Decision Support System for Evaluation and Treatment of Earth Slope Instability

DIMITRI A. GRIVAS AND JOHN C. REAGAN

Movements of earth slopes are common and often costly occurrences. The development of a decision aid to provide appropriate remedial actions and to restore slopes to acceptable degrees of safety is of considerable practical importance. Achievements to date in developing a decision support system for the evaluation and treatment of slope instability are presented. The conceptual design, applicability and functions of the system are established through a combination of techniques, including the use of an expert panel. The three main components for the system are knowledge base, supporting data bases, and analytical program support. Initial implementation has produced a personal computer–based prototype system, which is described and illustrated with an example. Conclusions drawn from this study include the following: (a) the domain of landslide analysis and treatment is well suited to the expert-system approach because it involves reasoning processes and data interpretations that are based on experience; (b) knowledge acquisition is a critical and involved activity in the system development effort, and simple techniques (interviews and questionnaires) appear to be inadequate for the creation of a robust knowledge base; (c) a fully implemented system requires a powerful computer environment with multitasking capabilities.

The selection of appropriate actions to control the movement of earth slopes and secure their safety represents an important activity in geotechnical engineering. Available expertise is typically scattered among the many facets of the problem, making it difficult to achieve decisions, especially under pressing or urgent conditions.

Delays or poor decisions in effectively controlling slope instability can have devastating effects. The damage is more acute for slopes located in urban settings. In such cases a potential slope instability may result in a major slide, which can cause economic and life losses. Estimates of direct and indirect damage to buildings and other structures due to slope failure in the United States alone are on the order of hundreds of millions of dollars a year. FHWA has estimated that an amount in excess of $50 million is spent annually for the repair of slope-related damage on the federally financed component of the U.S. highway network (*1*). The total number of fatalities due to all types of slope instability exceeds 25 a year nationwide (*2*). These figures can explain the continued interest in the study of the factors that trigger the movements of slope-forming materials and help justify the practical need for the development of aids for better and faster decisions in controlling such movements.

D. A. Grivas, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, N.Y. 12180-3190. J. C. Reagan, New York State Department of Transportation, Soil Mechanics Bureau, State Campus Building 7, Room 114, Albany, N.Y. 12232.

Recent developments in the use of expert systems in civil engineering have demonstrated the ability of such systems to aid in decision making and solution of complex problems. Expert systems are basically computer programs that imitate the performance of human experts. They embody factual, empirical, and procedural knowledge to address specific aspects of particular problems and to manipulate relevant knowledge expressed in symbolic description. Their success is due mainly to their ability to solve difficult problems in specific areas at least as well as human experts.

The paper presents the initial research effort on a project aiming at the development of a decision methodology for the evaluation and treatment of earth slope instability. The project is conducted jointly by personnel of Rensselaer Polytechnic Institute (RPI) and the Soil Mechanics Bureau of the New York State Department of Transportation (NYSDOT). The latter is the state agency responsible for the safety of all man-made or natural slopes in the transportation infrastructure of New York. The overall goal of the project is to collect, synthesize, and validate the knowledge available on the subject and encode it in a decision support system (DSS) (*3*) to provide uniform, consistent, and cost-effective decisions in selecting and implementing rehabilitative solutions to problems caused by slope instability. At the core of the DSS is an expert system which stores the knowledge base. Analytical and data base components supplement the knowledge base to form the complete system.

CONTROL OF MOVEMENT AND INSTABILITY OF EARTH SLOPES

The task of determining feasible alternative options to control movement and instability of earth slopes represents an involved process. Each slope, whether natural or man-made, is a unique structure, the performance of which is influenced by local conditions (e.g., geology, materials, loads, etc.). To make an informed decision, one must be knowledgeable about these conditions, be familiar with available options, and have experience about their effectiveness in achieving a desirable objective (e.g., reduction in driving forces, increase in shear strength, etc.). Cost and other constraints (e.g. unavailability of materials, inappropriate field conditions, etc.) often eliminate some options, but the basic objective of making a final recommendation for the solution of a diagnosed problem remains valid.

If an intelligent aid were available to achieve the above task, it would embody available factual and empirical knowledge and would imitate the thinking process of human experts.

The user of such an aid would then be able to arrive at a decision on the appropriate treatment, which would be supported by available data and experience.

Figure 1 shows the stages typically involved in arriving at a recommended solution. Each block in the figure represents a main activity, and the numbers show the order in which activities are typically pursued. A description of each main activity is given next.

Problem Identification

Problem detection and identification is typically based on observations of slope movement. The type of incurred movement is characterized according to specific attributes. One such attribute is the depth of the slope mass involved (i.e., whether the slope movement is deep seated or shallow). Additional attributes include type of material, rate of movement, geometry of the area affected, possible causes, degree of disruption of displaced mass, relation to geologic structure, and state of movement activity. There are several ways to classify slope movement, each having its own distinct advantages in the manner in which it utilizes pertinent features. In a synthesis on the subject (*4*) the type of movement and type of material were used to represent the primary and secondary criterion, respectively, for classification purposes. This is the classification system that is also followed in the present study.

