SRI LANKAN
GEOTECHNICAL CONFERENCE
1993

Theme

Computer Applications in Geotechnical Engineering

Organized by the

SRI LANKAN GEOTECHNICAL SOCIETY

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COMPUTER APPLICATIONS IN GEOTECHNICAL ENGINEERING

A G E N D A

8.15 – 8.45	Registration of Participants
8.45 – 9.00	Inauguration and Presidential Address by Prof. A. Thurairajah, President Sri Lankan Geotechnical Society
9.00 – 9.20	Computer Applications in Geotechnical Engineering Prof. B. L. Tennekoon
9.20 – 9.40	Mapping Applications in Geotechnical Data Management Mr. A. Raviskanthan & Mr. A.H. Perera
9.40 – 10.00	Computerised Databases in Management of Geotechnical Data Mr. A. Raviskanthan, Mr. A.H. Perera & Miss. R.P.C.J. Rajapakse
10.00 – 10.30	T E A
10.30 – 10.50	The Uses of Finite Element Packages in Geotechnics Dr. H. N. Senevirathna
10.50 – 11.10	Analysis of Retaining Wall Behaviour Using Finite Element Method Dr. S.A.S.Kulathilaka
11.10 – 11.30	Deterministic Approach in Slope Stability Analysis Dr. K. Jeyadaran, Mr. N. Thayalan & Miss. K. Rajaratnam
11.30 – 12.30	Discussion
12.30 – 13.30	L U N C H
13.30 – 13.50	Computer Controlled Experiments Dr. T. A. Peiris
13.50 – 14.10	Analysis of Foundations and Soil Testing Using Spread Sheets Mr. T. Aravinthan
14.10 – 14.45	Discussion & Summing up.
14.45 – 15.15	T E A
15.15 – 14.15	Vendor Presentation of PC – ARC/INFO By EMSO Ltd. (Earth Science Division)

Sri Lanka Geotechnical Conference 1993

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FOREWORD

In order to obtain solutions for design problems in Geotechnical Engineering using the methods available for solving boundary value problems in the field of continuum mechanics, much research effort has been put in to develop constitutive relationships for the engineering behaviour of geological materials. During the last three decades, Geotechnical Engineers have used computers widely carrying out calculations to obtain solutions to problems and for storage and retrieval of mass of geotechnical data.

The Sri Lankan Geotechnical Society is anxious to see that its membership keep abreast with recent developments taking place around the world in Geotechnical Engineering. The society seeks the assistance and support from the members of the engineering profession to keep the professional standard of our engineers on par with the engineers in the international scene.

Eight papers on "Computer Applications in Geotechnical Engineering" written by local specialists will be presented and discussed in the seminar. We look forward to active participation from the membership in the seminar leading to exchange of ideas and enhancement of knowledge.

If our engineering professionals have to remain self reliant, they should keep abreast with the professional development taking place internationally. Professional societies should ensure that facilities are provided to our engineers for their professional development. Those engineers who fail to maintain their professional knowledge on level with engineers from other countries will not be able to contribute satisfactorily to our economic development.

A Thurairajah

Prof. A Thurairajah
President
Sri Lankan Geotechnical Society

Use of Computers in Geotechnical Engineering

B. L. Tennekoon

University of Moratuwa

1. INTRODUCTION

The advent of computers in the early 1960's has revolutionized all branches of engineering. In the case of Geotechnical Engineering its impact can be seen on Testing, Analysis, Design, and Construction, i.e. virtually every aspect of this branch of engineering.

Until the computer came on the scene, methods of analysis and design of foundations and soil structures were usually relatively simple and confined to hand calculations. Thus not only were simple idealisations made for the soil behaviour, but also in many cases rigorous analytical procedures could not be done and simplifications were introduced to obtain solutions. Again in designs, one of the established principles is to analyse several alternatives before selecting the most suitable for implementation. But before the era of computers, even the checking of one design took a considerable length of time. Therefore, engineers always under pressure to design and construct quickly, tended to ignore this basic principle of design and analyse only one of the alternatives.

All this has changed with the availability of computers. The ever expanding memory capacity together with the rapidity of carrying out numerical calculations has opened up almost limitless possibilities for which a computer can be used. Their uses are so widespread that it is almost impossible for a single individual to keep track of its development and applications even in one's own speciality.

More complex and sophisticated mathematical models are being used to predict the behaviour of soils; new analytical tools involving numerical analysis are being developed to analyse structures and soil behaviour; new design methodologies are being proposed - e.g. non-deterministic methods for evaluating the subjective judgement of engineers, or the probabilistic nature of risk; new testing procedures are being developed as the computer along with Data Acquisition Units and high precision fluid control electronic servovalves are able to control soil testing machines in a manner unthinkable earlier; large data bases are being formed from which information can be retrieved quickly; etc.

2. THE COMPUTER AS USED IN THE REDUCTION AND PRESENTATION OF DATA FROM SOIL TESTS

Soils unlike many other engineering materials have very variable properties depending on their location, method of deposition or formation, stress history, etc. Whilst Soil Mechanics and other sciences in Geotechnical engineering would like to idealise these materials, when used as engineering materials they often have to be used in the manner that mother nature has created them. For this reason, a great deal of emphasis is placed on the field and laboratory testing of soils.

The manual reduction of test results is very time consuming and could be a source for frequent errors. Therefore, one of the earliest uses of computers was in the reduction and presentation of data from routine soil tests.

In its simplest form, the computers were used to carry out simple arithmetic operations. At the next level of sophistication, the computer was used to fit a required relationship between 2 sets of variables. For example, the computer could be programmed to fit the best straight line to a set of reduced data for the determination of the strength parameters (c, ϕ) in a traixial test.

Or, again, the computer could be programmed to fit a parabola whose axis is vertical to the data from a Proctor Compaction test for the determination of the maximum dry density and optimum moisture content.

These simple operations are still done today, but whereas in the past these were done using programming languages such as FORTRAN or BASIC, today they are found to be done easily using electronic spreadsheets e.g. LOTUS 1-2-3.

The use of spreadsheets has several advantages over the use of computing languages, which are:

(i) it is easier to learn than a programming language;

(ii) the ability to change numbers and formulae easily in the spreadsheet enable the user to interact with the computer, thus giving it a 'glass box' nature as opposed to the 'black box' nature when using a programming language;

(iii) it has a good graphics capability and the ability to get a good hard copy, whereas this is considerably more difficult when using a programming language.

Thus spreadsheets are a form of interactive programming where the user can communicate with and control the program during execution.

3. <u>THE COMPUTER AS USED IN THE CONTROL OF SOIL TEST MACHINES</u>

The scope and nature of laboratory testing of soils has been revolutionized by the development of small low cost computers, Autonomous Data Acquisition Units (Data loggers), and high precision fluid control electronic servovalves. Whereas previously all test machines were stress controlled (constant loads applied and displacements being measured), or strain controlled (boundary of test machine driven at a constant rate and force being measured); the advent of the computer with the accessories mentioned earlier enabled the test machine to be controlled to give any designed stress path. Data from the test machine (i.e. loads, pressures, displacements) are obtained using electric transducers which are sensitive to the changes of these parameters. The output from the transducer is converted to digital form using an Analog-Digital converter; the data is now reduced and/or stored, and calculations done as required by the computer; and then the appropriate servovalve input signal to follow a given stress path is transferred to the machine through a Digital/Analog converter.

This system of testing has the other advantage that the Data Acquisition Units can scan the transducers much faster than is humanly possible. This allow for a greater number of measurements to be made in a test so that actual variations across the sample can be determined rather than make the assumption that the parameter is uniform across the sample. Further, since the transducers can be scanned extremely fast, e.g. a scan can be done at 10 channels per second; a parameter can be monitored at shorter time intervals than is humanly possible. This is a very big advantage when measurements have to be taken in dynamic conditions or when a parameter varies rapidly even under static loading conditions.

An example of the use of computers for stress control has been described by Wijeyesekera(1992) where he describes a purpose built consolidometer to measure the coefficient of lateral earth pressure at rest, K_o. This parameter K_o is defined as the ratio of the effective lateral stress to the effective vertical stress under conditions of zero lateral strain. One method of determining K_o is in the laboratory using the consolidometer, but it has been suggested that the lower rate of strain measured in the field could significantly affect the value of K_o. Therefore the consolidometer was built with a facility to measure the pore pressure gradient across the consolidating sample, and then keep it constant throughout the test. Tests were conducted at constant hydraulic gradients (i.e. $i= \Delta u/\gamma_w h$) of 5, 10, 20 and 50.

The apparatus which is shown schematically in Fig. 1 is fitted with transducers to measure

(i) total vertical stress - at the top and at the base
(ii) total lateral stress - at the base and at mid-plane
(iii) pore water pressure - at the base and at mid-plane
(iv) vertical displacement
(v) volume change.

The basic components of the apparatus are the consolidation cell, the micro computer, the Autonomous Data Acquisition Unit(ADU), and the Process Control loading system. The latter consists of an air pressure actuator connected to an air-oil interface with a hydraulic jack. The loading system was close looped via the ADU with the time interval for each regulation being set at 5 seconds. Thus the Data Logger scans all the transducers every 5 seconds and feeds these results to the computer. The input data is then reduced by the computer to determine K_o at the base of the cell, K_o at mid-plane of the cell, and the hydraulic gradient. Any necessary correction to the hydraulic gradient is then effected by sending the required signal via the Process Control to the Stepper Motor.

4. THE COMPUTER AS A MEANS OF INFORMATION STORAGE AND RETRIEVAL

It is being said that after the last industrial revolution in the 17th and 18th centuries, the next revolution is that which is taking place today and this is in the field of Information Technology. We are living in a period that is characterised by an explosion of information; and the computer is at the centre both storing the information and retrieving it.

The earliest application was in the storage and retrieval of library information. In this application both the reference information and the search program are stored in the computer. A search is initiated by typing in the desired key words.

Another potential application is in the development of Geotechnical Maps using existing borehole data. Tennekoon et al. (1988) prepared manually Geotechnical Maps which would be useful for structural building purposes based on the available data at the time. More data is now available, and they need updating. The computer appears to be the best method of doing this, and a project was started at the NBRO for this purpose. However, it was found that the retrieval of information from this system is slow.

Special systems called Geographic Information Systems are being developed where the computer will not only store large data bases but would be able to at the same time to retrieve and manipulate required information. Such a system is being used currently at the NBRO in its Landslide Hazard Mapping Project.

Mention is made later in Sec.6, where using a classification system based on Windows, case histories are stored in the computer and are then retrieved by a suitable search algorithm to best resemble a project that is being studied.

5. THE COMPUTER AS AN AID TO DESIGN

At the next International Conference on Soil Mechanics and Foundation Engineering to be held in January 1994 at New Delhi, India, one of the parallel sessions is titled 'Computer applications in Geotechnical Engineering'. The sub-sections of this session clearly identify the areas in which research and new developments are taking place, and these are

- Computer aided design
- Expert Systems
- Numerical, reliability and probabilistic methods.

This section will cover the computer as an aid to design, whilst the other areas mentioned above will be covered in Sections 6,7,8 and 9.

Computer aided design (CAD) refers to the interactive programming where the user communicates with the computer during analysis and design. Consider, for example, the design of a slope. The user has to first describe the problem to the computer; i.e. geometry of the slope, soil parameters, loads, etc. Whereas earlier the data had to be read by typing in numbers, today the user has the added capability of communicating graphically with the computer. Thus he can draw the geometry of the slope on the screen rather than describe it by sets of co-ordinates. CAD programmes are also 'User friendly' where the data is fed in when requested to do so by the computer. Once all the data is in and the method of analysis specified, the computer will carry out the required stability analysis taking into account different assumed failure surfaces, and then will display on the screen the factor of safety, the critical failure surface, and any other parameters which are required for revising the design. At this stage, the Design Engineer would pause to inspect the results. Then drawing from his experience and using the results which have been output, he may decide to change some of the slope parameters. The computer will then be asked to re-analyse the results; and so it goes on. The engineer draws upon his experience to determine what design conditions should be analysed and to interpret the results of the analysis. The computer rapidly supplies numerical results which the engineer uses to guide his judgement. At the end of perhaps a few hours, man and machine have accomplished a study which is more thorough than which several men working for a week would have been able to do before the advent of computers.

There are other ways in which the computer can be used as an aid to design. Seneviratne(1984) gives an example of an optimum design of a strip footing where the design parameters consisting of the width of the footing (B), depth of footing (D), and thickness of footing (T) are evaluated as a minimisation problem. i.e. Having evaluated the cost of the foundation as a function of B,D and T, and further imposing the conditions that any satisfactory design should provide

(i) adequate safety against ultimate shear failure of soil,
(ii) adequate safety against structural failure,
(iii) adequate protection against excessive settlements under working load;

then the cost of the foundation can be minimised using non-linear programming techniques to determine B,D and T.

A more common type of geotechnical design application is found in the 'design - as-you-go' approach to geotechnical design. One of the unique features of soils and rocks is that often design parameters vary considerably across the project site, and adequate site investigations cannot be carried out with normally allotted budgets. A typical example of such a situation is the construction of embankments in peaty soils. In such cases, the designs should be such that they can be modified during construction incorporating amended soil properties. This procedure is most easily done through a computer.

A further area is mentioned in Sec. 6 where Expert Systems are now being developed in which the judgement of experts in the design and construction of geotechnical structures is passed on to general practitioners and students through the computer.

6. THE COMPUTER AS USED IN EXPERT SYSTEMS

Expert Systems consist of a methodology where the computer is made use of to obtain the 'best' solution or a group of potential solutions for a particular situation from a number of available alternatives. Many geotechnical engineering problems conform to this model; e.g. the selection of the foundation system; the soil improvement method to be selected; etc.

One of the requirements of an Expert System is that it should be able to translate the user's problem into a form which can be handled by the computer. Often a geotechnical engineer's comprehension of a problem is affected by a large number of factors which are case-specific, context-dependent, and subjective. It has been shown that the application of Fuzzy sets theory is a method by which such subjective information can be converted to numerical form.

An example of an Expert System developed for the selection of the most suitable ground improvement technique has been described by Chameau and Santamarina(1989). In the development of this system, the important parameters which affect the choice of method have been first identified. Some of these are type of project, time available importance of increasing strength importance of reducing deformation importance of modifying permeability position or depth of layer to be improved distance to adjoining property, size of area to be treated and depth to be treated, soi type, particle size, relative density, equipment availability, material availability, etc.

The next step is evaluating different methods of soil improvement. In their example, 40 different methods of soil improvement were considered. Some of these were Densification blasting, Vibrocompaction, Compaction piles, Heavy tamping, Vibratory rollers, Pre-loading, Pre-loading and drains, Surcharge fills, Surcharge fills and drains, Cement grouting, Chemical grouting, Admixture stabilization, Stone columns, Geotextiles, etc.

Then, taking any one soil improvement technique, each single parameter considered previously is given a rating between 0.0 and 1.0. A rating of 0.0 means that the parameter is of no importance and a rating of 1.0 indicating that the parameter is most important in selecting the type of ground improvement. The parameters of the project are then compared with the parameters of the method and an 'acceptability value' is determined. (The parameters of the project have to be provided by the user). The procedure is repeated for each of the soil improvement techniques and the computer will select/output the method with the highest overall acceptability.

Another advantage of Expert Systems is that it allows for the transfer of knowledge and experience of a few to a large number of practitioners.

This is because the system contains records of a large number of case histories, with details of design and construction guide lines. This aspect is particularly useful in a field such as Geotechnical Engineering where often decisions are taken based upon the experiences of previous cases. Therefore, case histories are stored in the computer in the same dimensional space that was used in evaluating/classifying the different methods of soil improvement. Thus, the computer can be programmed to select the case histories which resemble the actual project as close as possible, and then find out the solutions, design and construction methods, adopted by the expert. It is also possible to ask the computer why a certain method was not selected. Then the knowledge of the practitioner can be increased, or if there was an erroneous input this could be detected and the run repeated after correction.

7. <u>THE COMPUTER AS USED IN RELIABILITY AND PROBABILISTIC METHODS</u>

Engineering science until very recently has developed as a deterministic science in which analysis is carried out to determine stresses, strains, displacements, bending moments, shear forces, etc. However, it is now realized that there are several aspects of engineering for which deterministic methods are not available. e.g. If an engineer is asked to evaluate the serviceability of a bridge, or the safe functioning of a dam, or the distress condition of a highway pavement; then the subjective judgement of inspection engineers based on their experience and expertise is essential for this evaluation. A whole new branch of engineering is emerging where rating systems are being developed to answer this type of problem with Fuzzy Numbers and Fuzzy sets being employed to introduce human uncertainty. An example has been given by Gunaratne et al.(1988).

Another area of research which is going on is in the probabilistic analysis of slopes. It has been stated by Baecker(1982) that "The one sure thing in rock engineering is uncertainty. Rock masses are poorly characterized, engineering mechanics provides imperfect models, and load conditions are inadequately specified".
What Baecker has stated about rock slopes

are also true of the slopes we have in this country in residual soil formations. In the presence of uncertainly, absolute safety with respect to sliding is an unattainable goal. Therefore, the analysis and design of such slopes must include the consideration of risk as measured by the probability of failure. An example of how such a model can be developed has been provided by Chowdhury and Grivas(1982).

Another example of the application of reliability methods is given by Wickramasinghe(1986) where he determines the reliability of a pile foundation used in the North Sea. In the deterministic approach, the factor of safety of the pile is determined by using fixed values of known axial load, shear strength of clay layer, adhesion factor, bearing capacity factor.

In the probabilitic analysis, these parameters are used with some attached standard deviations and the probability of failure is determined. His results are shown in Table 1.

Depth of pile (m)	Deterministic Factor of safety	Probabilistic Probability of failure
60	0.66	0.918
80	0.94	0.448
100	1.22	0.074
120	1.50	0.006
140	1.78	0.001
160	2.06	$< 10^{-6}$

The availability of high speed computers has made these computations relatively simple, and the computer has been a catalyst in the development of new methods of analysis.

8. THE COMPUTER AS USED IN NUMERICAL ANALYSIS

Engineering science deals with the application of scientific principles to the analysis and design of engineering structures, processes, machines, etc. The capabilities of the computers are so great that today they are used almost everywhere that engineering science is applied. Their use ranges from the reduction of some simple experimental data to complete numerical analyses. In this section it is proposed to deal with some of the areas in which the Author has been working. Computer programmes for these are available with the Author.

8.1 THE COMPUTER AS USED IN THE STUDY OF OVERALL EQUILIBRIUM OF A SLIDING MASS OF SOIL

Even before the advent of computers, one of the methods of analysis for a class of Geotechnical engineering problems was to determine the failure loads in soils and rocks by the application of the Upper Bound Theorem of Plasticity. This method of analysis required the determination of the force required to cause failure along an assumed failure surface, and thereby determine the critical failure surface and the limiting failure load. Two such examples are given in this section.

8.1.1 Stability Analysis of slopes

In the stability analysis of slopes, the sliding mass is divided into a number of vertical slices, and equations of equilibrium are written both for the individual slices and for the overall sliding mass. However, because the number of equations available for solution are less than the number of unknowns, a further assumption is made with respect to the interslice forces.

For example, in the Swedish Slices Method, circular failure surfaces are assumed, and it is assumed that for each slice the interslice forces are equal and opposite. This leads to an equation for the Factor of Safety (F) of the form

$$F = \frac{\Sigma \{ c'l + (W \cos \alpha - ul) \tan \phi' \}}{\Sigma W \sin \alpha}$$

where the summation is done over all the slices and the parameters for each slice are as given in Fig.2.

Although this equation can be solved manually, it becomes time consuming when a large number of possible failure surfaces have to be considered, and changes in slope parameters have to be made during design.

Studies have shown that the Swedish Slices Method is not very accurate when seepage forces are present, and in such cases Bishop's Method has been recommended. In Bishop's Simplified analysis again circular failure surfaces are assumed, and the assumption for interslice forces is that these forces are horizontal. This leads to an equation for F as

$$F = \frac{\Sigma [\{ c'b + (W - ub) \tan \phi' \} \times M]}{\Sigma W \sin \alpha}$$

$$\text{where} \quad M = \frac{\sec \alpha}{\left(1 + \frac{\tan \alpha . \tan \phi'}{F}\right)}$$

Since F occurs on both sides of the equation, an iterative procedure has to be used for solution, and hence this method is most suitable for the computer.

Using Bishop's simplified Analysis, Bishop and Morgenstern(1960) have developed a set of stability charts to be used for Effective Stress Analysis. However, these charts were limited to a maximum slope of 2 H: 1 V; i.e. 26.5^{o}. Since many of the slopes in this country exceed this slope angle, the Author has with the help of 3 undergraduate students extended these charts to cover slopes upto 90^{o}. A typical set of curves is given in Fig. 3.

8.1.2 Bearing Capacity adjacent to slopes

Terzaghi's equation for the ultimate bearing capacity for a strip footing on a flat ground is written as

$$q_{ult} = c\,N_c + q\,N_q + (\gamma B/2)\,N_\gamma$$

where N_c, N_q, N_γ are called the bearing capacity factors which are a function only of the friction angle .

When the footing is placed close to the edge of a slope as in Fig. 4(a), it is clear that the ultimate bearing capacity would be reduced depending on the distance to the edge of the slope. The Author with another set of 3 undergraduate students has developed computer programmes for the solution of this problem using the method proposed by Saran, Sud and Handa(1989).

In this analysis, it is assumed that one sided failure would occur along a surface such as DEK. The curve EK is assumed as a log spiral whose pole would vary along the extension of EA, and ADE is an elastic wedge. The resistance of the soil on the side of the flat ground (i.e. region DEFG) is only partially mobilized, and this is characterized by a mobilization factor 'm'. Thus the shear stress on EFG is given by the equation

$$\tau = m \; (c + \sigma \tan \phi)$$

The magnitude of the bearing capacity depends on the value of m which is yet unknown. In order to determine m, a graphical procedure is used, and this will be illustrated with reference to the determination of N_γ .

N_γ is determined for the case c=0, q=0 .

The forces on the elastic wedge under the footing are as shown in Fig. 4(b).
It should be noted that both $P_{p\gamma}$ and $P_{pm\gamma}$ vary with m.

Selecting any value for m,

$P_{p\gamma}$ is first determined by the upper bound method as the minimum of the force on AE. Similarly, $P_{pm\gamma}$ can be determined and hence the ratio of ($P_{p\gamma}$ /$P_{pm\gamma}$) . These calculations are repeated for different values of m, and a graph is plotted of ($P_{p\gamma}/P_{pm\gamma}$) with m. This is shown in Fig. 4(c). The ratio of ($P_{p\gamma}/P_{pm\gamma}$) is then determined by considering the equilibrium of the wedge AED. A second graph of ($P_{p\gamma}/P_{pm\gamma}$) with m is drawn, and the point of intersection of the 2 sets of curves gives the mobilization factor 'm'. (see Fig. 4(c). Thus N_γ can be determined.

8.2 THE COMPUTER AS USED IN THE NUMERICAL SOLUTION OF GOVERNING DIFFERENTIAL EQUATIONS

When using engineering science to analyse Geotechnical engineering problems, often differential equations are obtained for which there are no exact solutions.
Such equations can be solved using numerical methods, but most of these solutions would not have been practicable without the availability of computers. Some of the method of solution are : numerical integration; finite deference method; method of weighted residuals; method of characteristics; and methods of integral trasform. The use of some of these methods will be illustrated in this section.

8.2.1 Use of Finite Difference Methods to study the consolidation of clays

Geotechnical engineering problems are sometimes classified into

(i) Equilibrium or steady state problems where the time t is not a variable; e.g. stability of slopes, bearing capacity, seepage through a dam, etc.

(ii) Transient or propagation problems where time is a variable.
The consolidation of clays belongs to this second category.

The theoretical model for 1-D consolidation of a saturated clay proposed by Terzarghi gives the partial differential equation

$$\partial u/\partial t = C_v \; . \; \partial^2 u/\partial z^2$$

where u is the excess pore water pressure at depth Z and at time t.

Analytical solutions for the progress of consolidation are available only for a few relatively simple cases. However, for these and more complex cases, the consolidation equation can be solved using the Finite Difference Method.

Two methods of Finite Difference solution are available - the Explicit Method of solution and the Implicit Method of solution. Their formulation is shown in Fig. 5. The Explicit Method frequently imposes an unreasonably small limit on the time step used. Hence the Implicit Method of solution (corresponding to the Crank - Nicolson solution) is preferred.

There are other theoretical models for consolidation, and often the Geotechnical engineer has to make the decision as to which model he should use for predicting field settlements from laboratory test results. In the method given by Tennekoon(1990), each of the consolidation models are considered in turn, and the constants of the model are obtained by curve fitting to the measured laboratory settlement-time relationship. Then using these constants, the predicted pore pressure-time relationship is obtained for each model with assistance from the computer. The predicted relationships are compared with the measured relationship to select the most appropriate model.

8.2.2 <u>Use of Method of Characteristics to study bearing capacity</u>

The application of the principles of continuum Mechanics to soil gives 2 partial differential equations of equilibrium which are:

$$\partial\sigma_x / \partial x + \partial\tau_{xy} / \partial y = 0$$

$$\partial\tau_{xy} / \partial x + \partial\sigma_y / \partial y = \gamma$$

When considering failure condition, i.e. in the limit state, the third equation to solve for the 3 unknowns (σ_x, σ_y, τ_{xy}) is the Mohr-Coulomb failure criterion which can be written as

$$\{(\sigma_x+\sigma_y)/2+c \cot\phi\}\sin\phi = \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2 + (\tau_{xy})^2}$$

It can be shown that these 3 equations form a hyperbolic set of equations for which a solution can be obtained using the method of characteristics; i.e. for equations of this type there is at every point two directions called the characteristic directions along which the partial differential equations get transformed to ordinary differential equations.

This method has been applied to the study of the bearing capacity of foundations, where starting from a boundary at which the stress conditions are known, the characteristics are developed and the simple differential equations are integrated along the characteristics to obtain the stress conditions at another boundary. The characteristics as obtained in the bearing capacity problem are shown in Fig. 6. (Tennekoon(1970)

8.2.3 <u>Use of Integral Transform Method to study soil structure interaction.</u>

When studying the stresses and strains, displacements, etc. under working load conditions, the 2 equilibrium equation given in Sec. 8.2.2 are solved with a third equation which is related to the material idealisation. For example, if the material is assumed to be an isotropic elastic material where the stresses and strains are related through Hooke's Law, the 3rd equation takes the Laplace form

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) (\sigma_x + \sigma_y) = 0$$

In the integral transform method, using special functions these partial differential equations are transformed to ordinary differential equations; and at the same time the transformation ensures that the boundary conditions are satified.

An application of this method is found in the program FOCALS (1975) (Foundations On Cross Anisotropic Layered Soils) developed at the CSIRO, Australia. As the name implies, the program can take into account horizontally layered soils which are elastic but cross-anistropic. i.e. the elastic constants in the vertical direction are different from those in the horizontal directions.

The structure and the soil are considered jointly so that displacements of foundations affect the stress conditions in the superstructure. The stiffnesses of structural elements and the foundation elements are computed using the SAP program; and the stiffness of the ground continuum is calculated by the application of the Double Fourier Transform as the transform function. This gives the force matrix [P] in terms of the displacement matrix [X] through the stiffness matrix [K].

i.e. $[P] = [K][X]$

Hence $[X] = [k]^{-1} [P]$

Some examples of their use are given in Figs. 7a and 7b.

8.3 THE COMPUTER AS USED IN FINITE ELEMENT ANALYSIS

The development of the finite element method has revolutionized the analysis of Geotechnical engineering problems. In contrast to the many traditional approaches, the method is capable of handling such complicated aspects of real soil behaviour such as non-linearity, non-homogeneity and anisotropy; the method can handle almost any shape of boundary and soil profile; and the method allows variable surface and body forces to be introduced. The accuracy of the method depends on the type of elements used. The equations relating [P],[K] and [X] are as indicated in Sec. 8.2.3; and hence the major restriction of the method is that the total number of elements that can be used are limited by the memory and speed of the computer. However, it can be stated that the analytical capability of this method far exceeds that of the geotechnical engineer to measure the properties required as input to the analysis.

A very simple example of its application will be given where using line elements only raft foundation can be analysed as series of strip foundations or combined footings.

8.3.1 Flexible analysis of a combined footing

In the design of foundations, there are 2 different methods of analysis based on the assumption regarding the pressure distribution under the foundation. In the Rigid Analysis the pressure distribution is assumed to be linear or planar whilst in the Flexible Analysis the pressure distribution is assumed to vary depending on the deformation of the foundation at each point. The latter is referred to as Soil Structure interaction.

One of the earliest methods of soil structure interaction studies was based on the Winkler assumption that the foundation pressure at any point is proportional to the defelection at that point. Bowles (1974) has developed a computer program to analyse a combined footing using this assumption.

The beam is first divided into a series of line elements by suitably placed nodes. Nodes are selected among other points to be at points of load application. The relationship between the loads [P] and the displacements [X] is as shown in Sec. 8.2.2.

The Author with a set of 3 undergraduate students has analysed the raft foundation of the Sri Lanka Institute of Architects building by dividing the raft into a series of strips. The bending moment diagram as obtained for one of these strips according to the flexible analysis with varying stiffness of the foundation relative to the soil is given in Fig. 8.

