Friendship highway, Muak Lek district, Sara Buri province (slope no.16).

A-4.5 Slope No.17

The slope no.17 at km 133-134 is located on Friendship highway. The slope location is 47 P 0729186 and UTM 1619102 of GPS system (Figures A.46 to A.47). The slope is classified as bedded rock. The slope height is 10 m and the length is 40 m. The strike of the slope face is 90 degrees. The dip angle is 45 degrees. The rock type is slaty-shale. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has three joint sets (Figures A.48 to A.49), as follows.

Joint No.1 (bedding plane) has a strike of 080 degrees, with 43 degrees dip angle. The joint spacing is 0.05-0.1 m. The joint aperture is 5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1. The joints are filled with clay.

Joint No.2 has a strike of 210 degrees, with 75 degrees dip angle. The joint spacing is 0.55 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.3 has a strike of 002 degrees, with 83 degrees dip angle. The joint spacing is 0.7 m. The joint aperture is 1-2 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

A-5 PANDS Barite Mining Route

PANDS barite mine is location in Chieng Kan district, Loei province (Figure A.50). There are six slopes (slope nos.18 to 23) as shows in Figures A.51 to 53.

A-5.1 Slope No.18

The slope no.18 is located in the south footwall. The slope is classified here as massive rock. The slope height is 15 m and the length is 40 m. The strike of the slope

Figure A.46 The bedded slope of slaty–shale is located at km 133-134 of Friend ship highway**,** Muak Lek district, Sara Buri province (slope no.17).

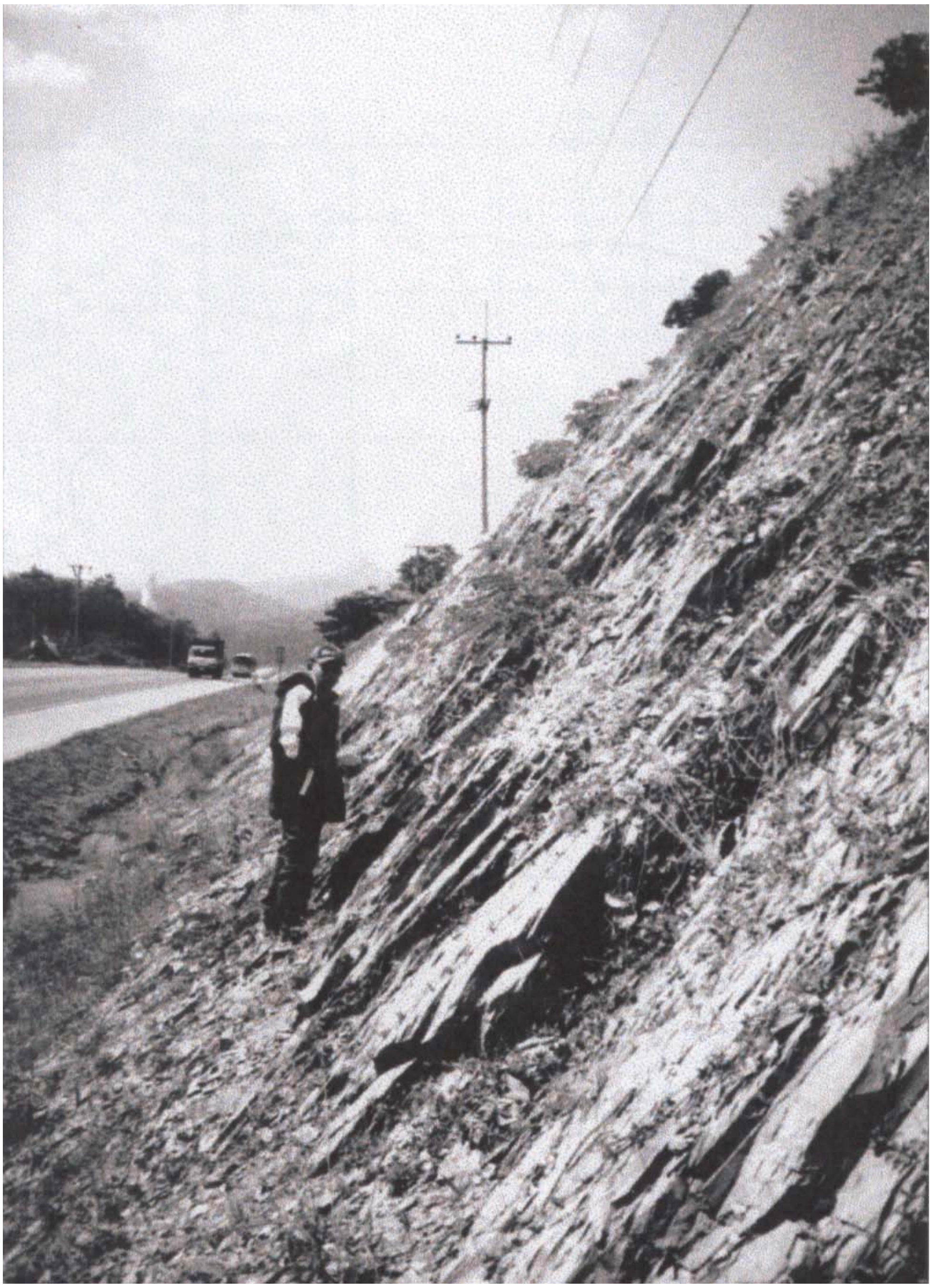

Figure A.47 The bedded slope of slaty–shale is located at km 133-134 of Friend ship highway**,** Muak Lek district, Sara Buri province (slope no.17).

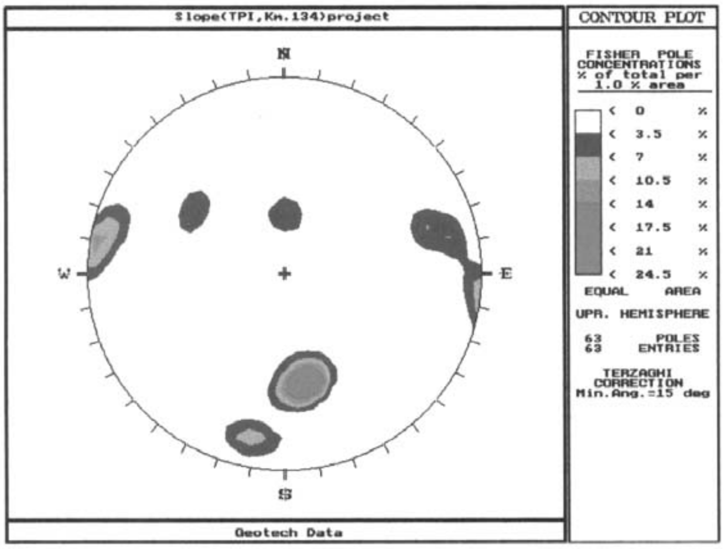

Figure A.48 The contour plot of discontinuity set for slaty-shale is located at km 133-134 of Friend ship highway (slope no.17).

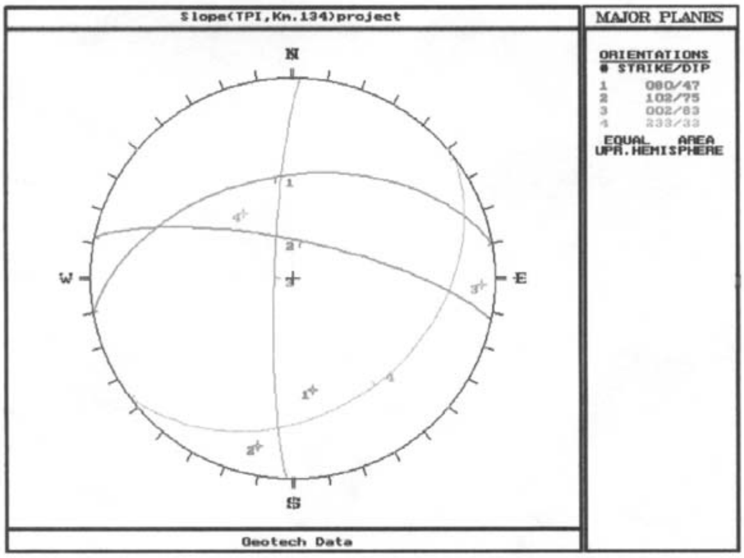

Figure A.49 Representative plane of discontinuity set for slaty-shale is located at km 133-134 of Friend ship highway (slope no.17).

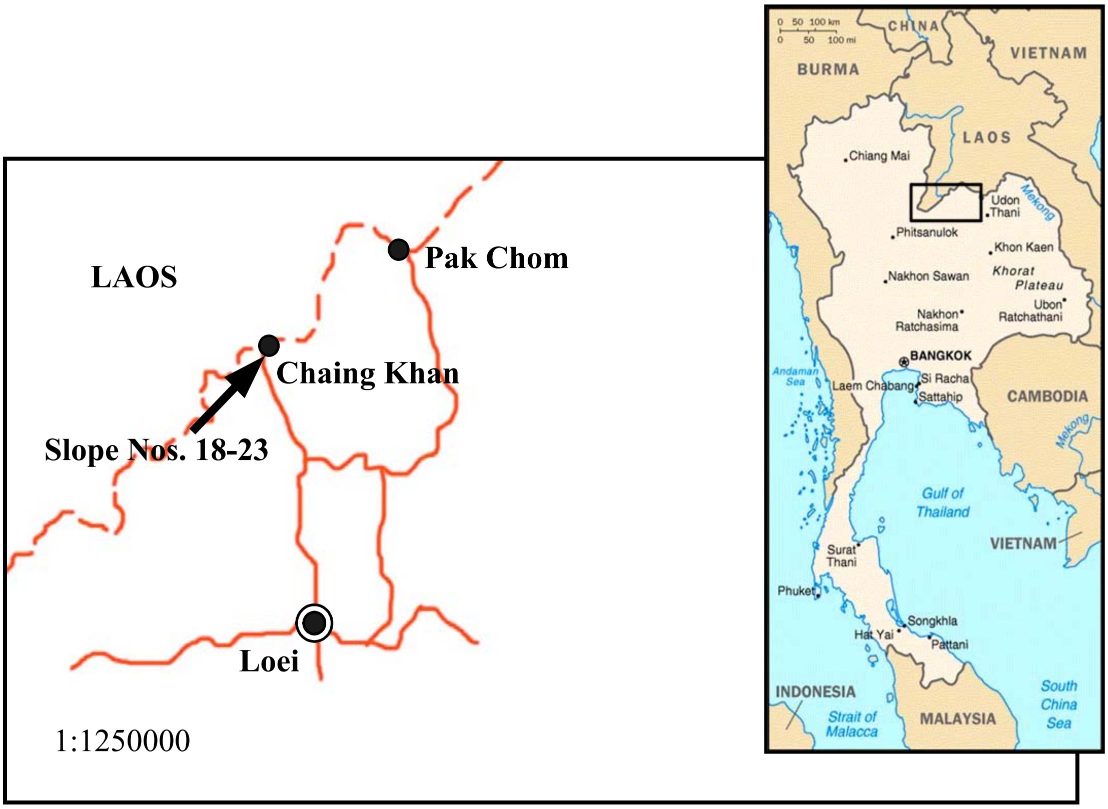

Figure A.50 Slope locations at PANDs Barite mining route, Chieng-Kan Loei province.

Figure A.51 Footwall and Hanging wall of Barite mining, Chaing Khan district, Loei province (slope nos.18-23).

Figure A.52 Footwall and Hanging wall of Barite mining, Chaing Khan district, Loei province (slope nos.18-23).

Figure A.53 The footwall rock of Barite mining, Chaing Khan district, Loei province (slope nos.18-23).

face is 356 degrees. The dip angles are from 50 to 75 degrees. The rock type is dolomitic limestone. The UCS of the intact rock is about 50-100 MPa. The slope is stable. The rock has three joint sets (Figures A.54 to A.55), as follows.

Joint No.1 (bedding plane) has a strike of 143 degrees, with 30 degrees dip angle. The joint spacing is 0.4-1.5 m. The joint aperture is 0.1 cm. Persistence of the rock joint is about 30-40%. The JRC is estimated as 3-5. The joints are filled with ferrous oxide.

Joint No.2 has a strike of 282 degrees, with 80 degrees dip angle. The joint spacing is 0.2-0.7 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 20-40%. The JRC is estimated as 3-5. The joints are filled with ferrous oxide.

Joint No.3 has a strike of 356 degrees, with 71 degrees dip angle. The joint spacing is 0.7 m. The joint aperture is 1-2 cm. Persistence of the rock joint is about 80 %. The JRC is estimated as 5. The joints are filled with ferrous oxide.

The failures are small plane and wedge sliding. The failures are caused by the discontinuities of rock mass and slope angle.

A-5.2 Slope No.19

The slope no.19 is located in the south footwall. The slope is classified here as heavily jointed rock. The slope height is 5 m. The strike of the slope face is 356 degrees. The dip angle is 75 degrees. The rock type is shale. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has three joint sets (Figures A.56 to A.57), as follows.

Joint No.1 (bedding plane) has a strike of 143 degrees, with 30 degrees dip angle. The joint spacing is 0.05-0.1 m. The joint aperture is 1-2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

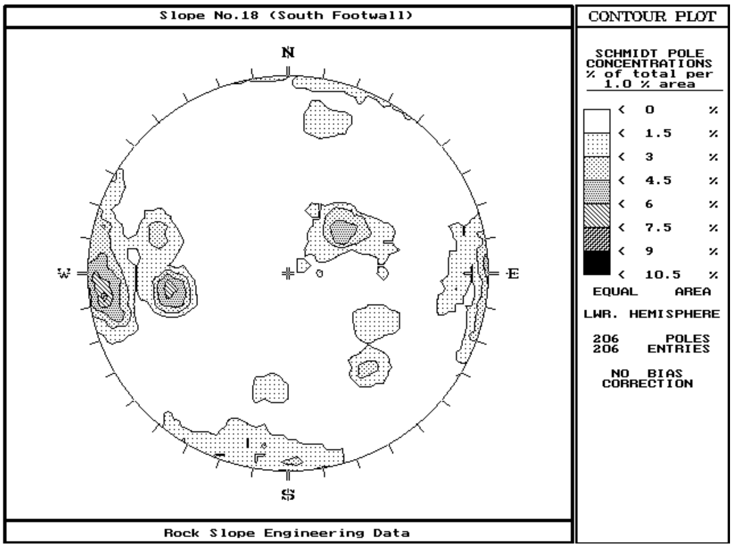

Figure A.54 The contour plots of limestone discontinuity for south footwall of barite mining, Chaing Khan district, Loei province (slope no.18).

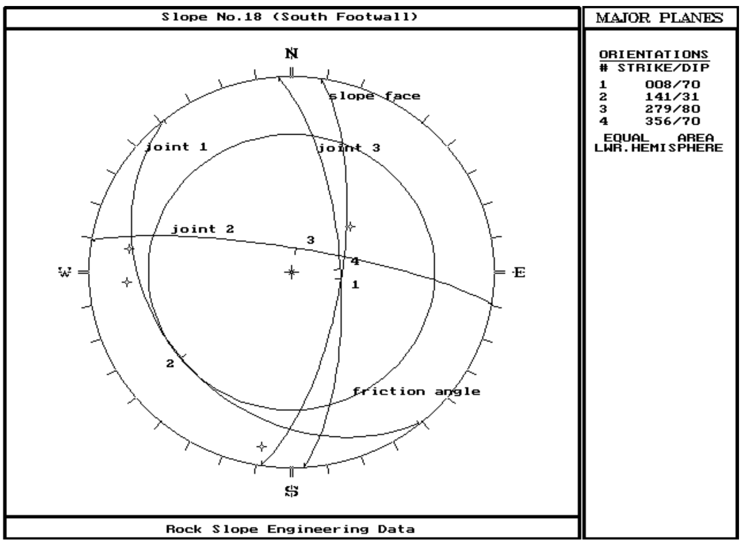

Figure A.55 Representative plane, slope orientation and friction angle of limestone discontinuity for south footwall of barite mining, Chaing Khan district, Loei province (slope no.18).

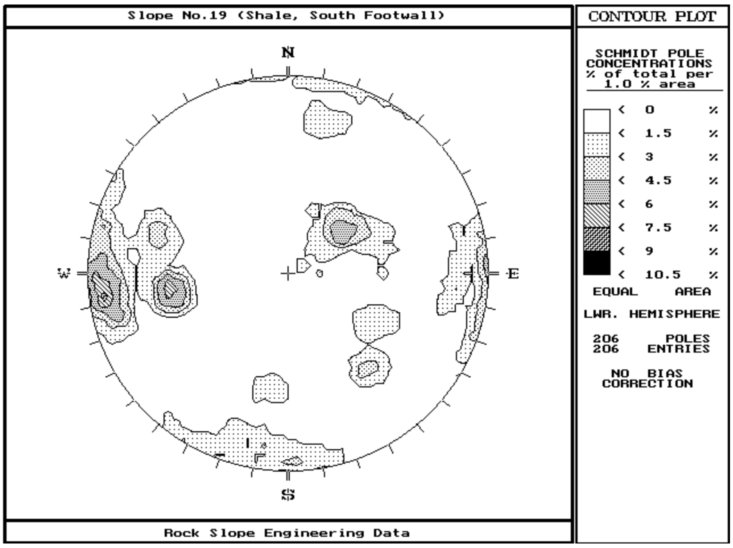

Figure A.56 The contour plots of shale discontinuity for south footwall of barite mining, Chaing Khan district, Loei province (slope no.19).

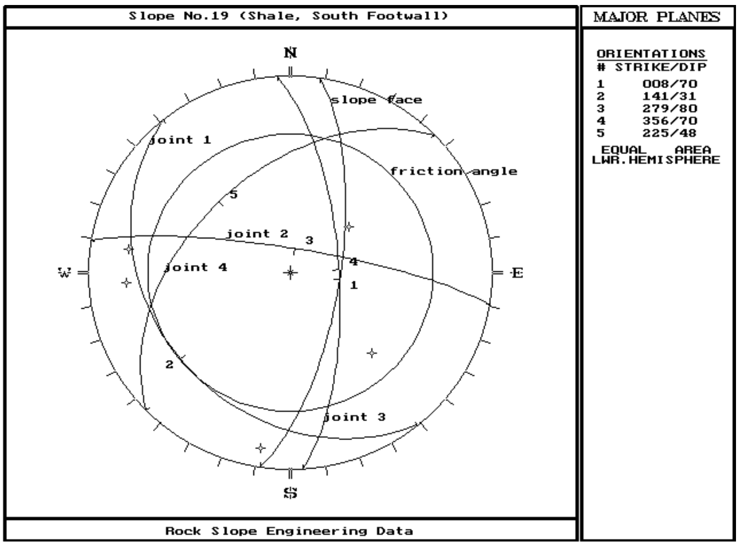

Figure A.57 Representative plane, slope orientation and friction angle of shale discontinuity for south footwall of barite mining, Chaing Khan district, Loei province (slope no.18).