Of practical importance during early stages of problem identification is the decision whether immediate action is necessary (e.g., closing a roadway, establishing a detour, initiating monitoring of the movement, etc.). This and other early decisions typically set the course of action to be followed during subsequent investigation.

Data Collection

This stage represents a fact-gathering activity. Several types of data are generally available to the person investigating a slope movement. Although the amount of data varies from

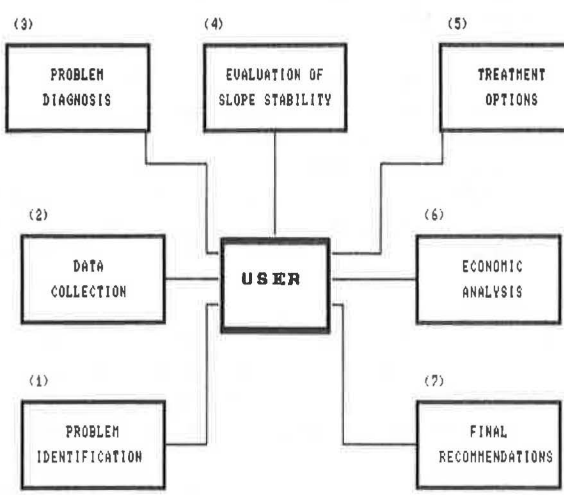


FIGURE 1 Schematic illustration of the activities involved in arriving at a final recommendation.

one case to another, some typical data types include the following:

- Geology of the region surrounding the slope site, available usually through maps, surveys, air photos, and field investigations;
- Boring log data;
- Test data on boring samples or in situ tests;
- Well data depicting groundwater fluctuation;
- Rainfall records; and
- Instrumentation data from slope indicators and the like.

The amount of data that is available at a given site is constantly changing. Thus, an important activity in investigating slope movements is the continuous updating and expanding of data files.

Problem Diagnosis

Problem diagnosis involves assessing the probable causes of slope movement. It is based on local experience and movement characteristics exhibited by certain types of materials.

Some primary causes are typically established during the data collection process (e.g., water-related problems, possible weak shear strength, etc.). They represent hypotheses that must be thoroughly examined during the problem diagnosis stage. In order to accept or reject a hypothesis, it may be necessary to conduct field tests, obtain drill holes, perform laboratory tests, review construction histories and other records in the area, and so forth. Although the task to precisely determine causes of instability is a challenging one, dominant factors can be identified reliably.

Evaluation of Slope Stability

This stage involves the use of analytical techniques to evaluate the safety of a slope. In the case of soil slopes, such methods are typically formulated on the assumption of limit equilibrium. If the analysis is based on a deterministic approach, the safety of a slope in terms of the commonly used "factor of safety" is assessed. If the analysis is based on a probabilistic approach that accommodates relevant uncertainties, the safety of a slope in terms of a "probability of failure" is assessed (*5*).

The finite element method (FEM) can also be used to provide stresses and deformations within soil masses. It requires, however, input data that is not always readily available or easy to obtain. Furthermore, a quantitative interpretation of results from finite element analysis requires some form of limit equilibrium calculation (*6,7*). These limitations are the primary reasons for the continued popularity of limit equilibrium methods for stability analysis of embankments and slopes (*8*).

Shown in Figure 2 is a classification of material conditions for the purpose of slope stability analysis. For natural slopes, the material may be broadly characterized as either coarse grained or fine grained. In the case of coarse-grained soils, a major distinction is given by density (i.e., loose or dense state); in the case of fine-grained soils, the distinction is be-

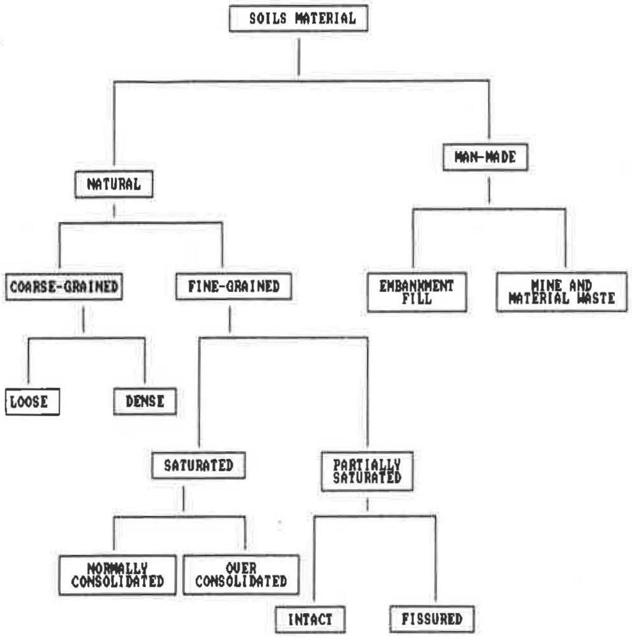


FIGURE 2 Classification of soil material conditions for stability analysis purposes.

tween saturated or partially saturated state. Further distinctions may also be made as shown in the Figure 2.