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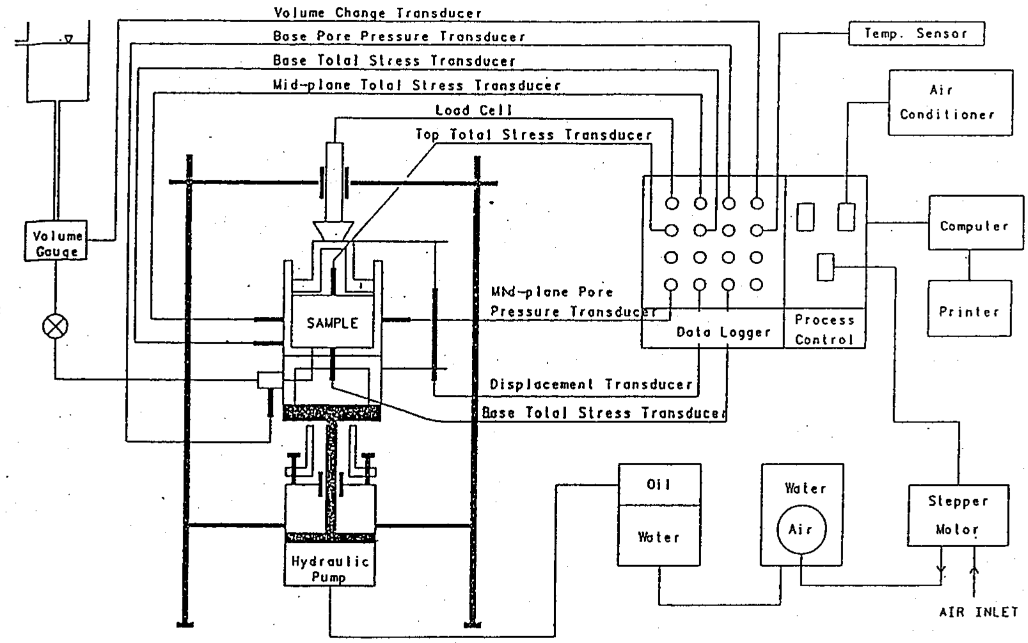


FIGURE 1 : Schematic Diagram of the Multipurpose Consolidometer
Ref. Wijeyesekara (1992)

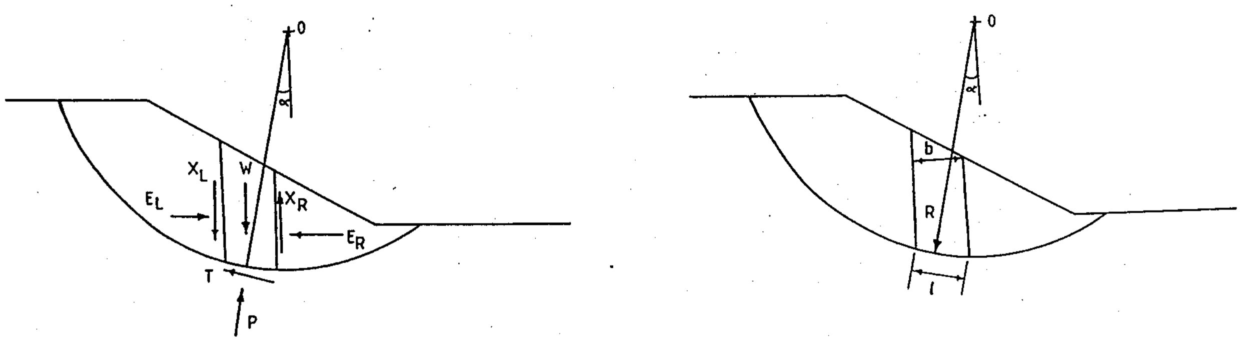
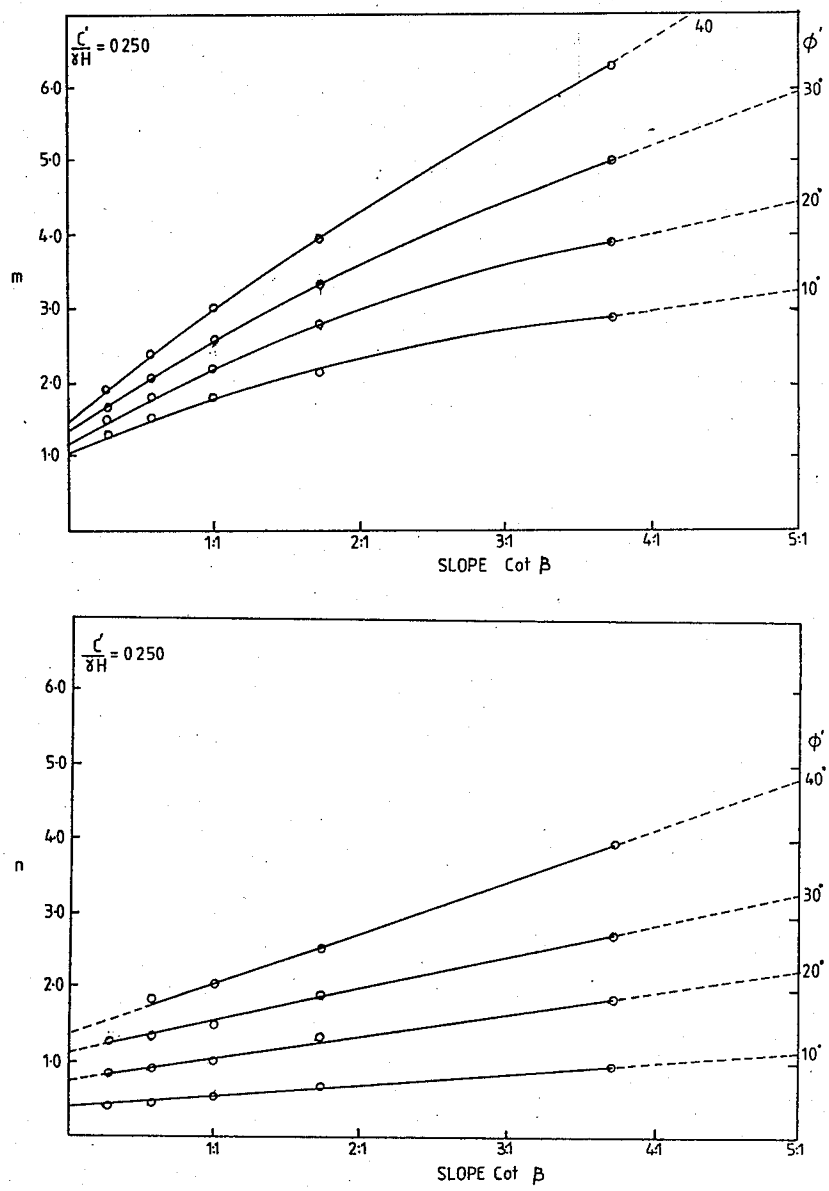


Fig. 2 - Notations Used in Slices Method for Stability Analysis



$F = m - n.r_u$

Fig. 3 - Extension of Bishop and Morgenstern Charts for Stability Analysis

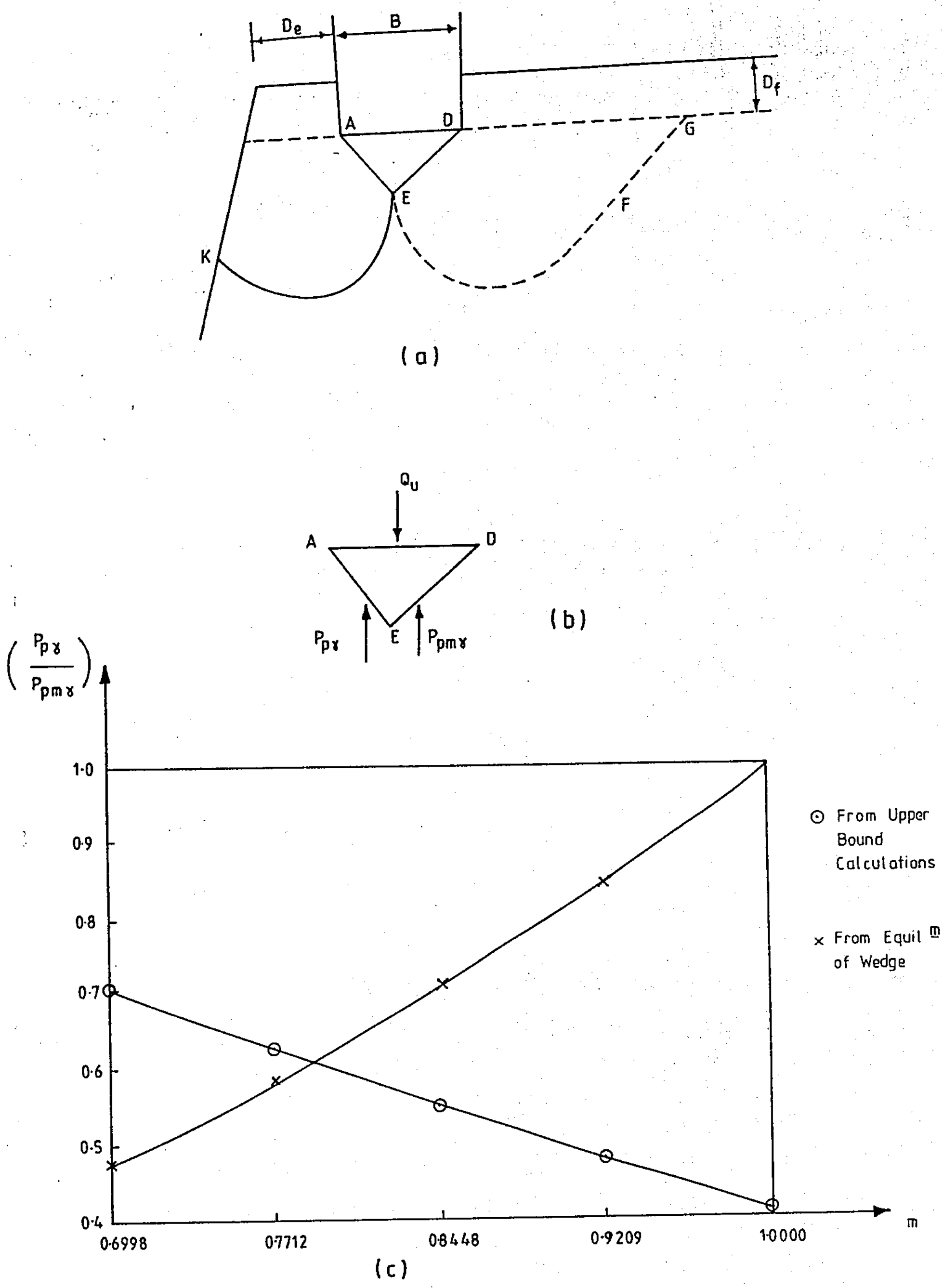
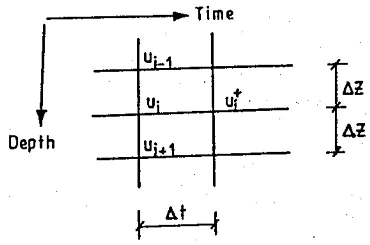


Fig. 4 - Analysis for Bearing Capacity adjacent to Slopes.

$$\frac{\partial u}{\partial t} = C_v \cdot \frac{\partial^2 u}{\partial z^2} \qquad \text{——— (1)}$$

Explicit Method of Solution



$$\frac{\partial u}{\partial t} = (u_i^+ - u_i) \,/\, \Delta t$$

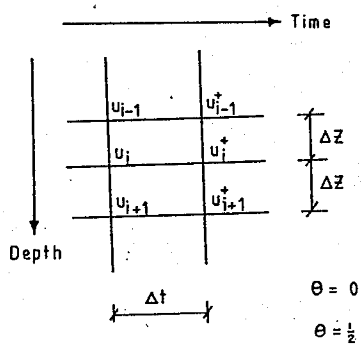
$$\frac{\partial^2 u}{\partial z^2} = (u_{i+1} - 2u_i + u_{i-1}) \,/\, (\Delta z)^2$$

$$\frac{(u_i^+ - u_i)}{\Delta t} = C_v \frac{(u_{i+1} - 2u_i + u_{i-1})}{(\Delta z)^2}$$

$$u_i^+ = u_i + \beta \left\{ u_{i+1} - 2u_i + u_{i-1} \right\} \qquad \text{——— (2a)}$$

$$\beta = \frac{C_v \cdot \Delta t}{(\Delta z)^2} \qquad \text{——— (2b)}$$

Implicit Method of Solution



$\theta = 0$

$\theta = \frac{1}{2}$

$\theta = 1$

$$\frac{\partial u}{\partial t} = (u_i^+ - u_i) / \Delta t$$

$$\frac{\partial^2 u}{\partial z^2} = \frac{1}{(\Delta z)^2} \left\{ \theta \left(u_{i+1}^+ - 2u_i^+ + u_{i-1}^+ \right) + (1-\theta)\left(u_{i+1} - 2u_i + u_{i-1} \right) \right\}$$

$$0 \leq \theta \leq 1$$

Fig. 5- Finite Difference Formulation of Terzaghi's equation of Consolidation

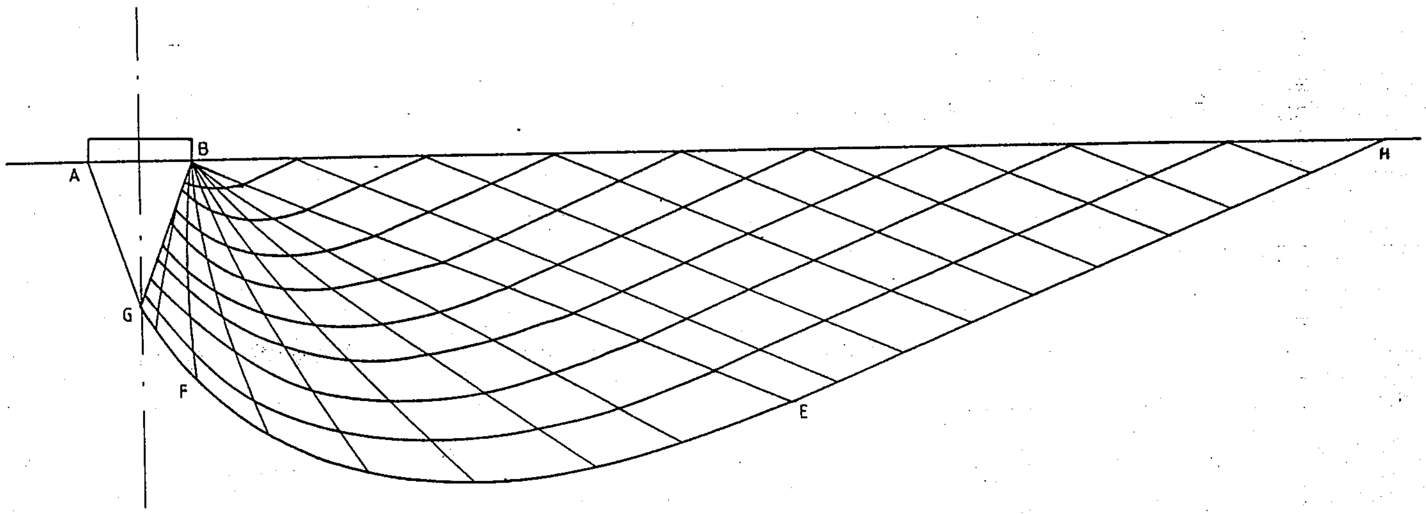


Fig. 6 - Characteristics for Bearing Capacity Problem
(Ref. Tennekoon 1970)

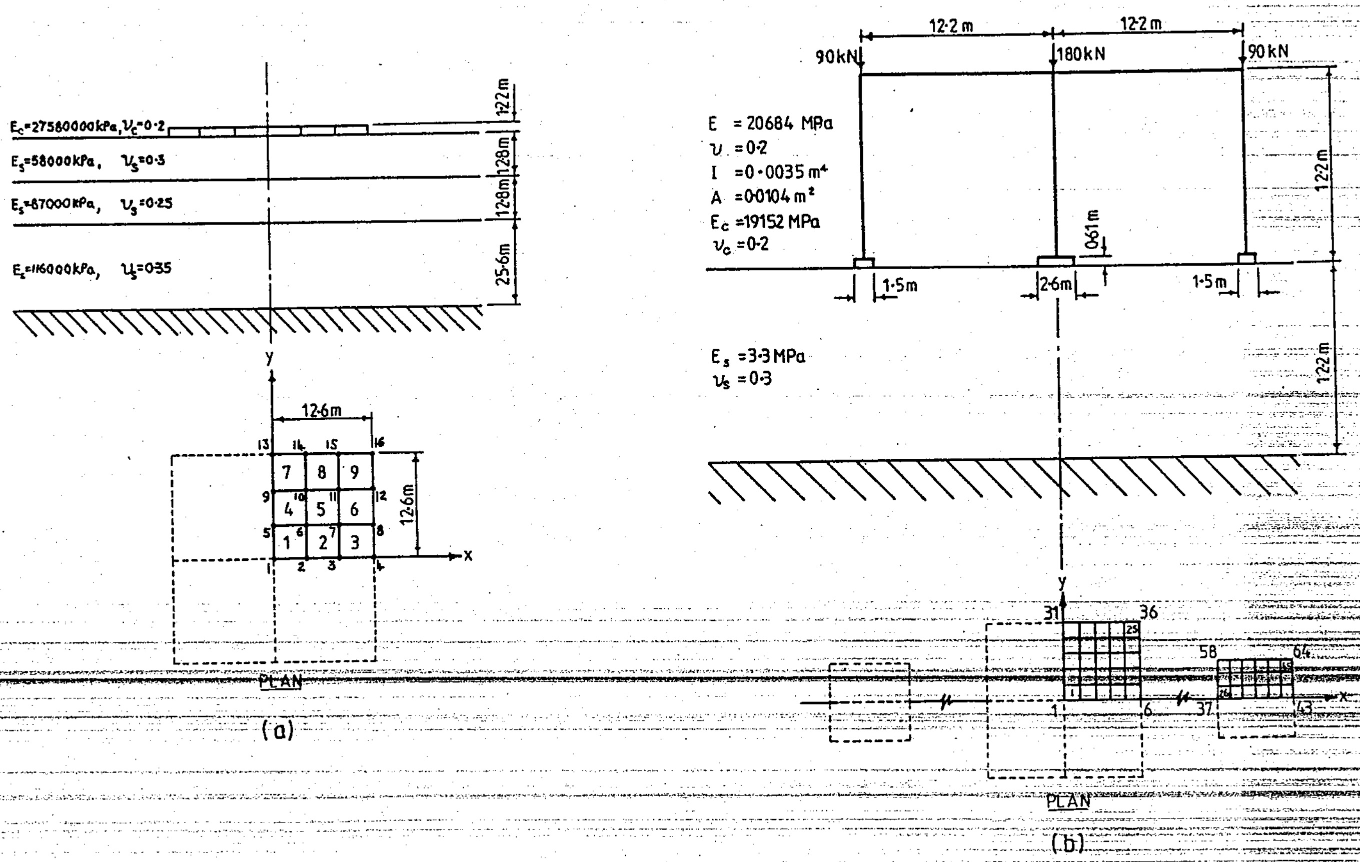
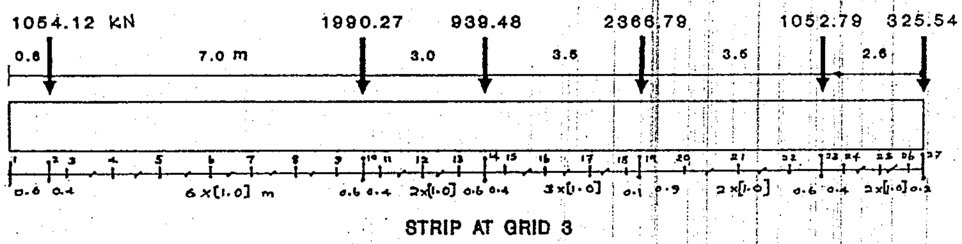


Fig. 7 - Applications of FOCALS Programme

Ref. FOCALS (1975)



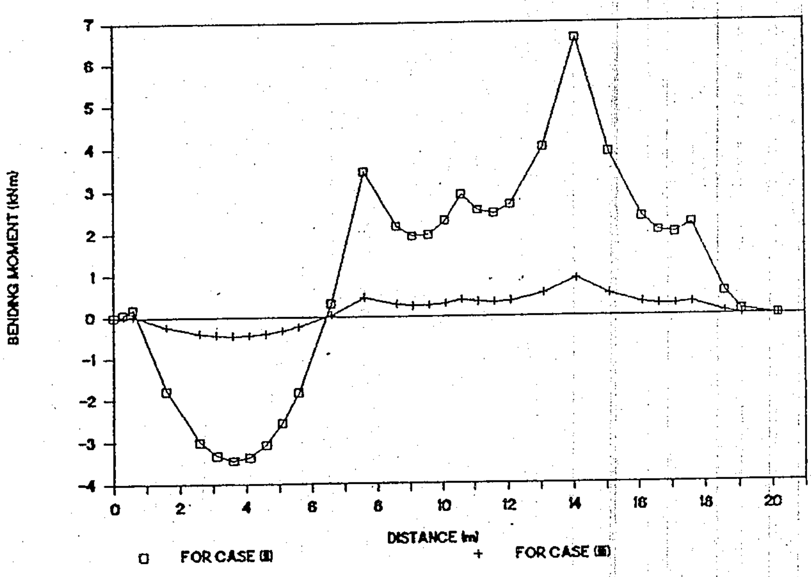


Fig. 8 - BM Diagram for Strip at Grid 3 using Bowles Program for varying stiffness of foundation

Mapping Applications in Geotechnical Data Management

A. Raviskanthan & A. H. Perera

National Building Research Organisation

ABSTRACT: The use of maps has always played a key role in Geotechnical Engineering, as maps have been liberally used to interpret results from data. The exercise of mapping however, was confined to manual procedures until recently. Mapping on computers required expensive equipment, which was often custom made to suit the purpose. Thus, the use was limited to specialised applications which needed the costly input, retarding the switch to computerised mapping.

The paper illustrates some of the mapping applications carried out in the National Building Research Organisation. These applications relate to many forms of maps such as former landslides and Colluvium maps, Bedrock Geology and Structure maps, Slope range and Slope Category maps, Land form and Erosion maps, Hydrology and Drainage maps, Rainfall maps, Human settlements and Infrastructure maps, and Landuse Management maps. The mapping of so many different kinds of maps posed special problems which had to be solved by customising the application software.

The data on computer has to be integrated, to reap the full benefit from the process of computerising. This requires the use of a Geographic Information System (GIS) or allied system capable of integrated data processing. The processed data allowed solutions to various queries to be identified and mapped.

The paper discusses Geotechnical Mapping from bore logs, which will allow the user to benefit from previous Geotechnical Investigations, in the vicinity of the site. The paper also discusses some hardware and software systems required for satisfactory applications.

1.0 Introduction

Maps have been used from ancient times, for many purposes such as navigating, military campaigns, and civil works. Modern maps include data from Soil profile and Geology which are used for a wide range of applications. These have been mainly used for placing geographic data along with other forms of data on two dimensional space. The notations and symbols used varied among applications, countries, etc. Different scales were used to suit the purpose of the map. These inturn caused problems in computerising, as we will see later.

Mapping efforts for a long time were manually carried out, as the tools of trade, for computerised mapping were prohibitively expensive. Recent advances in the Computer Industry have brought the prices of computer hardware down appreciably. The late seventies and eighties have seen the evolution of new disciplines such as Geographic Information Processing, which have benefited from these spectacular advances in Computer Hardware Technology. The continuing development of cheaper computing power, has brought the mapping ability to moderately budgeted projects, which can be undertaken by national agencies and institutions.

2.0 To Computerise or not

One of the crucial decisions in using maps for Geotechnical Applications, is to decide whether or not to computerise the data management. There are many advantages in computerising mapping work.

a) The simplest of all advantages is the ability to incorporate data collected by different agencies on one single map. Due to lack of a generally accepted standard scale, the maps were in different scales posing problems in collating and analysing data from different agencies. This has been improved in the last few years.

b) The symbols used in manual mapping had to be incorporated into the computerised map, so that the users do not have to change their accepted notations and symbols. These posed special problems to the authors, as many notations had to be customised for the mapping software, and will be discussed later.

c) The data once accumulated on the map could be analysed in any manner as seen fit, by experts. This would have posed serious limitations if carried out manually, as a humans could only analyse a few overlays at a time.

d) The outputs of the mapping analysis could also be inputs to future work, as data would already be available on Computers.

e) Reproduction of maps was easier, after computerisation. The maps also could be obtained in different scales, to suit the needs of the users.

Though many advantages are there, Computerised maps also pose difficulties. The time taken in data capture can be considerable. Though, contrary to popular expectations, the data capturing stage of mapping can take many months. Generally in Sri Lanka, mapping information is digitized into the computer by a laborious method, similar to tracing. This will take almost the same time as manually preparing the map, though after training operators can show performance gains over manual mapping, due to the special features available in the application software.

Modern techniques such as scanning, allowing reduction of time in capturing data are too costly to be recommended, unless for large or important jobs where costs could be justified. It should be remembered that the scanned image, should be converted to data types, such as lines, polygons etc., and cleaned before data could be analysed further.

Computerised mapping is generally costlier, than manual mapping, due to the hardware, software, and output costs. The output costs can be considerable unless proper care is not taken at the beginning of the exercise. The ability to access data quickly and analyse them in any complicated fashion, (not possible manually), makes them attractive to scientists.

3.0 Hardware and Software platforms for mapping

The computer systems that run mapping software ranges from personal computers to multi-user minicomputers. The authors used cheap computer systems for data capture. Digitizing was carried out using 80286 based processors, and processing was carried out in faster machines (80386 and 80486 based machines). The authors used machines with larger hard disk capacity, so that the temporary storage required by modern packages could be satisfied. In some cases temporary files of over 75 MB, were formed, and storage requirement of 4 - 5 times the data file size was a common occurrence.

The software platform was based on AutoCAD^{tm}, which was generally used as a drafting package in NBRO. Early versions of AutoCAD (Release 9 & 10) were used to facilitate digitizing by less powerful computers. The processing of data was done on Release 11 of AutoCAD to tap the advanced features of the GIS package.

Data available on maps was integrated using ArcCAD^{tm}, a hybrid software of AutoCAD and ARC/INFO^{tm}. The authors preferred ArcCAD to any other software as it was fully compatible with ARC/INFO, a leader of geospatial management software while working within AutoCAD. This also helped in combating a high staff turnover, as recruiting staff with knowledge of AutoCAD was easier.

4.0 Mapping using AutoCAD

The data capturing stage was digitizing, using AutoCAD. Data for several state of nature maps were captured. One of the difficulties of mapping was to select the sketching increment. This value, determined the spacing between points, picked up during digitizing and had a direct bearing on the accuracy of the contour maps. A larger increment would have made the contours coarse, while allowing ease of data manipulation. A smaller increment, would have increased the size of the map, causing problems, in storage and delays in processing of data. After many trials the authors selected the increment of sketching as 10, for the base map of 1:10,000 scale. This increment was used to digitize contours, which formed a basis of slope category map.

4.1 Slope range and Slope Category maps

The Slope range provides a critical input for many Geotechnical Applications. Building regulations, stipulate areas, which are too dangerous to build on. These are also used in Macro Planning, and in Threshold Analysis, (Kozlowski et al.) which allow Engineers and Planners to leave out large tracts of areas, as unsuitable or suitable with constraints (financial and technical).

The authors found that, the facility to generate slopes off the computers, is not available as a built in feature in most GIS packages. High end packages such as, ARC/INFO (TIN), GENASYS are some which offer these.

The slope range maps were generated by programming, in AutoCAD, and QuickBASIC. The data available on computer as contours, was used as input for slope processing. Of the two types of computer based methods, the authors adopted the raster based method of using cells, which were either rectangular or square. The properties were assigned to the centroid of the cell and, the analysis was carried out by assigning attributes or values to each cell.

An AutoLISP routine was used to generate more points by smoothening quadratic splines and extracted the data as a DXF file for subsequent processing in QuickBASIC. The QuickBASIC routine extracted, the X,Y,Z ordinates of points. The authors (1992) used methodology, to evaluate the cell heights based on weighted averages based from known points. A neighborhood analysis was used to evaluate the slope value and classify the cell into the desired category.

The classified slope categories were then written into the DXF file along with other necessary information such as limits, text and legend so that they could readily be transferred into AutoCAD. The maps are continuously being improved so that, better solutions are found.

4.2 Bedrock Geology and Structure maps

AutoLISP, the programming interface available in AutoCAD was extensively used by authors to help digitizing. These routines considerably reduced work, so that only the starting and ending points along with the dip or strike value were needed to complete the entry, to indicate dip and strike directions in a Geology map. Appendix A gives a sample of the legend used in the mapping of Geology maps, and former landslide maps.

4.3 Former landslides and Colluvium maps

As in conventional mapping, different maps needed different symbols and legend based on the information coming on it. These symbols ranged from hatch patterns to special symbols and boundaries which could not be covered by conventional AutoCAD symbols sets.