Joint No.2 has a strike of 225 degrees, with 48 degrees dip angle. The joint spacing is 0.05 m. The joint aperture is 1-2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.3 has a strike of 282 degrees, with 80 degrees dip angle. The joint spacing is 0.2-0.7 m. The joint aperture is 0.1-1.0 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.4 has a strike of 356 degrees, with 71 degrees dip angle. The joint spacing is 0.3 m. The joint aperture is 1-2 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

The failures are small plane and wedge sliding. The failures are caused by the discontinuities of rock and slope angle.

A-5.3 Slope No.20

The slope no.20 is located in the north footwall. The slope is classified as heavily jointed rock. The slope height is 5 m. The strike of the slope face is 356 degrees. The dip angle is 75 degrees. The rock type is shale. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has three joint sets (Figures A.58 to A.59), as follows.

Joint No.1 (bedding plane) has a strike of 023 degrees, with 38 degrees dip angle. The joint spacing is 0.05-0.3 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.2 has a strike of 272 degrees, with 77 degrees dip angle. The joint spacing is 0.05-0.3 m. The joint aperture is 0.1-0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

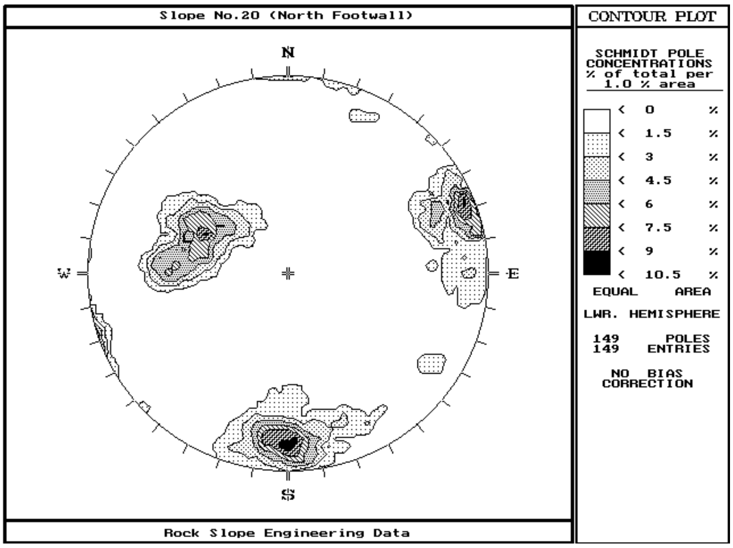

Figure A.58 The contour plots of shale and siltstone discontinuity for south footwall of barite mining, Chaing Khan district, Loei province (slope no.20).

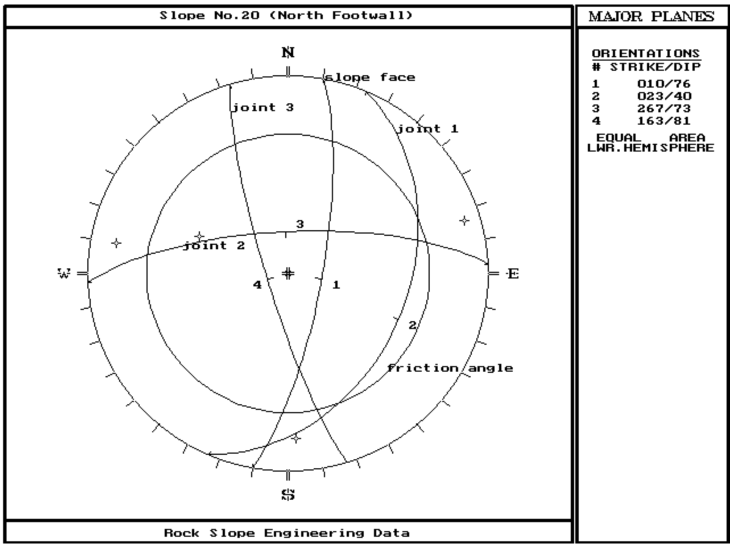

Figure A.59 Representative plane, slope orientation and friction angle of shale and siltstone discontinuity for south footwall of barite mining, Chaing Khan district, Loei province (slope no.20).

Joint No.3 has a strike of 163 degrees, with 80 degrees dip angle. The joint spacing is 0.1-0.3 m. The joint aperture is 0.3 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

A-5.4 Slope no.21

The slope no.21 is located in the north hanging wall. The slope is classified as heavily jointed rock. The slope height is 5 m. The strike of the slope face is 356 degrees. The dip angle is 65 degrees. The rock type is shale. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has four joint sets (Figures A.60 to A.61), as follows.

Joint No.1 (bedding plane) has a strike of 204 degrees, with 22 degrees dip angle. The joint spacing is 0.1 m. The joint aperture is 0.2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.2 has a strike of 142 degrees, with 47 degrees dip angle. The joint spacing is 0.1 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.3 has a strike of 341 degrees, with 63 degrees dip angle. The joint spacing is 0.1-0.2 m. The joint aperture is 0.2-1 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.4 has a strike of 066 degrees, with 88 degrees dip angle. The joint spacing is 0.1 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

A-5.5 Slope no.22

The slope no.22 is located in the south hanging wall. The slope is classified as massive rock. The slope height is 8-15 m. The strike of the slope face is 20 degrees.

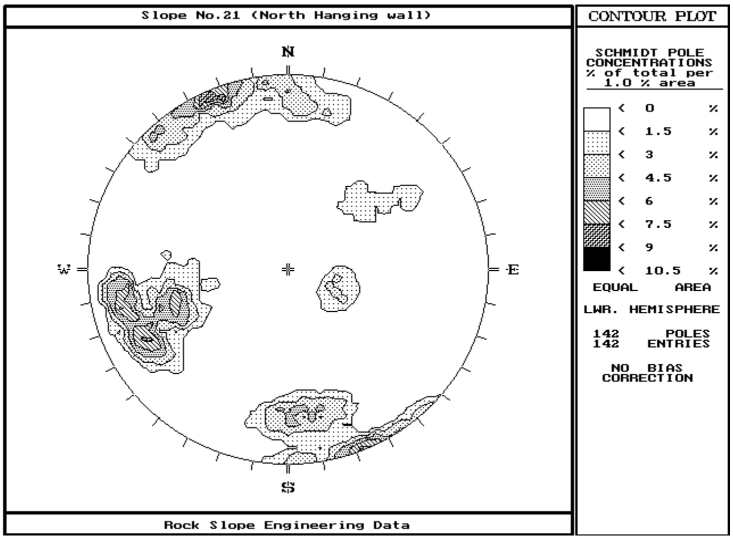

Figure A.60 The contour plots of shale and siltstone discontinuity for north hanging wall of barite mining, Chaing Khan district, Loei province (slope no.21).

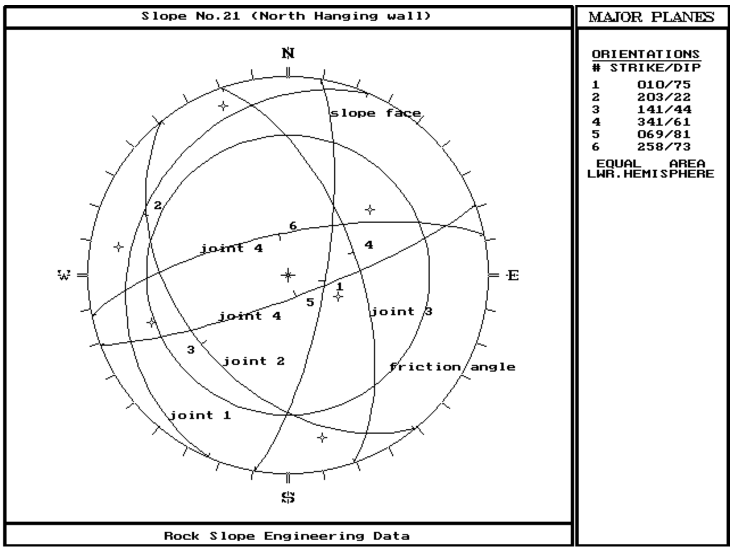

Figure A.61 Representative plane, slope orientation and friction angle of shale and siltstone discontinuity for north hanging wall of barite mining, Chaing Khan district, Loei province (slope no.21).

The dip angle is 65 degrees. The rock type is limestone. The UCS of the intact rock is between 50-100 MPa. The slope is stable. The rock has three joint sets (Figures A.62 to A.63), as follows.

Joint No.1 has a strike of 354 degrees, with 81 degrees dip angle. The joint spacing is 0.5 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 20%. The JRC is estimated as 5. The joints are filled with ferrous oxide.

Joint No.2 has a strike of 178 degrees, with 86 degrees dip angle. The joint spacing is 0.5 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 20-30%. The JRC is estimated as 5. The joints are filled with ferrous oxide.

Joint No.3 has a strike of 270 degrees, with 80 degrees dip angle. The joint spacing is 0.3-0.5 m. The joint aperture is 0.2-1 cm. Persistence of the rock joint is about 20-30%. The JRC is estimated as 5. The joints are filled with ferrous oxide.

A-5.6 Slope no.23

The slope no.23 is located in the south hanging wall. The slope is classified as heavily jointed rock. The slope height is 5-15 m. The strike of the slope face is 25 degrees. The dip angle is 65 degrees. The rock type is shale. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has four joint sets (Figures A.64 to A.65), as follows.

Joint No.1 (bedding plane) has a strike of 201 degrees, with 32 degrees dip angle. The joint spacing is 0.2 m. The joint aperture is 0.2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.2 has a strike of 354 degrees, with 81 degrees dip angle. The joint spacing is 0.2 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-3. The joints are filled with clay.

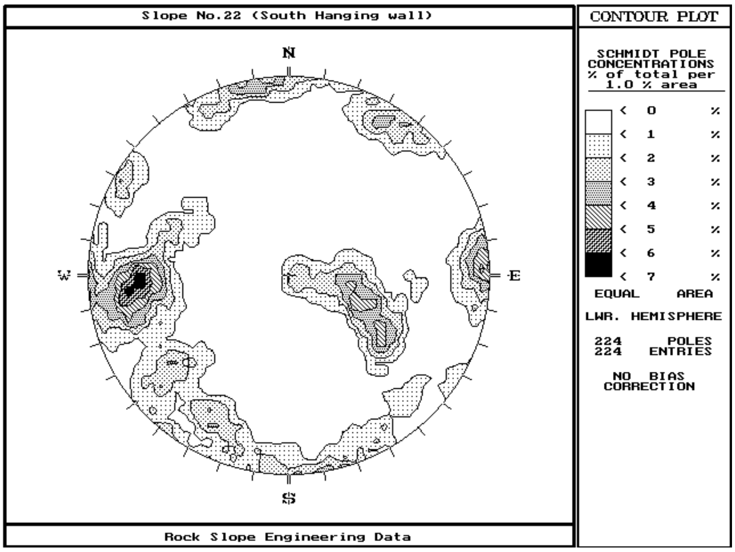

Figure A.62 The contour plots of limestone discontinuity for south hanging wall of barite mining, Chaing Khan district, Loei province (slope no.22).

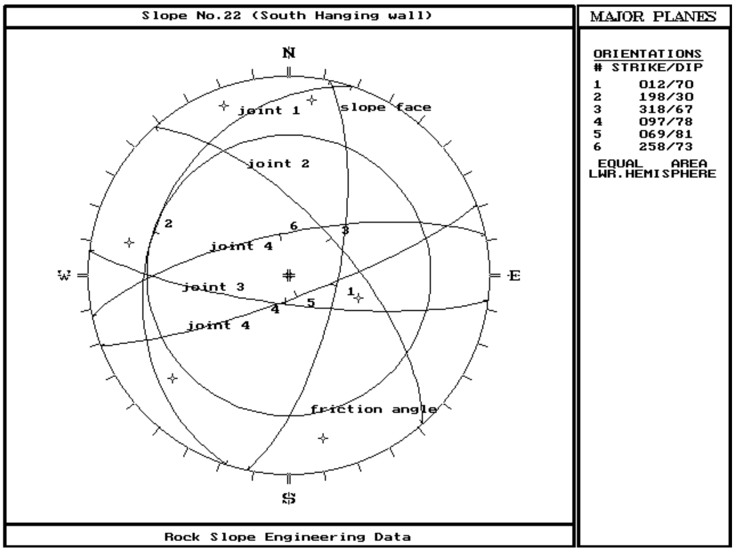

Figure A.63 Representative plane, slope orientation and friction angle of limestone discontinuity for south hanging wall of barite mining, Chaing Khan district, Loei province (slope no.22).

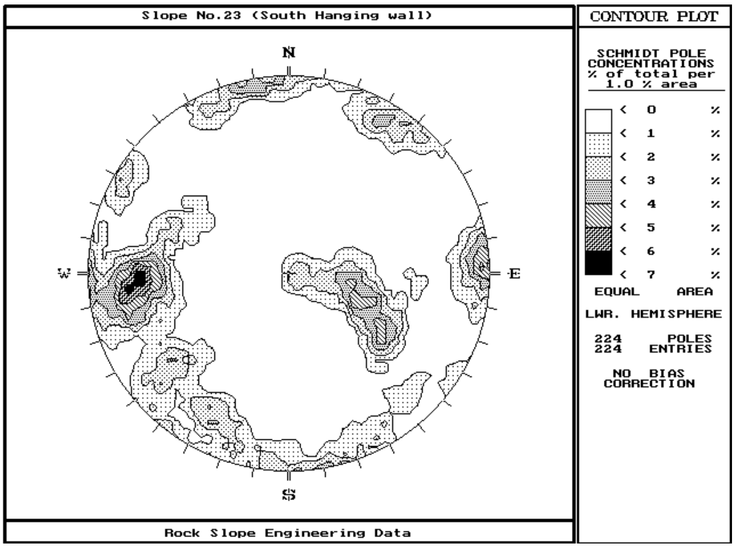

Figure A.64 The contour plots of shale discontinuity for south hanging wall of barite mining, Chaing Khan district, Loei province (slope no.23).

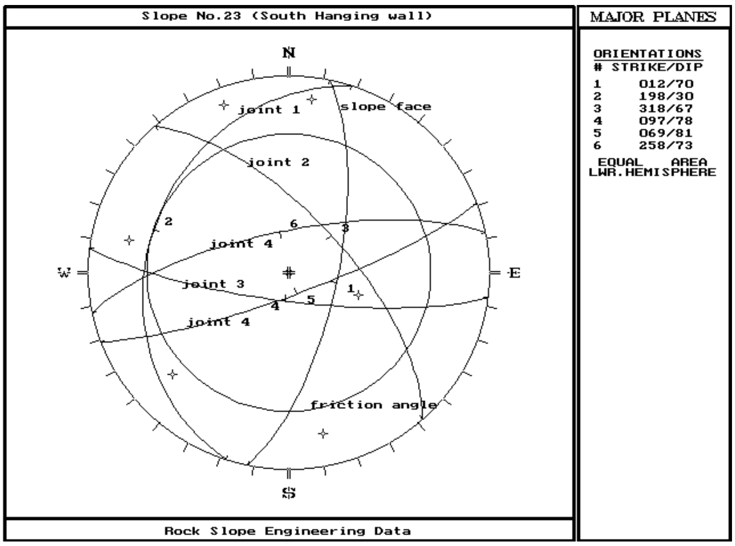

Figure A.65 Representative plane, slope orientation and friction angle of shale discontinuity for south hanging wall of barite mining, Chaing Khan district, Loei province (slope no.23).

Joint No.3 has a strike of 178 degrees, with 86 degrees dip angle. The joint spacing is 0.07 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

Joint No.4 has a strike of 076 degrees, with 87 degrees dip angle. The joint spacing is 0.05 m. The joint aperture is 0.2-0.5 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-3. The joints are filled with clay.

A-6 Highway No.12 (Lomsak-Chumpae) Route

Lomsak-Chumpae highway was constructed over 20 years ago to shorten the distance from the north to the northeast of Thailand. It is 120 kilometers long, cutting across Phetchabun province and Khon Kaen province (Figure A.66). The slope failures along the road cuts have repeatedly occurred on some locations. The slopes can be classify into three groups are bedded rock, heavily jointed rock and soft rock. The modes of failure are circular, plane, wedge and toppling failures.

A-6.1 Slope no.24

The slope No.24 at km 70-71 found on Lomsak-Chumpae highway. The slope location is 47 Q 0797746 and UTM 1842167 of GPS system (Figures A.67 and A.68). The slope is classified as massive rock. The slope height is 20 m and length is 140 m. The strike of the slope face is 290 degrees. The dip angle is 75 degrees. The rock type is limestone. The UCS of the intact rock is about 50-100 MPa. The rock has three joint sets (Figures A.69 and A.70), as follows.