Once a failure model is adopted and a method of stability analysis is established, parametric studies can be conducted to determine the relative importance of the various factors and lead the way to the treatment selection.

Treatment Options

Selection of appropriate treatments follows a pattern that is generally directed from the results of the problem diagnosis, failure model development, and stability analysis. The goal of each treatment option is to halt slope movement and secure the overall safety of the slope. There are several ways of achieving this goal (e.g., reducing the driving forces, increasing resistance, etc.). Certain treatment options place special constraints on the solution of the problem. For example, slope flattening or use of berms requires that adequate space is available. Ease of construction and overall cost are additional considerations.

Economic Analysis

Once a set of alternative treatments has been identified, designed, and verified, a cost analysis for each treatment is conducted. NYSDOT cost estimates are based on earthwork items and other required engineering activities (e.g., control of traffic, etc.). Some treatments may necessitate the acquisition of additional rights-of-way, the cost of which must be incorporated in the economic analysis. Typically no benefit-cost analysis is undertaken on stabilization projects because treatments are expected to secure slope stability permanently. In cases in which controlled failure concepts are applied, an economic analysis includes estimated annual maintenance costs.

Final Recommendations

The final selection from the set of eligible treatment options is generally based on the minimum overall cost. Other factors include the urgency of the problem, availability of contractors to perform the work, the timing of the construction, and the ever-present political considerations.

SLOPE MOVEMENT AND STABILITY CONSULTANT

The DSS under development is expected to serve as an intelligent slope stability consultant (STABCON). In this capacity, its mission is to offer guidance in pursuing the tasks involved in the evaluation and treatment of slope instability problems. The initial implementation of STABCON is in a prototype that incorporates knowledge on significant aspects of the problem. Limitations are mainly in reference to types of slope failure mechanisms and number of treatments considered. The complete system is expected to expand the domain of applicability of STABCON without altering its architecture.

Problem Solving

A variety of problem-solving strategies may be followed using expert system techniques. Most applications can be formulated on the basis of a derivation or formation approach (*9*). In the derivation approach, a list of appropriate solutions for a problem is placed in the knowledge base, and the problem conditions produce the final recommendation. In contrast, in the formation approach only important aspects of the solution are placed in the knowledge base, and the final recommendation is synthesized from those aspects that are rendered valid by the problem conditions. Depending on the nature and overall complexity of the problem under investigation, the design of an expert system may use either the derivation approach, the formation approach, or both.

The implementation of STABCON was done through the use of the expert system tool Insight II+. In addition to meeting the requirement for a personal computer–based solution, Insight II+ has a number of features that make programming easy. Examples of such features include the ability to provide explanations for the reasoning process and built-in interfaces to external analysis programs and databases. Its control structure is based on a backward chaining methodology that falls in the category of the derivation approach described above. Thus, a goal state is selected and the system checks to establish whether supporting conditions are met. If this is not the case, the system pursues the state under consideration as a subgoal. This process is repeated until the original goal state is acceptable or disqualified.

Functions Pursued by STABCON

A functional overview of STABCON designed to support the landslide investigation and treatment methodology is shown in Figure 3. The first function involves the selection by the

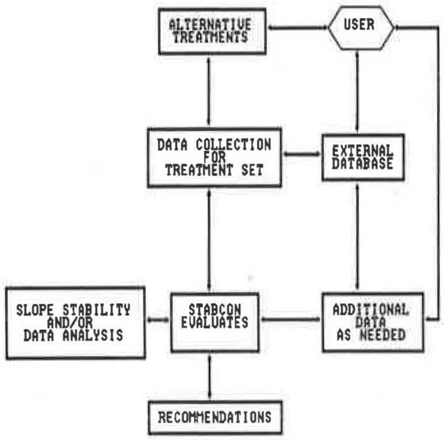


FIGURE 3 Schematic illustration of functions pursued by STABCON.

user of a goal, or set of goals, to be achieved. This function involves the identification of one or several alternative treatments for the slope movement or instability problem at hand. In using STABCON, it is also possible not to select a specific treatment at the goal identification stage. In such a case the system pursues its reasoning by considering all feasible goals (treatments) in accordance with the specified problem conditions. This feature may be desirable in practice for conditions under which no obvious treatment alternative is identifiable at the outset.

Depending on the goal selected, STABCON initiates the data collection activity to obtain data required to evaluate the selected goal. This represents the second phase in the search for the validation of a selected goal (or identification of feasible goals, if none was selected).