Some of the symbols were generated on computer using programming (for hatch patterns) wherever possible. The authors found the emulation of colluvium and boulder symbol sets to be a difficult task as AutoCAD had a limitation in its hatch pattern definition, which limited the patterns to one based on straight lines or dots. Thus rings or irregular boulder patterns could not be defined as hatch patterns. This was overcome by defining them as blocks and inserting them manually, wherever required. Similarly boundaries represented by complex symbols posed difficulties, which were overcome by defining blocks and inserting them on the boundary, with the measure and insert option. All these while solving the immediate problem of mapping, posed other problems when collating data from different maps and integrating them together to form one spatial database, which will be discussed later.

4.4 Landform, Landuse and Human Settlement maps

These maps did not make any special difficulties, as the areas could be digitized directly, without the use of special symbols. The legend had only text entities, and these could readily be transferred to the GIS as annotations, and used.

4.5 Prototype Maps

Prototype maps were developed and used for each category maps so that legend, logo and other details which were common to each category, were inserted directly into each map. Refer Appendixes B through F for more details.

5.0 Integration of data

The digitized data was checked whether it could fit into the necessary forms of data recognized by a Geographic Information System (GIS). Spatial data occurs in three forms, points, lines, and polygons or areas. A soil type or slope category appears as a polygon. Rivers and roads are lines (skinny polygons), and wells, stream intersections and public utility locations such as street lamps, fire hydrants etc. are points. In a similar fashion, all features of the landscape should be defined to one of these three spatial data categories.

Because of the above requirement, the authors found it difficult to denote colluvium deposits, as rings. They used different sets of data for entities that could not be defined directly into one of the three data types. The redundant set of data consisting of rings in the case of colluvium, was replaced by a polygon, which indicated the boundary of the deposit. The requirement to have a closed polygon, placed demands on the field investigators to provide the extent of the colluvium deposit, which was at times difficult to define.

5.1 Defining the spatial database

The authors determined the category into which the entities were to be input. The possible categories comprised of the following: polygon, line, point, annotation and record. The annotation consists of a text entry to depict a name such as a street, or the name of the AGA division. A block with an attribute was extensively used to define landform, landuse and human settlement properties of the region. The attributes of this block was read into a record theme while features were being added to the polygon theme consisting of additional data. The authors used a similar method (1993) to tag the borelog data to borehole locations, through an external database, as explained later.

A theme was defined based on the state of nature map such as geology, and the database associated with it from AutoCAD drawing was created. The drawing areas defined by polygons were cleaned, to remove of any dangles and over shoots. The sliver polygons were also removed with fuzzy tolerance, to link the drawing database to the theme as a coverage.

Any other information attached to the spatial features can be added to the basic database thus created, using database commands by joining or relating fields of information in order to create a comprehensive record containing the information related to the various spatial objects. For example a polygon entity that represents a parcel of land may contain social information, in addition to its locational and topological data, such as information related to its population, damage potential etc., to be used in zoning the hazard areas. The software allows as much as 256 categories of information depending on the specific requirements of the user.

5.2 Geospatial Analysis of data

Primary GIS operations include basic functions such as area and distance measurement, buffer generation, re-classification, and boolean operations (+, -, *, /, log, exp). Overlay analysis of maps depicting different parameters, weighted region and data aggregation, buffer creation, and record data matching with entities are some of the very powerful features useful for geotechnical applications. Buffer creation was used to simulate the effect of a slide on its neighborhood. Similar option of joining maps, make the neighborhood analysis easy. The weighted region approach also has been used to analyse data.

The landslide hazard assessment by integration of one or more state of nature maps by Bhandari et. al. (1993), defines the rating to be assigned as a percentage. Each category such as colluvium with slope range and rainfall attribute to a fixed percentage of rating. Similarly, other clusters (consisting of bedrock Geology, and colluvium) add up the rating percentage to 100. Based on the grand total of hazard rating, an area is classified into the risk category.

5.3 Simulation Modeling

The GIS can be used in studying the effect of varying parameters using "Simulation Modeling". The effect of changing landuse, human settlements etc., and varying climatic conditions may very well alter a harmless slope into a hazardous killer area. These simulations can be used to consider changing hazard ratings and predict the effect of variables on the area under consideration.

6.0 Geotechnical database of a region

The soil parameters of an area are of interest to many professionals, to obtain data regarding sub soil conditions. Since boring, and other forms of sub-soil exploration can be costly and time consuming, bore hole data can be stored on computer, to benefit from past drilling and testing. Raviskanthan et. al. (1988) attempted to map soil properties of low-lying areas on computer using AutoCAD. The system however, had the limitation when interpreting data from adjacent boreholes.
The map of Colombo was digitized, to provide a spatial base for information. With GIS technology, authors sucessfuly created an external database on dBASE III[tm], which is linked as a record theme to programs like ArcCAD. The database can be used with GIS functions such as locating peat within 1km of desired location, possible water table depths, Depth of bedrock and can be used to predict soil profile of the site.

7.0 Outputs

The success of mapping applications, depends on the maps produced themselves. These outputs, need costly resources such as plotters. In Sri Lanka, (A1 size) pen plotters are used for obtaining mapping outputs. Inkjet color printers, have limitations in size and cost. Electrostatic plotters, while ideal for the job are prohibitively expensive. Thus pen plotters take the brunt of plotting mapping outputs.

These have the limitation of taking a long time for plotting, specially GIS outputs based on shaded areas. It may be useful to bear in mind that, thematic mapping capabilities like shaded areas, dot density, proportional symbols and lines, proportional pattern fill Bi-variate maps are some of the other geographic analysis capabilities in software. The avoidance of shaded areas, and use of dot density, will cut down plotting time, and improve the quality of output. A clever mix of patterns and hatching, will allow photocopiers to be used for cheap reproduction.

8.0 Conclusions

The use of mapping and GIS technology, in Geotechnical Applications has not fully reached its potential yet. Impressive software developments and plunging hardware costs have made these as one of the fastest growing fields in recent years.

These developments have made it possible, for complex operations such as landslide hazard mapping involving an assortment of multidisciplinary professionals to be analysed and investigated more thoroughly than ever before. The present day mapping facilities with their growing power, provide an excellent tool in the hands of Engineers and Scientists to correlate spatial data, and generate maps to be used in day to day work.

9.0 Acknowledgments

The authors wish to express their gratitude, to the Director General, National Building Research Organisation for granting his approval to present this paper. They note with appreciation, the guidance from Dr. R. K. Bhandari, Chief Technical Advisor and his team of National Consultants. They also wish to record their thanks to their colleagues involved in Landslide Studies, Geotechnical Engineering and Computer Applications for extending their fullest cooperation in publishing this paper.

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APPENDIX - A

Legend for Landslides & Geology maps

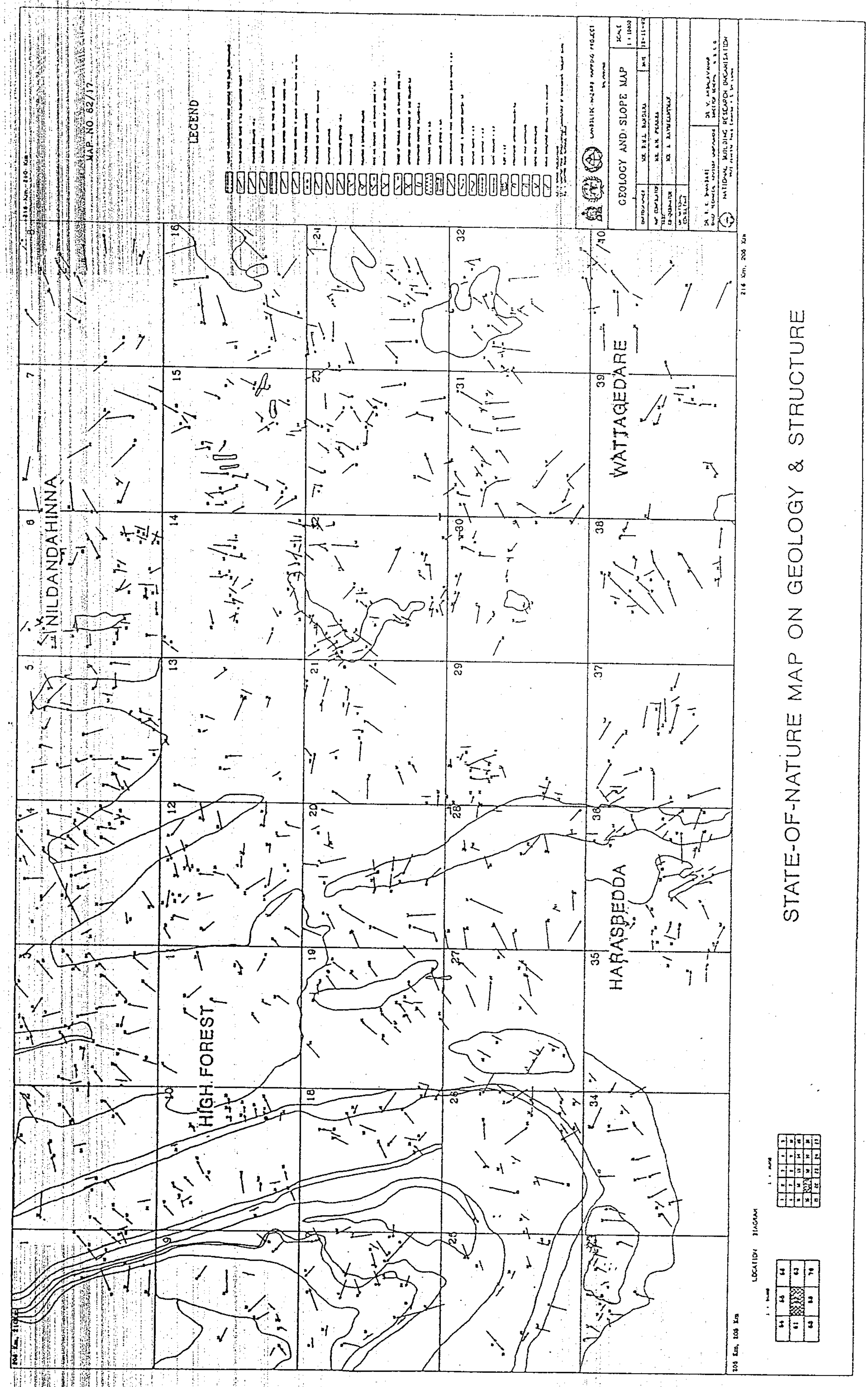
- ACTIVE SLOPE EROSION (Red)
- AREA OF POTENTIAL BANK FAILURE
- AREA OF ACTIVE SUBSIDENCE (RED) - O.P.
- AREA OF POTENTIAL LANDSLIDES (Red)-I.S
- AREA OF POTENTIAL ROCKFALL (Red) -I.S
- AREA OF PROBABLE SUBSIDENCE (RED) - O.P.
- ALLUVIAL DEPOSITS OF CLAY, SILT & SAND (BLACK) - N.A
- BANK FAILURE \EARTH SLIP (Red)
- BOULDERS, COBBLES (BLACK) -I.S
- COLLUVIUM, TALUS, DETRITUS (BLACK) - I.S
- CLAY (BLACK) -I.S
- DEBRIS FLOW (EARTH,MUD) (Red) -I.S
- GRAVEL (BLACK) -I.S
- INFERRED AREA OF SLOPE MOVEMENT (RED) - O.P.
- LANDSLIDE CUM ROCK FALL (RED) - O.P.
- OLD AND ACTIVE LANDSLIDE
- LANSLIDE (RED) - O.P.
- SLOPE EROSION (Red)
- ROCK EXPOSURE (BLACK)
- ROCK FALL (RED) - I.S.
- SAND (BLACK) -I.S
- SCARP -SHARP (Brown)-I.S
- SCARP -ROUNDED (Black)-I.S
- SILT (BLACK) -I.S
- TENSION CRACK (Brown)

- GARNET -CHARNOCKITIC GNEISS (PURPLE WITH BLACK DOTS&MARKS)
- MARBLE (LIGHT BLUE) - N.A. CALCAREOUS GNEISS
- QUARTZITE (YELLOW) -N.A
- GRANITE (PINK)
- GRANITIC GNEISS (RED WITH BLACK MARKS)
- HORNBLEND BIOTITE GNEISS (LIGHT GREEN) -N.A
- BIOTITE GNEISS (RED). If garnet present black dots are used.
- Gr Gn — GRANULITIC GNEISS (ORANGE)
- WEATHERED ROCK (MW-CW) (Dark Brown)
- GRANULITE (ORANGE)
- CHARNOCKITE (PURPLE) -N.A
- FOLIATION (BLACK)
- FOLIATION & LINEATION (BLACK)
- JOINT SET, DENSITY AND SPACING (RED) - O.P.
- SYNFORM SHOWING PLUNGE OF AXIS (BLACK) -N.A
- STRIKE OF VERTICAL JOINTS AND SPACING (RED) -O.P.
- ANTIFORM SHOWING PLUNGE OF AXIS (BLACK)-N.A
- OVERTURNED SYNFORM (BLACK)-N.A
- PEGMATITE (PINK) - O.P.
- KHONDALITE (PINK) - O.P.
- UNDIFFERENTIATED ROCK METASEDIMENTS (LIGHT BROWN) - O.P.
- SLOPE ANGLE & DIRECTION (BLUE)- I.S
- COMPLEX SLOPE - O.P.
- SLOPE CONVEX - O.P.
- SLOPE CONCAVE - O.P.
- CLIFF - O.P.
- OVERTURNED ANTIFORM (BLACK)-N.A
- MINOR FOLD (ANTICLINE)
- MINOR FOLD (SYNCLINE)
- SHEAR ZONE,FAULT (Showing relative moment)

N.A. - ADOPTED FROM NATIONAL ATLAS
I.S. - ADOPTED FROM INTERNATIONAL ASSOCIATION OF ENGINEERING GEOLOGY (IAEG)
O.P. - OTHER PUBLICATIONS

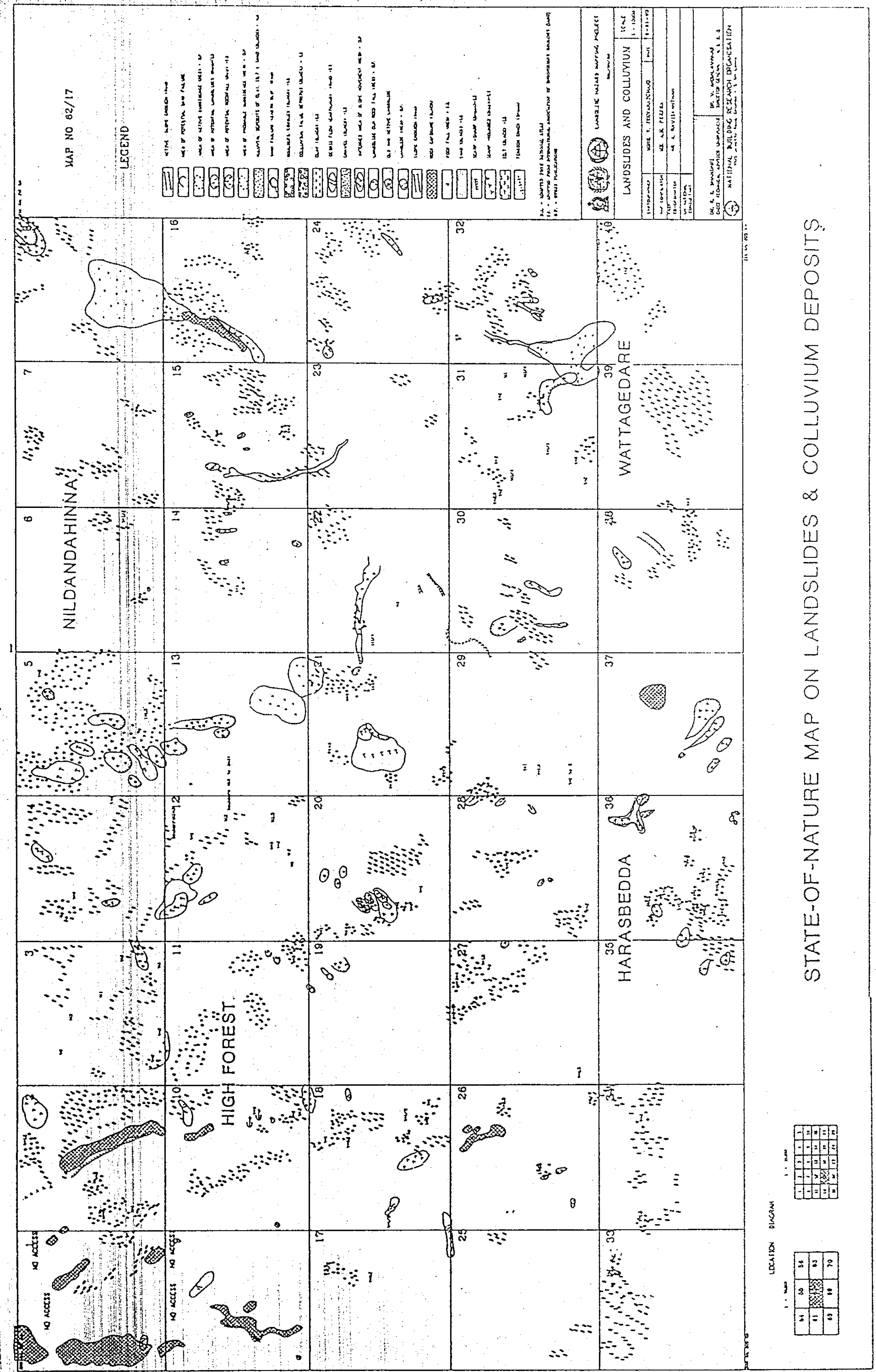
APPENDIX - B

State-of-Nature Map on Geology & Structures



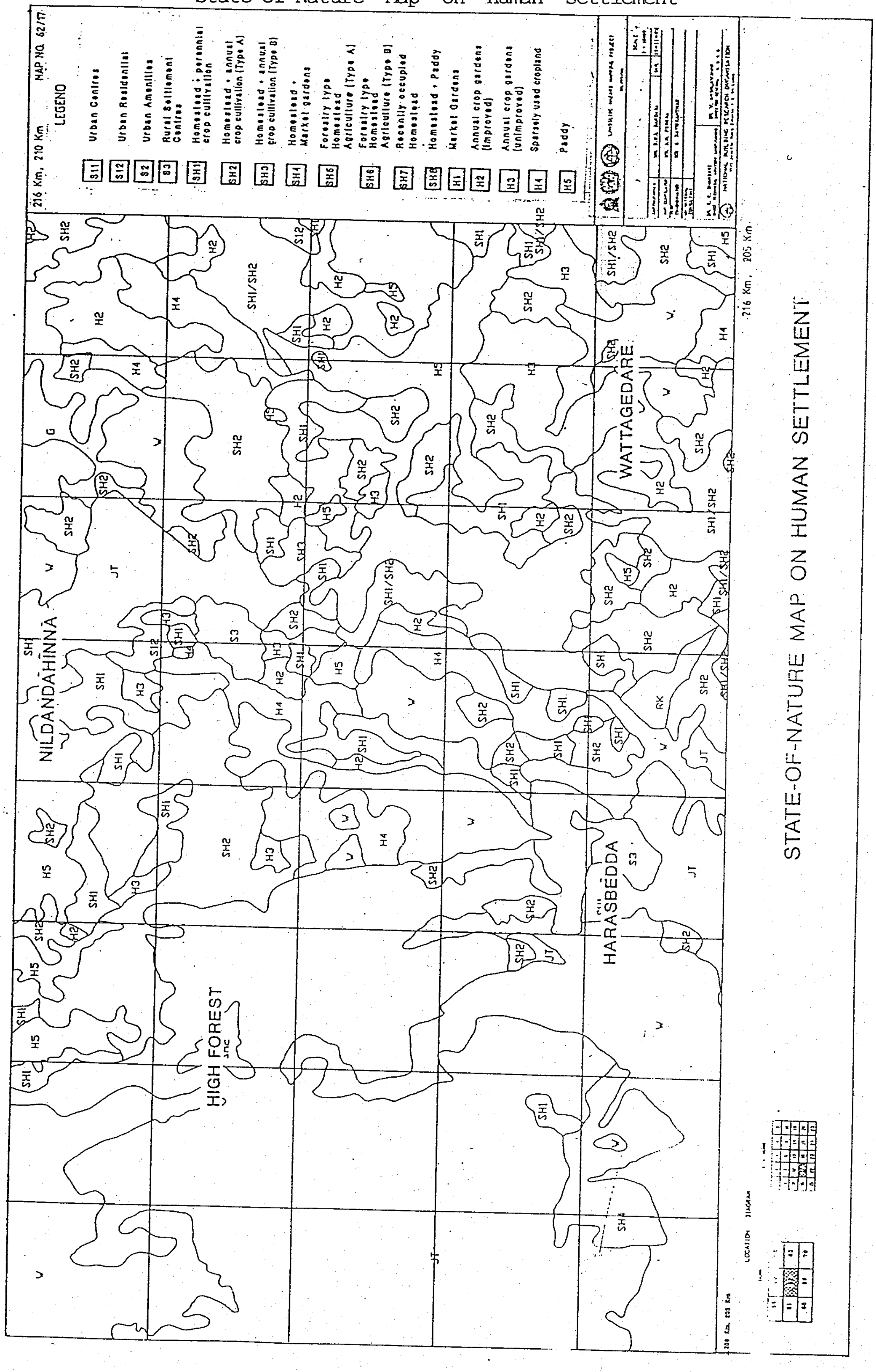
APPENDIX - C

State-of-Nature Map on Landslides & Colluvium deposits



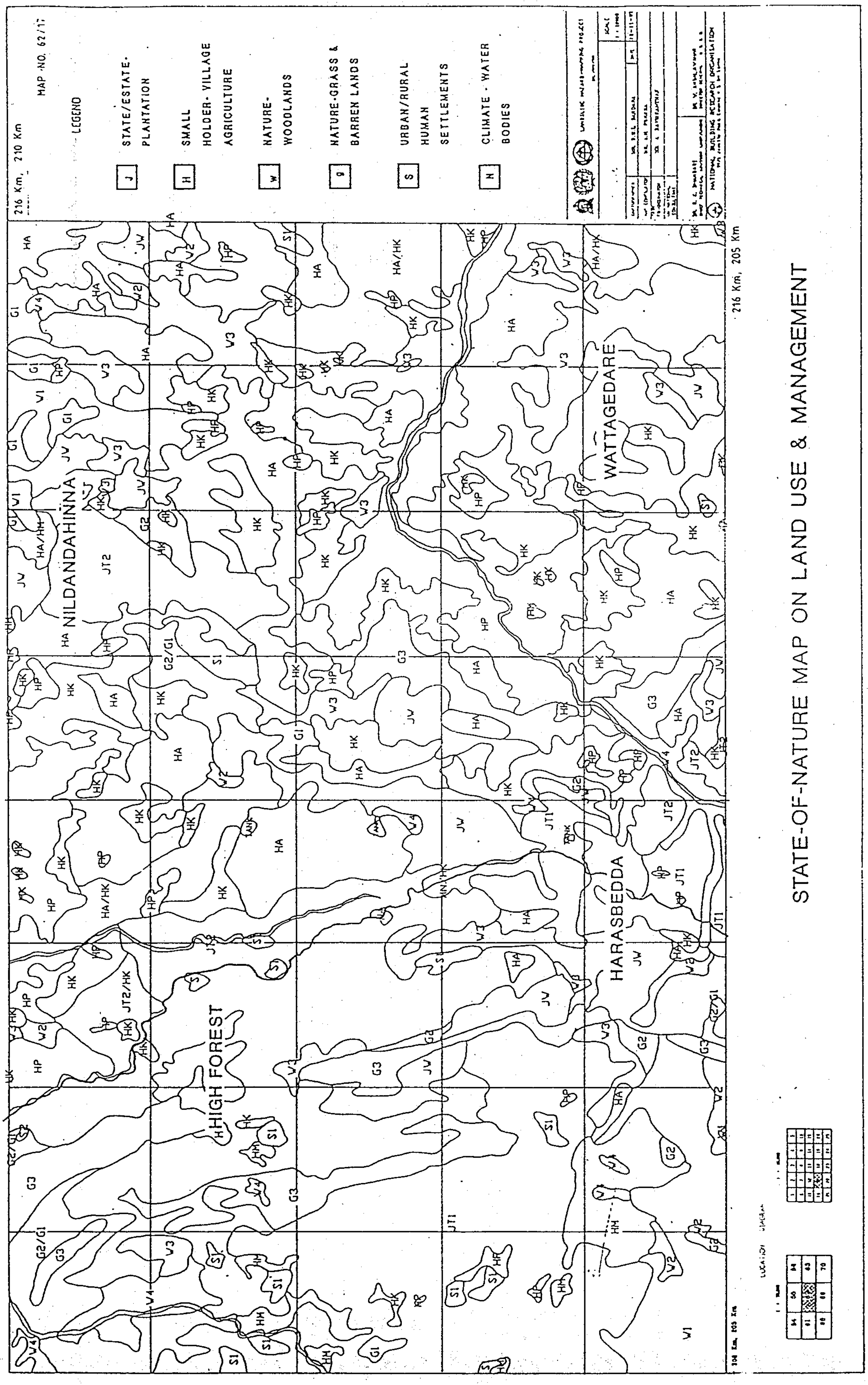
APPENDIX - D

State-of-Nature Map on human settlement



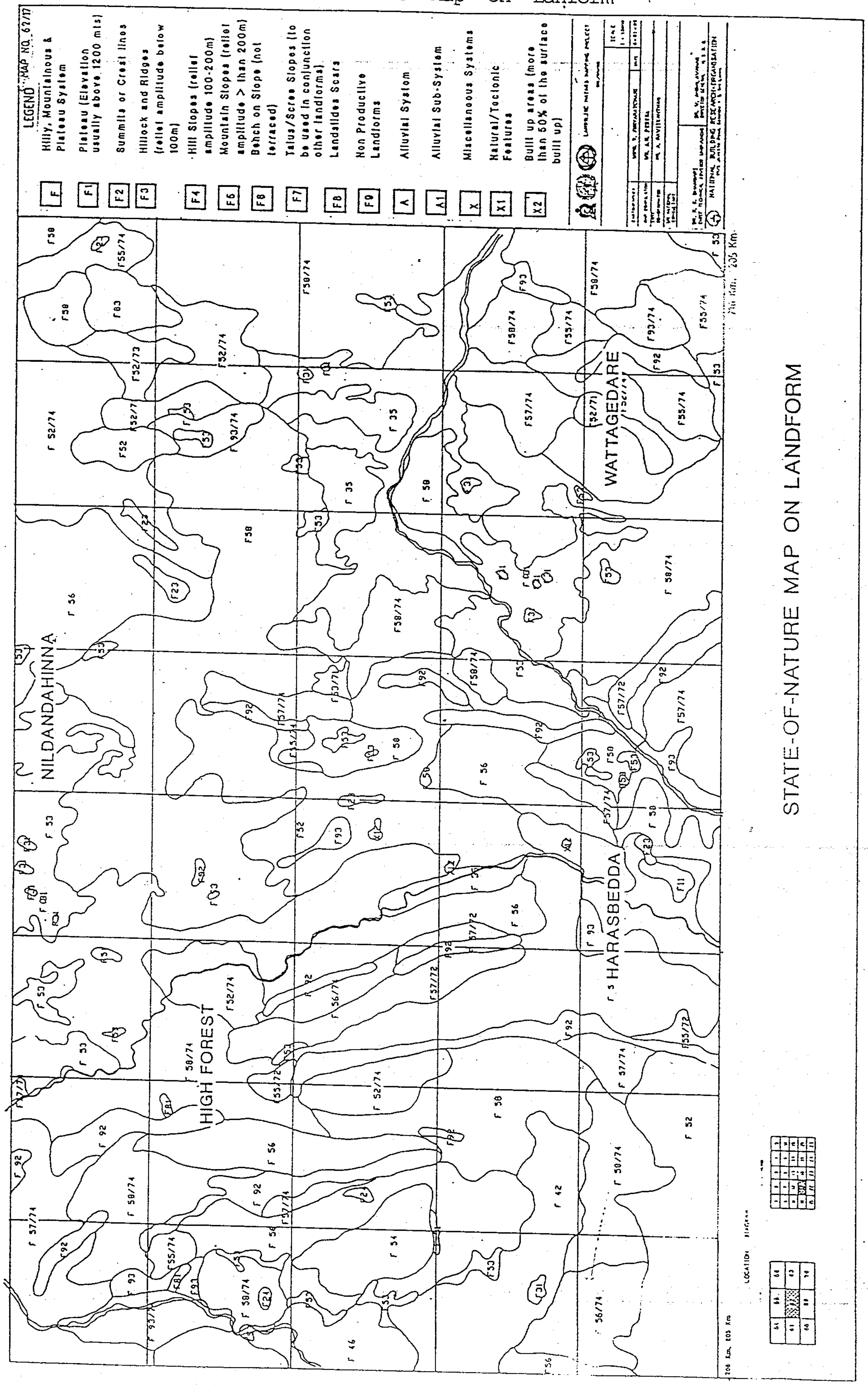
APPENDIX - E

State-of-Nature Map on Landuse & Management



APPENDIX - F

State-of-Nature Map on Lanform



Computerised Databases in Management of Geotechnical Data

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Abstract.

The paper describes some attempts by the authors to use computers in the management of geotechnical data. It exposes the reader to the concept of database management and the process of setting up and using databases in Geotechnical Applications. It also informs on hardware requirements and software selection criteria that could be used in the process of setting up a geotechnical database.