Joint No.1 (bedding plane) has a strike between 030 to 080 degrees, with varies from 40 to 65 degrees dip angle. The joint spacing is 0.05-2.5 m. The joint

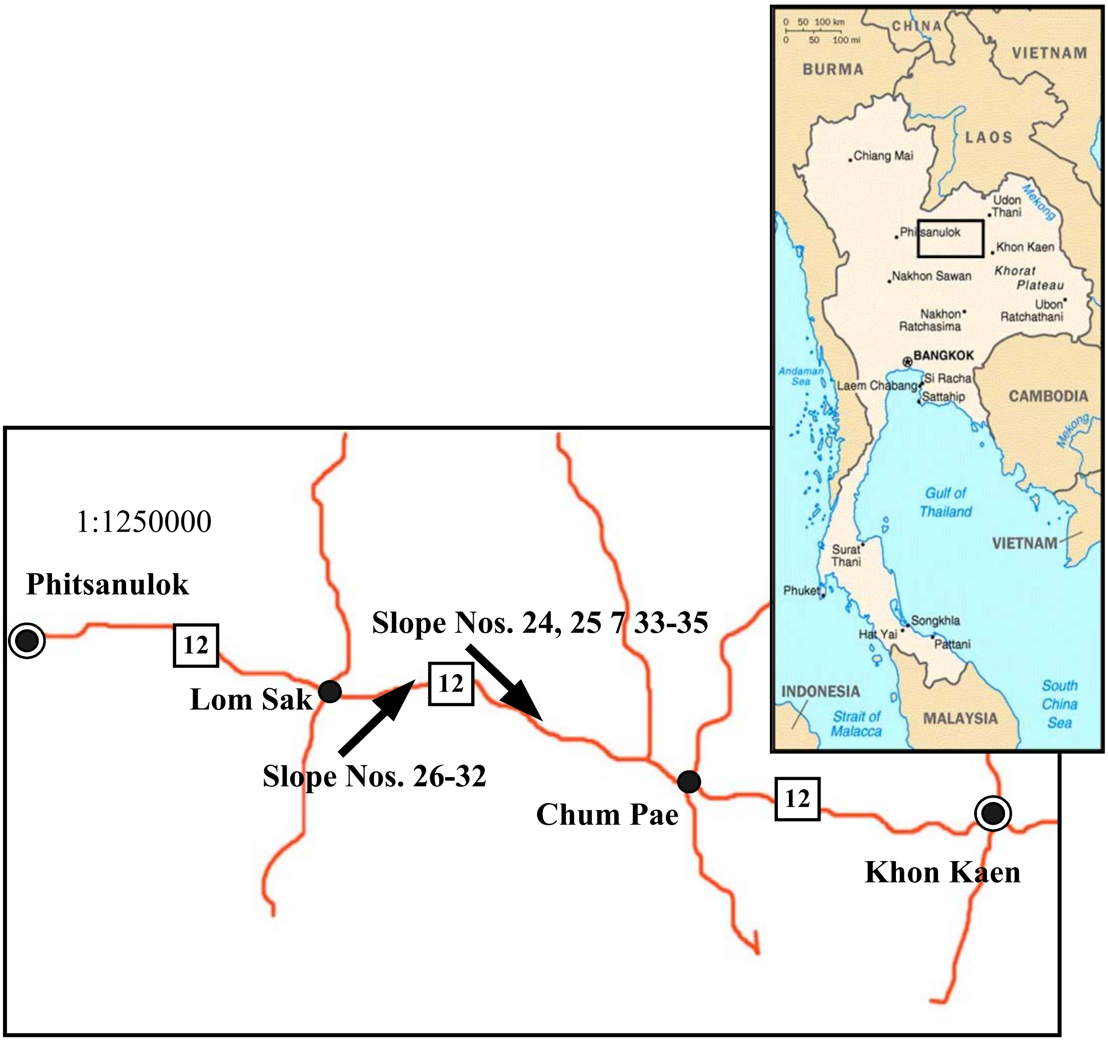

Figure A.66 Slope locations along highway no.12 route, Chum Pae to Lom-Sak districts, Khon-Kaen to Petchabun provinces.

Figure A.67 The limestone slope is located at km 70-71of highway no.12, Chum Pae to Lom Sak district, Khon Kaen and Petchabun province (slope nos.24 and 25).

Figure A.68 The falling rock of limestone at the toe of slope (slope nos. 24 and 25).

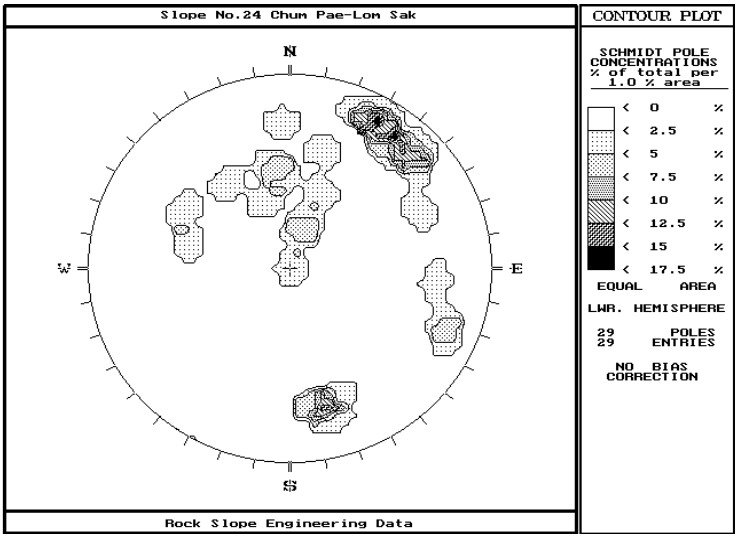

Figure A.69 The contour plots of limestone discontinuity sets for slope on highway no.12 (slope no.24).

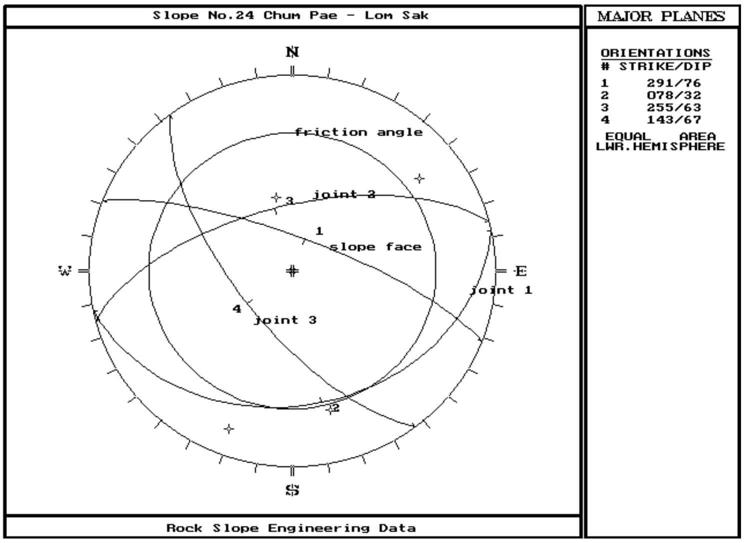

Figure A.70 Representative plane, slope orientation and friction angle of limestone discontinuity for slope on highway no.12 (slope no.24).

aperture is 2-3 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike between 185 to 260 degrees, with varies from 60 to 75 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 30-40%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.3 has a strike between 105 to 155 degrees, with varies from 58 to 80 degrees dip angle. The joint spacing is 0.5 m. The joint aperture is 0.1-0.5 cm. Persistence of the rock joint is about 60%. The JRC is estimated as 3-5. The joints are filled with clay.

The failure is small toppling of the vertical joint in massive limestone (size is $0.2 \times 0.2 \times 0.3$ m^3). The failure is caused by the rock discontinuities.

A-6.2 Slope No.25

The slope no.25 at km 70-71 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0797746 and UTM 1842167 of GPS system (Figures A.67 and A.68). The slope is classified as massive rock. The slope height is 18 m and length is 140 m. The strike of the slope face is 115 degrees. The dip angle is 78 degrees. The rock type is limestone. The UCS of the intact rock is about 50-100 MPa. The slope is stable. The rock has three joint sets, as follows.

Joint No.1 (bedding plane) has a strike between 030 to 050 degrees, with varies from 35 to 53 degrees dip angle. The joint spacing is 0.05-2.5 m. The joint aperture is 2-3 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike between 185 to 260 degrees, with varies from 60 to 75 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-1 cm. Persistence of the rock joint is about 30-40%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.3 has a strike between 105 to 155 degrees, with varies from 58 to 80 degrees dip angle. The joint spacing is 0.5 m. The joint aperture is 0.1-0.5 cm. Persistence of the rock joint is about 60%. The JRC is estimated as 3-5. The joints are filled with clay.

A-6.3 Slope No.26

The slope no.26 at km 19-20 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0752546 and UTM 1850965 of GPS system (Figures A.71 and A.72). The slope is classified as bedded rock. The slope height is 50 m and length is 60 m. The strike of the slope face is 195 degrees. The dip angle is 46 degrees. The rock type is slaty-shale. The UCS of the intact rock is about 25-50 MPa. The slope is stable. The rock has three joint sets (Figures A.73 and A.74), as follows.

Joint No.1 (bedding plane) has a strike between 187 to 190 degrees, with varies from 44 to 60 degrees dip angle. The joint spacing is 0.02-0.2 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike between 110 to 120 degrees, with varies from 75 to 85 degrees dip angle. The joint spacing is 0.01-0.4 m. The joint aperture is 0.3-1 cm. Persistence of the rock joint is about 70-90%. The JRC is estimated as 1-2. The joints are filled with clay.

Figure A.71 The slaty-shale slope is located on 19 to 20-km of highway no.12, Lom Sak district, Petchabune province (slope no.26).

Figure A.72 The bedded slope is located on 19 to 20-km of highway no.12, Lom Sak district, Petchabune province (slope no.26).

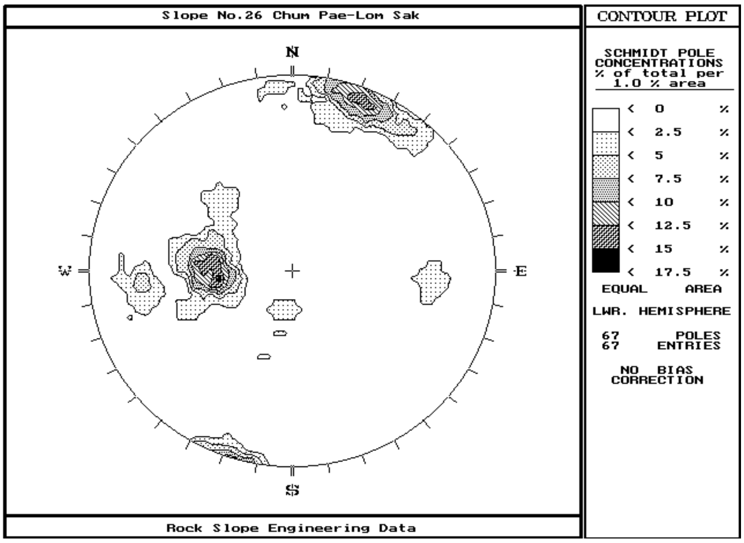

Figure A.73 The contour plots of slaty-shale discontinuity for bedded slope on highway no.12, Lom Sak district, Petchabun province (slope no.26).

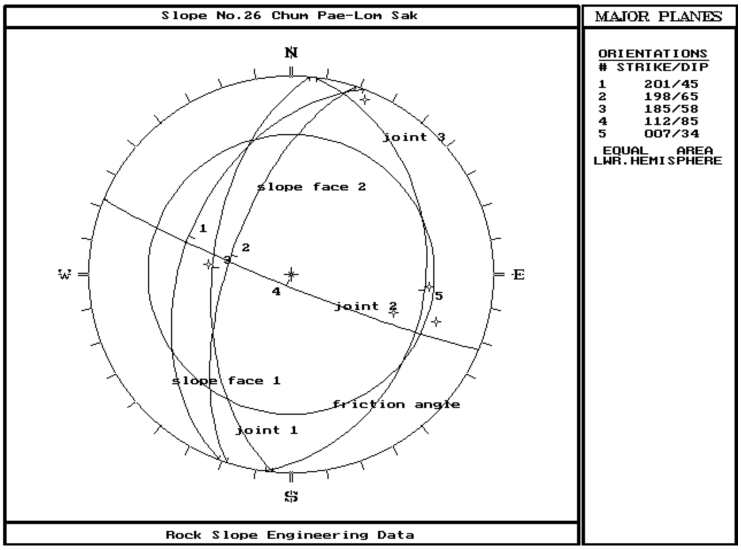

Figure A.74 Representative plane, slope orientation and friction angle of slaty-shale discontinuity for bedded slope on highway no.12, Lom Sak district, Petchabun province (slope no.26).

Joint No.3 has a strike between 005 to 020 degrees, with varies from 70 to 75 degrees dip angle. The joint spacing is 0.05-0.4 m. The joint aperture is 0.1-0.5 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-2. The joints are filled with clay.

A-6.4 Slope No.27

The slope No.27 at km 20-21 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0754024 and UTM 1851415 of GPS system (Figures A.75 and A.76). The slope is classified as heavily jointed rock. The slope height is 30 m and length is 25 m. The strike of the slope face is 225 degrees. The dip angle is 55 degrees. The rock type is weathered shale. The UCS of the intact rock is about 5-25 MPa. The slope is unstable. The failure mode is circular. The existing supports include shotcrete, drained holes, ditch and gabion. The rock has three joint sets (Figures A.77 and A.78), as follows.

Joint No.1 (bedding plane) has a strike between 320 to 345 degrees, with varies from 35 to 40 degrees dip angle. The joint spacing is 0.07 m. The joint aperture is 0.1 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike between 195 to 200 degrees, with varies from 50 to 60 degrees dip angle. The joint spacing is 0.04-0.4 m. The joint aperture is 0.3-1 cm. Persistence of the rock joint is about 90%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 085 degrees, with 64 degrees dip angle. The joint spacing is 0.07-0.4 m. The joint aperture is 0.1-0.5 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-2. The joints are filled with clay.

Figure A.75 The heavily jointed slope is located on 20 to 21-km of highway no.12, Lom Sak district, Petchabun province (slope no.27).

Figure A.76 The mode of failure is circular on the top of heavily jointed slope (slope no.27).

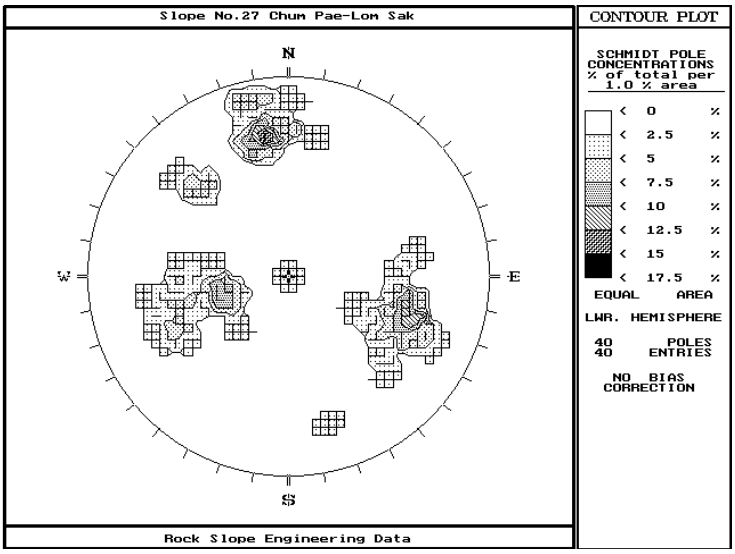

Figure A.77 The contour plots of slaty-shale discontinuity for heavily jointed slope on highway no.12 (slope no.27).

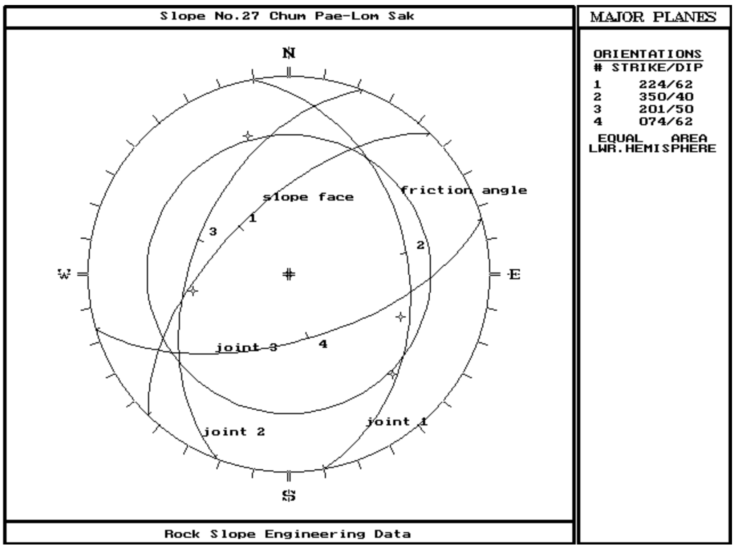

Figure A.78 Representative plane, slope orientation and friction angle of slaty-shale discontinuity for heavily jointed slope on highway no.12 (slope no.27).

A-6.5 Slope No.28

The slope no.28 at km 22-23 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0754604 and UTM 1851201 of GPS system (Figures A.79 and A.80). The slope is classified as heavily jointed rock. The slope height is 18 m and length is 40 m. The strike of the slope face one is 110 degrees. The dip angle is 48 degrees and face two is 055 degrees of strike and 54 degrees of dip angle. The rock type is weathered shale. The UCS of the intact rock is between 5-25 MPa. The slope is unstable. The failure mode is surface circular. The existing supports include shotcrete, drained holes, ditch and gabion. The rock has three joint sets (Figures A.81 and A.82) as follows.

Joint No.1 (bedding plane) has a strike of 210 degrees, with 55 degrees dip angle. The joint spacing is 0.02-0.1 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.2 has a strike of 102 degrees, with 82 degrees dip angle. The joint spacing is 0.02-0.2 m. The joint aperture is 0.3-1 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 310 degrees, with 80 degrees dip angle. The joint spacing is 0.02-0.1 m. The joint aperture is 0.1-2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

A-6.6 Slope no.29

The slope no.29 at km 23-24 is located on Lomsak-Chumpae highway (Figures A.83 and A.84). The slope is classified as heavily jointed rock. The slope height is 12 m and length is 20 m. The strike of the slope face one is 040 degrees. The

Figure A.79 The heavily jointed slope is located on 22 to 23-km of highway no.12, Lom Sak district, Petchabun province (slope no.28).

Figure A.80 The mode of failure is circular on the top of heavily jointed slope (slope no.28).

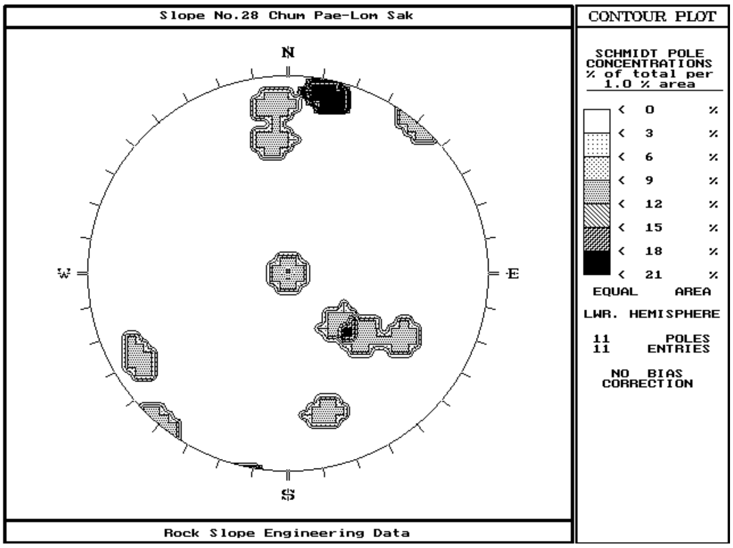

Figure A.81 The contour plots of slaty-shale discontinuity for heavily jointed slope on highway no.12 (slope no. 28).