Once data collection is completed, STABCON uses an inference strategy, in which the viability of the selected treatments in controlling the movement or instability of the slope under investigation is evaluated. This represents the third phase in the search process during which, in addition to evaluating the rules stored in its knowledge base, STABCON may need additional data on which to base its judgment. Thus, in the functional structure of the system (Figure 3), a branch is created to request user input, extract information from the data base, or, if necessary, access external programs to pursue slope stability calculations and data analysis.

The last function of STABCON involves an evaluation of the various treatment alternatives. In cases in which required information is not available, no final recommendation is offered. Instead, STABCON provides a list of data that must be obtained in order to complete the evaluation. In all other cases STABCON produces viable final recommendations.

IMPLEMENTATION OF STABCON

Knowledge Base

Once the conceptual design was defined and the knowledge structure for the system was acquired the next phase of the study was focused on the implementation of the prototype. Figure 4 shows the three principal functional components of the STABCON system: knowledge base, data bases, and analytical functions.

The knowledge acquisition process aimed to identify the critical elements of landslide investigation and treatment recommendations. To this end, a panel of experts was formed, the membership of which included representatives from the Soil Mechanics Bureau of NYSDOT. The initial focus of the panel was on the features and architecture of the proposed STABCON model (*10*). Also addressed were the principal methods used for correcting landslide areas.

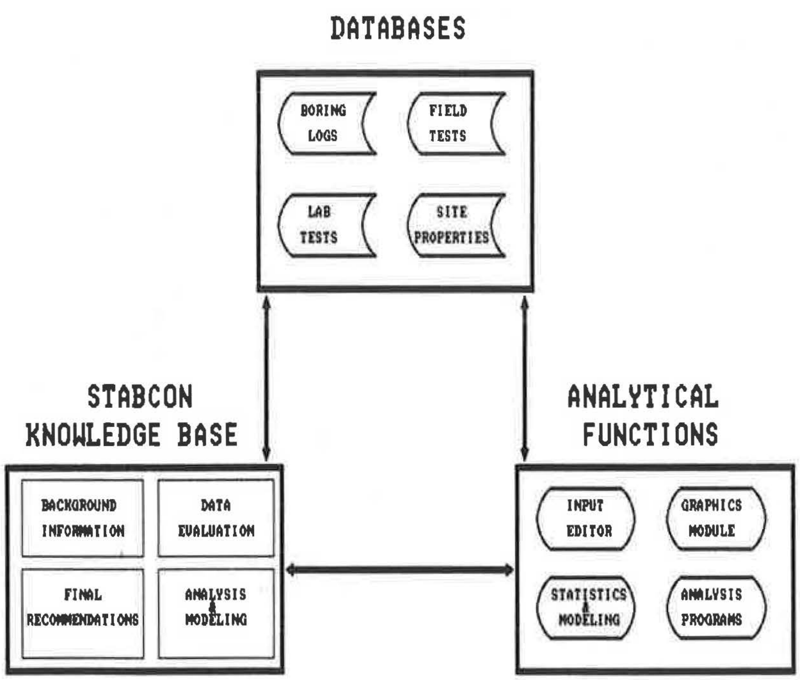


FIGURE 4 STABCON's primary functional components.

Once a general consensus was reached concerning the scope and domain of the system, a description of the approach to knowledge acquisition and of procedures to conduct the detailed design of the system was distributed to the panel. Factors important to landslides that were identified by the panel are as follows:

1. Artesian water pressure,
2. Type of roadway cross section,
3. Type of slide,
4. Average inclination of existing slope,
5. Field observations,
6. Shear strength parameters,
7. Old failures,
8. Recent construction activity,
9. Streams and creeks,
10. Rainfall,
11. Soil stratigraphy,
12. Creep (deep and shallow),
13. Leaching,
14. Surface water infiltration,
15. Progressive failure,
16. Strength softening,
17. Clay mineral,
18. Anisotropy,
19. Rate of movement,
20. Type of clay (fissure, intact, etc),
21. Number and shape of soil layers,
22. Number and value of water tables,
23. Slope of possible failure plane,
24. Relative permeability of strata,
25. Surface water,
26. Subsurface water,
27. History of area, and
28. Geology and topography.

Information on each of the factors was recorded on a knowledge acquisition form. A special form was created to collect information for the knowledge base as well as to clarify the relative importance of each factor in the landslide analysis process. It also addressed the manner in which missing or incomplete information could be generated. The information gathered was vital for developing the knowledge base and constructing the consultation paradigm.

After factors that influence landslides were identified, the system development process was focused on describing the landslide investigation process from each panelist's perspective. This resulted in the process summary shown in Figure 5. This process was consistent with NYSDOT's past practices and guidelines for slope maintenance and restoration in a related FHWA report (*11*).