Further it gives details of some applications of computerized databases in Geotechnical Engineering. These applications comprise four databases, one in storage and retrieval of borehole log data and three in landslide studies. The database on borehole logs enables the user to store data obtained from borehole logs such as location, depth, soiltype, and SPT value. Retrieval of data is possible by location, depth and soil type. The databases on landslide data are designed to store data on landslide physical characteristics, references of literature on landslides and social impact data of landslides each in a separate database. Retrieval of data can be carried out on a search criteria of one field or an appropriate combination of fields depending on the purpose of inquiry of the user.

1.0 Introduction

Data storage and retrieval in the recent past has been a relatively time consuming and laborious process. However, with developments in computer technology it has now become possible to use computerised databases to store and retrieve data with greater ease than possible before, enabling the application of the computerised database approach in many fields of engineering where large volumes of data need to be stored and analysed. Therefore Geotechnical Engineering is only one of the many branches of Science that can benefit from computerised databases.

One can be Drowning in data but starved of information. There was a large wealth of data that was routinely being collected in the course of soil investigations but no significant attempts to analyse this data and glean information from it were being made. The interpretation of geotechnical data related to soil investigations was being done mainly at a micro level, and macro level studies were not being attempted due to the large volume of data that had to be wrestled with.

Therefore, it was necessary to organize the data being collected, and make it available to researchers for use in their work. It was decided to use personal computers to perform this task, due to the convenient availability of data at site and the suitability of the task for computerization using appropriate software. This was accomplished by the use of computerised databases which were made accessible to many by means of computer networks. However, it should be noted that computer networks are not essential for this process.

2.0 The Computerised Database Approach

The importance of information is becoming quite acute in engineering as it can be visualised as the lubricant for the operations and decisions carried out in modern organizations. Through the use of awesome computing power, we are entering an era of information intensive production. Harnessing and using information resources can make both labour and capital equipment more productive. Therefore, information is becoming an increasingly valuable organizational resource that must be managed. It could also be looked upon as the organizational memory.

The database approach is rooted in an attitude of sharing valued data resources, releasing control of those resources to a common responsible authority and cooperating in the maintenance of those shared data resources. These were the objectives to be met in the organization of geotechnical data and the attitude with which data organization in geotechniques was approached at NBRO.

Another aspect of following the database approach in organizing geotechnical data, is to avail of the functions of a database management system. These functions comprise of definition of databases, database creation (storing data in a defined database), retrieval (query and reporting), Update (changing the contents of the database), programming user facilities for system development, database revision and restructuring, database integrity control, and performance monitoring.

2.1 Types of Database Systems

A computer database management system (CDBMS) is just one type of data system. These data systems can be broadly categorised into into five types, along the type of data processed which may be in the form of arbitrary strings of text or words, references to other sources of information or formatted into specific items of information.

(1) Reference system - Used to store and retrieve references to items such as books. Rather than storing the content of each item the system stores subject descriptors to represent the content of each item and provide selection criteria. This system could be expanded to retrieve actual documents. This type of system is not very popular locally.

(2) Text processing system - Used to compose and record text in a computer and to analyse the stored text to derive meaning in the form of key words. The ubiquitous word processing system is an example of this type of data system. This type of system is popularly used.

(3) Bibliographical system - A combination of reference and text processing system used to store and retrieve bibliographic reference information, subject descriptors, and a textual abstract of each document. Such systems are commonly called information storage and retrieval systems. This type of system was used to store the literature references on landslides.

(4) Database system - Used to store and retrieve formatted data for any application environment. The database consists of a collection of specific data item values. Sometimes called formatted file system or fact retrieval system to distinguish from text, reference, and bibliographic systems. This type of system was used in the storage of historical evidences of landslides and results of the social impact of landslides. This forms a popular basis for developing database applications.

(5) Dedicated database system - A special purpose database system, tailored to process a high volume of a prescribed set of transactions in real-time. Tailoring to a particular environment is necessary to handle the high volume of through put; dedicating the system is feasible with a fixed set of transactions. Such a system sacrifices evolvability to obtain economic and operational feasibility. The database to store bore-hole logs is a dedicated database system in that it is used specifically in storage and retrieval of bore-hole logs. Thus when information regarding soil tests which are not catered to in the database are available then the database and the access programs will have to be changed.

3.1 Criteria for Computer Hardware

For data entry PC/XT machines were adequate. The authors however used the 80286 based machines for query and analysis, as they are faster. The IBM compatible computers usually come with at least 640 KB of RAM which is usually sufficient for the operation of computerised databases. A hard disk is a useful device in database management as freequent accesses to harddisks is made. The display units and printing devices do not have any impact on the management of data. Therefore it is apparent from the foregoing that the hardware requirements to set up and run a computerised system are not prohibitively expensive.

3.2 Criteria for Computer Software

In selection of software user friendliness and data portability between different software products are some of the major criteria that could be used to judge appropriateness, apart from the specific requirements arising from the data management task required by each job. Retrieval of data ie. query and reporting and the ability to update and add data ie. changing the contents of the data base are also important criteria to consider in the selection of database management software. Other important though subordinate criteria are programmability for greater flexibility in accessing and analysing data, ease of database revision and restructuring and database integrity control, ie. protection of data, and existence of database, maintenance of quality of data and ensuring privacy of data.

The authors used dBASE III+ for most of their database applications. The database on landslide literature, was developed on CDS/ISIS a special library information software, which allows special query functions suitable to extracting and locating information.

4.0 Applications of Databases in Geotechnical Engineering

The applications of databases in geotechnical engineering carried out a t NBRO are in Soil Mechanics in the organizing of bore-hole logs and in Geology in landslide studies.

4.1 Bore Hole Data - City of Colombo and Suburbs

In Geotechnical Engineering, information is derived mainly from data about soils whose properties and characteristics are subject to a high degree of variability and uncertainty. Further, the mechanical properties of soil and the geological characteristics of rock masses represent the information required in design of structures. However, assembly of information required to carry out a design of a structure usually requires field investigation which are very costly. Therefore, by storing data regarding soil investigations carried out previously it is possible to predict with a greater degree of confidence the geotechnical characteristics of soils in sites close to those where data is available. Thus, geotechnical data storage and retrieval could help to reduce the costs of investigations and help to focus on carrying out specific tests rather than doing all the tests. Hence, it is in data storage and retrieval that computers are of considerable importance in Geotechnical Engineering.

The coverage of area was limited to Colombo and its suburbs as the construction density was highest in these areas and is likely to grow in the future. The data input format is shown in Appendix 1. The internal database structure of the borehole log database is shown in Appendix 2. Actually, the database consists of three databases. Data in this structure was arranged in the form of a family tree. Each SPT test could be thought of as the child, whose parent is the layer, whose grandparent is the borehole and project. Actually another generation could have been added to contain the project. However this was not done as each project has at most only about three to four boreholes and the data compression would have not been significant. This structure was chosen in order to minimise data redundancy and to achieve compactness of data base.

The Database of Borehole logs was stored in dBASE III+ computer databases and programs written in dBASE III+ were used to store and retrieve data. The database operations were menu drivn and the menu options are shown in Appendix 2. The data display format is shown in Appendix 3. Data can be queried by location and soiltype, which are available as options of the menu. Appendix 4 shows the results of a search done by location and soiltype. The query options can be made more informative, but will require programming.

By coupling this database with a geographic information system (GIS) or spatial a database of the Colombo city area it is possible to create soil profile maps (Raviskanthan, et. al., 1993). These computerised maps can be queried to get an idea of the possible bed rock depth, water table location, soil type and properties of soil at various depths at a given location. This is useful in deciding on suitable foundation types and predicting bearing capacities for use in foundation analysis and design.

4.2 Database Applications in Landslide Studies

Use of computerised databases is not only confined to Soil Mechanics but is being widely used in many applications. The study of landslides has received considerable attention in the country and at the National Building Research Organization (NBRO) in recent times. Information on likely causative factors of landslides has been collected and stored in computerised data bases to help in prediction and rating of areas according to the level of landslide hazard inherent in them due to the presence of these causative factors. Three databases were created to study landslides. They comprise storage of historical data on landslides, literature referances on landslide studies, and documentation of the social impact of landslides.

4.2.1 Historical Landslide occurrence data

This database contains the historical records of destruction wrought by landslides, and can be used to find out if there are relationships between landslide causative factors. That is to ascertain if there are patterns in the seemingly random nature of the phenomena of landslides.

Here, the bias is towards data on physical characteristics of landslides. However social characteristics of landslides too have been collected, such as damage caused to human life and property. The main purpose of this database is for use in the rating of landslide hazard as previous history of landslides has been found to be a parameter in the hazard function being developed by researchers at NBRO. Thus, in rating an area for hazard one can access the database to query the previous history of landslides for the area under consideration.

Much of the data was collected from field visits and surveys at locations of landslides, field stations, kacharies, Geological Survey Department, and from organizations which are members of the Technical Advisory Group (TAG) on landslides like the Road Development Authority and the Ceylon Government Railways. The data collection and input format is shown in Appendix 5.

The database was created using dBASE III† one of the leading software for databases management. Storage, retrieval and analysis of this data can be carried out using the assist menu provided with the software. When more complicated analyses are required dBASE programming can be resorted to. Also, data can be transferred to Lotus 1-2-3 to avail of the graphics capability of Lotus. This software has the most sophisticated of the database management capabilities in a program of its class besides being very userfriendly through the assist menu.

The data input format is shown in Appendix 5, which consists of locational data, date, slope, land use, drainage, geological observations, damage caused and data for classification of the landslide. Appendix 6, shows the fields of the records of the database which correspond very closely to the data input format. The data input is facilitated by the screen format facility of dBASE shown in Appendix 6. A sample output is shown in Appendix 7. Data can be queried using the query facilities of dBASE. For example it is possible to build a search condition to determine the number of landslides occurring on slopes between 30% and 84%, with slope cover of tea, with drainage, being between good and satisfactory, and occurring in marble. A sample query on slope category between 30% and 84% and with poor drainage has been carried out to find out the geology and damage caused, this is shown in Appendix 8.

4.2.2 <u>Landslide literature database</u>

The database on landslide literature was created to aid the capability building process in landslide studies. Scientists researching landslides can access this database and query it to do literature surveys based on keywords or topics of interest in landslide studies. The outputs would be a list of references for a particular topic defined in the search.

This database was created on a customised software platform distributed by UNESCO among libraries in our research institutions. Since the database was created on a customised software created for library information systems, it can be ported to leading libraries in the country, and the user can also benefit from scanning into databases in libraries in other organizations. The salient feature of this software model is that it can scan text across fields unlike most commercially available database systems where searching is done only across records. However, one disadvantage is that it cannot deal with numeric data, but this is not a serious drawback in the light of the application which deals mainly with alphabetic data.

Bibliographical information was collected from libraries and books read by researchers at NBRO. The input format is shown in Appendix 9, and comprises the following fields, category of the book, author co-author and their initials, title of the book, publication, publisher, language, where available, pages where items of interest are located, year of publication, volume number and ten key-words. The structure of the database is shown in Appendix 10. The screen input format is shown in Appendix 11.

Search and query of information could be done by category, author, and just about all the fields in the database. An example of a search performed on Geotechnical Aspects of Landslides is shown in Appendix 12. In addition it is possible to define keywords, from among which it is possible to perform a search using words and even whole sentences.

4.2.3 Landslide Awareness Program Survey Data, database

The database on landslide awareness programmes contains data on the social impact of landslides. The collection of data for the compilation of the database had a two fold purpose. One was to help the Assistant Government Agents (AGA) to become aware of the factors relevant in landslide hazard and to help them keep a historical record so that new agents could refresh themselves on these factors ie. to aid continuity. The other was to help in research. At NBRO researchers are aware that landslides have occurred in a particular area but timing of these events were sometimes not available. Therefore, by collecting this information it was possible to correlate date and time of occurrence of slides and say the rain fall which is also time tagged.

The feedback from awareness programs conducted by NBRO among village folk was collected by the AGA's. The data collection format is shown in Appendix 13. Each occurrence of a landslide was treated as a record and the attributes of these records are as follows, general data - district, AGA division and Grama Niladari division, and details of the officer filling form and details of landslide and its impact on people and property - date and year of occurrence, exact location, type of crop damaged and extent, duration of cultivation, damage to property, where the affected families were relocated to and present land use.

This data was stored in a database using the database facilities of Lotus 1-2-3. This software was used as it has the best graphical capabilities of the database software packages available. Appendix 14, shows the arrangement of data in the lotus spreadsheet. One of the plus points in favor of using this software is that data can be ported to dBASE and vice-versa.

This data is summerised using the data table commands in lotus. The summary consists of the year of landslide, number of landslides and number of families affected. This summary can be graphed and an example of the text and graphical summary is shown in Appendix 15. The records in the data base are accessible more easily than in other databases as they are in the spreadsheet which is like a full screen editor. Therefore modification of data base format and editing are performed quite easily. Thus, the lotus database facilities are the most flexible and easiest to use. More complicated analyses can be performed by modifying the data base. For example, by adding a column in front of land use with a code for the different types of land use one can find out what type of land use has been affected the most due to landslides. This information can be coupled with say geological data on rock types prevalent in the area and a hypothesis built up and tested.

5.0 Future Improvements

The database management system can be made sophisticated by using high storage capacity hard disks (600 MB-4 GB) and network servers to support a multi-user and multitasking environment in data processing. More query options can be added to the menus and some of the databases could be made menu driven. However, this is a scenario that could be anticipated so as to be able to cater to increasing demand for these databases in the future. Migration to open systems platforms which make data transparency possible among different operating systems and software is another horizon to look forward to in the field of computing in the future which is going to have an indirect though significant impact on the storage and retrieval of geotechnical data and information.

6.0 Conclusions

Opportunities are there for combining different disciplines, but opportunities will remain opportunities unless seized upon and converted into tangible tools to aid in finding solutions to geotechnical problems. Therefore, generation of useful geotechnical information from data stored and subsequent storage and retrieval of this information could be a powerful tool in Engineering Design. However, in order to realise this tool a lot of initial ground work is required and it is this stage that is most critical to the success of setting up computer databases. Once the initial commitment is made and a simple database is created, one would be surprised at the momentum generated for the continuance of the project. This is summed up in a Chinese proverb, thus, In order to go on a long journey, you must start somewhere.

The databases should be continuously updated and made current, with newer data. Unless this committment is religiously practised, the full benefits of computerised databases may never be reaped.

7.0 Acknowledgments

The authors wish to thank the Director General of NBRO for kindly consenting to allow the presentation of this paper. Further, they note with appreciation the contribution made by Dr. Bhandari and his team of National Consultants in providing advice during the preparation of this paper. They also acknowledge the cooperation of their colleagues engaged in Landslide studies.

8.0 References

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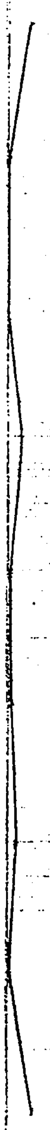
LOG OF BOREHOLE

NAME OF PROJECT : Soil Investigation Attidiya Road, Ratmalana		Bore Hole	BH 2
		ground elevation	
Location : Attidiya		depth of bore hole	9.59 m
boring method : Wash boring	commenced on : 11.04.1991	Water struck at GL – m	
drilling mud : Bentonite	completed on : 11.04.1991	GWL on completion of bore hole	GL – 1.40 m

Depth below GL m		Classification & Description of Soil	Type and Depth of Sampling m		STANDARD PENETRATION TEST DATA: depth tested GL m	number of blows per 15cm: 1	2	3	N-value for 30cm	N-value graphical presentation (0 20 40)
0.00	SM	Reddish brown silty sand with significant amount of gravel. (Lateritic fill)	DS	0.00 - 0.30	0.00	Auger sample				
1.00			DS	1.00 - 1.45	1.00	3	3	4	7	
1.30										
2.00	CH	Very soft, grey, high plasticity clay.	DS	2.00 - 2.45	2.00	1	0	0	0	
2.15	OL Pt	Very loose black, organic silt with partially decomposed vegetation. Sample not recovered.								
3.00				3.00 - 3.50	3.00	11	0	0	0	
3.75										
4.00	Pt	Peat with undecomposed and partially decomposed vegetation.	DS	4.00 - 4.45	4.00	1	1	3	4	
4.30	CL	Soft to medium stiff, sandy clay.								
5.00	CL	Sample not recovered. (Grey sandy clay)	*UDS	5.00 - 5.45	5.00	1	0	1	1	
6.00	SC	Very loose, whitish grey, clayey sand.	DS	6.00 - 6.45	6.00	1	0	0	0	
7.00		Sample not recovered. (Grey meidum to fine grained clayey sand).		7.00 - 7.45	7.00	1	0	2	2	
7.75										
8.00	SM	Very loose, grey with bands of white and yellow medium to fine grained silty sand.	DS	8.00 - 8.45	8.00	1	0	1	1	
9.00		Sample not recovered.		9.00 - 9.45	9.00	3	3	4	7	
		Sample not recovered.		9.55 - 9.59	9.55	50/4	Refusal to penetration			
9.59		Borehole terminated at 9.59m depth								



LOGGED BY : Deepthika Herath	GEOTECHNICAL ENGINEERING DIVISION NATIONAL BUILDING RESEARCH ORGANISATION	DATE :

Note * Collected from an adjasent location

```
                    MENU
                    ----

        1.INPUT DATA

        2.ACCESS DATA

        3.SEARCHING DATA ON A PARTICULAR TYPE OF SOIL

        4.PRINT DATA

               EXIT-0

               ENTER SELECTION
```

Structure for database: A:DES.dbf
Number of data records: 9
Date of last update : 02/27/93

Field	Field Name	Type	Width
1	TITLE1	Character	30
2	TITLE2	Character	30
3	MBH	Character	5
4	MGE	Numeric	5
5	MLOC	Character	15
6	MDEPTH	Numeric	5
7	MBM	Character	20
8	MDM	Character	10
9	MCOMM	Character	8
10	MCOMP	Character	8
11	MWS	Numeric	5
12	MGWL	Numeric	5
13	MNO	Character	5
** Total **			152

Bore Hole Database

Structure for database: A:bh2.dbf
Number of data records: 79
Date of last update : 01/01/80

Field	Field Name	Type	Width
1	MNO	Character	5
2	LNO	Character	5
3	SNO	Character	5
4	MBH	Character	5
5	SAMPTYPE	Character	3
6	TESTDEPTH	Numeric	5
7	FIR15	Numeric	2
8	SEC15	Numeric	2
9	LAS15	Numeric	2
** Total **			35

SPT Test Data Done on Layer

Structure for database: A:blog.dbf
Number of data records: 48
Date of last update : 01/01/80

Field	Field Name	Type	Width
1	MNO	Character	5
2	LNO	Character	5
3	MBH	Character	5
4	DEPLOW	Numeric	5
5	DEPHIGH	Numeric	5
6	CLASS	Character	3
7	DESC	Character	47
8	DESC1	Character	47
9	DESC2	Character	47
10	DESC3	Character	47
** Total **			217

Layer Data in Bore Hole

LOG OF BOREHOLE

Name of the Project	:	Soil Investigation for
Title2	:	Mahapola Complex, Ratmalana
Bore Hole	:	BH1
ground elevation	:	0.00
Location	:	Attidiya
depth of bore hole	:	13.37
boring method	:	Wash boring
drilling mud	:	Bentonite
commenced on	:	10.04.91
completed on	:	13.04.91
Water struck at GL	:	0.00
GWL on completion	:	1.75

Project No.: 1

GET DETAILS OF LAYERS (Y/N)

LAYER DATA

Project Number : 1 layer No.: 1

Borehole Number : BH1

Depth at upper limit of the layer: 0.00

Depth at lower limit of the layer: 1.35

Classification of soil : SC

Description of soil : Loose, reddish brown clayey sand with significant amount of gravel.(Laeritic fill)

GET DETAILS OF SPT VALUES (Y/N)

SPT VALUES

Project No. : 1

Borehole Number : BH1 Layer No.:1

Type of Sampling: DS

SPT No.: 2

Depth Tested : 1.00

Number of Blows per 15cm

At First 15cm : 4

At Second 15cm : 3

At Third 15cm : 3

DO YOU WANT TO CONTINUE (Y/N)

LAYER DATA

Project Number : 1 layer No.:

Borehole Number : BH1

Depth at upper limit of the layer:

Depth at lower limit of the layer:

Classification of soil : MH

Description of soil :

LAYER DATA

Project Number : 1 layer No.: 6

Borehole Number : BH1

Depth at upper limit of the layer: 5.75

Depth at lower limit of the layer: 8.75

Classification of soil : MH

Description of soil : Very loose, white mottled yellowsh red, clayey slit with sand.

DO YOU WANT TO GET SPT VALUES OF THIS LAYER (Y/N)

SPT VALUES

Project No. : 1
Borehole Number : BH1 Layer No.:6

Type of Sampling: DS

SPT No.: 1

Depth Tested : 6.00

Number of Blows per 15cm

At First 15cm : 1

At Second 15cm : 1

At Third 15cm : 2

DO YOU WANT TO CONTINUE (Y/N)

APPENDIX 5

NATIONAL BUILDING RESEARCH ORGANISATION - COLOMBO
LANDSLIDE HAZARD MAPPING PROJECT(SRL89/001)
PROFORMA FOR REPORTING ON LANDSLIDE AFFECTED AREAS

CO-ORDINATES LONG E ☐☐☐☐☐☐☐ CO-ORDINATES LAT N ☐☐☐☐☐☐☐

DISTRICT: ☐☐☐☐☐☐☐☐☐☐☐ QUADRANGLE NO: ☐☐☐☐☐☐☐

AGA DIVISION: ☐☐☐☐☐☐☐☐☐☐ VILLAGE/ ☐☐☐☐☐☐☐☐☐☐☐
GN DIVISION ☐☐☐☐☐☐☐☐☐☐ ESTATE ☐☐☐☐☐☐☐☐☐☐☐

ROAD/RAILWAY ☐☐☐☐☐☐☐☐☐☐☐

DATE OF 1ST OCCURRENCE ☐☐☐☐☐☐☐☐

DATE OF 2ND OCCURRENCE ☐☐☐☐☐☐☐☐

SLOPE CATEGORY ☐

1 0 - 5% - flat to almost flat
2 5 - 10% - gently sloping
3 10-20% - moderately sloping
4 20-30% - moderately steep
5 30-60% - steep
6 60-84% - very steep
7 84% + - extremely steep to preciptous

SLOPE COVER ☐ ☐ ☐ ☐

1 Natural Forest
2 Tea
3 Rubber
4 Coconuts
5 Tobbaco
6 Vegetable Cultivation
7 Paddy fields
8 Wildlife reserves
9 Grass lands
10 Chena
11 Mixed crops
12 Scrub
13 Homestead Gardens
14 Sugarcane
15 Reafforestation
16 Others (specify)

DRAINAGE ☐

1 Very Good 2 Good 3 Satisfactory 4 Poor

GEOLOGICAL OBSERVATIONS AND MEASUREMENTS ☐ ☐ ☐ ☐
(Outcrops / Exposures)

1 Charnockites
2 Biotite Gneiss
3 Quartzite
4 Granite Gneiss
5 Charnockitic Gneiss
6 Calcareous Gneiss
7 Marble
8 Undifferentiated meta sediments

DAMAGES CAUSED HUMAN LIFE

☐☐☐ Died ☐☐☐ Injured ☐☐☐ Missing

DAMAGES CAUSED PROPERTY ☐ ☐ ☐ ☐ ☐ ☐

1 Buildings
2 Agriculture
3 Temple/Church/ Kovil
4 Schools
5 Houses
6 Forestcover
7 Telecommunication
8 Road damaged wipeout
9 Hospital
10 Animal life
11 Bridges/Culvert
12 Embankments
13 Factory
14 Vehicle
15 Other (specify)

NATIONAL BUILDING RESEARCH ORGANISATION – COLOMBO
LANDSLIDE HAZARD MAPPING PROJECT(SRL89/001)
PROFORMA FOR REPORTING ON LANDSLIDE AFFECTED AREAS

CLASSIFICATION OF LANDSLIDES [ ]

[1] Circular – single
[2] Circular – successive
[3] Circular – multiple
[4] Non circular
[5] Planer slip
[6] Compound slide
[7] Debris slide
[8] Sudden spreading failure
[9] Rock falls
[10] Rock topple
[11] Rock lateral spread
[12] Rock slide

DEPTH OF LANDSLIDES [ ]

[1] Surficial
[2] Shallow
[3] Deepseated

TYPE OF MATERIAL INVOLVED IN THE LANDSLIDE [ ]

[1] Colluvium
[2] Residual soil
[3] Weathered soil/ jointed rock

HAZARD GRADATION BASED ON VISUAL INSPECTION [ ]

[1] High degree of stability
[2] Fair degree of stability
[3] Active landslides
[4] Old landslides
[5] Potential landslides

____

Signature , Name & Designation

Organisation

(Please return the completed form to Head / Computer Division, National Building Research Organisation, 99/1, Jawatha Road, Colombo – 5.)

COMPUTERISED INVENTORY OF LANDSLIDES
DATA ENTRY FORM

LONG E : 804750 LAT N : 070710
DISTRICT : NUWARAELIYA QUAD_NO : 0
AGA_DIV : HANGURANKETA ESTATE :

DATE OF OCCURENCE
1. : 19860225
2. :
3. :

VILLAGE
1. : DEHIPE
2. :
3. :

SLOPE CATEGORY : 3

SLOPE COVER1 : 13 SLOPE COVER2 : 14
SLOPE COVER3 : 7 SLOPE COVER4 : 0

DRAINAGE RATE : 3

GEOLOGICAL OBSERVATIONS AND MEASUREMENTS
OBSERVATION 1 : 3 OBSERVATION 2 : 2
OBSERVATION 3 : 0 OBSERVATION 4 : 0

DAMAGE CAUSED - HUMAN LIFE
DIED : 0 INJURED : 0 MISSING : 0

DAMAGE CAUSED - PROPERTY
1. 0 2. 0 3. 0 4. 0 5. 0 6. 0

LANDSLIDE CLASSIFICATION : 0

DEPTH OF LANDSLIDE : 2

TYPE OF MATERIAL INVOLVED IN LAND SLIDE : 2

HAZARD GRADATION BASED ON INSPECTION : 5

Structure for database: F:LSINVEN.dbf
Number of data records: 92
Date of last update : 09/17/92

Field	Field Name	Type	Width
1	DISPLAYMEM	Character	3
2	LONG_E	Character	6
3	LAT_N	Character	6
4	DISTRICT	Character	25
5	QUAD_NO	Numeric	8
6	AGA_DIV	Character	25
7	ESTATE	Character	25
8	DA_OF_OCC1	Character	8
9	NEAR_VILL1	Character	25
10	DA_OF_OCC2	Character	8
11	NEAR_VILL2	Character	25
12	DA_OF_OCC3	Character	8
13	NEAR_VILL3	Character	25
14	SLOPE_CAT	Numeric	1
15	INF_SC_DA	Numeric	2
16	INF_SC_DA1	Numeric	2
17	INF_SC_DA2	Numeric	2
18	INF_SC_DA3	Numeric	2
19	DRAIN_RATE	Numeric	2
20	GEO_OB_ME	Numeric	2

....Cont.