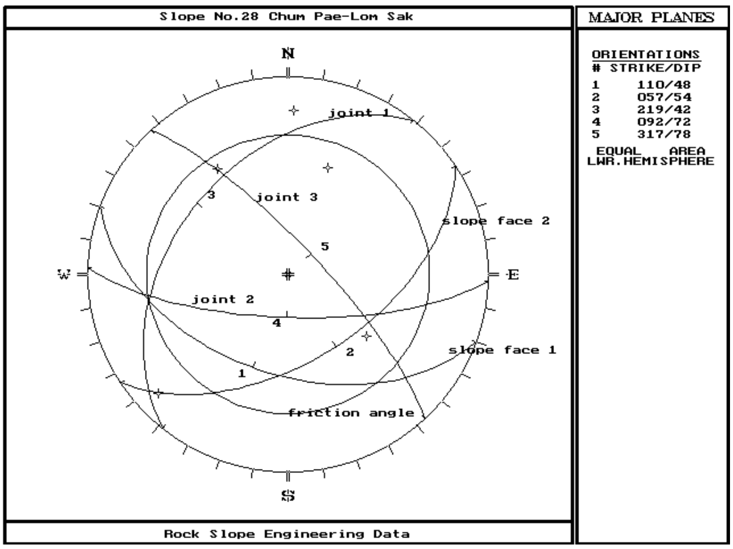

Figure A.82 Representative plane, slope orientation and friction angle of slaty-shale discontinuity for heavily jointed slope on highway no.12 (slope no.28).

Figure A.83 The heavily jointed slope is located on 23 to 24-km of highway no.12, Lom Sak district, Petchabun province (slope no.29).

Figure A.84 The modes of failure are combination of plane and wedge sliding on the siltstone slope (slope no.29).

dip angle is 65 degrees. The rock type is silty-sandstone. The UCS of the intact rock is between 25-50 MPa. The slope is unstable. The failure modes are plane, wedge and toppling. The existing supports include wire mesh, ditch and gabion wall. The rock has three joint sets (Figures A.85 and A.86), as follows.

Joint No.1 (bedding plane) has a strike of 300 degrees, with 40 degrees dip angle. The joint spacing is 0.2-0.5 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 40-60%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike of 195 degrees, with 50 degrees dip angle. The joint spacing is 0.15-0.3 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.3 has a strike of 050 degrees, with 30 degrees dip angle. The joint persistence is 60%. The JRC is estimated as s 3-5. The joints are filled with clay.

A-6.7 Slope No.30

The slope no.30 at km 16-17 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0750708 and UTM 1850850 of GPS system (Figures A.87 and A.88). The slope height is 50 m and length is 40 m. The strike of the slope face one is 070 degrees. The dip angle is 65 degrees. The rock type is shale. The UCS of the intact rock is between 5-25 MPa. The slope is unstable. The failure mode is small surface circular. The existing supports include shotcrete, drained holes, ditch and gabion.

A-6.8 Slope No.31

The slope No.31 at km 17-18 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0751256 and UTM 1850768 of GPS system (Figures A.89 and A.90).

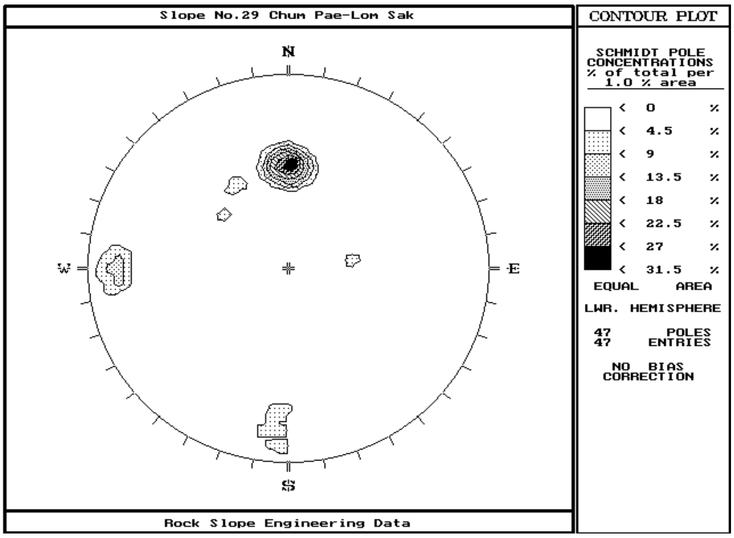

Figure A.85 The contour plots of siltstone discontinuity for slope on highway no.12 (slope no.29).

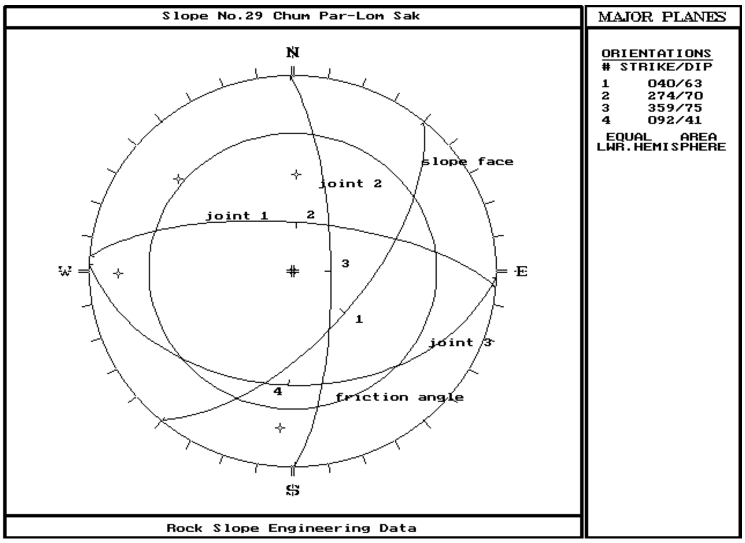

Figure A.86 Representative plane, slope orientation and friction angle of siltstone discontinuity for slope on highway no.12 (slope no. 29).

Figure A.87 The stable slope is located at km 16 -17 of highway no.12, Lom Sak district, Petchabun province (slope no.30).

Figure A.88 The surface failure of heavily jointed rock, Lom Sak district, Petchabun province (slope no.30).

Figure A.89 The stable slaty-shale slope is located at km 17 to 18 of highway no. 12, Lom Sak district, Petchabun province (slope no.31).

Figure A.90 Heavily jointed of slaty-shale on slope is located at 17-18 of highway no.12, Lom Sak district, Petchabun province (slope no.31).

The slope height is 35 m and length is 40 m. The strike of the slope face one is 070 degrees. The dip angle is 72 degrees. The rock type is slaty-shale. The UCS of the intact rock is between 25-50 MPa. The slope is stable.

A-6.9 Slope No.32

The slope No.32 at km 18-19 is located on Lomsak-Chumpae highway. The slope location is 47 Q 0752212 and UTM 1850850 of GPS system (Figures A.91 and A.92). The slope height is 20 m and length is 30 m. The strike of the slope face one is 320 degrees. The dip angle is 55 degrees. The rock type is shale. The UCS of the intact rock is between 25-50 MPa. The rock slope is unstable. The failure mode is small surface circular. The existing supports include wire mesh, drained holes, ditch and gabion.

A-6.10 Slope No.33

The slope No.33 at km 36-37 is located on Lomsak-Chumpae highway (Figures A.93 and A.94). The slope location is 47 Q 0766446 and UTM 1853761 of GPS system. The slope is classified as bedded rock. The slope height is 20 m and length is 30 m. The strike of the slope face one is 320 degrees. The dip angle is 50 degrees. The rock type is shale. The UCS of the intact rock is between 5-25 MPa. The slope is unstable. The failure modes are plane and wedge. The existing supports include shotcrete and ditch. The rock has three joint sets (Figures A.95 and A.96) as follows.

Joint No.1 (bedding plane) has a strike of 293 degrees, with 55 degrees dip angle. The joint spacing is 0.02-0.5 m. The joint aperture is 0.1-0.2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Figure A.91 The shale slope is located at km 18-19 of highway no.12, Lom Sak district, Petchabun province (slope no.32).

Figure A.92 Gabion wall at the toe of slope, Lom Sak district, Petchabun province (slope no.32).

Figure A.93 The failure of slaty-shale slope is located at km 36-37 of highway no. 12, Chum Pare district, Khon Kaen province (slope no.33).

Figure A.94 The failure of slaty-shale slope is located at km 36 to 37 of highway no.12, Chum Pare district, Khon Kaen province (slope no.33).

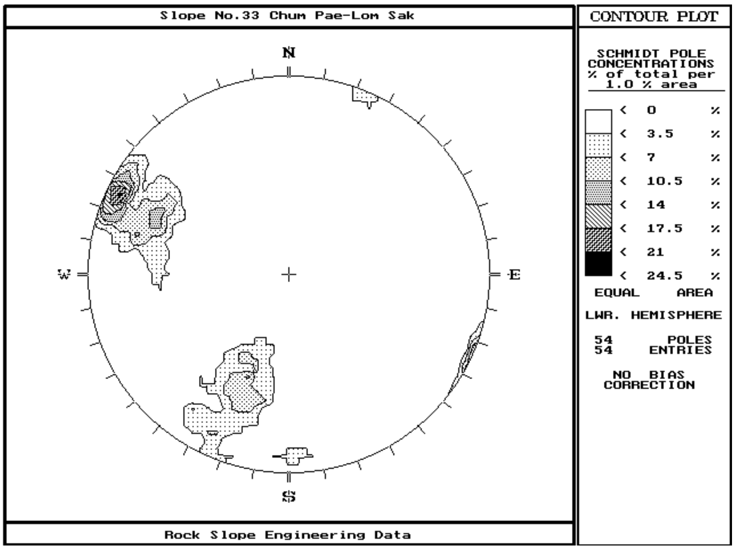

Figure A.95 The contour plots of slaty-shale discontinuity for slope at km 36-37 of highway no.12, Chum Phae district, Khon Kaen (slope no.33).

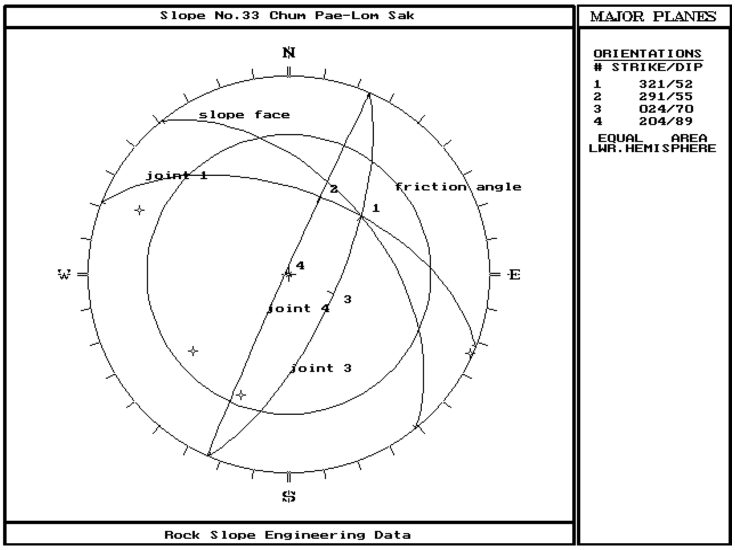

Figure A.96 Representative plane, slope orientation and friction angle of slaty-shale discontinuity for slope at km 36-37 of highway no. 12, Chum Phae district, Khon Kaen (slope no.33).

Joint No.2 has a strike of 025 degrees, with 80 degrees dip angle. The joint spacing is 0.05-0.3 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 308 degrees, with 65 degrees dip angle. The joint spacing is 0.3 m. The joint aperture is 0.5 cm. The joint persistence is 80%. The JRC is estimated as 1-2. The joints are filled with clay.

A-6.11 Slope No.34

The slope no.34 at km 36-37 located on Lomsak-Chumpae highway (Figures A.97 and A.98). The slope location is 47 Q 0766878 and UTM 1853357 of GPS system. The slope is classified as bedded rock. The slope height is 15 m and length is 20 m. The strike of the slope face one is 303 degrees. The dip angle is 55 degrees. The rock type is shale. The UCS of the intact rock is between 25-50 MPa. The slope is unstable. The failure modes are combination of plane, wedge and toppling. The existing supports include shotcrete, drained holes and ditch. The shotcrete remains on the slope face. Figures A.97 and A.98 shows failure surface exposed after massive slope failure. The failure brought down earthen and installed materials. The remaining shotcrete appears on the left side of the slope face. The rock has three joint sets (Figures A.99 and A.100).

Joint No.1 (bedding plane) has a strike of 293 degrees, with 55 degrees dip angle. The joint spacing is 0.02-0.5 m. The joint aperture is 0.1-0.2 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with clay.

Figure A.97 The failure of slaty-shale slope is located at km 36+600 of highway no.12, Chum Phae district, Khon Kaen province (slope no.34).

Figure A.98 Rock slope at km 36+600. Failure surface exposed after massive slope failure. The failure brought down both earthen and installed materials. The remaining shotcrete appears on the left side of the slope face (slope no.34).

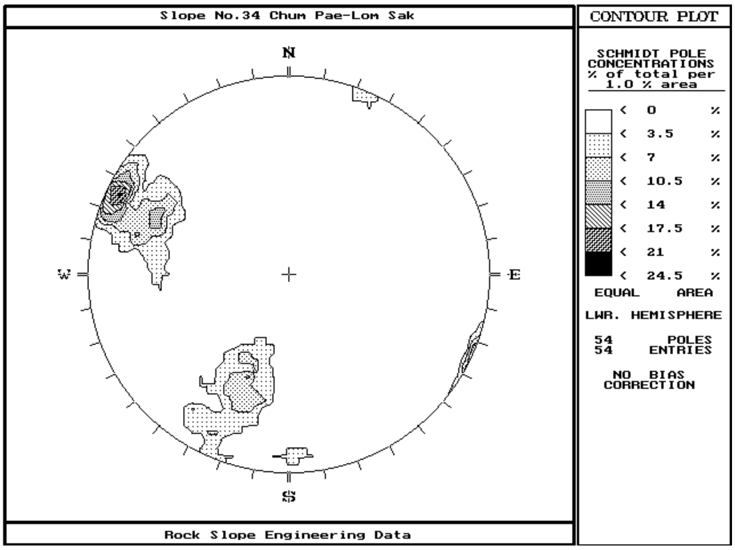

Figure A.99 The contour plots of slaty-shale discontinuity at km 37 of highway no.12, Lom Sak district, Petchabun province (slope no.34).

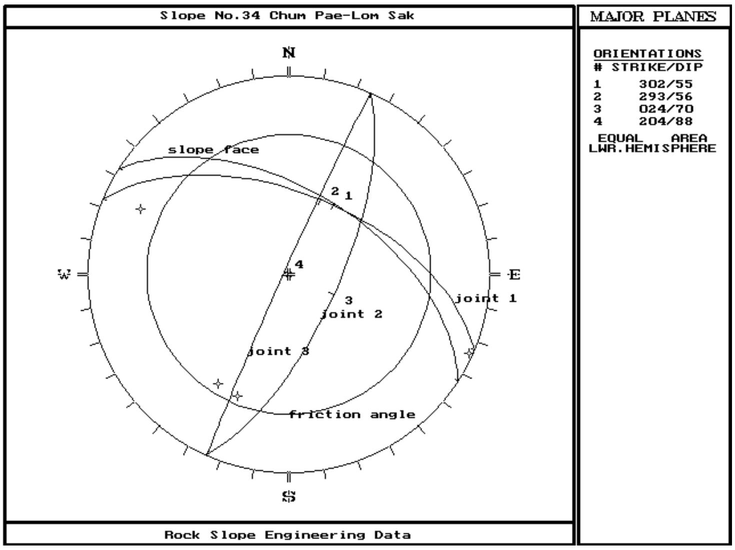

Figure A.100 Representative plane, slope orientation and friction angle of slaty-shale discontinuity at km 37 of highway no.12, Lom Sak district, Petchabun province (slope no.34).

Joint No.2 has a strike of 025 degrees, with 80 degrees dip angle. The joint spacing is 0.05-0.3 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 1-2. The joints are filled with clay.

Joint No.3 has a strike of 308 degrees, with 65 degrees dip angle. The joint spacing is 0.3 m. The joint aperture is 0.5 cm. The average joint persistence is 80%. The JRC is estimated as 1-2. The joints are filled with clay.

A-6.12 Slope No.35

The slope no.35 at km 76-77 located on Lomsak-Chumpae highway (Figures A.101 and A.102). The slope location is 47 Q 0784421 and UTM 1847721 of GPS system. The slope is classified as hard-soft interbedded rock. The hard formation is sandstone. It has 0.6 to 1.0 meter in thickness. The soft formation is mudstone. It has 0.2 to 0.8 meter thickness. The slope height is 15 m and length is 30 m. The strike of the slope face one is 156 degrees. The dip angle is 55 degrees. The UCS of the intact rock is between 5- 25 MPa for mudstone and about 25-50 MPa for sandstone. The slope is unstable. The failure modes are plane and wedge. The existing support is ditch. The rock has three joint sets (Figures A.103 and A.104), as follows.

Joint No.1 (bedding plane) has a strike of 007 degrees, with 35 degrees dip angle. The joint spacing is 0.1-0.5 m. The joint aperture is 0.1-0.8 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3-5. The joints are filled with clay.

Joint No.2 has a strike between 114 and 185 degrees, with 60 and 80 degrees dip angle. The joint spacing is 0.5-1.0 m. The joint aperture is 1-2 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 3. The joints are filled with clay.

Figure A.101 The siltstone slope at km 76-77 of highway no. 12 is located in Chum Pae district, Khon Kaen province (slope no.35).

Figure A102 The size are 0.15×0.2×0.2 to 0.6×0.5×0.3 m^3 of falling rock at the toe of slope (slope no.35).

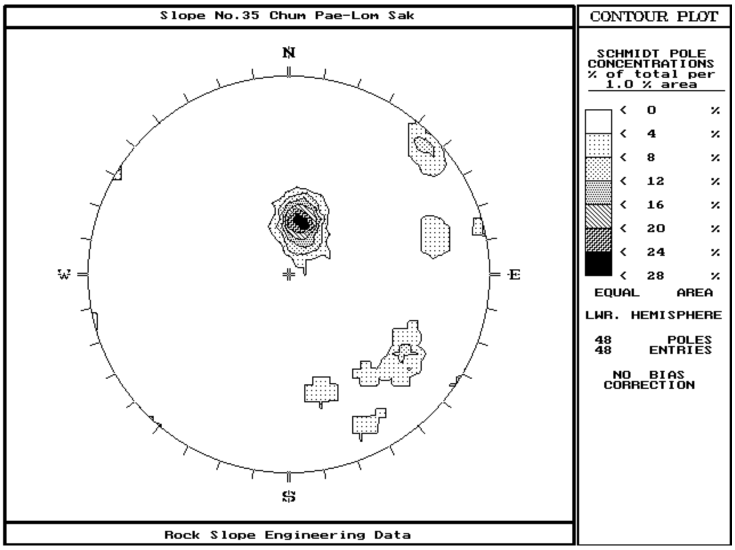

Figure A.103 The contour plots of siltstone discontinuity at km 76-77 of highway no. 12 is locate in Chum Pae district, Khon Kaen province (slope no.35).