Further interaction with the panel examined how geotechnical engineers approach a typical landslide investigation. The generated information served as background for describing the reasoning followed by experts and the manner in which they deal with the numerous factors that are associated with each landslide site. It was relatively easy for the panel to describe in detail an expert's approach to site familiarization, field investigation and preliminary analysis. However, it was not easy to describe in a rigorous manner the process of detailed investigation and the criteria for accepting a final treatment recommendation, areas in need of additional studies and research.

FIGURE 5 Landslide investigation process.

KNOWLEDGE REPRESENTATION

The acquired knowledge was used to formulate the knowledge base and process structure of the system. The prototype was created in a PC-based environment using Insight II+ as the software development tool. Main features of this tool include the Production Rule Based language (PRL), interfaces to DBII and DBIII databases, an internal database (DBPAS), and an explanation facility. A typical rule from the knowledge base is as follows:

CONF (the water conditions ARE artesian) = −2
THEN water conditions unknown
AND DISPLAY unknown water conditions

Rules similar to the above were derived on the basis of the knowledge retrieved from the expert panel. They were then formulated in a forward chaining inference mechanism used by STABCON, and input screens and supporting explanation screens were constructed.

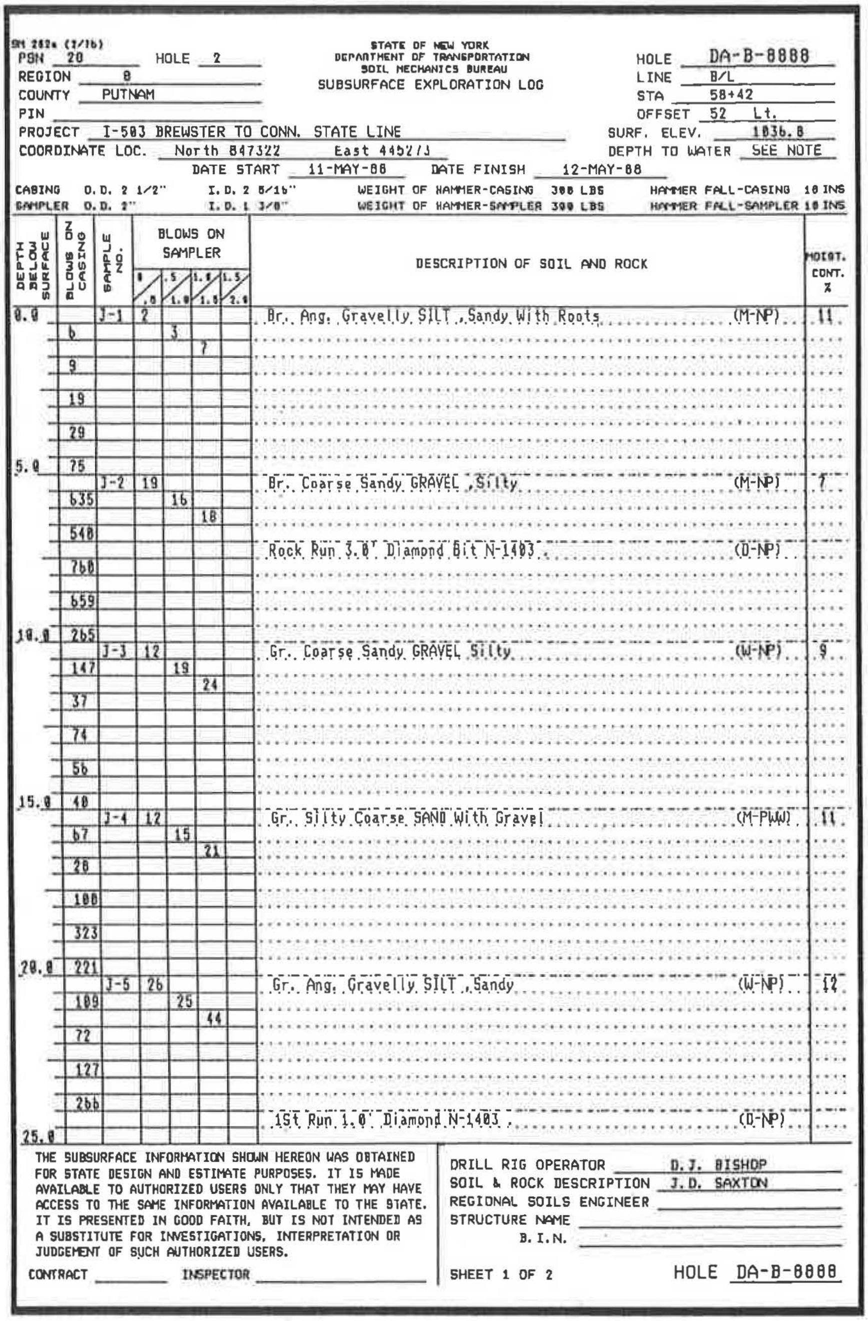
EXTERNAL DATABASES

Boring Logs

Borings taken at failure sites aid in determining possible causes for incurred failures and in establishing additional investigative paths. The importance to landslides of the information generated through borings requires that STABCON be able to call on it on an as-needed basis. To achieve this system objective, data are maintained in a PC-based ORACLE relational data base system. Programmatic interfaces are required to recall the data in conjunction with the knowledge base. An example of a boring log used at NYSDOT is shown in Figure 6.