Field	Field Name	Type	Width
21	GEO_OB_ME1	Numeric	2
22	GEO_OB_ME2	Numeric	2
23	GEO_OB_ME3	Numeric	2
24	DIED	Numeric	3
25	INJURED	Numeric	3
26	MISSING	Numeric	3
27	PROP1	Numeric	2
28	PROP2	Numeric	2
29	PROP3	Numeric	2
30	PROP4	Numeric	2
31	PROP5	Numeric	2
32	PROP6	Numeric	2
33	LS_CLASS	Numeric	2
34	LS_DEPTH	Numeric	1
35	LS_MAT_TYP	Numeric	1
36	HAZ_GRA	Numeric	1
Total **			243

DISTRICT	FOLI NO	QUA NO	AGA_DIV	VILLAGE	ESTATE	CO-ORDINATION LONG_E	CO-ORDINATION LAT_N	OCCURENCE DATE	DAMAGE CAUSED DIED	DAMAGE CAUSED INJURED	DAMAGE CAUSED MISSING	DAMAGE CAUSED BUILD-ING	DAMAGE CAUSED AGRICUL-TURE	DAMAGE CAUSED TEMPLE	PREVIOUS OCCURENCE
BADULLA	039	0	HALDUMMULLA	BATGODA		80°54'20"	06°45'48"	1966/11/12	3	0	0	5	0	0	
BADULLA	037	0	HALDUMMULLA	HALDUMMULLA	NEEDWOOD	80°54'06"	06°45'53"	1983	0	0	0	0	0	0	
BADULLA	048	0	BADULLA	KEENAKELE	KEENAGASHENA	81°01'10"	07°03'10"	1986/01/06	0	0	0	0	0	0	
BADULLA	045	0	BADULLA	KEENAKELE	KEENAKELEWATTA - B	81°01'10"	07°03'20"	1986/01/06	0	0	0	0	0	0	
BADULLA	042	0	BADULLA	OLIYAMANDI RATHPAHA		81°03'10"	07°00'20"	1986/01/06	0	0	0	1	5	0	
BADULLA	040	0	UVAPARANAGAMA	ILUKWELLAGAMA		80°55'15"	07°00'15"	1986/01/06	2	0	0	5	0	0	
BADULLA	041	0	UVAPARANAGAMA	WEWAGAMA	GAMPAHAESTATE	80°55'30"	07°00'05"	1986/01/07	1	0	0	5	0	0	
BADULLA	050	0	UVAPARANAGAMA	BAMBARAPANA	KIRIKLEES(BECKINGTON DIV)	80°57'05"	06°59'55"	1986/01/07	0	0	0	13	5	0	
BADULLA	057	0	HALIELA	LUNUGALLA	LEDGERWATTA-C	81°00'10"	07°01'15"	1986/01/07	7	0	0	5	0	0	
BADULLA	054	0	HALIELA	UDUWARA		81°03'44"	06°54'58"	1986/01/07	0	0	0	0	0	0	
BADULLA	043	0	HALIELA	LUNUGALA	LEDGERWATTA - B	81°00'20"	07°01'10"	1986/01/07	0	0	0	0	0	0	
BADULLA	044	0	UVAPARANAGAMA	WEWAGAMA	GAMPAHAESTATE	80°55'45"	06°59'30"	1986/01/07	0	0	0	5	0	0	
BADULLA	058	0	HALIELA	LUNUGALA	LEDGERWATTA-D	81°00'05"	07°01'20"	1986/01/07	0	0	0	5	0	0	
BADULLA	056	0	HALIELA	LUNUGALA	LEDGERWATTTA-A	81°00'05"	07°01'05"	1986/01/07	0	0	0	0	0	0	
BADULLA	051	0	BADULLA	RAMBUKPOTHA	WESTMORELAND	81°05'40"	06°59'30"	1986/01/07	0	0	0	0	0	0	
BADULLA	053	0	UVAPARANAGAMA		KIRKLEES(LOWER DIVISION)	80°56'50"	06°59'20"	1986/01/07	0	0	0	0	0	0	
BADULLA	059	0	HALIELA	LUNUGALA	LEDGERWATTA-E	81°00'00"	07°01'15"	1986/01/07	0	0	0	1	0	0	
BADULLA	047	0	BADULLA	VINEETHAGAMA		81°06'04"	06°58'15"	1986/01/08	0	0	0	0	0	0	
BADULLA	055	0	WELIMADA	HULANKAPOLLA		80°49'30"	06°55'00"	1986/01/08	0	0	0	5	0	0	
BADULLA	052	0	HALIELA	NILBOELE		81°02'00"	06°56'40"	1986/01/09	0	0	0	5	0	0	
BADULLA	061	0	BADULLA	BADULUSIRIGAMA		81°04'20"	06°59'00"	1986/01/09	0	0	0	0	0	0	
BADULLA	038	0	HALDUMMULLA	KIRIMETIYA		80°51'54"	06°46'20"	1986/01/09	0	0	0	0	0	0	
BADULLA	032	0	PASSARA	AGARATENNE		81°08'00"	06°58'30"	1986/01/10	0	0	0	0	0	0	
BADULLA	060	0	PASSARA	MAHAKELE		81°07'25"	06°58'00"	1986/01/10	0	0	0	0	0	0	
BADULLA	046	0	BADULLA	KATUPELELLEGAMA		81°00'00"	06°59'45"	1986/01/10	0	0	0	5	0	0	
BADULLA	049	0	HALDUMMULLA	KIRUWANAGAMA	BLACKWOOD	80°55'25"	06°45'40"	1987/05/22	0	0	0	5	0	0	
KALUTARA	017	0	AGALAWATTA		DARTONFIELD				0	0	0	2	12	0	
KALUTARA	018	0	AGALAWATTA	KITULGODA					0	0	0	0	0	0	
KALUTARA	019	0	AGALAWATTA	KITULGODA		80°10'34"	06°30'12"	1984/05/22	0	0	0	0	0	0	
KALUTARA	022	0	PASDUNKORALE EAST	PANTIYA		80°05'40"	06°32'40"	1984/05/22	0	0	0	5	0	0	
KALUTARA	023	0	PASDUNKORALE EAST	WANDURABBA		80°09'30"	06°31'18"	1984/05/22	0	0	0	0	0	0	
KALUTARA	024	0	PASDUNKORALE EAST	PINNAGODA	DARTONFIELD	80°10'00"	06°30'40"	1984/05/22	13	0	0	12	13	2	
KALUTARA	021	0	PASDUNKORALE EAST	PANTIYA		80°05'40"	06°32'40"	1984/05/22	11	0	0	5	1	13	
KALUTARA	020	0	PASDUNKORALE WEST	OWITIGALA	SIRIKANDURA	80°08'20"	06°29'40"	1984/05/22	0	3	0	12	2	0	
KANDY	029	0	UDADUMBARA	NUGATENNA		80°51'24"	07°17'12"	1957/12/25	0	0	0	5	0	0	1951/01/12
KANDY	027	0	PASBAGEKORALE	NAWALAPITIYA-GAMPOLA ROA		80°32'10"	07°03'40"	1957/12/25	0	0	0	0	0	0	
KANDY	031	0	UDAPALATHA	AMBULAWA		80°33'10"	07°09'50"	1982	0	0	0	0	0	0	1947
KANDY	028	0	UDADUMBARA	DENAPITIYA		80°51'18"	07°17'48"	1985/12/24	0	0	0	5	9	0	1957/01/01
KANDY	030	0	UDADUMBARA	KALUGALA		80°53'46"	07°24'00"	1986/01/07	0	0	0	0	0	0	1947/01/01
KEGALLE	036	0	DEHIOWITA	KATULANDA		80°21'00"	06°58'05"	1984/05/21	0	0	0	0	0	0	1925
KEGALLE	026	0	WARAKAPOLA	PALLEPELPITIYA		80°16'10"	07°07'15"	1985/06/05	10	0	0	2	0	0	1965
KEGALLE	025	0	RUWANWELLA	WAHARAKA		80°12'00"	07°05'34"	1986/01/07	0	0	0	0	0	0	
NUWARAELIYA	005	0	HANGURANKETA	DARA-OYA		80°44'30"	07°07'16"	1957/12/24	0	0	0	5	0	0	
NUWARAELIYA	003	0	HANGURANKETA	LOOLKANDURA		80°42'12"	07°07'48"	1983/01/01	0	0	0	2	5	0	
NUWARAELIYA	014	0	NUWARAELIYA	UNIQUEVIEWHILL		80°45'20"	06°57'50"	1985/06/23	0	0	0	5	0	0	
NUWARAELIYA	012	0	KOTMALE SANGILIPALAMA	NIYANGANDORA		80°39'30"	07°02'40"	1985/06/26	0	0	0	1	5	0	
NUWARAELIYA	011	0	HANGURANKETA	WELLAGIRIYA	GOODWOOD	80°47'15"	07°03'30"	1986/01/04	0	0	0	5	0	0	
NUWARAELIYA	010	0	UVAPARANAGAMA	MADULLA		80°55'10"	07°01'50"	1986/01/05	0	0	0	0	0	0	
NUWARAELIYA	016	0	WALAPANAWELA	KURUPANAWELA		80°54'45"	07°00'55"	1986/01/06	0	0	0	0	0	0	
NUWARAELIYA	004	0	HANGURANKETA	MANSARANNUWARA	COURTLODGE	80°47'15"	07°01'05"	1986/01/06	4	2	0	5	0	0	
NUWARAELIYA	015	0	WALAPANE	KETAYAPATHANA		80°48'20"	07°04'05"	1986/01/06	0	0	0	5	0	0	
NUWARAELIYA	006	0	WALAPANE	RUPAHA		80°53'00"	07°02'10"	1986/01/06	0	0	0	2	5	0	
NUWARAELIYA	008	0	WALAPANE	AMBELIYADDA		80°53'50"	07°01'50"	1986/01/06	0	0	0	13	5	0	
NUWARAELIYA	009	0	WALAPANE	MADULLA		80°55'45"	07°02'45"	1986/01/06	0	0	0	5	0	0	
NUWARAELIYA	013	0	WALAPANE	MATURATA NILGALA WANGU		80°48'20"	07°04'30"	1986/01/08	0	0	0	5	-0	0	
NUWARAELIYA	007	0	WALAPANE	MULHALKELE		80°51'00"	07°06'00"	1986/01/08	0	0	0	8	0	0	
NUWARAELIYA	002	0	HANGURANKETA	WELLAGIRIYA		80°47'10"	07°04'10"	1986/01/08	0	0	0	5	0	0	1943
NUWARAELIYA	001	0	HANGURANKETA	DEHIPE		80°47'50"	07°07'10"	1986/02/25	0	0	0	0	0	0	
RATNAPURA	034	0	PELMADULLA	PATULPANA		80°27'10"	06°39'20"	1982/06/06	12	12	0	5	13	0	
RATNAPURA	035	0	PELMADULLA	HANDURUKANDA		80°31'40"	06°36'10"	1982/06/06	0	0	0	5	0	0	
RATNAPURA	033	0	RATNAPURA	MIHITIYA		80°25'05"	06°42'05"	1982/06/08	0	0	0	0	0	0	

Set Up Create Update Position Retrieve Organize Modify Tools 10:43:35 am

OBJECTIVE - to find Geology of slide & damage to life in slides occuring on slopes between 30% & 84% with poor drainage.

SEARCH CONDITION - Slopes between 30% & 84% with Poor drainage.

Record#	GEO_OB_ME	GEO_OB_ME1	GEO_OB_ME2	GEO_OB_ME3	DIED	INJURED	MISSING
4	3	0	0	0	4	2	0
10	3	5	0	0	0	0	0
15	1	3	0	0	0	0	0
16	5	1	0	0	0	0	0
27	2	3	0	0	0	0	0
33	1	5	0	0	0	0	0
36	3	0	0	0	0	0	0
73	0	0	0	0	5	0	0
74	0	0	0	0	0	0	0
83	0	0	0	0	2	0	0
90	0	0	0	0	3	0	1

ASSIST ‖<F:>‖LSINVEN ‖Rec: 1/92 ‖ ‖

Press any key to continue work in ASSIST.

SLOPE CATEGORY

- 1 0 – 5% – flat to almost flat
- 2 5 – 10% – gently sloping
- 3 10–20% – moderately sloping
- 4 20–30% – moderately steep
- 5 30–60% – steep
- 6 60–84% – very steep
- 7 84% + – extremely steep to preciptous

DRAINAGE

1 Very Good 2 Good 3 Satisfactory 4 Poor

GEOLOGICAL OBSERVATIONS AND MEASUREMENTS
(Outcrops / Exposures)

- 1 Charnockites
- 2 Biotite Gneiss
- 3 Quartzite
- 4 Granite Gneiss
- 5 Charnockitic Gneiss
- 6 Calcareous Gneiss
- 7 Marble
- 8 Undifferentiated meta sediments

NATIONAL BUILDING RESEARCH ORGANISATION – COLOMBO
LANDSLIDE HAZARD MAPPING PROJECT(SRL89/001)
COMPUTERISED LIBRARY INFORMATION SYSTEM FOR LANDSLIDE
QUESTIONNAIRE

Key words:

1. Geological Aspects of Landslide
2. Geotechnical Aspects of Landslide
3. Slope Instrumentation, Monitoring & Forecasting
4. Environmental Aspects
5. Landslide Hazard Zonation Mapping
6. Landslide Hazard Management
7. Landuse Planning & Human Settlement Aspects
8. Miscellaneous

Year: 1970 | Vol.: | No.:

Author: DR. HOEK (Surname) | Initials: E

Co-Author:

Co-Author:

Title: BIBLIOGRAPHY OF SLOPE STABILITY

Publication: IMPERIAL COLLEGE ROCK MECHANICS RESEARCH REPORT

Publisher:

Languages: Eng Frn Ger Sin Tam — X (Eng)

Availability: CTA/SEA NBRO

pp. 1 from 30 to

NATIONAL BUILDING RESEARCH ORGANISATION – COLOMBO
LANDSLIDE HAZARD MAPPING PROJECT(SRL89/001)
COMPUTERISED LIBRARY INFORMATION SYSTEM FOR LANDSLIDE
QUESTIONNAIRE

Keywords

Name & Signature

Organisation

(Please return the completed form to Head / Computer Division, National Building Research Organisation, 99/1, Jawatha Road, Colombo – 5.)

APPENDIX 10

Field Definition Table (FDT) Data Base: LIB

?	Tag	Name	Len	Typ	Rep	Delimiters/Pattern
_	5	Category	50	X		
_	10	Author	30	X		
_	15	Initials	5	X		
_	20	CO-AUTHOR	30	X		
_	25	CO-AUTHOR INITIALS	5	X		
_	30	CO-AUTHOR	30	X		
_	35	CO-AUTHOR INITIALS	5	X		
_	40	TITLE	100	X		
_	45	PUBLICATION	100	X		
_	50	PUBLISHER	100	X		
_	55	LANGUAGES	25	X		
_	60	AVAILABILITY	50	X		
_	65	FROM PAGES	5	X		
_	70	TO PAGES	5	X		
_	75	YEAR	4	X		
	80	VOL	5	X		
_	85	NO	5	X		

A - Insert (after) | B - Insert (before) | C - Change line | D - Delete line
P - Previous page | N - Next page | T - Top | E - Bottom
X - Exit | ↲ - Next line

Author	: Dr. Hoek		Initials	: E.
Co-author	:		Initials	:
Co-author	:		Initials	:
Title	: Bibliography of Slope Stability			
Publication	: Imperial College Rock Mechanics Research Report			
Publisher	:			
Languages	: ENGLISH			
Availability	: CTA/SEA NBRO			
From Pages	: 1		To Pages	: 30
Year	: 1970	Vol. :	No	:
Category	: GEOTECHNICAL ASPECTS OF LANDSLIDE			

M - Modify	R - Right just	S - Shift	D - Delete	C - Center
A - Add field	<TAB> - Previous	┘ - Next	X - Exit	
		LIB / 2		

APPENDIX 12

NATIONAL BUILDING RESEARCH ORGANISATION – COLOMBO

LANDSLIDE HAZARD MAPPING PROJECT(SRL89/001)

COMPUTERISED LIBRARY INFORMATION SYSTEM FOR LANDSLIDE

CATEGORY	:	GEOTECHNICAL ASPECTS OF LANDSLIDE
YEAR	:	1987
TITLE	:	BIBLIOGRAPHY ON LANDSLIDES IN ASIA
PUBLISHER	:	ASIAN INFORMATION CENTER FOR GEOTECHNICAL ENGNEERING
AVAILABILITY	:	CTA/SEA NBRO
LANGUAGE	:	ENGLISH
FROM PAGE	:	1 TO PAGE 92

CATEGORY	:	LANDSLIDE HAZARD ZONATION MAPPING
YEAR	:	1985
AUTHOR	:	CHRISTOPHER S. ALGER & EARL E. BRABB
TITLE	:	BIBLIOGRAPHY OF UNITED STATES LANDSLIDE MAPS AND REPORTS
PUBLISHER	:	U.S. GEOLOGICAL SURVEY
AVAILABILITY	:	CTA/SEA NBRO
LANGUAGE	:	ENGLISH,FRENCH
FROM PAGE	:	1 TO PAGE 119

CATEGORY	:	GEOTECHNICAL ASPECTS OF LANDSLIDE
YEAR	:	1970
AUTHOR	:	DR. E. HOEK
TITLE	:	BIBLIOGRAPHY OF SLOPE STABILITY
PUBLICATION	:	IMPERIAL COLLEGE ROCK MECHANICS RESEARCH REPORT
AVAILABILITY	:	CTA/SEA NBRO
LANGUAGE	:	ENGLISH
FROM PAGE	:	1 TO PAGE 30

CATEGORY	:	GEOTECHNICAL ASPECTS OF LANDSLIDE
YEAR	:	198O
TITLE	:	PROCEEDING INTERNATIONAL SYMPOSIUM ON LANDSLIDES
PUBLICATION	:	SARITA PRAKASHAN
AVAILABILITY	:	CTA/SEA NBRO
LANGUAGE	:	ENGLISH
FROM PAGE	:	1 TO PAGE 469

CATEGORY	:	GEOTECHNICAL ASPECTS OF LANDSLIDE
YEAR	:	1984
TITLE	:	IV INTERNATIONAL SYMPOSIUM ON LANDSLIDES
AVAILABILITY	:	CTA/SEA NBRO
LANGUAGE	:	ENGLISH,FRENCH
FROM PAGE	:	1 TO PAGE 734

Landslide Hazard Mapping Project, National Building Research Organisation

District : Badulla
AGA Division : Uva Paranagama
GN Division : Maspanna

Name of the officer: D.M.L. Bandara
Designation : Scientist
Address : No.7, Mahawa Rd., Kurunagala

Date & Year of landslide	Location/Village (nearest km post on approached road)	Land use of the affected area and land area affected	For how lang that practice has been there	No. of houses affected	If the affected families were relocated indicate where	Present land use in the affected area
1986	Balagallagama Nayakandura near Kaluwa Watta Junction	1/4 acre	for 30 yrs	1	Relocated in Puwakgas Watta Gedara	
1986	Wethalawa Gs Wasama Nayathalawa	5 acre	40 yrs	7	Relocated in Galathiha school	

Note : Land Use
- (a) homestead
- (b) Cultivated Land
  1. Paddy
  2. Vegetable
  3. Tea ,,
  4. Others (Specify)
- (c) Forests
- (d) Patna
- (e) Others (Specify)

** Please state any other specific problems in your area

LANDSLIDE HAZARD MAPPING PROJECT NBRO

INFORMATION FROM SORANATOTA DIVISION

BADULLA DISTRICT

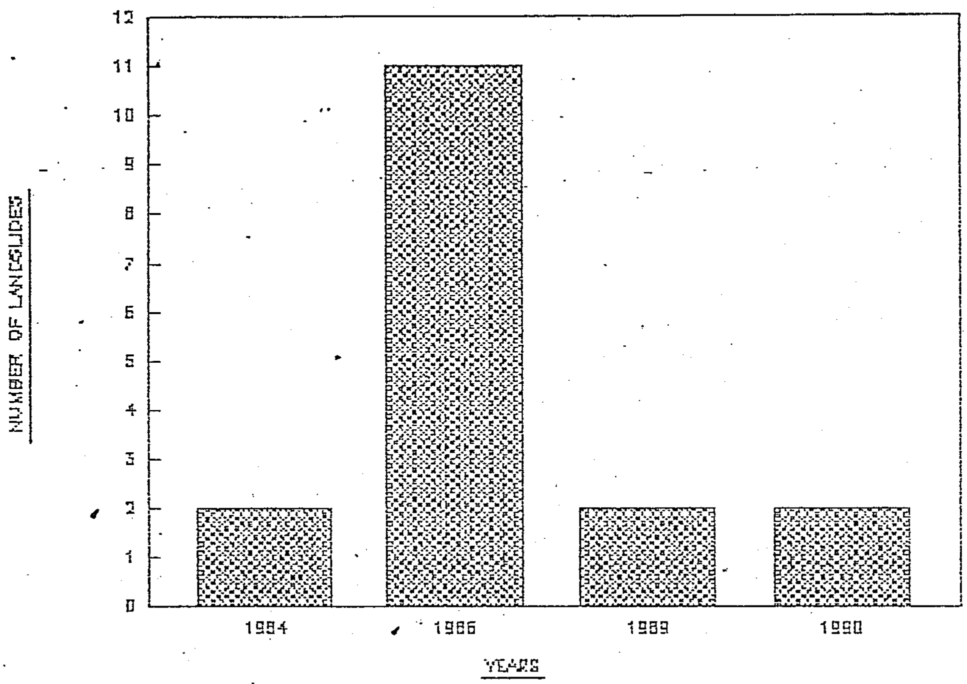
Serial No	Grama Niladhari Division/Name	Date of Landslide	Location/Village	Land Area & Land Use of the Affected Area	Period of Use	No.of Houses/ Families Affected	Relocation of Affected Families	Present Land Use	Remarks
HA22	R D Podiappu 77A Kekatiyamaluwa	Jan 7,8 1986	Diyadullakandura Haidya Kumbura Luvinugallagama 7 mile post of Galauda Badulla Rd	38 acres affected 10 acres slided	traditional homesteads	7	relocated in Udanigama Lunugolla	reserve land	
HA23	R D Karunadasa 77B Jagulla	5-12-90	5 1/2 post Galauda Rd	1 acre homestead	35 yrs	1		still continued to live	
HA24	R V Nandawathe 84A Unagolla	5-1-90	Unagollagama 1/8 mile post Badulla Wewelhinna road	1/2 km	Road reserve & JEDB lands	5	relocated in Medagama	abandoned except one family still continue to stay	
HA25	G B Sudubanda 84B Gadigama		no landslides						
HA26	H A Chandrasekera 85 Meddagama Wasama Nili Ehagoda	10-12-90	Meddagama main road at 117 km post Galaboda Ella Naya	about 1/2 km tea/vegetable	homesteads for	30	lands were given from Kalanawasama Attampitiya	still continue to live continued	
HA45	D M Dissanayake Samagipura	1990	Arawa Haliela Welimada 2km post	human settlements on abandaned tea lands	50			cultivation is continued	

APPENDIX 15

SUMMARY

YEAR	No.of LANDSLIDES	HOUSES/FAMILIES AFFECTED
1984	2	-
1986	11	7
1989	2	10
1990	2	1

LANDSLIDES IN SORANATOTA DIVISION



The Uses of Finite Element Packages in Geotechnics

H.M. Nimal Senevirathna

University of Peradeniya

1. INTRODUCTION

Finite element method has evolved considerably over the past two decades and has become undoubtfully the most popular and versatile computer method of solving boundary value problems. Problems involving complicated geometry, inhomogeneity, anisotropy, varying loading and loading procedures , complex material behaviour and, coupled behaviour of stress - strain, water flow or heat flow etc. may be solved using finite element techniques. In geotechnics, finite element method may be used in solving problems involving stress-strain, failure and stability, ground water and seepage and, several other aspects of soil behaviour. However, the attention in this paper is confined to the use of displacement formulation of finite element method in solving load - deformation problems in soils and rocks. Even though a finite element package some times may appear simple superficially, to obtain meaningful results, a user would need at least some knowledge of the stress-strain behaviour of the material and the basics of finite element techniques. Some useful references here may be Zienkiewicz (1977), Desai and Abel (1972) and Britto and Gunn (1987). This paper is aimed at highlighting the basic concepts of finite element displacement method and, the use of finite element packages in geotechnics with special reference to CRISP and AFENA programs, developed at University of Cambridge, U.K. and University of Sydney, Australia respectively.

2. FINITE ELEMENT DISPLACEMENT METHOD

2.1 Introduction

In the finite element method the domain to be analysed is subdivided into a finite number of subdomains called elements which are interconnected at a finite number of points called nodes. The discretisation is entirely mathematical but may be viewed as a physical process for simplicity of understanding. Consider the analysis of a force displacement problem. The variation of displacements within an element is described using a shape function and the nodal values of displacements, *d*. The relation between the nodal displacements and the resultants of element stresses, *p*, may be expressed using an element stiffness matrix, *k*, formulated using the governing equations so that $p = k.d$. The process of formulation of k is the heart of finite element method and may be carried out in several ways, e.g., using weighted residual methods (weak formulations) or, using variational principles which may include physical statements like principle of virtual work. The element stiffness relations are assembled to obtain the global stiffness matrix, K. The boundary conditions are used to obtain the global nodal force vector P and to remove the redundancies from the system. The relationship between P and the global nodal displacement vector, D may be expressed as a system of equations $P = K.D$, which is solved to obtain the nodal displacements and then the element stresses. Any integration during the formation of k and also during the calculation of stresses are usually carried out at specially selected points called integration points to minimise errors particularly associated with non-linear behaviour. A similar procedure is followed in the solution of problems not involving stress - strain behaviour as well.

2.2 Element Types and Shape Functions

Element shapes may be arbitrary but bars or beams in 1-D, triangles, rectangles, and quadrilaterals in 2-D and, tetrahedra, cubes and rectangular blocks in 3-D are convenient forms. Some of the commonly used elements are illustrated in Fig. 1. Bar and beam elements may be used as structural components e.g. to model soil reinforcement or flexural members or, in analysing 1-D problems. 2-D elements are used in plane stress, plane strain or axisymmetric analyses. The number of nodes in an element need not be the minimum number required to define it's geometry. The introduction of additional nodes either at the sides or within an element facilitates the use of higher order shape functions. A triangle with six nodes (see Fig. 1) produces a linear variation of strain within an element with the use of a quadratic shape function for the displacement. In contrast, a triangle with nodes only at the vertices produces a constant strain within it. If the number of nodes used to define the displacement shape function is greater than that used to define the geometry the element is called subparametric; if the two numbers are equal the element is isoparametric. All the variables within an element need not be described by shape functions of the same order . For e.g., if the displacement shape function is cubic, pore

pressure shape function may be quadratic to match the order of strains which are of order one less than the displacements.
Interface elements and transition elements are used to fill an area in between different order elements or to describe an interface behaviour (e.g. Fig. 2). It is possible to model tensile separation etc. in this manner. The properties of an element are geometrical parameters like the element thickness and the parameters associated with the material behaviour within the element (e.g. linear elastic plane strain, axisymmetric Mohr-Coulomb with consolidation etc.). In finite element packages, element libraries incorporating different types of elements and material behaviour are given so that a user may select whatever is required.

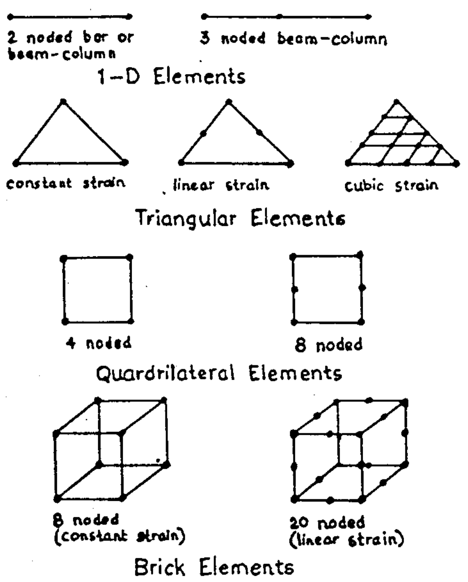


Fig. 1 Element types

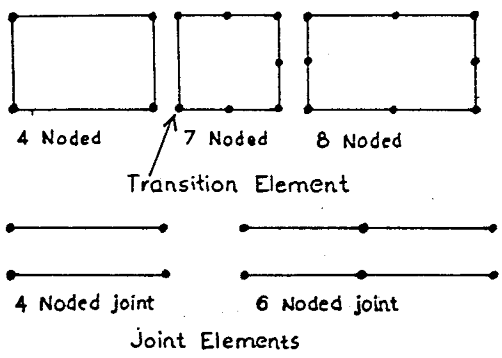
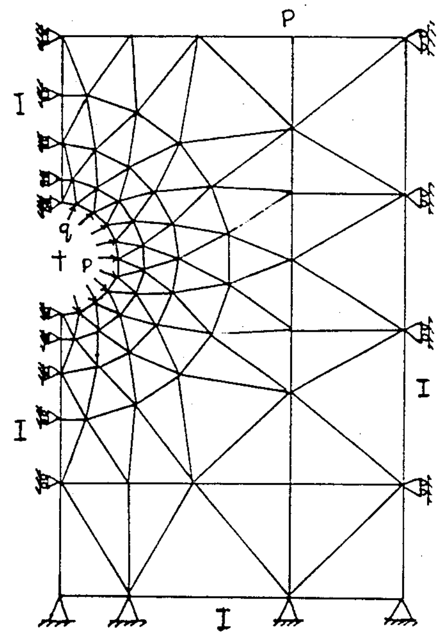


Fig. 2 Special elements

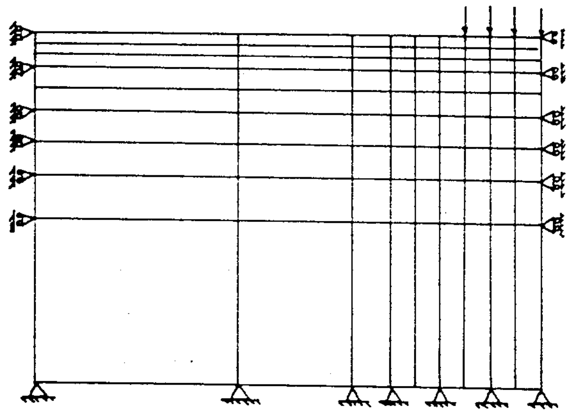
2.3 Discretisation

The first step in an analysis is the idealisation which includes idealisation of material, geometry, boundary conditions and, loading so that the physical problem can be replaced by a problem amenable for analysis without any significant loss of accuracy. Fig. 3 illustrates two finite element meshes used in the analysis of idealised problems of stress-strain behaviour around a plane section tunnel and a circular footing.



I - impermeable : P - permeable

a. Plane section tunnel under internal pressure



b. Flexible circular footing under central load

Fig. 3 Examples of finite element mesh

The discretisation involves decisions on;

a. Types of elements to be used in the mesh,
b. Number of elements of each type,
c. Dimensions of elements which are somewhat directly related to b.,

d. In cases with infinite boundaries extent of the mesh.