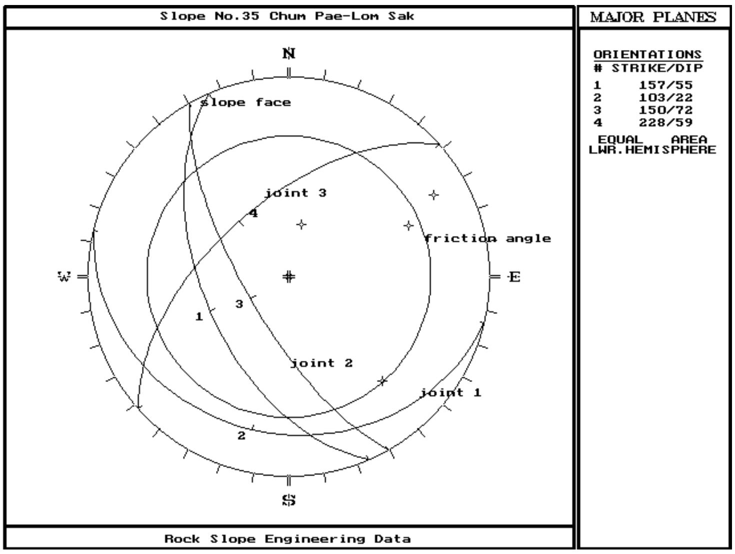

Figure A.104 Representative plane, slope orientation, friction angle of siltstone discontinuity at km 76-77 of highway no.12 is locate in Chum Pae district, Khon Kaen province (slope no.35).

Joint No.3 has a strike of 289 degrees, with 88 degrees dip angle. The joint spacing is 0.2-0.6 m. The joint aperture is 0.5-1 cm. The average joint persistence is 60%. The JRC is estimated as 3. The joints are filled with clay.

A-7 Highway No. 105 and Ubonrat Dam Routes

Highway no.105 or Tak–Mae Sot is shortening the distance from the middle parts to the western of Thailand. It is 105 kilometers long, cutting across Tak province (Figures A.105 and A.106). The slope failures along the road cuts have repeatedly occurred on some locations. The slope can be classify into three groups are bedded rock, heavily jointed rock and soft rock. The modes of failure are circular, plane, wedge and toppling failures.

A-7.1 Slope No.36

The slope no.36 at km 17-18 located on highway no.105 (Figures A.107 and A.108). The slope location is 47 Q 0498146 and UTM 1858567 of GPS system. The slope is classified as blocky rock. The slope height is 16 m and length is 40 m. The strike of the slope face one is 125 degrees. The dip angle is 80 degrees. The rock type is amphibolites schist. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The existing support is ditch. The rock has three joint sets (Figures A.109 and A.110), as follows.

Joint No.1 (bedding plane) has a strike of 324 degrees, with 33 degrees dip angle. The joint spacing is 0.4-1 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 5-7. The joints are filled with mica.

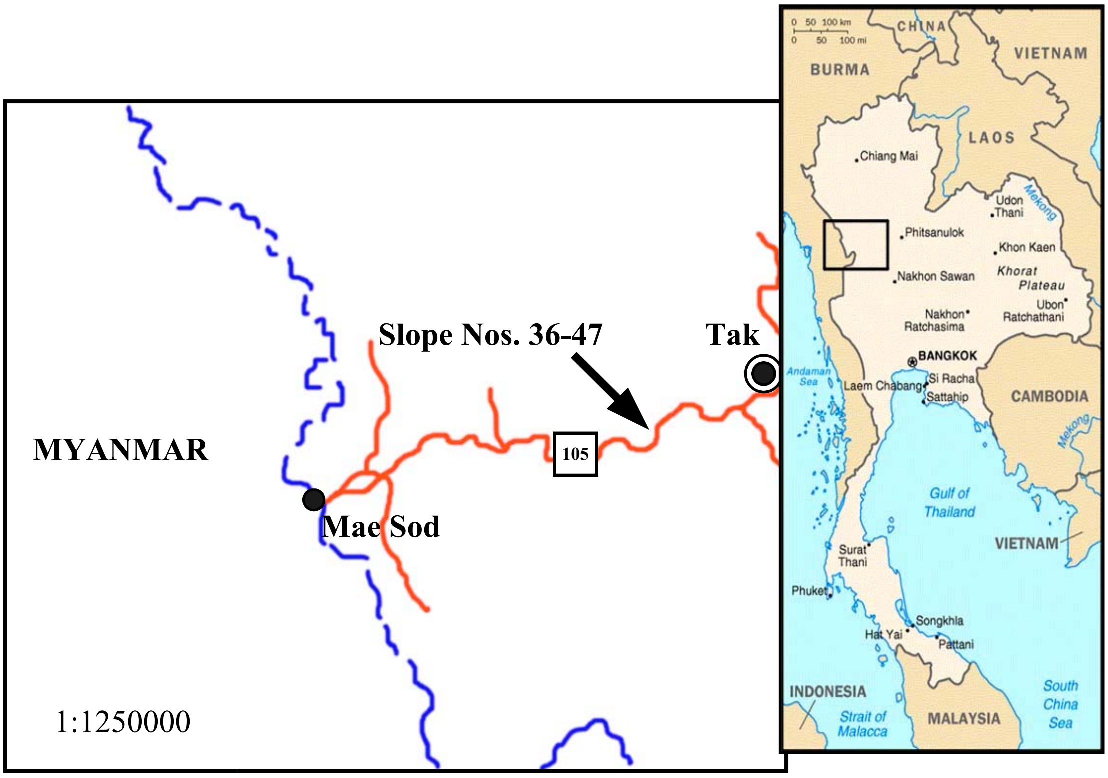

Figure A.105 Slope locations along highway no.105 route, Mae Sod district, Tak province.

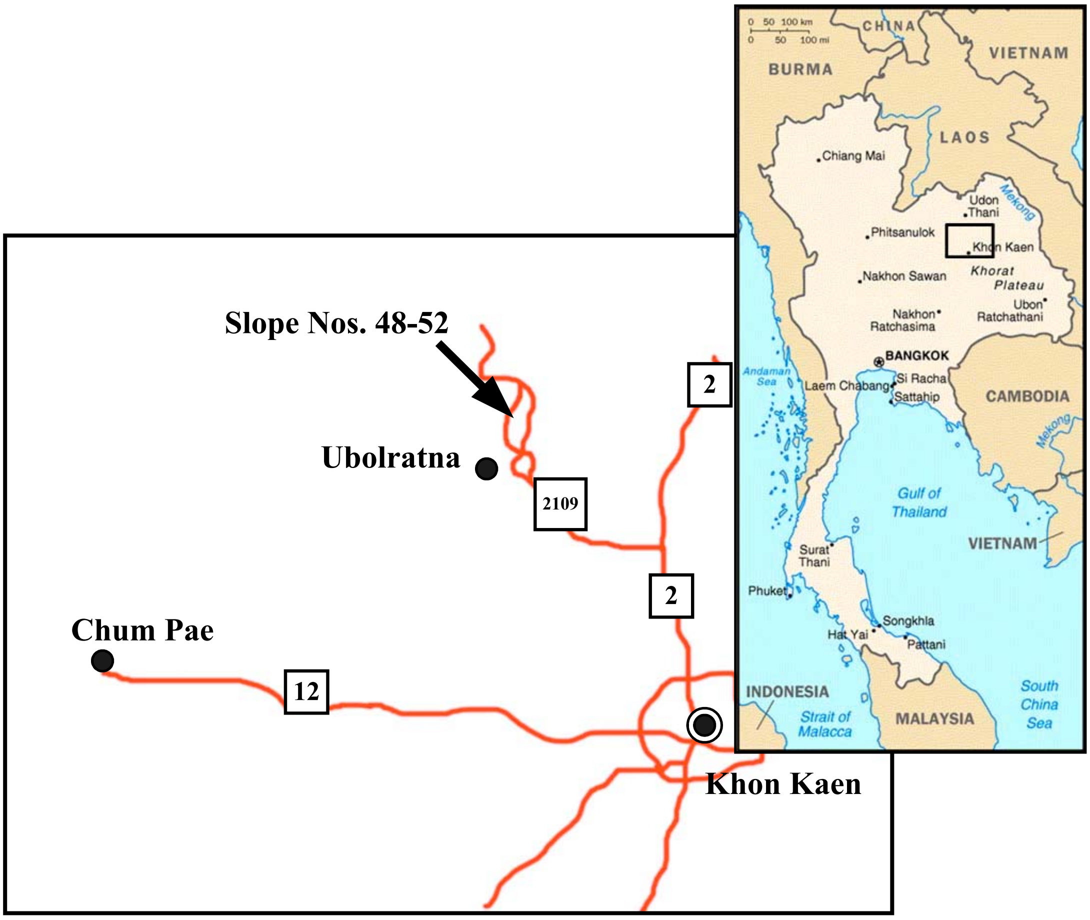

Figure A.106 Ubonrat dam route, Khon Kaen province.

Figure A.107 The blocky rock at km 17-18 of highway no.105, Tak province (slope no.36).

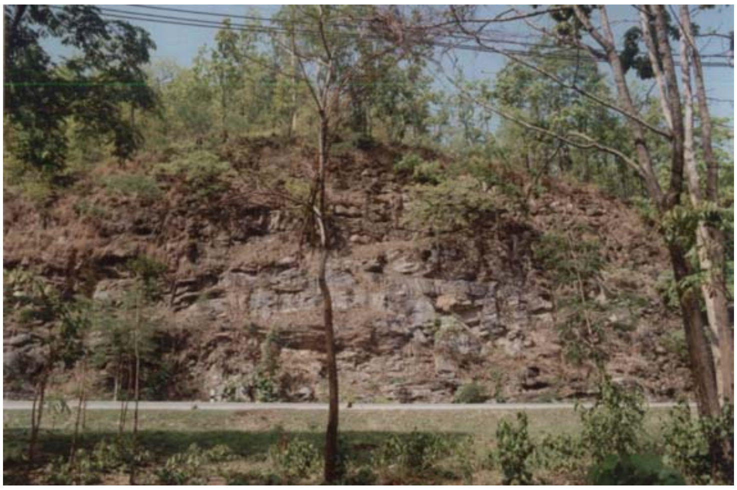

Figure A.108 The blocky rock at km 17-18 of highway no.105, Tak province (slope no.36).

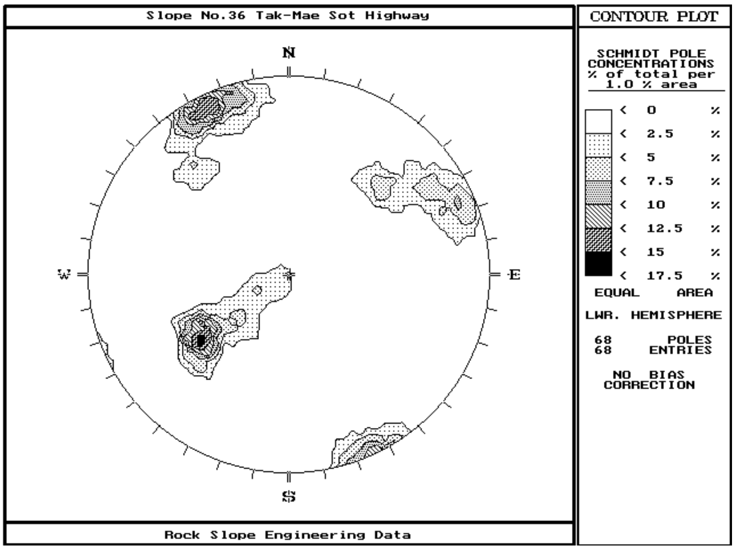

Figure A.109 The contour plots of Amphibolite schist discontinuity at km 17-18 of highway no.105, Tak province (slope no.36).

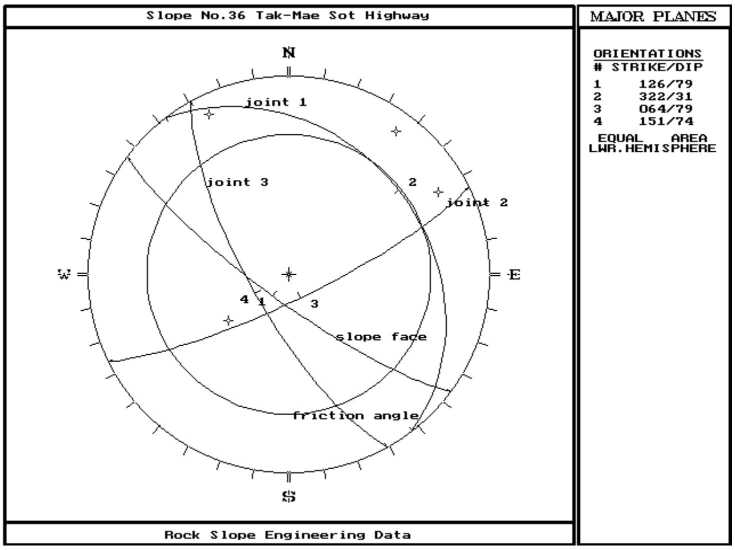

Figure A.110 Representative plane, slope orientation and friction angle of Amphibolite schist discontinuity at km 17-18 of highway no.105, Joint No.2 has a strike of 064 degrees, with 80 degrees dip angle. The joint spacing is 0.05-0.4 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 3-5. The joints are filled with mica.

Joint No.3 has a strike of 151 degrees, with 75 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-1 cm. The joint persistence is 50%. The JRC is estimated as 3-5. The joints are filled with sand and mica.

A-7.2 Slope No.37

The slope no.37 at km 68-69 located on highway no.105 (Figure A.111). The slope location is 47 Q 0462229 and UTM 1853800 of GPS system. The slope is classified as bedded rock. The slope height is 20 m and length is 50 m. The strike of the slope face one is 190 degrees. The dip angle is 52 degrees. The rock type is shale. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The existing support is ditch. The rock has three joint sets (Figures A.112 and A.113), as follows.

Joint No.1 (bedding plane) has a strike of 317 degrees, with 34 degrees dip angle. The joint spacing is 0.01-0.2 m. The joint aperture is 0.1-0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 1-2. The joints are filled with sand and clay.

Joint No.2 has a strike between 124 and 180 degrees, with 36 and 80 degrees dip angle. The joint spacing is 0.02-0.4 m. The joint aperture is 0.3 cm. Persistence of the rock joint is about 50%. The JRC is estimated as 1-3. The joints are filled with sand and clay.

Joint No.3 has a strike of 087 degrees, with 51 degrees dip angle. The joint spacing is 0.2 m. The joint aperture is 0.3 cm. The joint persistence is 70%. The JRC is estimated as 1-2. The joints are filled with sand and mica.

Figure A.111 The shale slope at km 68-69 of highway no.105 is located in Mae Sot district, Tak province (slope no.37).

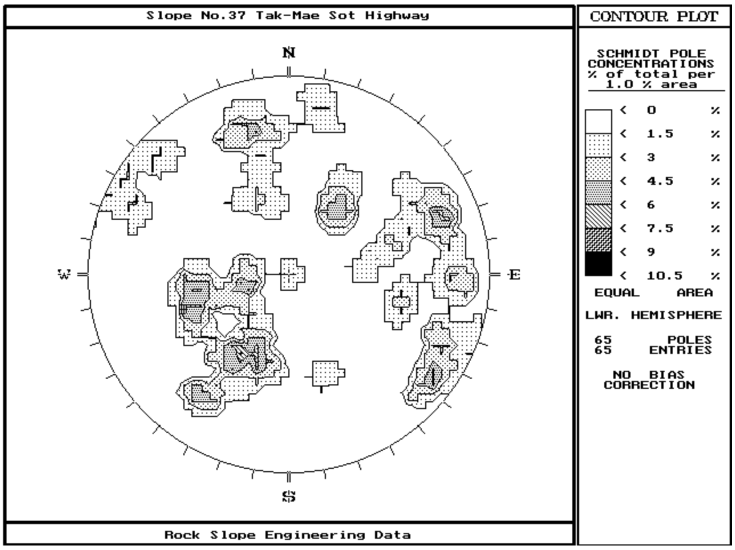

Figure A.112 The contour plots of shale discontinuity at km 68-69 of highway no.105 (slope no.37).

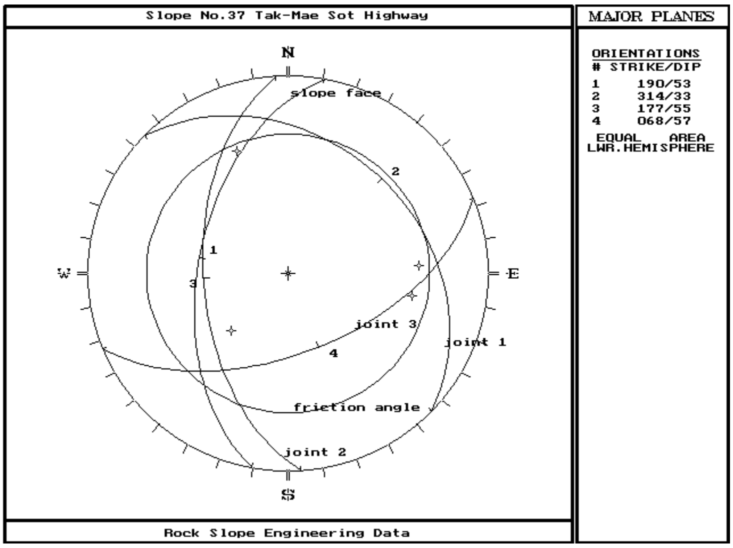

Figure A.113 Representative plane, slope orientation and friction angle of shale discontinuity at km 68-69 of highway no.105 (slope no.37).

A-7.3 Slope No.38

The slope no.38 at km 61-62 located on highway no.105 (Figures A.114 and A.115). The slope location is 47 Q 0466571 and UTM 1854099 of GPS system. The slope is classified as soft rock. The slope height is 12 m and length is 50 m. The strike of the slope face one is 350 degrees. The dip angle is 80 degrees. The rock type is argillaceous limestone. The UCS of the intact rock is between 5-25 MPa. The rock has highly weathered. The slope is unstable. The failure mode is circular failure. The failure is caused by the combination of water saturation, ground vibration (by heavy traffic) and the high angle slope face. The existing support is ditch.