An examination of the boring log suggests that the data structure of the boring log can be decomposed into a group of common categories. This decomposition represents the normal form for the relational data base design. The principal divisions are as follows:

1. Boring data: general information on boring location and details,
2. Boring sample: data on each sample in the boring,



SM 282a (7/76)

STATE OF NEW YORK
DEPARTMENT OF TRANSPORTATION
SOIL MECHANICS BUREAU
SUBSURFACE EXPLORATION LOG

PSN 20 HOLE 2 — HOLE DA-B-8888
REGION 8 — LINE B/L
COUNTY PUTNAM — STA 58+42
PIN — OFFSET 52 Lt.
PROJECT I-503 BREWSTER TO CONN. STATE LINE — SURF. ELEV. 1036.8
COORDINATE LOC. North 847322 East 445273 — DEPTH TO WATER SEE NOTE
DATE START 11-MAY-88 DATE FINISH 12-MAY-88

CASING O.D. 2 1/2" I.D. 2 5/16" WEIGHT OF HAMMER-CASING 300 LBS HAMMER FALL-CASING 18 INS
SAMPLER O.D. 2" I.D. 1 3/8" WEIGHT OF HAMMER-SAMPLER 300 LBS HAMMER FALL-SAMPLER 18 INS

DEPTH BELOW SURFACE	BLOWS ON CASING	SAMPLE NO.	BLOWS ON SAMPLER 0/.5	.5/1.0	1.0/1.5	1.5/2.0	DESCRIPTION OF SOIL AND ROCK	MOIST. CONT. %
0.0		J-1	2				Br. Ang. Gravelly SILT, Sandy With Roots (M-NP)	11
	6			3				
					7			
	9							
	19							
	29							
5.0	75							
		J-2	19				Br. Coarse Sandy GRAVEL, Silty (M-NP)	7
	635			16				
					18			
	540						Rock Run 3.0' Diamond Bit N-1403 (D-NP)	
	760							
	659							
10.0	265							
		J-3	12				Gr. Coarse Sandy GRAVEL Silty (W-NP)	9
	147			19				
					24			
	37							
	74							
	56							
15.0	48							
		J-4	12				Gr. Silty Coarse SAND With Gravel (M-PWW)	11
	67			15				
					21			
	28							
	100							
	323							
20.0	221							
		J-5	26				Gr. Ang. Gravelly SILT, Sandy (W-NP)	12
	109			25				
					44			
	72							
	127							
	266							
							1St Run 1.0' Diamond N-1403 (D-NP)	
25.0								

THE SUBSURFACE INFORMATION SHOWN HEREON WAS OBTAINED FOR STATE DESIGN AND ESTIMATE PURPOSES. IT IS MADE AVAILABLE TO AUTHORIZED USERS ONLY THAT THEY MAY HAVE ACCESS TO THE SAME INFORMATION AVAILABLE TO THE STATE. IT IS PRESENTED IN GOOD FAITH, BUT IS NOT INTENDED AS A SUBSTITUTE FOR INVESTIGATIONS, INTERPRETATION OR JUDGEMENT OF SUCH AUTHORIZED USERS.

CONTRACT ____ INSPECTOR ____

DRILL RIG OPERATOR D.J. BISHOP
SOIL & ROCK DESCRIPTION J.D. SAXTON
REGIONAL SOILS ENGINEER
STRUCTURE NAME
B.I.N.

SHEET 1 OF 2 HOLE DA-B-8888

FIGURE 6 Typical boring log.

3. Boring visual: visual description of major subdivisions within the boring (interpreted by driller), and
4. Water readings: data describing water readings during boring.

The boring log data entry application is currently in prototype mode on an IBM 4381 system. Plans call for porting the application to the PC-based ORACLE products to support the STABCON system.

Earth and Rock Slope Evaluation System

Information of importance to STABCON is available in the existing Earth and Rock Slope Evaluation System (EARSES). EARSES is a data base that contains ratings of all critical rock and earth slopes in New York State. EARSES currently operates on an IBM 4381 and is not directly accessible by the STABCON prototype system. Future developments will include the creation of an interface between STABCON and EARSES that will eliminate the present redundancy in entering site data and will contribute toward automation of slope evaluation.

Field Instrumentation

A field instrumentation data base is also important to the STABCON system. At a failure site, measurements of displacement and pore water pressure are often essential to evaluating stability. Rates and magnitudes of movements are of extreme importance when critical stability decisions, which impact the safety of the traveling public, are made. The implementation of a complete field instrumentation data base is among future developments of the system.