In selecting the number and types of elements to be used in an analysis the following points should be considered. A selected element should be able to represent the expected material behaviour completely; for e.g., to analyse a consolidation problem an element formulated considering stress-strain behaviour as well as transient water flow is necessary. A higher order element (an element with a higher order shape function) usually would give a better approximation but needs more computer time and space. In many problems the solution given by a small number of higher order elements may be reproduced using a larger number of lower order elements. Complex material behaviour and/or concentrations of stress or any other element variable, may be modelled using higher order elements or, in some cases using a large number of lower order elements; for e.g. a linear variation of strain is about the lowest order of shape function necessary to model plastic behaviour. For accurate results any boundary between two different types of materials and/or elements should be bridged using transition elements.
The dimensions of elements should be selected so that the following conditions are satisfied. The variation of nodal and element variables within an element should not be too large and be of the same order in all elements. The latter may reduce the possibility of ill-conditioning in the solution matrix thereby improving the accuracy of the solution. Acute apex angles in triangles or tetrahedras and, very large/very small length to breadth ratios in quadrilaterals and rectangular blocks should be avoided. The following procedure may be useful in generating a reasonable mesh for a stress-strain problem.

a. Generate a basic mesh primarily using a standard element (i.e. not higher order) either using experience or solutions available in the literature (e.g. a classical solution of a simplified version of the given problem) as a guidance. The symmetry of a problem if any, may be used to reduce the size of the mesh. For the basic mesh higher order or special types of elements (e.g. transition) should be used only where it is inevitable.
b. Carry out a linear elastic analysis of the problem using the basic mesh. If in the solution there are areas with high stress concentrations and/or exhibiting numerical problems consider increasing the number of elements or the introduction of higher order elements in such areas. This also may be necessary close to boundaries if the boundary conditions are not adequately satisfied. However, it is prudent to avoid using too many types of elements unless it is absolutely necessary.The number or in some cases the order of the elements in very lightly stressed zones if any, should be reduced.
c. In the problems involving distant boundaries compare the changes in variables at boundary nodes given by the linear elastic analysis with what is expected at the boundary according to the boundary conditions. It may be necessary to extend the mesh if the comparison is not satisfactory.
d. Increase the number of elements by subdividing the entire basic mesh repeatedly and carry out linear elastic analyses. A plot of the variation of some important nodal variable with number of elements used in the analyses (e.g. Fig. 4) may enable the user to select a reasonable number of elements for the mesh.
e. If the actual analysis (i.e. not linear elastic) is not time consuming the above procedure may be carried out incorporating the material behaviour to be used in the analysis proper instead of linear elasticity.

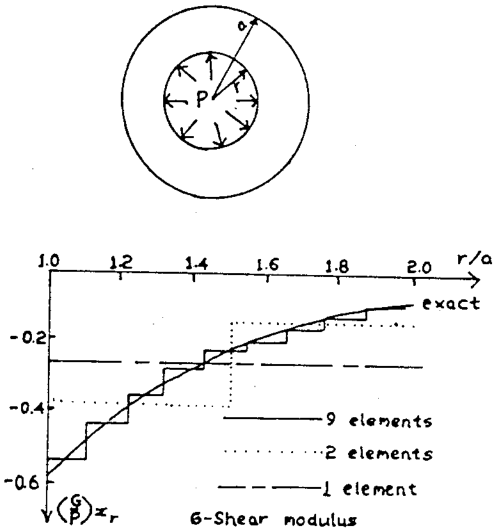


Fig. 4 Effect of No. of Elements (Thick cylinder problem)

There are mesh generation programs available with some finite element packages which may help a user to generate the complete mesh or portions of it. In more sophisticated finite element programs excavation or filling may be modelled by addition or subtraction of elements from the original mesh.

2.4 Types of analyses

The analyses most frequently carried out in soils/rocks are of drained, undrained and, consolidation types. In a drained analysis excess pore pressures in the material are not considered; the effective and total stresses are

the same or their difference given by the magnitude of steady state pore pressure (if any) which remains constant throughout the analysis. In an undrained analysis pore pressure changes are allowed but no transient water flow permitted. This type of analysis is carried out using the actual bulk modulus of water or, more frequently assuming that the material is fully incompressible. A fully incompressible analysis requires an infinite bulk modulus of water and the material, which would certainly run into numerical problems. This may be avoided by choosing a not unnecessarily large value for the bulk modulus of water so that the analysis is numerically stable with near incompressible material behaviour. In a consolidation analysis the material behaviour is modelled considering in addition to the stress-strain behaviour the transient water flow which is usually assumed to be governed by Darcy's law and the continuity condition.
If the material behaviour and governing equations are linear the analysis can be carried out in one step without using increments of loading or time. This is usually the case with linear elastic drained or undrained analyses. The simplest way of tackling non-linear problems is by using explicit (non-iterative) procedures so that the next increment (of loading or time etc.) can be readily calculated using the current properties and the historic variables (current stresses, voids ratio etc.). An example of this procedure for non-linear material behaviour is the use of tangent stiffness (see Fig. 5). An explicit procedure would obviously give better results when small load/time increments are used. In contrast, implicit procedures (i.e. iterative methods which are not described here) are more accurate and can be used with comparatively larger increments.

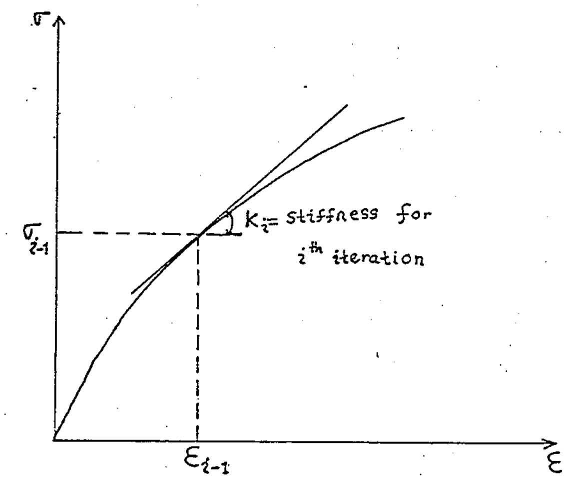


Fig. 5 Expilicit tangent stiffness method

2.5 Specification of Boundary Conditions and Nodal Variables

The boundary conditions in a stress-strain problem are the specified nodal displacements (not necessarily zero) in all types of analyses described above and, additionally in consolidation analyses, the specified nodal pore pressures. The displacement boundary restraints may be of roller type (smooth boundary) or with fixity in both directions (rough boundary). A minimum number of displacement boundary conditions (equal to the degree of freedom of the whole body) should be specified in an analysis to prevent rigid body translation and rotation. Pore pressures are specified at nodes on permeable boundaries through which transient water flow may take place. Refer the example problem of a circular near surface tunnel (Fig. 3) for typical boundary conditions in a consolidation analysis. It is only possible to specify at a node at the same instant either the displacement or the force in a particular direction and not both. Similarly water flow and pore pressure at a node cannot be specified at the same time. Usually finite element programs would not allow change of status at a node from displacement/pore pressure specification to a force/water flow specification during an analysis.
External forces applied along the boundaries and self weight loading within elements should be specified during an analysis at the nodes which are not restrained. In some finite element programs the nodal forces required for the equilibrium of body forces and initial stresses are calculated internally and a user has to specify only the external loading. Usually if no loads are defined at an unrestrained boundary node the load at that node is assumed to be zero by the program.

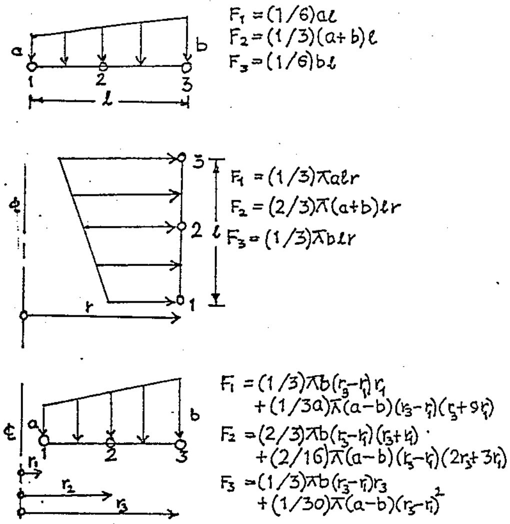


Fig. 6 Calculation of nodal forces for linear strain axisymmetric/plane strain elements

The formula for calculation of nodal forces due to an external load distributed along the edge of an element is dependent on the element shape function. Examples of how the loads are calculated for shape functions with a linear variation of strain are illustrated in Fig. 6.
In a consolidation analysis water flow at a node also should be specified if there is external water flow.
The external loads in non-linear analyses are applied in increments; the increment size should be carefully determined. If the size of increment is too large the results would be inaccurate but if it is too small more computing time is required. It may be necessary to reduce the increment size at the stage when the yielding or failure is taking place in the analysis. A time step is sometimes used to define an arbitrary axis in drained or undrained analyses to show the variation of load, for e.g. in a construction sequence. In consolidation analyses the passage of time also would give rise to loads due to seepage forces; the time increments in such cases are real. Better results in consolidation analyses are obtained by increasing the size of time increment with time perhaps using a rationale like the linearity of log time or root time settlement behaviour.

2.6 Material Behaviour and Properties

The material properties, both type and the parameters, should be specified for all elements used in a finite element analysis. Usually a program would allow the use of a number of material types to cater for the inhomogeneity and each element is assigned a specified material type. Continuum models based on the effective stress concept are frequently used in the analysis of stress-strain problems in soils. Some of them are linear/non-linear, isotropic/anisotropic elastic models and, elasto-plastic models like Mohr-Coulomb and, critical state models like Cam Clay and Modified Cam Clay. Cam Clay models (Roscoe et al (1963), Roscoe and Burland (1968), see Britto & Gunn (1987) for details) are known to give good results in soft clays. In the analyses in rocks, in addition to elastic models given above, ubiquitously jointed elastic model may be used. Elasto-plastic Mohr-Coulomb joint elements along with elastic continuum elements can be used to model problems involving rock joints filled with soil.
The selection of accurate models is one of the most difficult and important decisions to be made in an analysis. Every model has its own advantages and limitations. A linear elastic model may be simple but accurate only in some cases involving small changes of stress from the initial state, provided that the elastic parameters are derived at the initial stress level. A non-linear elastic analysis is much better but is incapable of modelling situations close to failure or post-yield behaviour including dilation and shear compression of soils. In contrast, an elasto-plastic model may be more time consuming and complicated but may give much better results provided that the model used is capable of accurately representing the material behaviour and the correct material properties are used in the analysis.

Once a material type is chosen the parameters required for the definition of the model should be selected. The accuracy of results of an analysis is directly related to the accuracy of parameters selected for the analysis. According to some computer cynics, the use of unreliable parameters with sophisticated models is a way of using the computer in "GIGO" (Garbage in-Garbage out) mode. In simple models like linear elastic model parameters should be selected to represent the real material behaviour at the initial stress level as close as possible. For more sophisticated models like Modified Cam Clay model a minimum amount of field testing or laboratory testing of undisturbed material specimen is absolutely necessary.
In non-linear analysis, it is necessary to specify in addition to the material properties, the initial condition of stress and other variables like voids ratio etc. Usually in finite element packages this initial calculations may be carried out within the program. The user is required only to specify the parameters like surcharge, the unit weight of soil, the coefficient of earth pressure at rest, the position of water table etc. If the soil is not homogeneous the above parameters may be specified for different layers like in the case of material properties. In some programs once the initial stress distribution is specified the forces required to maintain the equilibrium of the whole body considered would be calculated and enforced internally.

3. FINITE ELEMENT PACKAGES

3.1 Introduction

This section describes the essential features and the running instructions of the finite element packages, CRISP and AFENA, both available in micro- and mini- computer versions for the analysis of stress-strain boundary value problems in soils and rocks. CRISP was developed by the members of Soil Mechanics Group of the University of Cambridge, U.K. in late 1970's and 1980's. AFENA was developed at the Centre for Geotechnical Research of University of Sydney in 1980's. Further details of these packages are given in the User's Instruction Manuals of the programs (Gunn and Britto (1990), Carter and Balaam (1990)).

3.2 Essential Features of CRISP

The acronym CRISP stands for CRItical State Program(s). CRISP is capable of carrying out undrained, drained and consolidation analyses of 3-D or 2-D plane strain or axisymmetric solid bodies. Stress-strain models available with CRISP are, linear elastic, anisotropic elastic and inhomogeneous elastic (properties varying with depth) models, Cam Clay and Modified Cam Clay critical state models and elasto-plastic models with Tresca, Mohr-Coulomb or Drucker-Prager yield/failure criterion. The element types available with CRISP include linear or cubic strain triangles and linear strain quadrilateral for 2-D analyses and, 20 noded brick element for 3-D analyses. bar/beam elements and interfaec elements are available to to model structural components, material interfaces and, soil-structure interaction. The solution technique is based on incremental tangential stiffness approach and frontal method of storage optimisation. The boundary conditions can be given at element sides in the form of prescribed incremental displacements, excess pore pressures, and/or in the form of nodal loads and pressure loads on the side of elements. The program allows the removal or addition of elements simulating excavation and filling and automatically calculates the additional loads due to them. Supporting features include, mesh generation programs, plotter routines for checking the mesh as well as for post processing and, stop-restart facility using disc space or magnetic tapes.

3.3 Essential Features of AFENA

The acronym AFENA stands for 'A Finite Element Numerical Algorithm'. AFENA is capable of handling 3-D and 2-D plane strain and axisymmetric problems in solid mechanics. It has better facilities than CRISP in handling problems in rocks. The element types available with AFENA are bar/beam-column elements (1-D), linear strain quadrilaterals (2-D), 8 noded rectangular bricks (3-D) and, 4 or 6 nodedjoint elements. In addition to the stress-strain models available with CRISP (many of them are given in the last section), AFENA has over 20 stress-strain models, a particularly important one being ubiquitously jointed elastic model which may be used in solving problems in rocks. The solution technique is based on incremental tangential stiffness approach and 'skyline' optimisation method. The facilities for excavation and filling and, supporting software for checking the mesh and post processing are somewhat similar to those available with CRISP.

3.4 Running CRISP

The mini-computer version of CRISP is run in two modules, namely, Geometry Program and Main Program (micro-computer version has more modules created by subdivision of the two modules). The basic data required in running geometry program are as follows;

a. Title of the analysis
b. Name of Link file for storing output from the geometry program for running the main program
c. Parameters defining the size of the problem including the number of elements and nodes, maximum number of nodes per element, the identification number of the element type with the most number of nodes and, the number of dimensions of the problem
d. The order of nodal coordinates and numbers can be arbitrary if frontal optimising routine is used
e. For each element, the node numbers of vertices in anticlockwise order, the element type and the material property number, i.e. the material in which the element is in
f. Output options for plotting the mesh and print output.

The results of the geometry program can be checked by plotting the mesh and also by the print output. When this is satisfactory main program can be run. The basic data required for running the main program are given below;

a. Title of the analysis
b. Name of the link file containing geometric data
c. Control data; type of analysis, i.e. plane strain, axisymmetric or 3-D, number of material types, starting increment number for the run, finishing increment number for the run
d. Parameters for each material type
e. Specification of insitu stresses, this is usually optional but mandatory for non-linear analyses and is carried out using a separate node system representing each layer
f. Specification of nodal fixities
g. Specification of initial nodal forces and/or pressures on element sides
h. For restart of an old analysis records d-g are not necessary; the following data can be given for each increment or in increment blocks to reduce the number of data entries
i. Increment number or increment block details
j. Details of elements added or removed to simulate excavation or filling
k. Current increments of nodal forces and/or prescribed displacements or in the case of consolidation analysis also the time increment
l. Output options for the printer and plotter
k. Repeat records i to k for all increments or increment blocks.

3.5 Running AFENA

The micro-computer version of AFENA is run in a single module. The input data is given in block form using macro commands to specify the type of data. The basic data required for running AFENA are as follows;

a. Title of the analysis
b. Control data; total number of nodes, elements, material sets, spatial dimensions (2-D or 3-D), Maximum number of variables at a node, maximum number of integration points, maximum number of historic variables for non-linear analysis,
c. Coordinates of nodal points given using COOR macro command
d. Element types, their numbers, element node numbers in order and, material type within elements, given using ELEM macro command
e. Material types and parameters defining each material given by MATE macro command
f. Displacements and pore pressure boundary conditions specified using BOUN macro command
g. Nodal forces specified using FORC command and non-zero displacements, if any, specified using FORC and BOUN commands
h. Insitu stresses and other historic variables for non-linear analyses described using GEOS command, it is possible to define uniform values or stresses linearly varying with depth
i. Special features include change of mesh during increments using MESH command, Change of material type* during execution

using CHMA command, automatic mesh generation using GNQ8 command, automatic calculation of nodal forces for uniform pressure using TRAC command and, definition of planar displacement boundary conditions (i.e. rigid body translation or rotation) using LICR command

j. Commands used during the execution stage include the following;

k. DATA command to give time increment during running

l. TIME command to update time during each increment

m. LOOP and NEXT commands to define incremental blocks and other repeated operations

n. PROP command to define increments of nodal loads varying linearly or exponentially with time

o. Removal or addition of elements using EXCA and FILL commands respectively

p. CONS, FORM, SOLV, TANG, UPDT etc. commands to form and solve the equations and update the historic variables for each increment

q. STRE and DISP commands to update stresses and to calculate stresses and displacements after each increment and if necessary to print them

r. printer and plotter options using PLTM, PLTT, CURV (write selected nodal variables to a file), SPRT and NOPR (control the amount of printing) commands

s. Write data necessary for a restart into a file using DUMP command

t. Special run time commands like EQUI, force the current stresses into equilibrium, REAC, calculate nodal forces etc.

In all finite element analyses dimensions and units of geometric and material parameters and, specified variables should be consistent. A consistent set of units is given in Table 1.

TABLE 1

Quantity	Metric Units
Length, thickness, displacement	m
Force, weight	kN
Mass	t
gravity/acceleration	m/s^2
Deformation modulus, stress, pressure	kPa
Moment	kNm
Permeability	m/s
Unit weight	kN/m^3

CONCLUDING REMARKS

A detailed description of the use of finite element packages in geotechnics is beyond the scope of a paper of this nature. What is attempted here is to highlight some important aspects of a finite element analysis and to describe some basic features of two finite element packages. A user would need considerable experience to become a finite element expert. A good understanding of the constitutive behaviour of soil/rock and the theories of elasticity and plasticity would certainly be an advantage.
The accuracy of a finite element prediction is directly related to the accuracies of idealisation, the analysis and, the material parameters. The theory of finite elements is sufficiently advanced nowadays hence the analytical errors can be small. However, there are limitations in existing constitutive models in fully describing all aspects of soil/rock behaviour, particularly in residual soils, expansive soils and organic soils. Further improvements are also necessary in field testing techniques and in sampling and laboratory testing so that correct parameters for models could be obtained from site investigation.
Despite the above shortcomings the finite element method can still give good predictions under many circumstances provided that sufficient attention is given to idealisation, selection of model and, site investigation. A reasonable analysis may give information on displacements, distribution of stresses/strains and, mechanisms of load transfer and failure modes.

ACKNOWLEDGEMENTS

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Analysis of Retaining Wall Behaviour Using Finite Element Method

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Synopsis

Development of Finite Element techniques over the last two decades has caused significant advances in the retaining wall studies. Existing field conditions and constructional operations such as excavation, backfilling and compaction of the backfill etc can be numerically simulated using FE techniques yielding accurate information about forces and deformations in the retaining wall system. The paper presents a FE model developed by the author and some results obtained by analysing a hypothetical wall and two case histories using the model.

1. Introduction

Retaining walls have been in use over several centuries to support otherwise unstable soil. Coulombs theory developed around 1776 was one of the earliest developments in Geotechnical Engineering. Subsequently several other theories were developed to explain or predict retaining wall behaviour and thus to use in their design. Nevertheless in day to day practice there had not been much change from Coulomb's theory. Even the current British code of practice for the design of earth retaining walls is CP 2 (1951) is based on Coulomb's theory.

Traditional design methods assume that wall undergoes sufficient lateral movements to mobilise limiting conditions of equlibrium at its back.
Wall dimensions required or depths of embedment required to ensure stability is then estimated using a limit equilibrium approach. In the absence of methods for accounting for the mobilisation of the shear strength in soil with the deformation undergone such assumptions were necessary.

With the development of finite element techniques over the last two decades, considerable advances were made in the study of retaining wall behaviour. Current methods can account for the existing geological condition in the ground and simulate the construction operations carried out and make accurate predictions about the stresses and deformations in the system.

2. Descritisation of the Problem

In the Finite Element analysis of a problem, system under study is represented by a mesh. There the system is divided in to a number of small units named as elements. Elements may take shapes such as triangles, quadrilaterals etc, sides being either straight or curved. Cornes are termed as nodes. Each element can be assigned properties related to strength and stiffness. Thus if there is stratification or any other spatial variation in the field it can be properly modelled. A typical FE mesh used in retaining wall studies is presented in Figure 1. Wall elements are assigned properties of concrete and foundation soil properties are also appropriately assigned. Properties of backfill material are assigned to the backfill. At the interface of wall and soil one dimensional interface elements are used and their properties are also assigned accordingly.

3. Constitutive Models

Traditional limit equilibrium design approaches implies that soil behaves as a rigid plastic material. From the observed stress - strain behaviour of all geotechnical material it is clear that this is unrealistic. Shear strength is mobilised as the material deforms and the behaviour is more realistically modelled by non linear hyperbolic, elastic ideally plastic or number of such models.

Finite element analysis provides a complete solution to a problem satisfying equilibrium, compatibility and constitutive relationships simultaneously and a realistic stress - strain behaviour as mentioned above can be incorporated in to the analysis. Parameters required in the analysis for the representation of the soil behaviour by an appropriate model may be obtained by carrying out conventional triaxial type tests or more advanced tests where the expected stress paths in the field are simulated in the laboratory.

Interface between the soil and the structure is also of critical importance. As this is a boundary between two materials of significantly different stiffness values, relative movements will take place. In finite element method provisions can be made for this by employing interface elements at such boundaries. Parameters for the elements can be obtained by carrying out interface tests in the laboratory simulating the expected behaviour at the particular interface. In this paper some results obtained by modelling the stress strain behaviour by an elastic ideally plastic model is presented. Interface between the wall and soil is modelled by a trilinear relationship and a non linear hyperbolic type relationship.

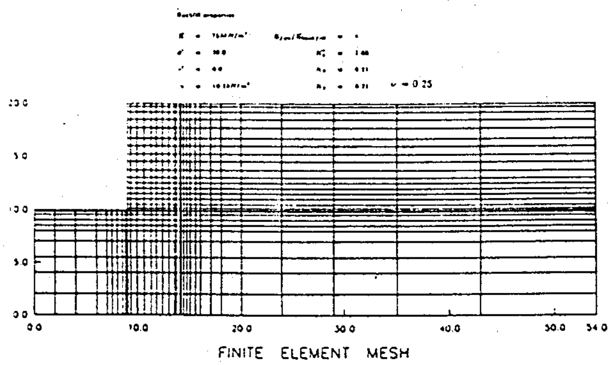

Figure 1 - A Typical FE Mesh

4. Simulation of Construction Process

Traditional methods cannot account for the initial stress conditions in the ground or construction processes such as backfilling, compaction or excavation. This drawback is overcomed in the finite element method and construction process can be very closely simulated by numerical methods.

4.1 Backfilled Walls

Gravity type retaining walls made up of mass concrete or masonry and semi gravity type walls made of reinforced concrete with or without lateral stiffening are considered under this category. In the construction process of these walls, initially the excavations will be made for the foundations and any unstable areas in a existing natural slope would be made flat and stable. Thereafter wall will be constructed and backfilled in layers. Each layer could have been compacted prior to the placement of next layer. This full process can be numerically simulated.

Existing natural ground is represented by part of a mesh as shown in Figure 1. Initial stresses in these elements can also be inputted or computed with the knowledge of bulk density and k_o value. Any excavations done prior to the construction can be simulated by applying forces at the nodes in the excavated boundary. Magnitude of the forces are computed by averaging the stresses acting on the elements to the either side of the boundary and the direction is opposite to that of the stresses. Deformations in the system can be obtained by solving the basic FE stiffness equation and resulting stress arrangements can be then computed. Construction of the wall is then modelled by application of the forces due to weight of the wall at the appropriate node points. Deformations and resulting stress changes are then computed similarly using the FE principles.

When a layer of backfill is placed it is assumed to have a weight but no stiffness. Forces due to weight and lateral pressure of the filled layer are then applied at the relevant nodal points and the FE stiffness equations are solved and stress rearrangements in the already existing soil are computed.

If the backfill is compacted prior to the dumping of the next layer that is simulated using the compaction simulation model.Compaction of a backfill by a number of passes of a roller is essentially a loading/unloading process. Soil underneath is loaded while the compactor is on the surface causing increases in both the vertical and horizontal stress. When the compactor is removed vertical stress is reduced to the original overburden stress while there is only a partial reduction in the horizontal stress. Broms(1971) was the first to propose a model based on this phenomenon. Later Ingold (1979) made an attempt to extend this to yielding walls. Seed and Duncan (1983) proposed that there is a similarity in the loading/unloading process in compaction and k_o type cyclic loading unloading and named it as "Hysteretic k_o loading unloading model". Albeit complex it showed excellent agreement with the observed k_o test behaviour. Using empirical date this model has been approximated by a bi-linear model.

The fundamental idea of Kulathilaka's (1990) model was derived from the Seed and Duncan bi-linear model. Stress paths followed by soil elements at different initial stress states are depicted in Figure 2. With the employment of some numerical techniques model is incorporated with the elastic ideally plastic finite element model.

In the simulation of the compaction process all the already placed soil elements are taken through the model and residual lateral stress increases are computed. Special numerical procedures are adopted to ensure this.

Forces acting on the wall due to these residual stress increases are also computed and assembled. By solving the basic FE equation deformations in the system and resulting stress rearrangements are computed.

In this manner initial excavations, construction of the wall, backfilling in layers and compaction of each layer can be numerically simulated. At each stages deformations and stresses in the system are computed. Thus at the end of the process deformations in the system and stresses at the back of the wall are obtained without having to make any assumptions about the mobilisation.

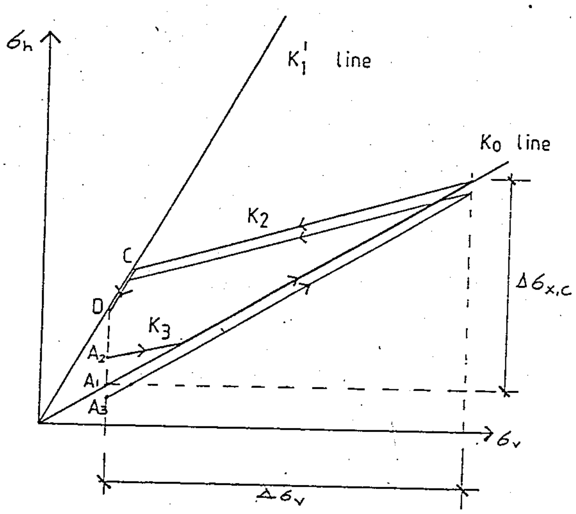

Figure 2 - Compaction Simulation Model

4.2 Embedded Walls

Sheet pile walls and Diaphragm or Bored pile walls are the walls considered under this category. With them first the wall will be installed and thereafter excavation is done to the desired level. Lateral support may be provided in the form of anchors, props laterally spanning slabs at a desired stage.

This type of walls are installed in urban areas during excavations for underground roads, basements etc and displacement control of the neighbourhood is a primary function of them. Displacements can be estimated accurately using a good FE simulation at the design stage. Traditional methods are incapable of providing that information.

Generally in FE simulations it is assumed that no significant changes in stresses or deformations would take place during the wall installation process. However this may not be true always. Excavation is simulated by application of forces that are computed by averaging out stresses on the excavated boundary. As before forces are applied in the opposite direction. Provision of a lateral support at any stage can be modelled by using a spring element at the corresponding node in the appropriate stage.

5. Behaviour of Backfilled Walls

FE analysis by Kulhawy (1974), simulating the construction of a 31.8 m high gravity retaining wall, showed that earth pressures at the back of the wall are only slightly reduced from the at rest values (K_o), due to insufficient wall movement. Goh (1984), performed parametric studies using the finite element methods to study the influence of the stiffness of the foundation soil on earth pressure distribution behind a wall. Foundation soil stiffness was measured by the ratio $E_{fd'n}/E_{backfill}$. For a clayey sand backfill earth pressure distributions obtained for different values of the above ratio are depicted in Figure 3. As the stiffness of the foundation soil increases the outward movement of the wall was restricted and mobilisation of full active conditions was prevented.

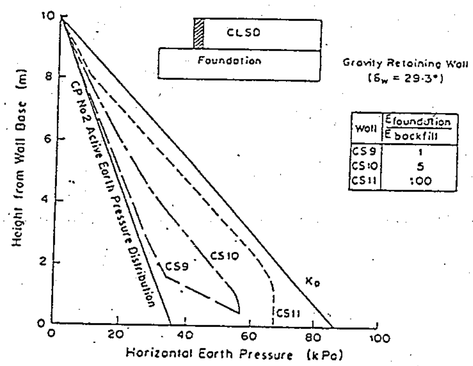

Figure 3 - Earth Pressure Behind Gravity Wall Goh(1984)

Backfilling and compaction of a cohesionless soil behind a 10 m high 5 m wide gravity retaining wall was simulated by the author. FE mesh shown in Figure 1 was used to simulated the problem. Compaction of the foundation soil, construction of the wall, backfilling in layers and their compaction was simulated in the manner described in the previous section. Wall was backfilled in 20 layers. The lateral stress profile at the back of the wall are compared in Figure 4. The case of a non compacted backfill is also presented there. It is clear that even when the backfill is not compacted lateral stresses are much greater than the active values. The case of the rigid wall represents a case where wall is assumed to have unmoved and lateral stress reductions due to movement are neglected. The difference between this and the FE simulated compacted backfill indicate the amount of stress relaxation due to yielding of the wall. The difference between compacted and non compacted profiles highlights the effects of compaction. It is evident that this difference is large closer to the top of the wall. This is because of the fact that the effect of surface compaction is extended only to a limited depth.