A-7.4 Slope no.39

The slope no.39 at km 53-54 located on highway no. 105 (Figure A.116). The slope location is 47 Q 0472233 and UTM 1852690 of GPS system. The slope height is 30 m and length is 40 m. The strike of the slope face one is 075 degrees. The dip angle is 45 degrees. The existing supports include shotcrete, rock bolt and wire mesh. Wire mesh is 6×7 cm in opening. Shotcrete is between 2 and 8 cm in thickness. The length of drained pipes is between 30 and 50 cm. The inner diameter of drained pipes is 6.5 cm and the outer diameter of drained pipes is 6.8 cm. The slope is stable.

A-7.5 Slope No.40

The slope no.40 at km 49-50 located on highway no.105 (Figure A.117). The slope location is 47 Q 0476575 and UTM 1853523 of GPS system. The slope is classified as blocky rock. The slope height is 20 m and length is 40 m. The strike of the slope face is 230 degrees. The dip angle is 61 degrees. The rock type is calcareous shale. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The

Figure A.114 The heavily jointed rock at km 62-63 of highway no.105, Mae Sot district, Tak province (slope no.38).

Figure A.115 The surface circular failure of calcareous shale at km 62-63 of highway no.105 (slope no.38).

Figure A.116 The stable slope at km 53+250 of highway no.105, Mae Sot district, Tak province (slope no.39).

Figure A.117 The heavily jointed rock at km 49-50 of highway no.105, Tak province.

existing support is ditch. The rock has three joint sets (Figures A.118 and A.119), as follows.

Joint No.1 (bedding plane) has a strike of 324 degrees, with 33 degrees dip angle. The joint spacing is 0.4-1 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 5-7. The joints are filled with mica.

Joint No.2 has a strike of 064 degrees, with 80 degrees dip angle. The joint spacing is 0.05-0.4 m. The joint aperture is 1.0 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 3-5. The joints are filled with mica.

Joint No.3 has a strike of 151 degrees, with 75 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-1 cm. The joint persistence is 50%. The JRC is estimated as 3-5. The joints are filled with mica.

A-7.6 Slope No.41

The slope no.41 at km 31-32 located on highway no.105 (Figures A.120 and A.121). The slope location is 47 Q 0488782 and UTM 1853952 of GPS system. The slope is classified as blocky rock. The slope height is 40 m and length is 60 m. The strike of the slope face is 130 degrees. The dip angle is 60 degrees. The rock type is highly weathered shale. The UCS of the intact rock is between 5-25 MPa. The slope is unstable. The rock has three joint sets (Figures A.122 and A.123), as follows

Joint No.1 (bedding plane) has a strike of 254 degrees, with 03 degrees dip angle. The joint spacing is 0.01-0.05 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 60-80%. The JRC is estimated as 3. The joints are filled with clay.

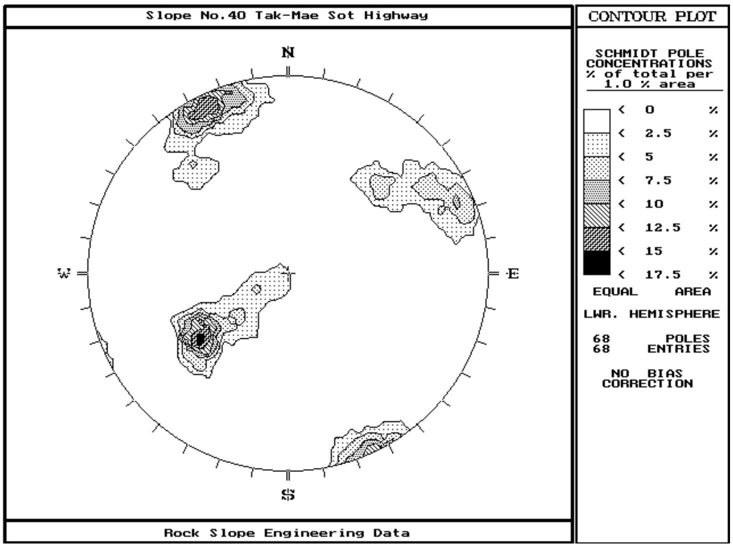

Figure A.118 The contour plots of Calcareous shale at km 49-50 of highway no. 105, Tak province (slope no.40).

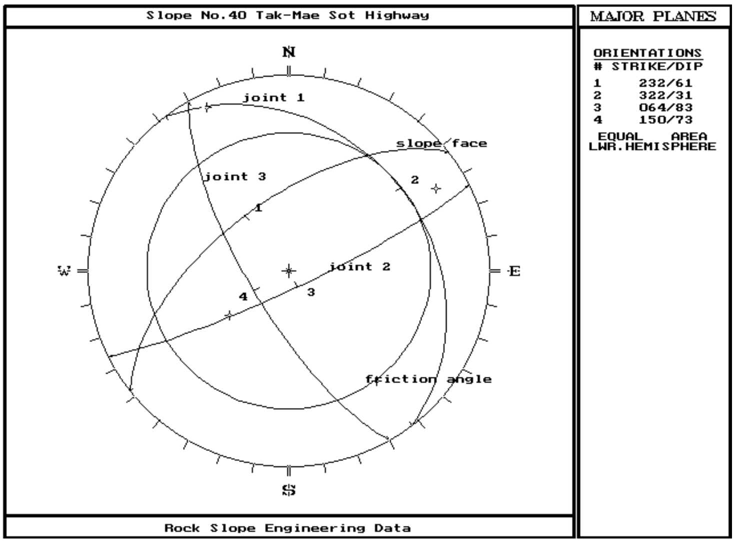

Figure A.119 Representative plane, slope orientation and friction of Calcareous Shale at km 49-50 of highway no.105, Tak province (slope no.40).

Figure A.120 The soft shale slope at km 31-32 of highway no.105, Mae Sot district, Tak province (slope no.41).

Figure A.121 The soft shale slope at km 31-32 of highway no.105, Mae Sot district, Tak province (slope no.41).

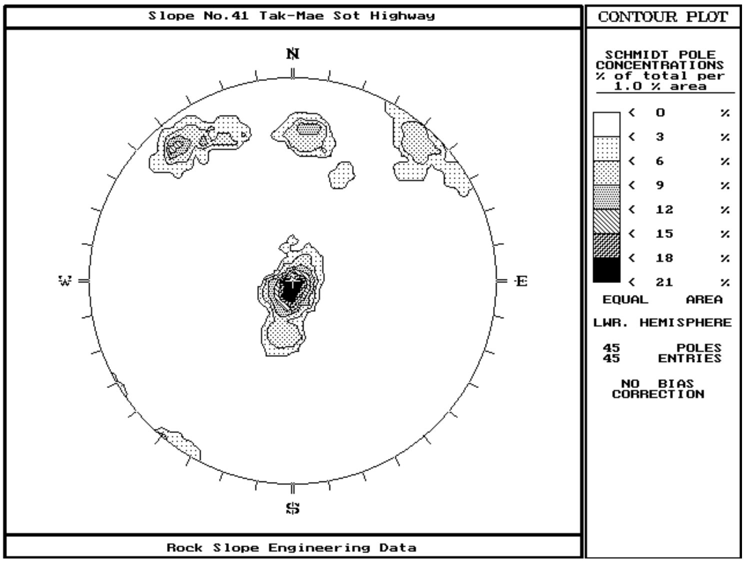

Figure A.122 The contour plots of soft shale at km 31-32 of highway no.105 (slope no.41).

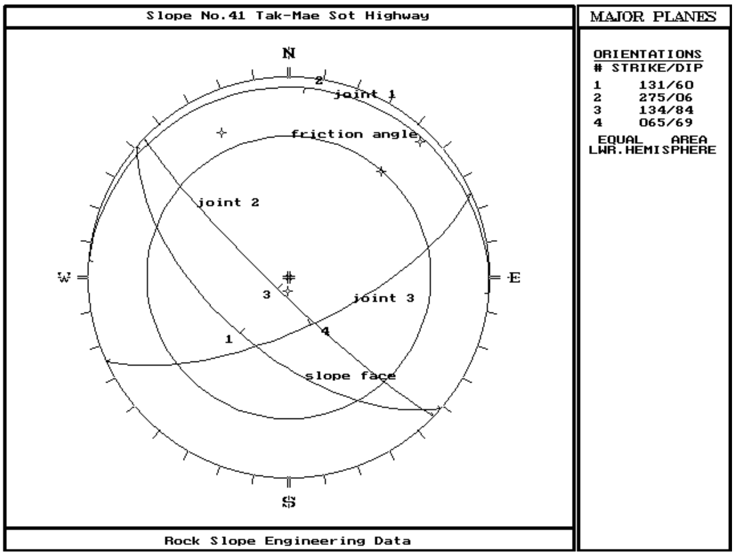

Figure A.123 Representative plane, slope orientation and friction angle of soft shale at km 31-32 of highway no.105 (slope no.41).

Joint No.2 has a strike of 134 degrees, with 80 degrees dip angle. The joint spacing is 0.02-0.15 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 70%. The JRC is estimated as 3. The joints are filled with clay.

Joint No.3 has a strike of 130 degrees, with 70 degrees dip angle. The joint spacing is 0.01-0.03 m. The joint aperture is 0.5-1 cm. The joint persistence is 50%. The JRC is estimated as 3. The joints are filled with clay.

A-7.7 Slope No.42

The slope no.42 at km 21-22 located on highway no.105 (Figures A.124 and A.125). The slope location is 47 Q 0495395 and UTM 1857734 of GPS system. The slope is classified as blocky rock. The slope height is15 m and length is 50 m. The strike of the slope face is 015 degrees. The dip angle is 70 degrees. The rock type is schist. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The rock has three joint sets (Figures A.126 and A.127), as follows

Joint No.1 (bedding plane) has a strike of 017 degrees, with 87 degrees dip angle. The joint spacing is 0.2-1.0 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 60%. The JRC is estimated as 3-5. The joints are clean.

Joint No.2 has a strike of 183 degrees, with 78 degrees dip angle. The joint spacing is 0.2-1 m. The joint aperture is 0.2 cm. Persistence of the rock joint is about 20%. The JRC is estimated as 3. The joints are filled with sand and mica.

Joint No.3 has a strike of 318 degrees, with 66 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-1 cm. The joint persistence is 30-50%. The JRC is estimated as 3. The joints are filled with mica.

Figure A.124 The schist slope at km 21-22 of highway no.105, Tak province (slope no.42).

Figure A.125 The toppling failure of schist slope 21-22 of highway no.105 Tak province (slope no.42).

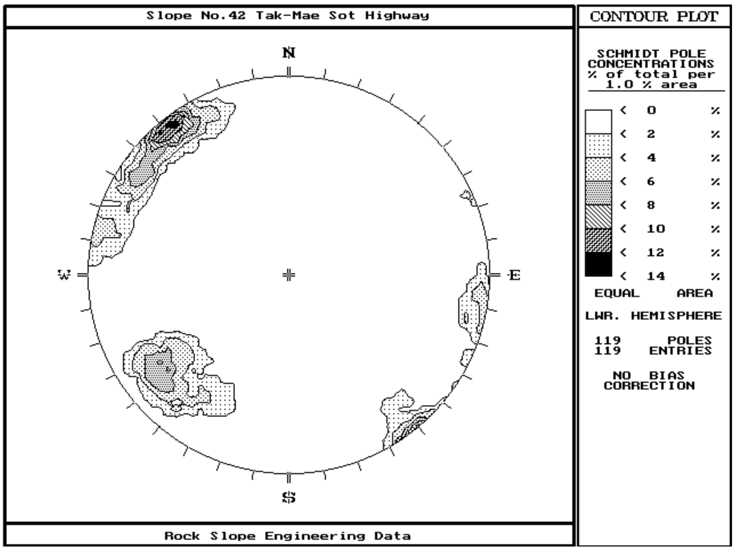

Figure A.126 The contour plots of schist discontinuity at km 21-22 of highway no.105 (slope no. 42).

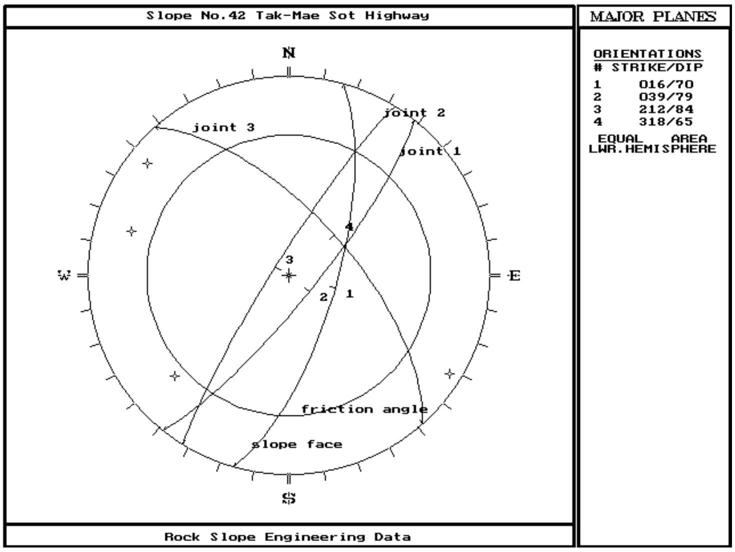

Figure A.127 Representative plane, slope orientation and friction angle of schist discontinuity at km 21-22 of highway no.105 (slope no.42).

A-7.8 Slope No.43

The slope No.43 at km 21-22 found on highway No.105 (Figures A.128 and A.129). The slope location is 47 Q 0495395 and UTM 1857734 of GPS system. The slope is classified as blocky rock. The slope height is 30 m and length is 200 m. The strike of the slope face is 060 degrees. The dip angle is 75 degrees. The rock type is schist. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The rock has three joint sets (Figures A.130 and A.131), as follows.

Joint No.1 (bedding plane) has a strike of 017 degrees, with 87 degrees dip angle. The joint spacing is 0.2-1.0 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 60%. The JRC is estimated as 3-5. The joints are clean.

Joint No.2 has a strike of 183 degrees, with 78 degrees dip angle.. The joint spacing is 0.2-1 m. The joint aperture is 0.2 cm. Persistence of the rock joint is about 20%. The JRC is estimated as 3. The joints are filled with sand and mica.

Joint No.3 has a strike of 318 degrees, with 66 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.5-1 cm. The joint persistence is 30-50%. The JRC is estimated as 3. The joints are filled with mica.

A-7.9 Slope No.44

The slope no.44 at km 20-21 located on highway no.105 (Figure A.132). The slope location is 47 Q 0495531 and UTM 1858081 of GPS system. The slope is classified as heavily jointed rock. The slope height is 50 m and length is 60 m. The strike of the slope face is 060 degrees. The dip angle is 68 degrees. The rock type is schist. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The rock has four joint sets (Figures A.133 and A.134), as follows

Figure A.128 The Schist slope at km 21-22 of highway no.105, Tak province (slope no.43).

Figure A.129 Schist slope failure at km 21-22 of highway no.105 (slope no.43).

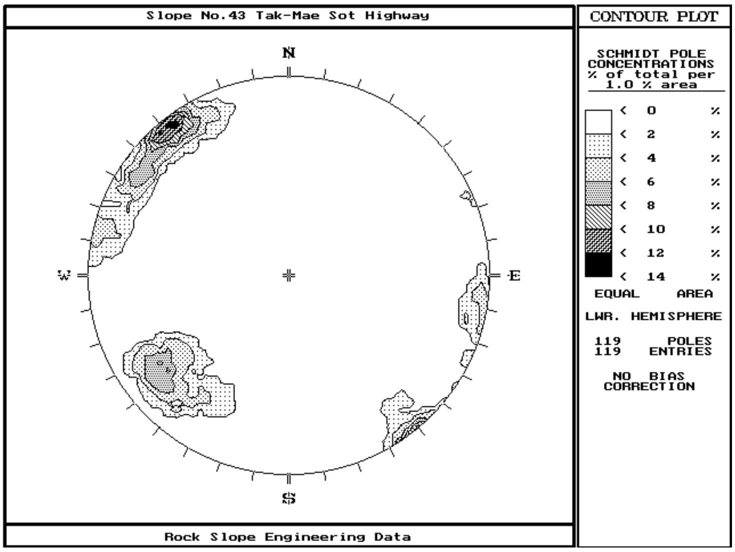

Figure A.130 The contour plots of schist discontinuity at km 21-22 of highway no.105, Tak province (slope no.43).

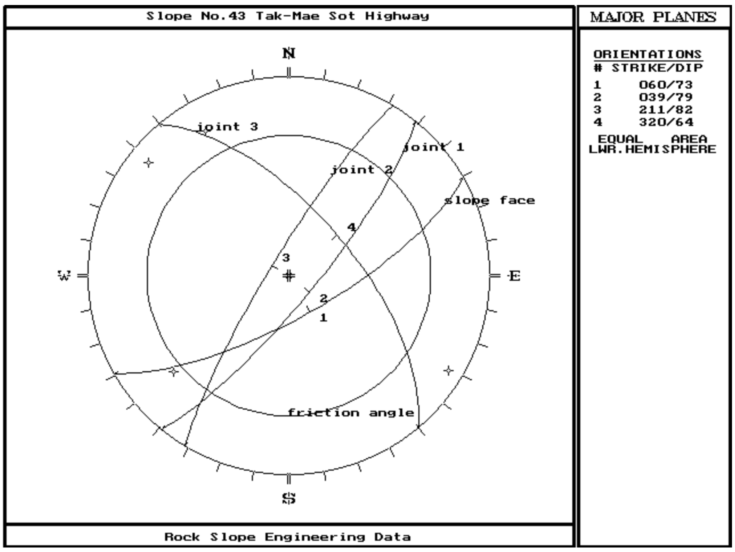

Figure A.131 Representative plane, slope orientation and friction angle of schist discontinuity at km 21-22 of highway no.105, Tak province (slope no.43).

Figure A.132 The schist slope at km 20-21 of highway no.105, Tak province (slope no.44).