Analytical Functions

Certain functions of STABCON require interfaces with analytical programs. Two significant analytical programs were identified for STABCON. One was the infinite slope analysis, which is used by engineers investigating landslides for preliminary analysis of failure sites. A goal of the STABCON system was to simplify the analytical interface and provide a means to use the analytical programs with minimal training.

Infinite slope analysis, structured as a separate module, has been placed in the knowledge base of STABCON in the form of rules and checks. Many other programs are available that perform stability analysis for geotechnical investigators. Among them is the commonly used STABL program, a version of which provides graphical screen output (GEOSLOPE). This makes it easy for the user to quickly review the cross section for obvious input errors. The screen output does not allow users to review soil properties associated with soil stratigraphy. Instead, users must compare data maintained in a data input file.

The use of this program in the STABCON environment led to creation of an improved input editor that eliminates the need for highly specialized skills to utilize the STABL program. The normal data structure of the input data was modified to include a soil type attribute. This enabled the knowledge base to perform checks and compare values of similar soil types. It also facilitated the creation of screen output, which reveals soil stratigraphy and properties in a straightforward manner.

Application of STABCON

When STABCON is initiated, it begins pursuing the process shown in Figure 7. To provide consultation, the system monitors the assertions in the knowledge base and, when conditions necessitate it, an advisory screen is automatically invoked. Help screens are available to assist users by supplying required background information.

A user may select as many geotechnical factors as considered applicable to the failure site. The user may also press a dedicated function key to bring up a detailed screen that explains each of the factors to be displayed. In this case, the user is also requested to state his confidence in his answer by entering a numerical value between 0 and 100 percent. A value of 0 means the answer is not certain, whereas a value

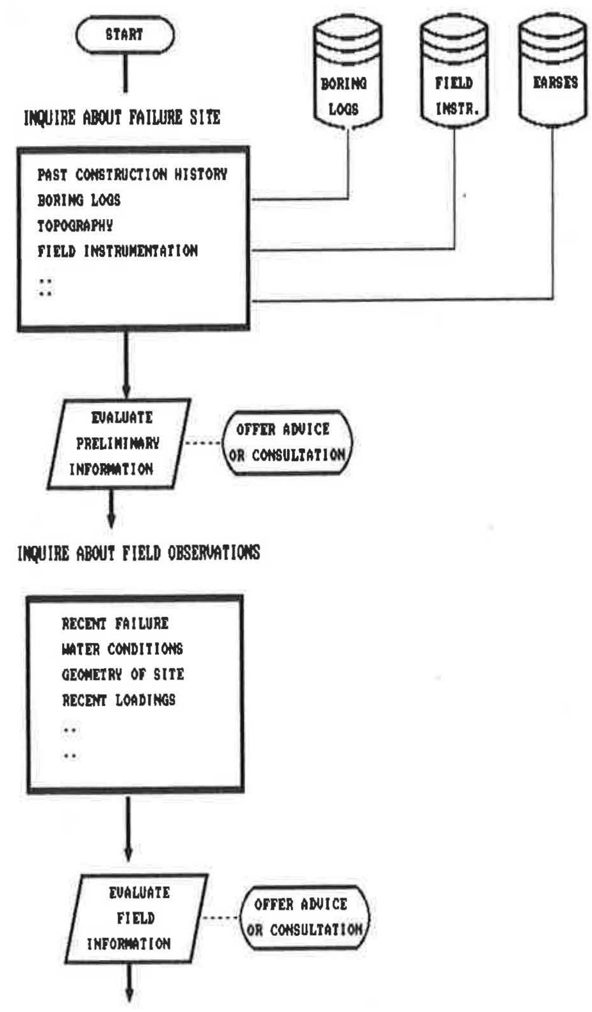


FIGURE 7 Sequence of activities in applying STABCON.

of 100 declares the answer to be known with certainty. Confidence factors are used by the system to evaluate additional investigation is required to reach a conclusion. After progressing through the general problem description screens, STABCON arrives at the preliminary analysis phase. STABCON asks whether a preliminary factor of safety has been established at the site. If the factor of safety has already been determined, STABCON pursues an additional check by invoking an infinite slope analysis.

The next assessment made by the system is the influence of water at the failure site. If water conditions are not known, STABCON offers some advice on how to establish them and provides guidelines for estimating their influence. In some instances, more detailed stability analysis is needed to interpret the sensitivity of the site to variable water conditions. To facilitate this analysis, an input editor to the GEOSLOPE stability program is used. The user invokes the input editor from the main menu of Insight II+ and is guided through a series of screens to describe the failure site. When completed, the input editor creates an input data file in a format that is accepted by the GEOSLOPE program. After the analysis is completed, the results are passed to the STABCON knowledge base, where the system performs a series of checks and makes further recommendations concerning the site. Possible alternatives at this stage include a request for additional field surveys or other investigations to better define the site and additional computer runs.