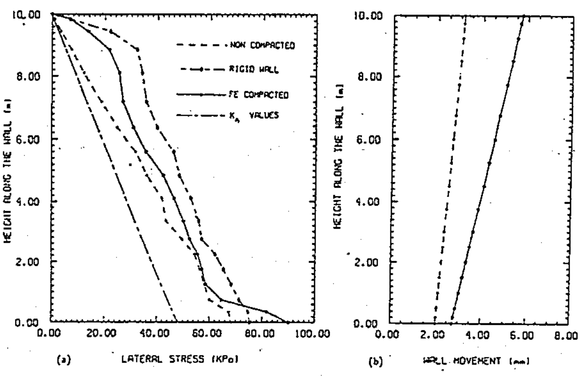

Figure 4 - Lateral Stress Disrtibution and Displacements 10 m High Gravity Wall

The case history of an experimental retaining wall set-up in TRRL London was also simulated. This set up consists of a metal retaining wall of 2m height and concrete retaining wall of 2.5 m height. Full details of the configuration of the set up is presented in Carder et al (1977). FE techniques were used to simulated the backfilling and compaction of the cohesionless backfill in this system. Full details of the simulation process are presented in Kulathilaka (1990). Figure 5 compares the results obtained with the numerical simulation with the observations made in the field. The results are in excellent agreement.

6. behaviour of Embedded Walls

The case of the cut and cover tunnel for a section of M25 mortorway, at Bell Common in Essex, UK was simulated by the author. The tunnel was formed from two secant pile walls, propped apart by a roofing slab which was simply supported on the walls and on a central line of piles. The secant pile walls were formed from 1.2m diameter reinforced concrete bored piles with an overlap of 100mm between adjacent piles. A section of the tunnel was extensively instrumented to measure the stresses and movement of the wall and in the adjoining ground.

The observations at the Bell Common have continued since construction and the behaviour of the wall in the longer term (after 4 years from construction) were described by Symons and Tedd (1989). Pore water pressure distribution and total stress distribution at 0.6 m away from the wall have shown little changes over these four years. Comparison of wall displacements obtained through instrumentation and Finite element computations done by author for various construction stages are shown in Figure 6.

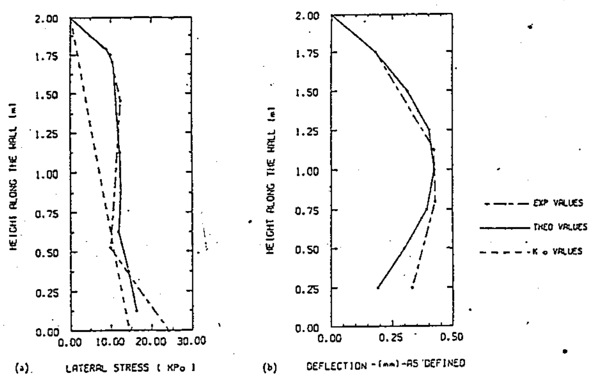

Figure 5 - Comparisons - TRRL Metal Retaining Wall

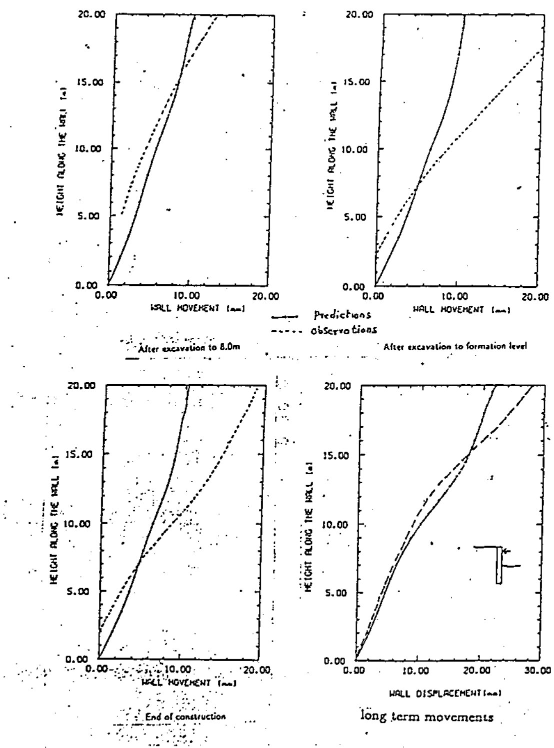

Figure 6 - Comparisons - Bell Common Tunnel

. Concluding Comments

The paper presented the basic techniques used in simulation of retaining wall construction using FE methods.

Parametric studies illustrated that active conditions does not mobiliseat the back of the retaining walls in all the instances as the wall movements could be inhibited by a stiff foundation. Compaction introduces higher stresses but some of that is relaxed due to the outward movement of the wall during the backfilling and compaction process.

With the case histories presented it is clear the FE simulations can provide very good predictions. There are instances where the neighbouring infrastructure relies on retaining wall for their displacement control as well. In such instances traditional methods cannot asses the situation. But an accurate FE simulation can provide a good estimate of the likely movements and if necessary measures may be adopted to reduce the deformations.

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Computer Controlled Experiments

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SYNOPSYS

The main aim of this paper is to provide a brief description of automated or computer controlled testing apparatus used in soil mechanics. The context is far from complete, but does at least cover the range of such compter controlled instruments presently used by researchers.
The automation of triaxial and hollow cylindrical apparatus is described. In addition a brief description is presented on the use of computers to perform on-line testing in which numerical analysis and testing are carried out simultaneously.

INTRODUCTION

Advancement of computer related analysis demands the accurate measurement of material properties. This results in developing new testing apparatus and improving the quality of apparatus available. This mainly enhances the quality and quantity of data aquisition and processing.
A number of new measuring devices have to be deviced, so that the computer and the testing apparatus can work together. In each case the designer attempts to find a means of converting a change in force, pressure or displacement into an electrical signal. Naturally, the aim is always to provide a sensitive but robust device that has good stability and gives repeatable characteristics relating the electrical output to the quantity being measured. Among the many devices, Differential pressure transducer(DPT), Pore pressure transducer, LVDT, and Load cell play an important role.

TRIAXIAL TESTING

In the triaxial test, a computer controlled electro-pneumatic loading system was used. This system has four major elements.

1. Micro-computer with Analog to Digital (A/D) and Digital to Analog (D/A) converters.
2. Electronic/Pressure transducers with relays.
3. A double acting piston (Bellorfam cylinder)
4. Volume booster (Amplifiers)

A schematic diagram of this system is shown in figure 1. A computer program could be written to control the load. Uniform, non uniform and irregular (random) loading tests could be conducted using this apparatus.
The output signals from the axial load cell, axial electronic dial guage and pore pressure transducers were read using a computer program developed in a personal computer. During the test all the data were stored immediately in a floppy disk or hard disk. In order to avoid some electrical noise that was observed in the first series of the tests, the sampling was done taking simultaneously 15 data per channel in 0.5 second approximately. The average data for each channel was stored in a floppy disk as the results of the test.

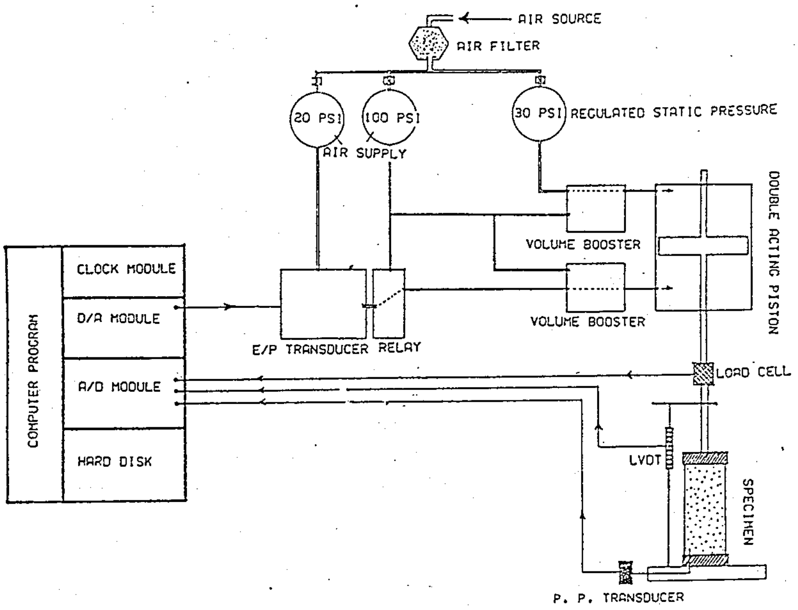


Fig. 1. Schematic diagram for the triaxial laoding system (after Wang et. al. 1989)

HOLLOW CYLINDRICAL APPARATUS

Many field problems involve the simple shear condition as typically observed for an element such as B shown in figure 2. In contrast to the triaxial behaviour, the simple shearing requires many controls, as can be clearly observed in figure 3. Consequentlly, the soil specimen is subjected to the simple shearing by means of automation very accurately. The automated hollow cylindrical apparatus is used to simulate the simple shear behaviour. Subjecting the hollow cylindrical soil specimen to a set of loads, the simulation can be achieved as discussed later in the testing method.

The torsional shear apparatus used by Pradhan et. al. (1988) can be described as follows. (see Fig. 3)

- The inner cell pressure p_i can be controlled independent of the outer cell pressure p_o. The volume change of the inner cylinder is measured by monitoring the amount of water expelled from or absorbed into the inner cylinder by means of a burette (10a in Fig. 3) and low capacity differential pressure transducers (DPT)(11). The effective inner cell pressure p'_i, which is the difference between p_i and the pore water pressure u, is measured by means of a high capacity DPT(13). The effective outer cell pressure $p'_o = p_o - u$ is measured similarly by means of another high capacity DPT(12)
- The volume change of specimen is measured very accurately (with an accuracy of $10^{-3}cm^3$) by means of an electronic balance (8 in Fig. 3)
- The axial stress is controlled independent of the other stress components by adjusting the air pressure p_a (15) in the upper room of the double action Bellofram cylinder (2 in Fig. 3)
- The pressures p_i, p_o and p_a are controlled automatically with the aid of a micro-computer so that the stress and strain condition of specimen during testing follows the intended path.

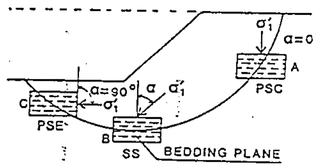


Fig. 2. Three representative soil elements deforming in plane strain

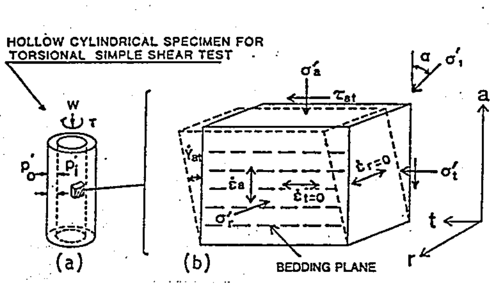


Fig. 3. Torsional simple shear deformation

Testing Method

The strain conditions of $\epsilon_t = \epsilon_r = 0$, during tortional shearing were achieved by using different techniques for drained and undrained tests. In this paper discussion is limited to the drained test.

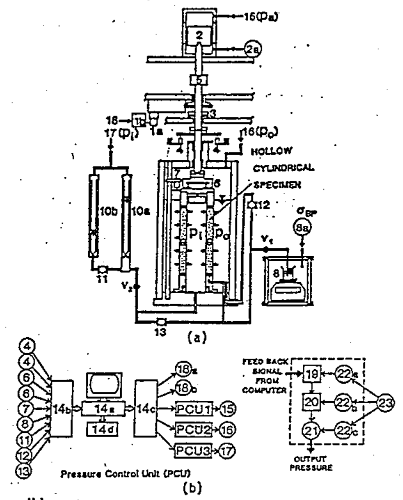
The simulation can be achieved by shearing the specimen at a constant rate of shear distortion while controlling correspondingly the axial stress σ'_a and the inner and outer pressures p'_i and p'_o.

Therefore, the behaviour when approaching the failure as well as the post peak behaviour could be measured as in the case of ordinary strain controlled tests.

A low strain rate of $\gamma'_{at} = 0.0002/min$ was employed for precise automatic controlling by a micro computer. The main structure of the servo-system is illustrated in Fig.3. The measured quantities are as follows (see Fig 3 for layout of numbers).

- 4; axial displacements measured at two opposite points.
- 6; torque and axial load.
- 7; rotational displacement.
- 8; volume change of specimen
- 11; volume change of inner cylinder
- 12; effective outer cell pressure $p'_o = p_o - u$
- 13; effective inner cell pressure $p'_i = p_i - u$

These data are converted from analogue to digital values by A/D converter (14b) and processed by a microcomputer (14a). Based on changes in the outer and inner radii r_o and r_i and the axial stress σ'_a as computed, the outputs from the micro-computer, after being converted to analogue values by D/A converter (14c), were used to control the three pressure control units (PCU1, PCU2 and PCU3) so that the prescribed stress and strain conditions are satisfied (i.e. $\sigma'_a = 0, r_o = 0$ and $r_i = 0$)



1a; Reversible motor
1b; Loading control unit
2 ; Double action Bellofram cylinder
2a; Regulator for constant air pressure
3 ; Clamp
4 ; Axial displacement transducer
5 ; Outer axial load cell
6 ; Inner two component load cell
7 ; Potentiometer for rotational displacements
8 ; Electronic balance for volume change measurement
8a; Regulator for constant back air pressure
9 ; Hollow cylindrical specimen
10a; Burette for inner volume change measurement
10b; Reference tube
11 ; Low capacity DPT for volume change measurement of inner cykindri space.
12 ; High capacity DPT for effective inner cell pressure measurement
13 ; High capacity DPT for effective outer cell pressure measurement
14a; Micro-computer
14b; A/D convertor
14c; D/A convertor
14d; Floppy/Hard disk
15 ; Controlled axial pressure
16 ; Controlled outer cell pressure
17 ; Controlled inner cell pressure
18 ; Controlled output voltage for motor control
19 ; Electric to pnumetic (E/P) transducer
20 ; Adjustable ratio relay
21 ; Positive bias relay
22a,d,c; Regulators for constant pressure supply
23 ; Main pressure supply

Fig. 4. Hollow cylindrical apparatus (after Pradhan et. al. 1988)

Test Results

Some of the results obtained by simple shearing of a hollow cylindrical specimen is shown in Fig. 5. This figure clearly indicates the accuracy to which the simple shear condition could be maintained throughout the test. Although, there were few noises observed, the horizontal strains (see Fig. 3) ϵ_r and ϵ_t were maintained at zero

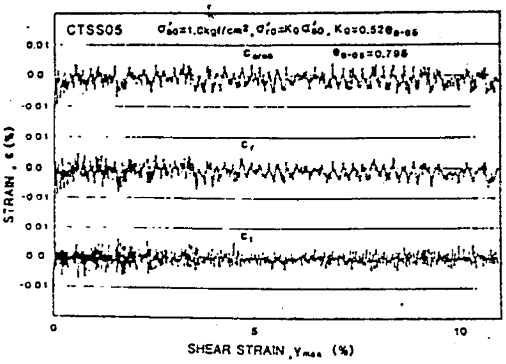


Fig. 5. Varaition of horizontal strain during a simple shearing test

CONCEPT OF PSEUDO TESTING (ON LINE TESTING)

Conventionally, in order to analyse a soil structure, some numerical model can be used. Verification of these models can be achieved by soil element tests and soil model tests. In the so called pseudo testing, the numerical analysis (usually Finite Element Method) is performed simultaneously with the soil element tests. The numerical analysis is carried out for the soil structure while the element tests are performed for selected few elements of the structure, applying the predicted stress strain condition on the soil specimen. Based on the behaviour of the soil specimen and the predicted results from the analysis, the necessary corrections or modifications for the next step of the analysis can be introduced. In this manner the analysis and testing can be performed step by step in order to observe the behaviour of the soil structure. The flow diagram for the on line testing is given in Fig. 6.

REMARKS

Computer controlled or automated testing apparatus are very usefull due to the quality and quantity of data that can be aquired and processed. However, the cost required for this automation is a key issue when consider their use. For monotonic loading with lesser number or stress and strain controls, the automation may not be that important. Data processing alone can be performed by computer. However, the cyclic/dynamic testing may need high frequency data aquisition for which the use of computer is inevitable. Also for testing apparatus in which a number of forces, pressures and displacement are to be controlled (e.g. Hollow cylindrical apparatus), the computer is a very usefull tool.

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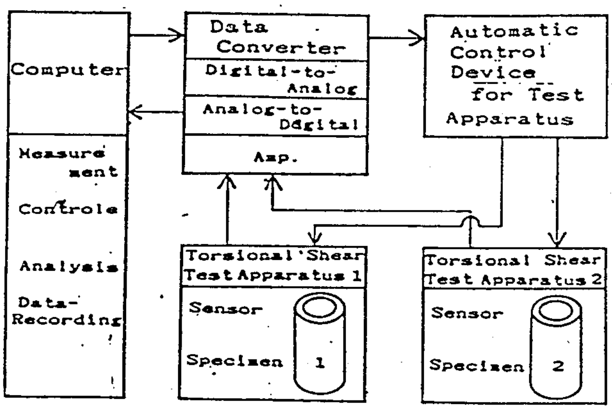

Fig. 6. Flow diagram for on-line testing (after Kasukabe 1991)

Application of Spreadsheets in Geotechnical Engineering

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University of Peradeniya

SYNOPSIS

Spreadsheets could be used as powerful tools by the geotechnical engineers in their day to day work to solve problems that are repetitive in nature. The facilities and capabilities of spreadsheet make them ideal packages to be used in this field. Their tabular form, graphical features, and commands available are suited for many geotechnical applications. This paper describes some applications of spreadsheets in geotechnical engineering.

The spreadsheet package Lotus 1-2-3 was used in developing a set of worksheets for the analysis of some routine soil tests and for the design of foundations. Given the necessary observations of tests, the soil properties could be determined using the appropriate worksheet. The design of a foundation could also be done similarly, by giving the basic parameters. The effective use of spreadsheets could cut down the time spent on repetitive calculations and reduce the possible errors in soil testings and in geotechnical designs.

1.0 INTRODUCTION

The invention of computers has made a tremendous contribution towards the advancement of science, and in particular, to the field of engineering. Personal computers are being widely used by the engineers in their daily work. The development of 'user-friendly' packages for numerical calculations, data processing, drafting and word processing has further improved this situation.

Spreadsheets could be used, to a great extent, to find solutions to many engineering problems. Previous researchers have explored the use of spreadsheets in structural analysis and design of concrete beams and columns, velocity and acceleration computation in slider crank mechanisms, heat flow problems, geotechnical problems, water management problems, load flow studies and in computer aided designs. Spreadsheets had been used for the analysis of seepage problems in dams by Kleiner (1985) and in the application of routine soil tests by Aravinthan (1992). The text by Orvis (1987) specifically deals with the application of spreadsheets for engineers and scientists.

The geotechnical engineer very often faces repetitive and similar design problems. It also becomes necessary for one to perform a series of tests to determine certain soil properties. In such circumstances, the use of computers will not only minimise the time spent on repetitive calculations and decision making, but also reduce the errors that may, otherwise, occur. This paper deals with the application of spreadsheets in geotechnical engineering. A set of worksheets developed using the spreadsheet package Lotus 1-2-3 for some routine soil tests and for foundation designs is briefly discussed.

2.0 FEATURES OF A SPREADSHEET

The first spreadsheet invented was Visicalc which got the name from VISIble CALCulator. From then many packages had been developed and had undergone various modifications for improvement. Among the many spreadsheet packages, Lotus 1-2-3, QuattroPro and PC Excel are some popular packages. The work discussed in this paper was developed using Lotus 1-2-3 which is an integrated electronic spreadsheet that contains a worksheet, database functions and graphical features. This package is easy to learn and use. It is more user interactive due its 'glass-box' nature. When a value of an entry is changed, the entire worksheet is automatically recalculated to reflect this change. These features make the spreadsheet a valuable tool for an engineer.

2.1 The Worksheet

The worksheet of Lotus 1-2-3 release 1 and 2 contains a set of rows and columns which is of a two dimensional form. The major improvement in release 3 is the introduction of sheets in addition to rows and columns thus having a three dimensional form. The release 2 which incorporated many useful functions and commands, is generally adequate for most of the engineering work, while the additional features found in release 3 could be made use for advanced work. The main advantage of the three dimensional form is that when there is a set of similar worksheets, all those could be stored in a single file with many sheets whereas in release 2 it could be only stored in different files.

2.2 Database Functions

Lotus 1-2-3 contains many database functions. Among them data-fill, data-table, data-sort and data-regression are some useful functions for engineering purposes. The data-fill command could be used to fill a range with a sequence of values. The data-table command is useful to create a table of values in a variable formula. To sort a database record in ascending or descending order the data-sort command could be used. A multiple linear regression analysis could be performed up to sixteen variables by the data-regression command. With this useful command most curve fitting tasks can be accomplished either with a simple straight line or with a complex polynomial approximation.

2.3 Graphical Features

Lotus 1-2-3 can basically plot line, Bar, X-Y and Pie graphs. X-Y plot is the one commonly used by the engineers. This has the ability to plot six different 'Y' ranges for a particular 'X' range. The latest release could also plot 'Y' ranges to two different scales. In addition the semi-log or log-log plots could be obtained by simply adjusting the scales to logarithmic scale.

2.4 Other Functions and Features

There are many other features in Lotus 1-2-3. Macro which could be defined as a capability to combine many actions into a few commands enables the user to cut down many keystrokes. The user could also create his own 'user-defined' menu which will be helpful in decision making in a 'user-friendly' way. The use of Copy command with absolute and relative cell references reduces the time taken in developing the worksheet. The printer options such as Header and Footer are useful for printing the worksheets and graphs with identification notes which are essential when there are many similar prints to be taken.

3.0 USE OF SPREADSHEET IN SOIL TESTS

The soil properties are determined by performing a series of laboratory and in-situ tests depending on the importance of the job. The amount of time spent for both the performance of the tests and the analysis of the results is considerable. The time spent on the calculations and plotting of graphs could be minimised by the use of spreadsheets. The observations, calculations and results of many soil tests are in tabular form. In addition many graphs are required to be plotted in order to obtain certain soil properties. Since the above requirements are readily available in an integrated spreadsheet, it becomes an ideal package to be used for soil tests. The application of spreadsheets for some routine soil tests had been discussed in detail elsewhere by the author [1]. The worksheets developed by the author at the Soil Mechanics Laboratory, Department of Civil Engineering, University of Peradeniya were used in analysing a series of samples brought to the laboratory for testing. Some of the tests analysed by the use of spreadsheet are described below.

3.1 Atterberg Limits

The Atterberg Limits test is done to determine the Liquid Limit and Plastic Limit and related indices of fine grained soils. The upper and lower limits of the range of moisture content over which a soil exhibits plastic behaviour are defined as the liquid limit and the plastic limit respectively. The cone penetration method was used to find the liquid limit and the thread method was used to obtain the plastic limit. The plastic limit by thread method is taken as the minimum moisture content at which the soil can be rolled into a thread of 3 mm diameter without crumbling. The liquid limit by the cone penetration method is taken as the moisture content at which a cone of standard weight will penetrate 20 mm when dropped from the surface and left for 5 seconds.

About four to five trials are done with different amount of water and the penetration values are observed. The moisture content of these samples are also obtained. From the semi-log graph of moisture content with penetration, the liquid limit of the soil is obtained. It is necessary to obtain the best fitting straight line from the observed points. The best fit which is done usually by eye estimation is questionable. But this task was easily done by the data-regression command available in Lotus 1-2-3. In this case a simple straight line approximation was sufficient. Also the value of correlation coefficient R^2 which is given with the regression output indicates how best the fit is. using the options available in the 'graph' mode, the test points were denoted by symbols and the predicted curve was drawn by a line. The liquid limit value was obtained from the values found by the regression analysis. However, sometimes it may be necessary to neglect some points that lie obviously outside the curve. This judgement depends on the experience of the operator in such tests. A typical plot of the graph necessary for the liquid limit test together with the regression output and a print of the worksheet is presented in Appendix-A.

3.2 Particle Size Analysis

The particle size analysis (mechanical analysis or grain-size analysis) is widely used in the engineering classification of soils. Most systems of soil classification depend to some extent upon the distribution of various sized particles in the soil. There are two stages of analysis in this test. The sieve analysis (coarse analysis) is done for particles larger than 0.074 mm and the sedimentation analysis or hydrometer analysis (fine analysis) is carried out for particles smaller than 0.074 mm. One will have to do a number of steps of calculations, especially in hydrometer analysis, before plotting the particle size distribution curve on a semi-log sheet.

The graphical features of Lotus 1-2-3 release 3 has the facility for plotting logarithmic graphs while this feature is not available in release 2. However it was observed that the grids drawn with automatic grid option were equally spaced on log scale. Due to this limitation it was necessary to manipulate the available facilities to obtain a plot as per requirements of the specifications BS 1377 (1975). Typical observation sheets with necessary calculations and a plot of gradation curve is given in Appendix-B.

3.3 Triaxial Compression Test

The triaxial compression test is done to obtain the shear strength parameters of a soil. Usually, one of the three main types of tests, namely, unconsolidated-undrained, consolidated-undrained and consolidated-drained tests is done depending on the requirement of strength parameters. The consolidated-drained test which is also called the slow test was carried out on some samples brought for testing. While the test itself takes a substantial amount of time by its nature, the calculations and plotting of graphs generally take some time due to large number of observations involved. The advantages of spreadsheet was much evident in this type of work and the results of the tests were obtained within a shorter period of time.

It was necessary to modify the worksheet by inserting or deleting the number of rows, depending on the number of observations. This was possible with the commands available in Lotus 1-2-3. From the peak and ultimate values of deviatoric stress and from the principal stress ratio, the major and minor stress values were calculated. With the values obtained from three to four samples, the values of effective cohesion and angle of internal friction were obtained. A straight line regression was used in this case. In some cases it was necessary to force the intercept to zero when it was observed to have a negative value. A typical observation sheet and some plots of this test are given in Appendix-C.

4.0 USE OF SPREADSHEET IN FOUNDATION DESIGN

In a geotechnical design such as a retaining wall or a foundation, repetitive calculations has to be done to get an economical design. Due to fatigue of repeated calculations, the designers tend to satisfy themselves with the solution which satisfies the necessary conditions though it may not be the best design. The spreadsheet becomes a very good design tool in these circumstances to overcome this problem and to achieve an improved design. The 'what-if' capability of spreadsheet is suitable for trial and error process such as designing of retaining walls and foundations. It enables the designer to alter the necessary parameters and arrive at the best possible solution which would, otherwise, go unnoticed. It is possible for the designer himself to develop the necessary worksheet to suit his particular problem.

4.1 Design of a Pad Foundation

The design of pad foundations is very often encountered in the geotechnical design. A worksheet named 'Footing' was developed for this purpose, which is very helpful in designing a pad foundation. When the necessary dimensions such as the width, breadth and depth of footing together with the necessary column loads and moments are entered, the worksheet checks the factor of safety. It also checks the immediate and consolidated settlements. It is possible for the user to do any modification if necessary. It was found that the spreadsheet was an ideal package for this type of trial and error design. Appendix-D gives an extract of this worksheet.

5.0 CONCLUSIONS

Spreadsheet could be used as a useful tool by the geotechnical engineer. In this study, spreadsheet has been successfully used to obtain the necessary properties from the observations of laboratory soil tests. It was found that the time spent for the calculations and plotting of graphs was reduced considerably. It is also possible to use the spreadsheets where repetitive and similar calculations are encountered, such as in the design of foundations. It is concluded that the proper use of spreadsheets in a soil testing laboratory or in a geotechnical design office will minimise not only the time spent for repetitive calculations and plotting of graphs but also the possible errors that may, otherwise, occur.