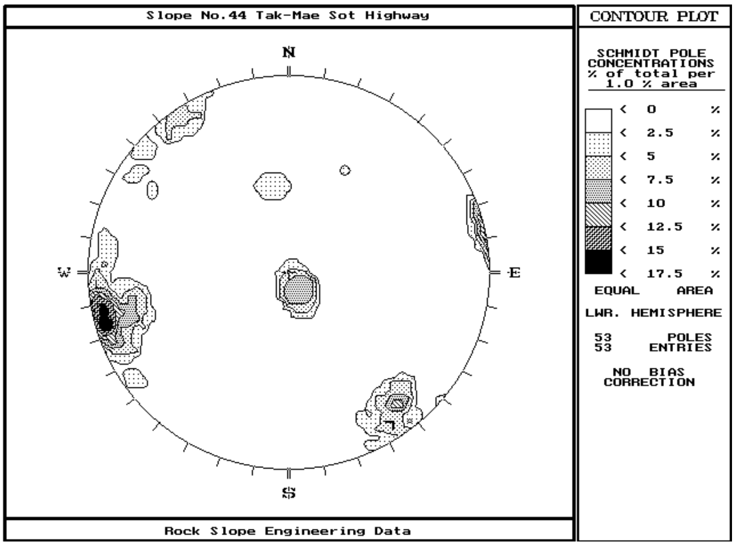

Figure A.133 The contour plots of schist discontinuity at km 20-21 of highway no.105 (slope no. 44).

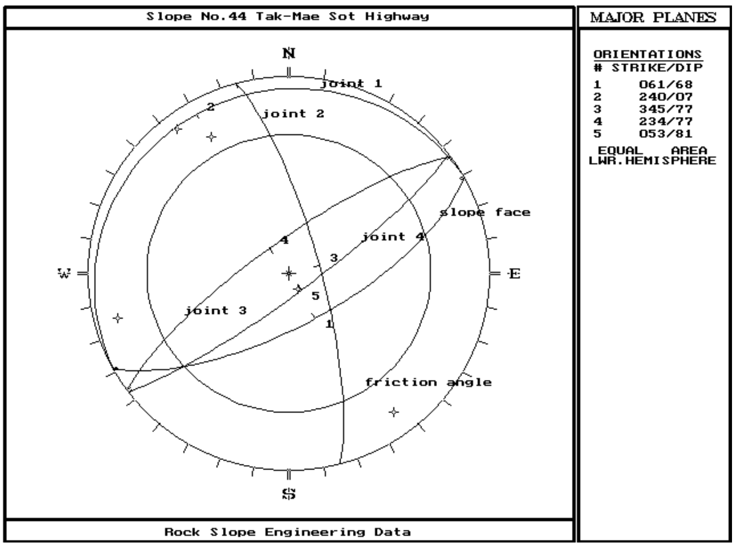

Figure A.134 Representative plane, slope orientation and Friction angle of schist discontinuity at km 20-21 of highway no.105 (slope no.44).

Joint No.1 (bedding plane) has a strike of 325 degrees, with 36 degrees dip angle. The joint spacing is 0.05-1.2 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 3-5. The joints are clean.

Joint No.2 has a strike of 346 degrees, with 79 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.1-0.3 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 9-11. The joints are filled with calcite.

Joint No.3 has a strike of 240 degrees, with 07 degrees dip angle. The joint spacing is 0.15-0.4 m. The joint aperture is 0.5-0.8 cm. The joint persistence is 20-30%. The JRC is estimated as 9-11. The joints are filled with calcite.

Joint No.4 has a strike of 234 degrees, with 76 degrees dip angle. The joint spacing is 0.3-0.8 m. The joint aperture is 0.5-2 cm. The joint persistence is 20-30%. The JRC is estimated as 5-9. The joints are filled with clay.

A-7.10 Slope No.45

The slope No.45 at km 20-21 found on highway No.105 (Figure A.135). The slope location is 47 Q 0495531 and UTM 1858081 of GPS system. The slope is classified as heavily jointed rock. The slope height is 50 m and length is 60 m. The strike of the slope face is 060 degrees. The dip angle is 68 degrees. The rock type is schist. The UCS of the intact rock is between 25-50 MPa. The slope is stable. The rock has four joint sets (Figures A.136 and A.137), as follows.

Joint No.1 (bedding plane) has a strike of 325 degrees, with 36 degrees dip angle. The joint spacing is 0.05-1.2 m. The joint aperture is 0.1-1 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 3-5. The joints are clean.

Figure A.135 The stable slope at km 20-21 of highway no.105, Tak province (slope no.45).

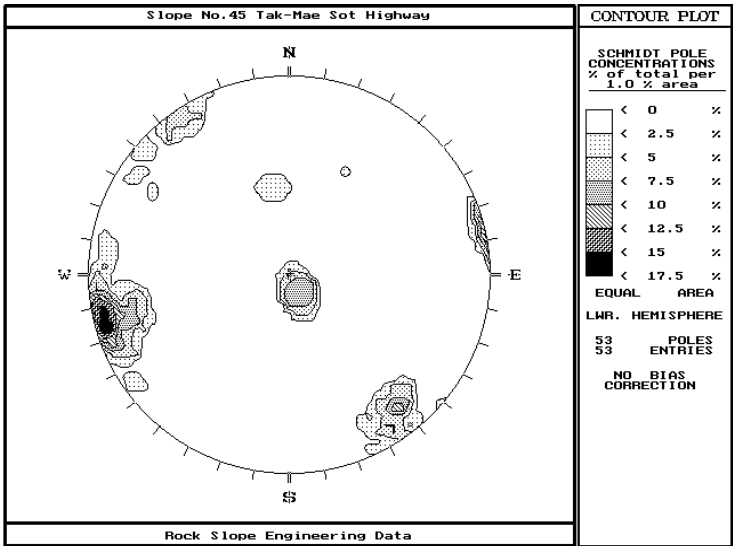

Figure A.136 The contour plots of schist discontinuity at km 20-21 of highway no.105, Tak province (slope no.45).

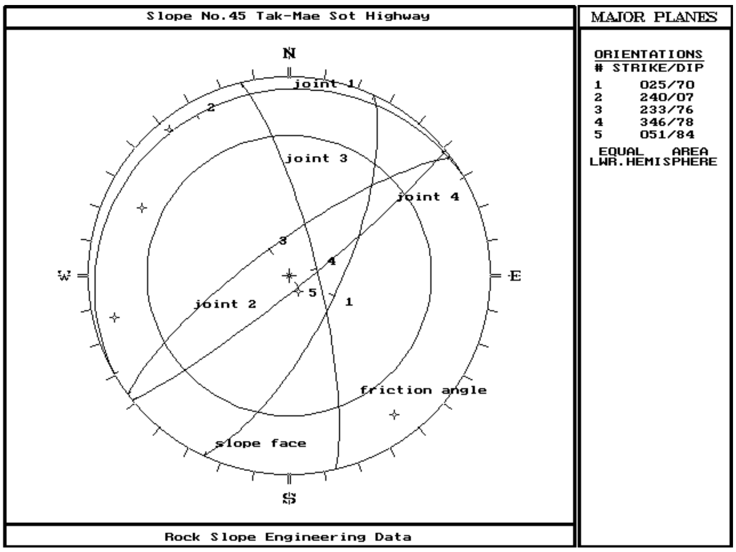

Figure A.137 Representative plane, slope orientation and Friction angle of schist discontinuity at km 20-21 of highway no.105, Tak province (slope no.45).

Joint No.2 has a strike of 346 degrees, with 79 degrees dip angle. The joint spacing is 0.2-0.4 m. The joint aperture is 0.1-0.3 cm. Persistence of the rock joint is about 80%. The JRC is estimated as 9-11. The joints are filled with calcite.

Joint No.3 has a strike of 240 degrees, with 07 degrees dip angle. The joint spacing is 0.15-0.4 m. The joint aperture is 0.5-0.8 cm. The ajoint persistence is 20-30%. The JRC is estimated as 9-11. The joints are filled with clay.

Joint No.4 has a strike of 234 degrees, with 76 degrees dip angle. The joint spacing is 0.3-0.8 m. The joint aperture is 0.5-2 cm. The joint is 20-30%. The JRC is estimated as 5-9. The joints are filled with clay

A-7.11 Slope No.46

The slope no.46 at km 19-20 located on highway no.105 (Figures A.138 and A.139). The slope location is 47 Q 0495531 and UTM 1858450 of GPS system. The slope height is 40 m and the length is 70 m. The strike of the slope face varies from 020 to 075 degrees. The dip angle is 70 degrees. The existing supports include rock bolt, wire mesh and ditch. Wire mesh is 6×7 cm in opening. The slope is stable.

A-7.12 Slope No.47

The slope no.47 at km 17-18 located on highway no.105 (Figure A.140). The slope location is 47 Q 0497475 and UTM 1858878 of GPS system. The slope is classified as heavily jointed rock. The slope height is 25 m and length is 50 m. The strike of the slope face is 012 degrees. The dip angle is 72 degrees. The rock type is schist. The UCS of the intact rock is between 25-50 MPa. The rock slope is fair stable. The rock has three joint sets (Figures A.141 and A.142), as follows.

Joint No.1 (bedding plane) has a strike of 329 degrees, with 49 degrees dip angle. The joint spacing is 0.02-0.7 m. The joint aperture is 0.1-0.5 cm. Persistence of

Figure A.138 The shale slope at km 19-20 of highway no.105, Tak province (slope no.46).

Figure A.139 The surface failure of shale and wire mesh on slope at km 19-20 of highway no.105, Tak province (slope no.46).

Figure A.140 The Schist slope at km 17-18 of highway no.105, Tak province (slope no.47).

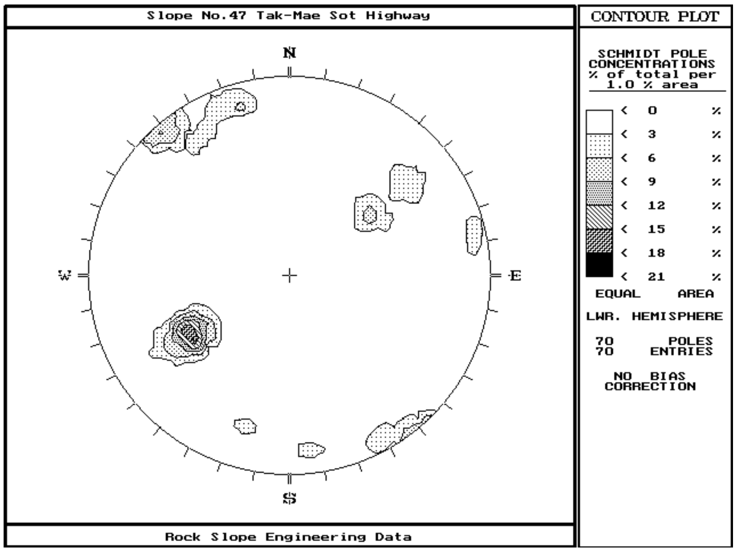

Figure A.141 The contour plots of schist discontinuity at km 17-18 of highway no.105 (slope no.47).

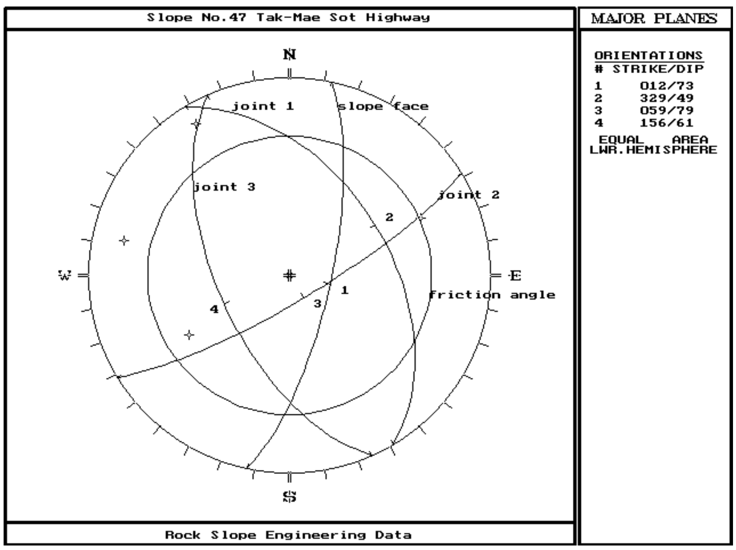

Figure A.142 Representative plane, slope orientation and friction angle of schist discontinuity at km 17-18 of highway no.105 (slope no.47).

the rock joint is about 70-80%. The JRC is estimated as 3-5. The joints are clean.

Joint No.2 has a strike of 059 degrees, with 80 degrees dip angle. The joint spacing is 0.1-0.8 m. The joint aperture is 0.1-0.3 cm. Persistence of the rock joint is about 60%. The JRC is estimated as 5. The joints are filled with mica.

Joint No.3 has a strike of 150 degrees, with 58 degrees dip angle. The joint spacing is 0.2 m. The joint aperture is 0.1 cm. The joint persistence is 20-40%. The JRC is estimated as 5-9. The joints are filled with mica

A-7.13 Slope No.48

The slope no.48 is located on the cress of Ubonrat dam (Figures A.143 and A.144). The slope location is 47 Q 0245671 and UTM 1859043 of GPS system. The slope is classified as blocky rock. The slope height is 20 m and length is 30 m. The strike of the slope face is 170 degrees. The dip angle is 90 degrees. The rock type is sandstone. The UCS of the intact rock is between 50-100 MPa. The rock slope is unstable. The failure is toppling of the vertical joint in massive sandstone (sizes are $0.2\times0.1\times0.3$ to $1.6\times2.0\times1.2$ m^3). The rock has three joint sets (Figures A.145 and A.146), as follows.

Joint No.1 (bedding plane) has a strike of 026 degrees, with 26 degrees dip angle. The joint spacing is 0.15-1 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with sand.

Joint No.2 has a strike of 270 degrees, with 83 degrees dip angle. The joint spacing is 1-2 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 30%. The JRC is estimated as 5-7. The joints are filled with clay and sand.

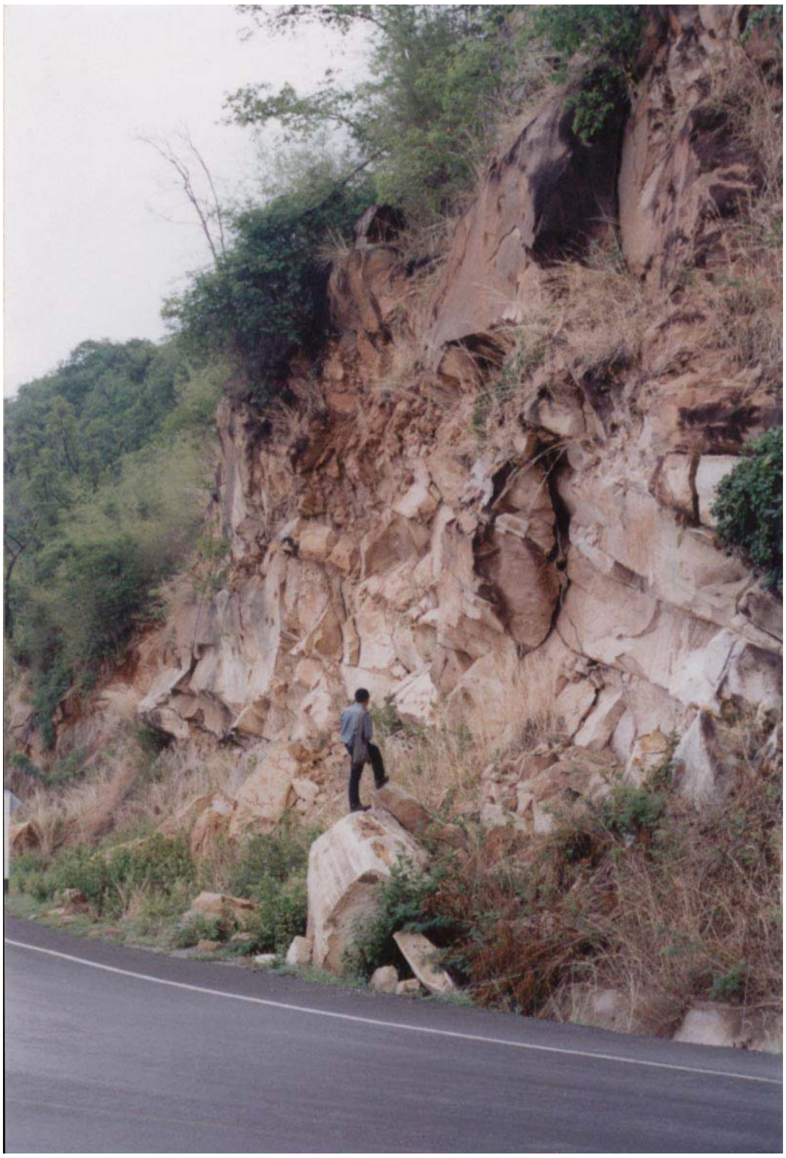

Figure A.143 The sandstone slope is located near with Ubonrat dam, Khon Kaen province (slope no.48).

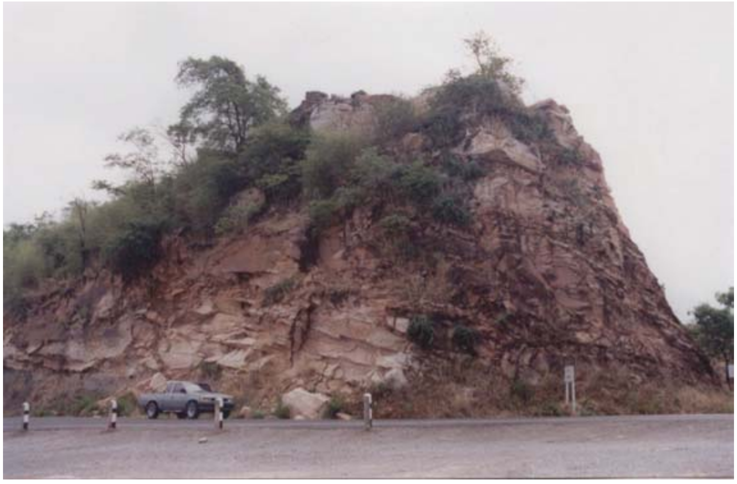

Figure A.144 The sandstone slope is located near with Ubonrat dam, Khon Kaen province (slope no.48).

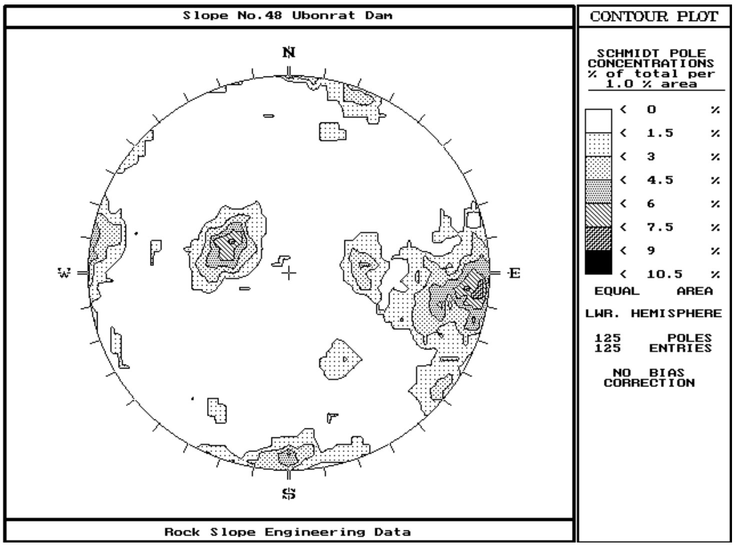

Figure A.145 The contour plots of sandstone discontinuity is located near with Ubonrat dam, Khon Kaen province (slope no.48).