DISCUSSION OF RESULTS

The approach to knowledge acquisition followed in this study generated a broad background from which to develop rules for the knowledge base. Difficulty was experienced in the attempt to identify specific requirements for various treatment options, and relationships in the domain were not readily apparent. The knowledge acquired was focused on procedures and supporting data, which are represented in the system by analytical programs and data bases. In this respect, the domain under study was intensive in its requirements for programmatic and data base interfaces. The interface to the stability program is an essential attribute of STABCON because it enables an independent verification of the stability analyses performed by users.

The use of Insight II+ as a development tool made the creation of input and output screens an easy task. Knowledge representation formats provided by the tool were adequate for knowledge base development at the prototype level. A challenging task in developing the system was consideration of the alternatives that exist when information is unknown or incomplete. These decision paths made debugging the system cumbersome because tracing the process flow can often be obscure. The main drawback in the selected tool was in the area of programmatic interfaces, namely, the lack of computer memory to keep the development tool resident and concurrently run the STABL computer program.

SUMMARY AND CONCLUSIONS

The objective of the study was to create a prototype system that could evaluate the application of knowledge based systems to the landslide treatment domain. In the initial phase of this study, an exhaustive review of factors that influence active landslides was conducted. This was followed by the conceptual design that defined the processes and performance of the system. Emphasis was placed on failures occurring through soil masses along circular or wedge-type surfaces. An expert panel from the NYSDOT Soil Mechanics Bureau was formed to review the conceptual design and assist in the knowledge base development for the prototype. STABCON was developed using the Insight II+ tool and was successful in implementing the early phases of the conceptual design.

Future development is expected to include studies and interviews with domain experts to expand and better define the knowledge base. Furthermore, data base and program interfacing will be added to support a more robust system. Moving the prototype to a larger development environment will allow an integration of the system with data bases and analytical programs.

On the basis of the development effort to date, the following conclusions may be drawn:

1. Landslide analysis and treatment is a domain well suited to an expert system approach. Reasons for this include (a) the reasoning commonly used and the interpretation of available data are based on experience; (b) decisions are often made on incomplete or missing information; and (c) the expertise of the limited number of experts on this subject is scattered over a broad field.
2. Extracting knowledge from experts on specific components of the domain is a difficult task. An alternative (to questionnaires) approach of acquiring knowledge from experts is needed to create a production level (as opposed to prototype) knowledge base.
3. It is essential that the decision methodology be supported by a comprehensive data base management system and analytical techniques in order to encompass all aspects of the landslide domain.
4. The Insight II+ development tool does not possess sufficient memory to enable concurrent use of knowledge base and stability analysis programs. A production system requires additional computer resources.

REFERENCES

1. R. G. Chassie and R. D. Goughnour. National Highway Landslide Experience. *Highway Focus*, Vol. 8, No. 1, 1979, pp. 1–9.
2. J. P. Knohn and J. E. Slasson. Landslide Potential in the United States. *California Geology*, Vol. 29, No. 10, 1976, pp. 224–231.
3. R. H. Sprague, Jr., and E. D. Carlson. *Building Effective Decision Support Systems*. Prentice-Hall Inc., Englewood Cliffs, N.J., 1982.
4. R. L. Schuster and R. J. Krizek (eds.). Special Report 176: Landslides: Analysis and Control. TRB, National Research Council, Washington, D.C., 1978, 234 pp.
5. D. A. Grivas. Probabilistic Evaluation of Safety of Soil Structures. *Journal of Geotechnical Engineering Division, ASCE*, Vol. 105, No. GT9 Sept. 1979, pp. 1091–1095.
6. C. B. Brown and I. P. King. Automatic Embankment Analysis-Equilibrium and Instability Conditions. *Geotechnique*, Vol. 16, No. 3, Jan. 1966, pp. 209–219.
7. K. Y. Lo and C. F. Lee. Stress Analysis and Slope Stability in

Strain-Softening Materials. *Geotechnique*, Vol. 23, No. 1, March 1973, pp. 1–11.
8. S. K. Sarma. Stability Analysis of Embankments and Slopes. *Journal of Geotechnical Engineering Division, ASCE*, Vol. 105, No. GT12, Dec. 1979, pp. 1511–1524.
9. M. L. Maher (ed.). Problem Solving Using Expert System Techniques. *Proc., Expert Systems in Civil Engineering*, ASCE, New York, N.Y., 1987, pp. 7–17.
10. D. A. Grivas and J. C. Reagan. An Expert System for the Evaluation and Treatment of Earth Slope Instability. *Vth International Symposium on Landslides*, Balkema Publishers, Lausanne, Switzerland, July 1988, Vol. 1., pp. 649–654.
11. G. Kleindinst, A. Munoz, and C. W. Niessener. *Guidelines for Slope Maintenance and Slide Restoration*. Report TS-85-231. FHWA, U.S. Department of Transportation, 1986.

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