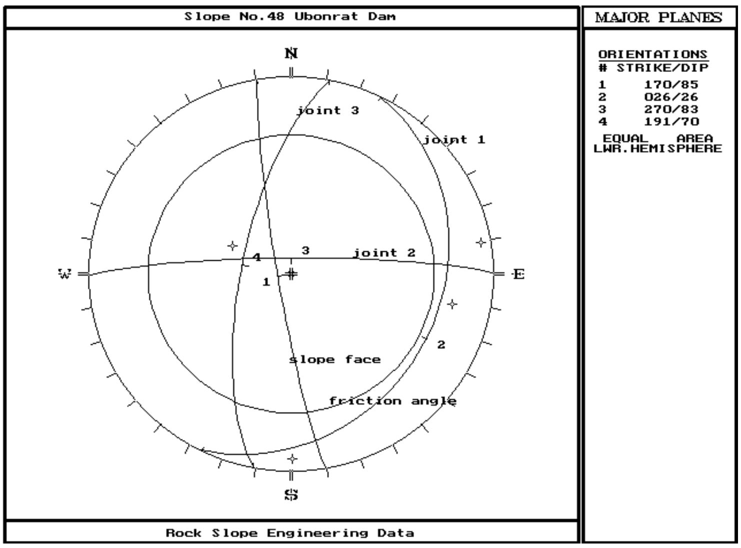

Figure A.146 Representative plane, slope orientation and friction angle of sandstone discontinuity is located near with Ubonrat dam, Khon Kaen province (slope no.48).

Joint No.3 has a strike of 189 degrees, with 76 degrees dip angle. The joint spacing is 0.2-1 m. The joint aperture is 3-10 cm. The joint persistence is 20-40%. The JRC is estimated as 7-9. The joints are filled with clay and sand.

A-7.14 Slope No.49

The slope no.49 is located on the cress of Ubonrat dam (Figure A.147). The slope location is 47 Q 0245671 and UTM 1859043 of GPS system. The slope is classified as blocky rock. The slope height is 20 m and length is 12 m. The strike of the slope face is 060 degrees. The dip angle is 75 degrees. The rock type is sandstone. The UCS of the intact rock is between 50-100 MPa. The slope shape is convex. The slope is stable. The rock has three joint sets (Figures A.148 and A.149), as follows.

Joint No.1 (bedding plane) has a strike of 026 degrees, with 26 degrees dip angle. The joint spacing is 0.15-1 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with sand.

Joint No.2 has a strike of 270 degrees, with 83 degrees dip angle. The joint spacing is 1-2 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 30%. The JRC is estimated as 5-7. The joints are filled with clay and sand.

Joint No.3 has a strike of 189 degrees, with 76 degrees dip angle. The joint spacing is 0.2-1 m. The joint aperture is 3-10 cm. The joint persistence is 20-40%. The JRC is estimated as 7-9. The joints are filled with clay and sand.

A-7.15 Slope No.50

The slope no.48 is located on the cress of Ubonrat dam (Figure A.150). The slope location is 47 Q 0245671 and UTM 1859043 of GPS system. The slope is classified as blocky rock. The slope height is 16 m and the length is 30 m. The strike

Figure A.147 The sandstone slope is located near with Ubonrat dam, Khon Kaen province.

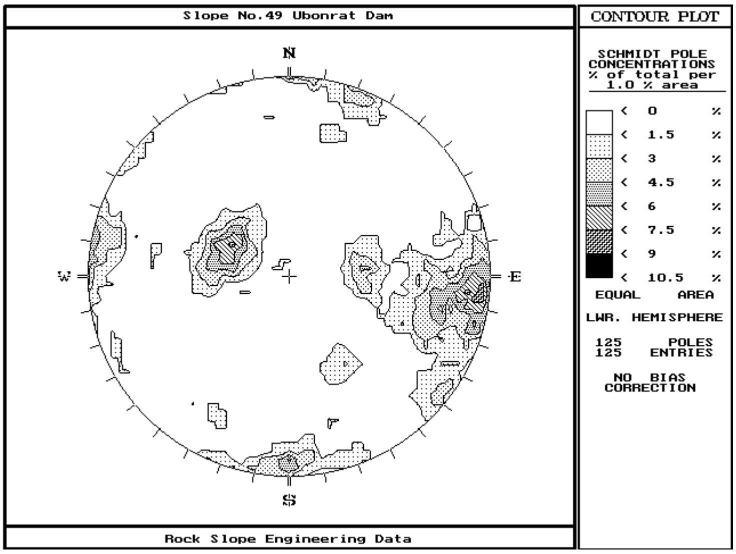

Figure A.148 The contour plots of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.49).

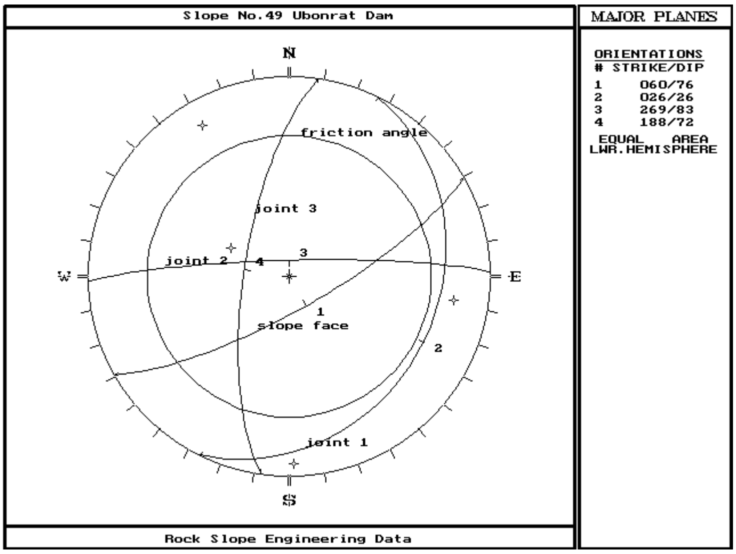

Figure A.149 Representative plane, slope orientation and friction angle of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.49).

Figure A.150 The sandstone slope, Ubonrat dam, Khon Kaen province (slope no.50).

of the slope face is 020 degrees. The dip angle is 72 degrees. The rock type is sandstone. The UCS of the intact rock is between 50-100 MPa. The slope is stable. The rock has three joint sets (Figures A.151 and A.152), as follows.

Joint No.1 (bedding plane) has a strike of 026 degrees, with 26 degrees dip angle. The joint spacing is 0.15-1 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with sand.

Joint No.2 has a strike of 270 degrees, with 83 degrees dip angle. The joint spacing is 1-2 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 30%. The JRC is estimated as 5-7. The joints are filled with clay and sand.

Joint No.3 has a strike of 189 degrees, with 76 degrees dip angle. The joint spacing is 0.2-1 m. The joint aperture is 3-10 cm. The joint persistence is 20-40%. The JRC is estimated as 7-9. The joints are filled with clay and sand.

A-7.16 Slope no.51

The slope No.51 is located on the cress of Ubonrat dam (Figure A.153). The slope location is 47 Q 0245671 and UTM 1859043 of GPS system. The slope is classified as blocky rock. The slope height is 18 m and length is 30 m. The strike of the slope face is 210 degrees. The dip angle is 60 degrees. The rock type is sandstone. The UCS of the intact rock is between 50-100 MPa. The slope is stable. The rock has three joint sets (Figures A.154 and A.155), as follows.

Joint No.1 (bedding plane) has a strike of 026 degrees, with 26 degrees dip angle. The joint spacing is 0.15-1 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with sand.

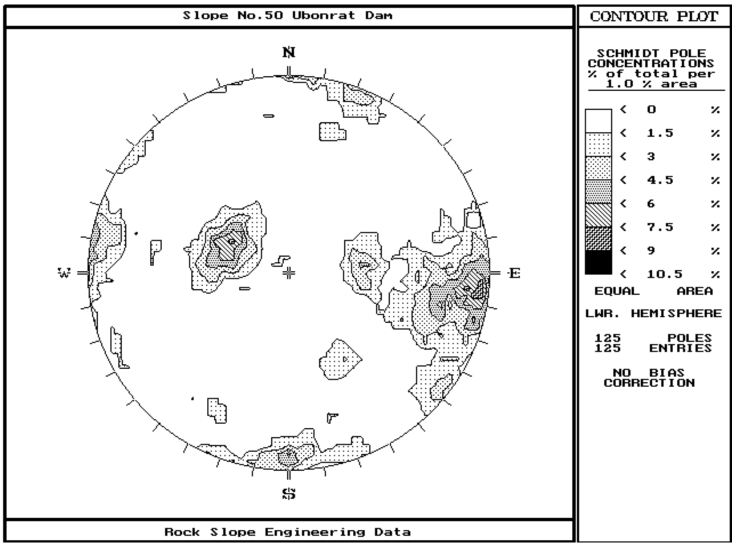

Figure A.151 The contour plots of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.50).

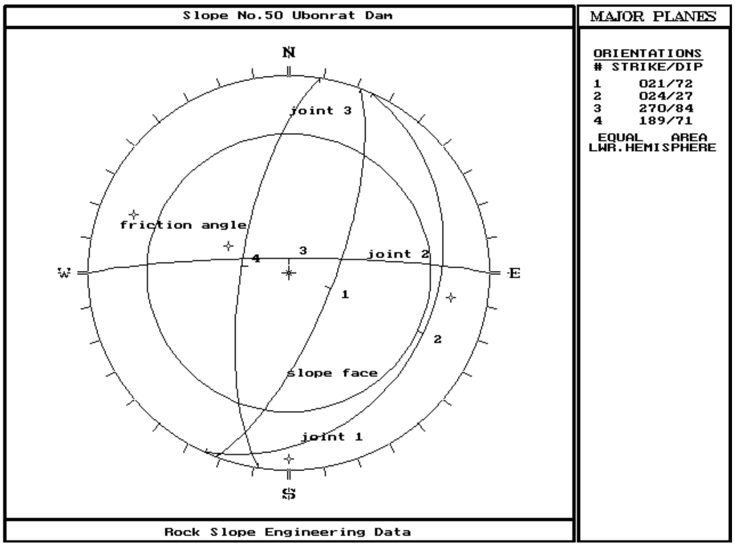

Figure A.152 Representative plane, slope orientation and friction angle of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.50).

Figure A.153 The sandstone slope, Ubonrat dam, Khon Kaen province (slope no.51).

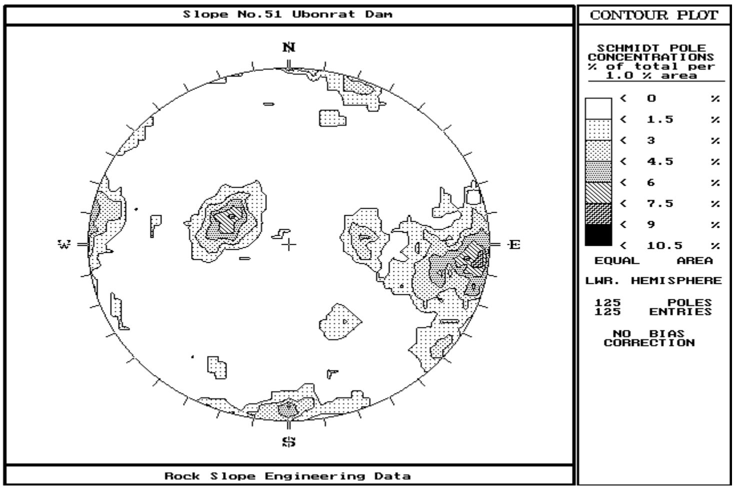

Figure A.154 The contour plots of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.51).

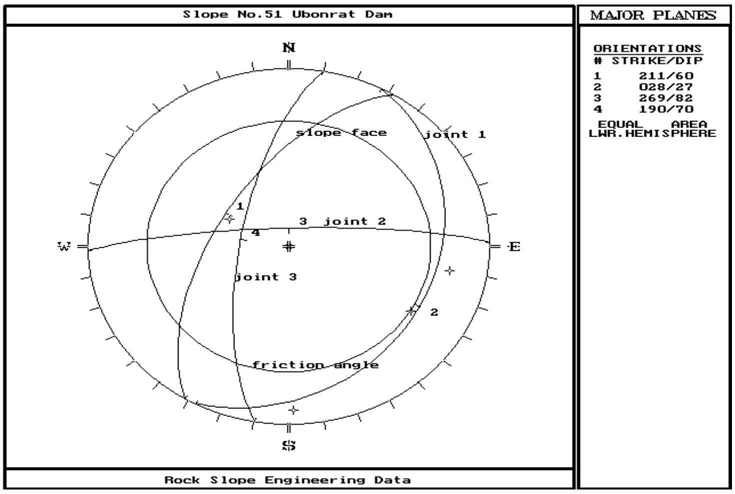

Figure A.155 Representative plane, slope orientation and friction angle of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.51).

Joint No.2 has a strike of 270 degrees, with 83 degrees dip angle. The joint spacing is 1-2 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 30%. The JRC is estimated as 5-7. The joints are filled with clay and sand.

Joint No.3 has a strike of 189 degrees, with 76 degrees dip angle. The joint spacing is 0.2-1 m. The joint aperture is 3-10 cm. The joint persistence is 20-40%. The JRC is estimated as 7-9. The joints are filled with clay and sand.

A-7.17 Slope no.52

The slope No.52 is located on the cress of Ubonrat dam (Figure A.156). The slope location is 47 Q 0245671 and UTM 1859043 of GPS system. The slope is classified as blocky rock. The slope height is 20 m, the length is 20 m. The strike of the slope face is 260 degrees. The dip angle is 60 degrees. The rock type is sandstone. The UCS of the intact rock is between 50-100 MPa. The slope is stable. The rock has three joint sets (Figures A.157 and A.158), as follows.

Joint No.1 (bedding plane) has a strike of 026 degrees, with 26 degrees dip angle. The joint spacing is 0.15-1 m. The joint aperture is 0.5 cm. Persistence of the rock joint is about 80-100%. The JRC is estimated as 3. The joints are filled with sand.

Joint No.2 has a strike of 270 degrees, with 83 degrees dip angle. The joint spacing is 1-2 m. The joint aperture is 5-10 cm. Persistence of the rock joint is about 30%. The JRC is estimated as 5-7. The joints are filled with clay and sand.

Joint No.3 has a strike of 189 degrees, with 76 degrees dip angle. The joint spacing is 0.2-1 m. The joint aperture is 3-10 cm. The joint persistence is 20-40%. The JRC is estimated as 7-9. The joints are filled with clay and sand.

Figure A.156 The sandstone slope, Ubonrat dam, Khon Kaen province (slope no.52).

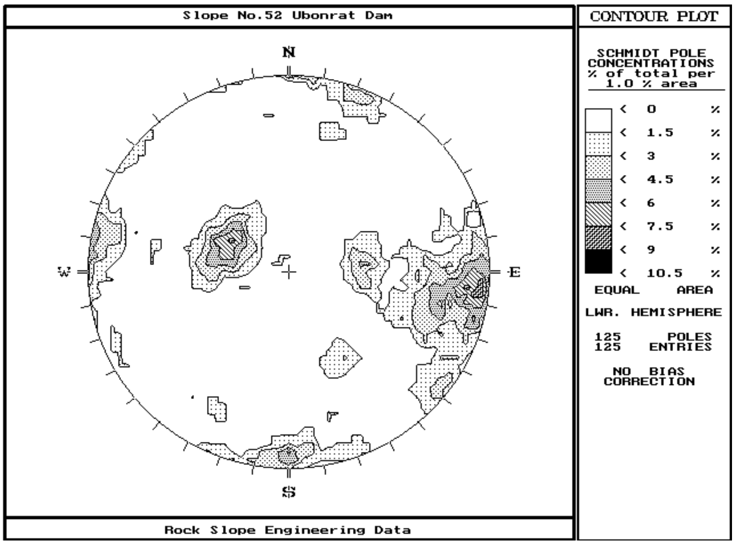

Figure A.157 The contour plots of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.52).

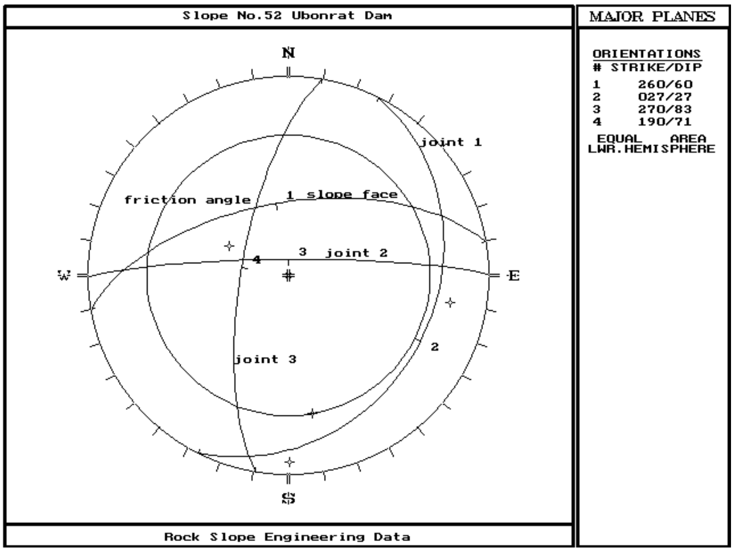

Figure A.158 Representative plane, slope orientation and friction angle of sandstone discontinuity, Ubonrat dam, Khon Kaen province (slope no.52).

BIOGRAPHY

Mr. Santhat Kamutchat was born on the 19rd of February 1976 in Nakorn Sawan province. He earned his Bachelor's Degree in Geotechnology (Geological Engineering program) from Suranaree University of Technology (SUT) in 2000. After graduation, he continued with his master's degree in the School of Geotechnology, Institute of Engineering at SUT with the major in Geological Engineering. Between of 2001-2004, he was a teaching assistant and research assistant at SUT. His strong background is in the areas of soil and rock mechanics, geology, hydrology and foundation engineering.