6.0 ACKNOWLEDGMENTS

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APPENDIX-A: EXTRACT OF THE WORKSHEET FOR ATTERBERG LIMITS

A1. Observation Sheet

Site: UDS-1 (B.H.No: 3 RDA) Depth : 1.90-1.31 m

DETERMINATION OF LIQUID LIMIT USING CONE PENETROMETER

Date : 27-10-1992 Sample No : UDS-1 (B.H.No: 3 RDA)
Site : Description: Air dried

Trial No:	01	02	03	04	05
Penetration Reading (d)	15.8 16.0	17.3 17.5	18.2 18.2	21.5 21.7	23.5 23.8
Average Penetration (d avg)	15.90	17.40	18.20	21.60	23.65
Container No.	15/46	37/15	42/84	16/37	82/47
Wt. of wet soil+Container/g	64.10	67.25	58.93	56.20	56.80
Wt. of dry soil+Container/g	45.35	46.95	41.55	40.15	40.20
Wt. of Container/g	17.70	17.20	17.13	18.70	18.75
Wt. of Dry soil (Wd)/g	27.65	29.75	24.42	21.45	21.45
Wt. of moisture (Wm)/g	18.75	20.30	17.38	16.05	16.60
Moisture content 100(Wm/Wd)	67.81	68.24	71.17	74.83	77.39
Log(d avg)	1.201	1.241	1.260	1.334	1.374

Record: Percentage passing through BS 200 Sieve

DETERMINATION OF PLASTIC LIMIT USING THREAD METHOD

Trial No:	01	02
Container No.	51/45	85/06
Wt. of wet soil+Container/g	44.93	54.52
Wt. of dry soil+Container/g	36.10	42.45
Wt. of Container/g	16.85	16.95
Wt. of Dry soil (Wd)/g	19.25	25.50
Wt. of moisture (Wm)/g	8.83	12.07
Moisture content 100(Wm/Wd)	45.87	47.33

RESULTS:

Liquid Limit of the soil: 73.0 %
Plastic Limit of the soil: 46.6 %
Plasticity Index of the soil: 26.4 %

A2. Output of Regression Analysis

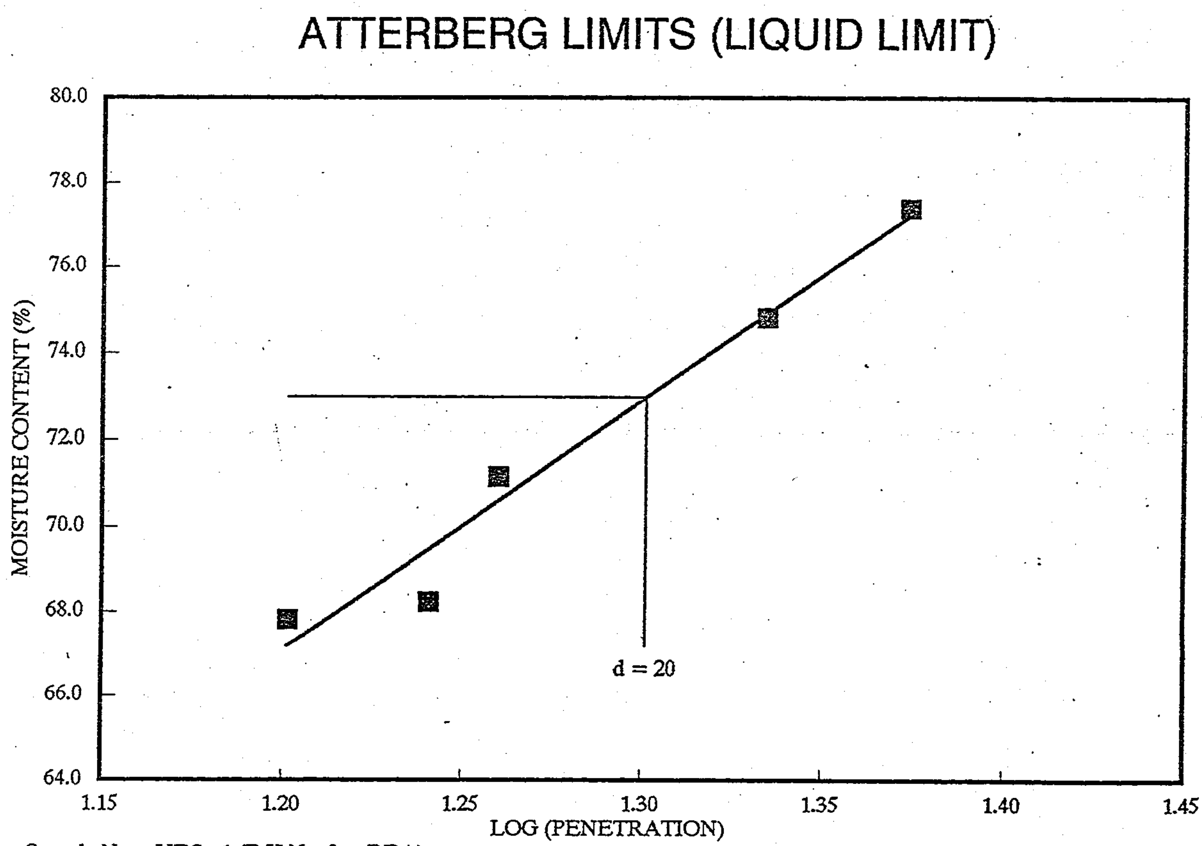
Site: UDS-1 (B.H.No: 3 RDA) Depth : 1.90-1.31 m

REGRESSION OUTPUT:
=================

Regression Output:	
Constant	-2.59372
Std Err of Y Est	0.869302
R Squared	0.967315
No. of Observations	5
Degrees of Freedom	3

X Coefficient(s)	58.09421
Std Err of Coef.	6.165386

A3. Plot of Graph



Sample No : UDS−1 (B.H.No: 3 − RDA)
Depth : 1.90 − 1.31 m (Air dried)

APPENDIX-B: EXTRACT OF THE WORKSHEET FOR PARTICLE SIZE ANALYSIS

B1. Observation Sheet of Sieve Analysis

Site: UDS-1 (B.H. 3 RDA) Depth : 1.90-1.31 m

MECHANICAL ANALYSIS OF SOIL

SITE:		DATE:	19-11-1992
SAMPLE No:	UDS-1	DESCRIPTION:	
BOREHOLE No:	03 - RDA	DEPTH:	1.90 - 1.31 m

SIEVE ANALYSIS OF SOIL (WET/DRY)

1.	Wt. of dry sample + Container	=	135.18
	Wt. of Container	=	55.18
	Wt. of dry sample	=	80.00
2.1	Wt. of coarse agg. + Container	=	0.00
	Wt. of Container	=	0.00
	Wt. of coarse aggregate	=	0.00
2.2	Wt. of fine agg. + Container	=	89.10
	Wt. of Container	=	55.18
	Wt. of fine aggregate	=	33.92

APERTURE (mm)	CONTAIN. +AGG. (g)	CONTAIN. (g)	AGG. RETAINED (g)	PERCENT RETAINED BY AGG.	PERCENT RETAINED BY TOTAL	TOTAL PASSING %	MAX. SIEVE LOAD (g)
76.20	0.00	0.00	0.00	0.0%	0.0%	100.0%	
63.50	0.00	0.00	0.00	0.0%	0.0%	100.0%	
50.80	0.00	0.00	0.00	0.0%	0.0%	100.0%	4500
38.10	0.00	0.00	0.00	0.0%	0.0%	100.0%	3500
25.40	0.00	0.00	0.00	0.0%	0.0%	100.0%	2500
19.10	0.00	0.00	0.00	0.0%	0.0%	100.0%	2000
12.70	0.00	0.00	0.00	0.0%	0.0%	100.0%	1500
9.50	0.00	0.00	0.00	0.0%	0.0%	100.0%	1000
4.75	0.00	0.00	0.00	0.0%	0.0%	100.0%	500

Total = 0.00 g
Loss = 0.00 g
Sample Passing 4.75 mm = 80.00 g

4.750	1.57	0.00	1.57	2.0%	2.0%	98.0%
2.000	2.65	0.00	2.65	3.3%	5.3%	94.7%
0.840	7.53	0.00	7.53	9.4%	14.7%	85.3%
0.590	3.10	0.00	3.10	3.9%	18.6%	81.4%
0.420	3.43	0.00	3.43	4.3%	22.9%	77.2%
0.250	2.40	0.00	2.40	3.0%	25.9%	74.2%
0.150	6.80	0.00	6.80	8.5%	34.4%	65.7%
0.075	5.03	0.00	5.03	6.3%	40.6%	59.4%
Passing	1.37	0.00	1.37	1.7%	42.4%	57.7%

Total = 33.88 g
Loss = 0.04 g

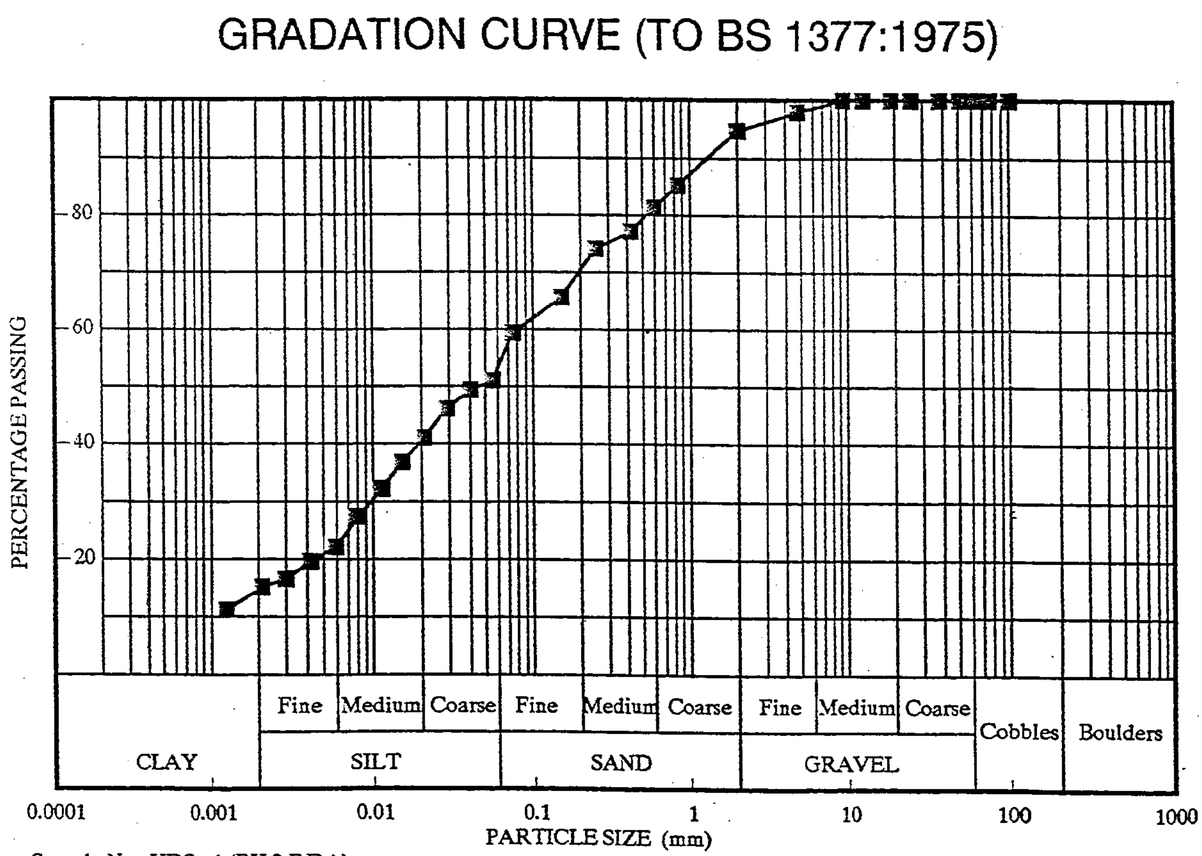
B2. Observation Sheet of Hydrometer Analysis

Site: UDS-1 (B.H. 3 RDA) Depth : 1.90-1.31 m

Mechanical Analysis - Hydrometer Method
Hydrometer No:

Clock hr min	Time after s hr	min	sec	Time sec	Temp. Deg(C)	Rh'	Rh'+Cm=Rh	Hr cm	(Hr/t)	D mm	Mt	Rh+Mt-Cd	% finer than D
			30	30	24.3	25.30	25.80	9.86	0.32859	0.0561	0.8949	23.295	51.0%
		1	0	60	24.3	24.50	25.00	10.03	0.16708	0.0400	0.8949	22.495	49.5%
		2	0	120	24.3	22.80	23.30	10.38	0.08650	0.0288	0.8949	20.795	46.1%
		4	0	240	24.3	20.20	20.70	10.92	0.04552	0.0209	0.8949	18.195	41.0%
		8	0	480	24.3	18.00	18.50	11.38	0.02372	0.0151	0.8949	15.995	36.7%
		15	0	900	24.3	15.70	16.20	11.86	0.01318	0.0112	0.8949	13.695	32.2%
		30	0	1800	24.3	13.30	13.80	12.37	0.00687	0.0081	0.8949	11.295	27.5%
	1	0	0	3600	24.5	10.50	11.00	12.95	0.00360	0.0059	0.9435	8.544	22.2%
	2	0	0	7200	24.9	9.00	9.50	13.26	0.00184	0.0042	1.0407	7.141	19.7%
	4	0	0	14400	25.8	7.00	7.50	13.68	0.00095	0.0030	1.2594	5.359	16.7%
	8	0	0	28800	26.4	6.00	6.50	13.89	0.00048	0.0021	1.4052	4.505	15.3%
	24	0	0	86400	24.2	5.10	5.60	14.08	0.00016	0.0013	0.8706	3.071	11.3%

B3. Plot of Graph



Sample No : UDS-1 (BH 3 RDA)
Depth : 1.90 - 1.31 m

APPENDIX-C: EXTRACTS OF THE WORKSHEETS FOR TRIAXIAL COMPRESSION TEST

C1. Observation Sheet

Site: UDS-3 (BH 3 RDA) 7.69-7.60m C.P. : 88.2 kPa

Displacement (.01mm)	P.R Dial reading (div)	Burette (Top) (cm^3)	Burette (Bottom) (cm^3)	Pore pressure (kPa)	Axial Strain (%)	P/A (61'-63') (kPa)	(61'/63')	Volume Change (%)
0	0.0	24.0	27.0	0.0	0.00	0.0	1.00	0.00
25	22.0	23.9	27.0	0.0	0.33	50.9	1.58	-0.12
50	33.0	23.8	27.0	1.0	0.66	76.2	1.87	-0.24
70	44.0	23.7	27.0	1.0	0.93	101.5	2.16	-0.35
100	54.5	23.5	27.0	1.0	1.32	125.5	2.43	-0.59
125	64.0	23.4	27.0	1.0	1.65	147.1	2.68	-0.71
150	72.5	23.4	27.0	2.0	1.98	166.0	2.90	-0.71
175	80.0	23.4	27.0	2.0	2.31	182.6	3.09	-0.71
200	86.5	23.3	27.0	2.0	2.64	197.0	3.26	-0.83
250	98.0	23.3	27.0	2.0	3.30	221.7	3.54	-0.83
300	108.0	23.2	27.0	2.0	3.97	242.9	3.79	-0.94
325	110.0	22.5	27.0	2.0	4.30	248.6	3.85	-1.77
328	110.0	22.5	27.0	2.0	4.34	248.5	3.85	-1.77
350	119.5	22.4	27.0	2.0	4.63	269.5	4.09	-1.89
400	122.0	22.4	27.0	2.0	5.29	273.2	4.13	-1.89
450	126.0	22.4	27.0	2.0	5.95	280.2	4.21	-1.89
500	129.0	22.4	27.0	2.0	6.61	284.9	4.27	-1.89
550	130.8	22.5	27.0	2.0	7.27	286.5	4.29	-1.77
600	131.0	22.5	27.0	2.0	7.93	284.9	4.27	-1.77
650	131.0	22.5	27.0	2.0	8.59	282.8	4.24	-1.77
700	129.0	22.5	27.0	2.0	9.25	276.5	4.17	-1.77
750	126.0	22.5	27.0	2.0	9.91	268.1	4.07	-1.77
800	123.0	22.6	27.0	2.0	10.57	259.5	3.98	-1.65
850	121.5	22.6	27.0	2.0	11.23	254.4	3.92	-1.65
900	120.0	22.6	27.0	2.0	11.90	249.4	3.86	-1.65
950	120.0	22.6	26.9	2.0	12.56	247.8	3.84	-1.77
1000	119.2	22.6	26.9	2.0	13.22	244.3	3.80	-1.77
1050	119.0	22.6	26.9	2.0	13.88	242.0	3.78	-1.77
1100	119.0	22.6	26.9	2.0	14.54	240.2	3.75	-1.77
1150	119.0	22.6	26.9	2.0	15.20	238.3	3.73	-1.77
1200	118.0	22.6	26.9	2.0	15.86	234.5	3.69	-1.77
1250	118.0	22.6	26.9	2.0	16.52	232.6	3.67	-1.77
1300	117.0	22.6	26.9	2.0	17.18	228.8	3.62	-1.77
1350	116.0	22.6	26.9	2.0	17.84	225.1	3.58	-1.77
1400	115.0	22.6	26.9	2.0	18.50	221.3	3.54	-1.77
1450	114.0	22.6	26.9	2.0	19.17	217.6	3.50	-1.77
1500	113.5	22.6	26.9	2.0	19.83	214.9	3.46	-1.77
1550	113.3	22.6	26.9	2.0	20.49	212.8	3.44	-1.77
1600	113.0	22.6	26.9	2.0	21.15	210.4	3.41	-1.77

		(61'-63')
peak	7.27	286.5
ultimate	19.83	214.9

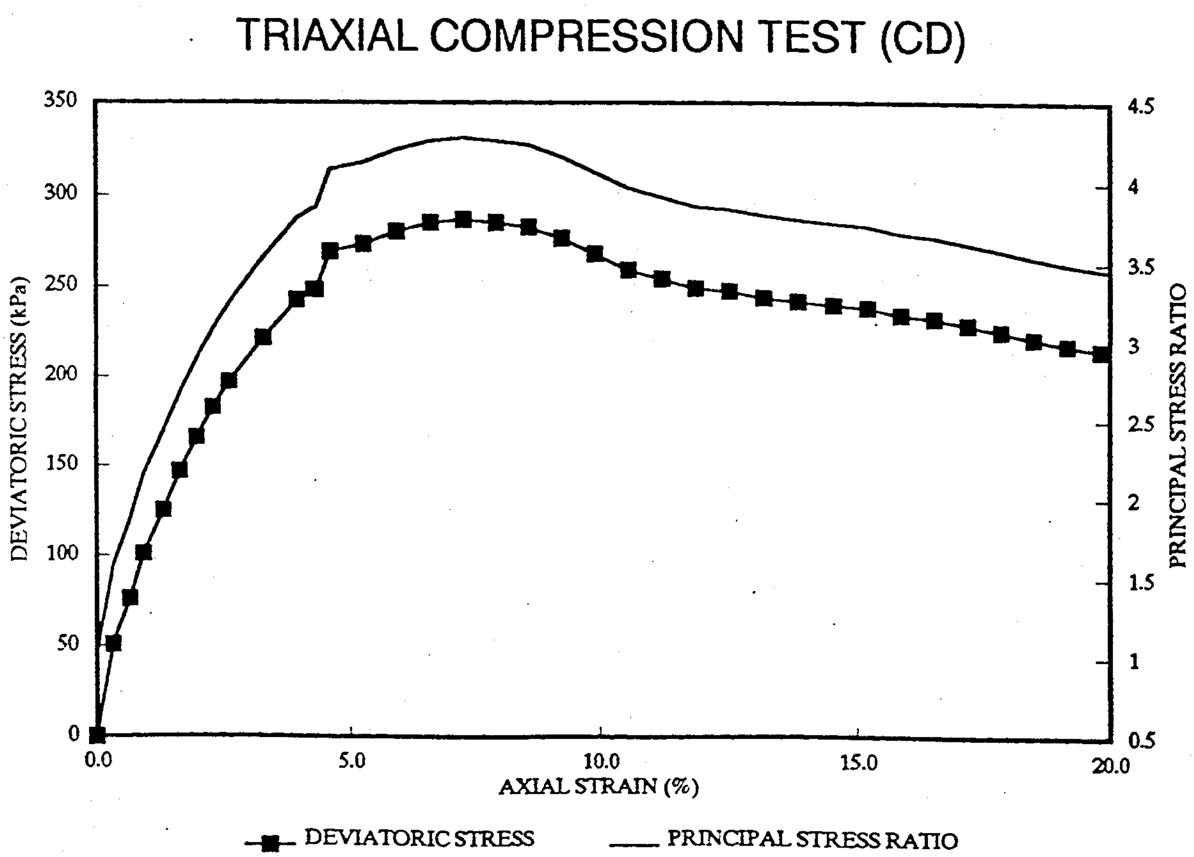
C2. Summary Sheet

Site: UDS-3 (BH 3 RDA) 7.69-7.60m C.P. : 88.2 kPa

TRIAXIAL TEST OBSERVATION:

Sample No	: UDS-3 (BH 3 RDA)	Date	: 30-11-1992
Depth	: 7.69-7.60m	Burette Reading :	
Height	: 7.63 cm	before applying the	
Diameter	: 3.81 cm	cell pressure :	cm^3
Cell Pressure	: 88.20 kPa	After applying the	
Wt. before test	: 160.70 g	cell pressure :	cm^3
Wt. after test	: g	Change in volume:	-2.2 cm^3
Before test :		Specific Gravity:	2.662
Wet wt. + cont.	: 71.70 g	Deformation Rate:	0.000007-0.002 "/min
Dry wt. + cont.	: 60.35 g	P.R. constant :	2.60 N/div
Wt. of container	: 17.75 g	Proving Ring No :	H63-109
After test :			
Wet wt. + cont.	: 176.10 g		
Dry wt. + cont.	: 140.57 g		
Wt. of container	: 17.00 g		

C3. Plot of Stress with Axial Strain



Sample No : UDS-3 (BH 3 RDA)
Depth : 7.69-7.60m CELL PRESSURE : 88.2 kPa

APPENDIX-D: EXTRACT OF THE WORKSHEET FOR PAD FOUNDA.

WORKSHEET FOR THE DESIGN OF PAD FOUNDA.

***** INPUT DATA *****

FORCES:	
Axial Load (P)	500.0 kN
Moments (Mx)	0.0 kNm
Moments (My)	0.0 kNm
DIMENSIONS:	
Length (L)	1.20 m
Breadth (B)	1.00 m
Depth (D)	1.00 m
SOIL PARAMETERS:	
Unit Weight of Soil (r)	17 kN/m^3
Effective Cohesion (c')	33 kPa
Friction Angle (phi)	27 Deg
Deformation Modulus (Eu)	6200 kPa
Coef.of Compressibility (mv	0.21 m^2/MN
OTHER FACTORS:	
Depth of Water Table (Dw)	2.00 m
Thickness of Clay Layer (H)	2.50 m
ALLOWABLE LIMITS:	
Min. Factor of Safety (Fmin	3.00
Allowable Settlement (Sa)	65 mm

***** CALCULATIONS *****

CHECK FOR BEARING CAPACITY:	Initial	Corrected
Factor for Surcharge (Nq)	13.2	24.5
Factor for Cohesion (Nc)	23.9	46.2
Factor for Unit Wt. (Nr)	9.3	6.2
Correction Factors:		
Shape factors:-		
For Surcharge (Sq)	1.42	
For Unit Wt. (Sr)	0.67	
Depth Factors:-		
For Surcharge (Dq)	1.30	
For Unit Wt. (Dr)	1.00	
Factor (K)	1.00	
Net Bearing Capacity (Qnet)	1975.7 kPa	
Foundation Pressure (q)	416.7 kPa	
Factor of Safety (F)	4.74	

CHECK FOR SETTLEMENT:		
Immediate Settlement:-		
H/B'	2.50	
L'/B'	1.20	
D/B'	1.00	
Input From Charts:-		
Uo	0.75	<----- FROM CHART
Ui	0.67	<----- FROM CHART
Immediate Settlement (Si)	33.8 mm	
Consolidation Settlement:-		
Uncorr. Settlement	210.7 mm	
Fox Correction:-		
D/@SQRT(A*B)	0.55	<----- for Chart
L'/B'	1.20	
Factor for Depth (Fox cor.)	0.60	<----- FROM CHART
Factor for Lateral Stress	1.00	
Rigidity Correction	1.00	
Corrected Con. Settlement (Sc)	126.4 mm	
Total Settlement (S)	160 mm	

***** RESULTS *****

Factor of Safety for bearing	4.74	O.K
Check for Settlement	160 mm	TOO MUCH *********

Deterministic Approach in Slope Stability Analysis

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1. Introduction

Landslides occur when the shear strength of soil is mobilized along the full length of the slip surface. No direct measurement of the soil strength is possible at a site. However, an estimate of this strength can be obtained by performing what has come to be called a "back analysis". This analysis is very useful in design and assessment of remedial measures for active landslides.

Back analyses are performed, for a known slip surface for which the factor of safety is unity, to determine what the strength of the soil must have been for the failure to have occurred. Determining soil strengths by back analyses avoids many of the problems associated with laboratory testing, and is widely used, especially in connection with landslide stabilization studies. This technique is an effective method of accounting for important factors that may not be well represented in laboratory tests, such as the structural fabric of the soil, the influence of fissures on the strength of the soil, and the effects of pre-existing shear planes within the soil mass.

However, back analysis would not yield a unique shear strength value for any particular slip failure. At best, it may provide number of sets of two strength parameters, namely cohesion and angle of friction (c' and Φ'). In principle it is possible to determine values of both c' and Φ' if the depth of the slip surface and the pore water pressure on the slip surface are known. In practice, however, as a result of progressive failure and the fact that the position of the slip surface may be controlled by strong or weak layers within the slope, the values of c' and Φ' cannot be inferred from the position of the slip surface.

In most cases the information regarding the conditions under which a slide occurred is incomplete to some degree, and this lack of complete information reduces the reliability of the back calculated strengths. The actual soil strengths can be obtained through back analysis only if information concerning the conditions at the time of the failure is not extensive and the necessary assumptions are supported by good judgement.

Back analyses are carried out for the failed slope at Watawala using the available data. Further exploration works are being carried out in order to fill the existing gap in the available information. As new information emerge, the analysis is improved to provide improvements in the design of remedial measures.

2. Background of Stability Analysis

Traditionally, geotechnical engineers have been interested mainly in a calculated value of the safety factor and in using this value in the most effective way based on experience and judgement. Therefore, various methods of limit equilibrium analyses have been developed over more than five decades and efforts continue to refine and improve these methods. Limit equilibrium analyses are based on a limited number of geotechnical parameters such as soil unit weight, cohesion, angle of internal friction and pore water pressure.

However, deformation analyses are often important for major construction jobs or important structures. These analyses require additional parameters to define the stress-strain behaviour of the soils. Finite element method was successfully used for the deformation analysis at all stress levels together with non-linear and stress-dependent soil behaviours. An important aspect of deformation analysis is that a knowledge of the initial stress state in a soil mass is required which is often lacking in any problem involving a natural slope. This explains why stress-deformation studies have not been used with much success in landslide analyses.

It is well known that a calculated safety factor more than one does not always mean a safe design in geotechnical problems. This is largely a consequence of uncertainties concerning geotechnical parameters and their variation. The most important example is pore water pressure in natural slope. This has led geotechnical engineers to consider method of analysis within the framework of statistics and probability. Probabilistic approaches complement the conventional deterministic studies: probabilistic analyses often use the geomechanics models used for deterministic analyses. Although the applications of statistics and probability has gained a great deal of acceptance in recent years, some doubts about the relevance of probabilistic methods remain. Deterministic analyses continue to be used and are unlikely to be replaced by probabilistic methods in the foreseeable future. Furthermore, as the probabilistic analysis requires lot more data to understand the variation of the geotechnical parameters, the use of probabilistic analysis is very much restricted.

3. Limit Equilibrium Analysis

Limiting Equilibrium analysis, utilizing the method of slices, is the most common method for analyzing the stability of slopes in practice. In the method of slices, the soil mass above the slip surface is divided into wedges or slices. Conventionally, this subdivision is by vertical lines, but this is by no means vital for the method, nor it necessary to have the slices all the same width. The simplest approach would then be to take each slice in turn, and to calculate its factor of safety in isolation: the factor of safety for the whole series of slices could then be the average.

It is well known that the differences in classical methods of limit equilibrium analysis are due to the differences in the latter assumptions, and the effects of these differences have been studied exhaustively in the past. It has been concluded that, if both moment and force equilibrium are satisfied, the differences in results obtained are small. A brief description of the methods incoparated in the computer analysis is discussed below.

3.1. Infinite Slope Analysis

Consider an infinite slope inclined at .. to the horizontal as shown in Fig 1. The slip surface is assumed parallel to the slope and located at a depth z below the surface. Since the slope is infinite, the interslice forces are assumed equal and opposite. The factor of safety F can be written as

$$F = \frac{c' + (\gamma z - \gamma_w h_w)\cos^2\alpha \tan\phi'}{\gamma z \sin\alpha \cos\alpha}$$

where z is the depth of the slip surface, τ is the unit weight of soil, τ_w is the unit weight of water and h_w is the height of the groundwater table above the slip surface.

For a non-cohesic equation for safety fa

$$F = (1 - r_u)\frac{\tan}{\tan}$$

where r_u is the pore pressu defined as the ratio between $\gamma_w h_w$ and the total pressure surface.

3.2. Generalized Swedish Slice Me

This method can be employed to ana having

(a) irregular ground slope
(b) varying soil strata
(c) tension cracks with or without water
(d) partial or full drawdown of external level.

In this analysis the failure is assumed to occu by rotation of a block of soil on a cylindrica slip surface. The sliding block is broken up into a series of vertical slices and the inter slice forces on each slice are assumed to be parallel to the base. The factor of safety is calculated as the ratio between the shear strength and the mobilised shear stress.

For a slope without any water within the tension crack, the factor of safety can be written as

$$F = \frac{\sum\{c'l + (W\cos\alpha - ul)\tan\phi'\}}{\sum W\sin\alpha}$$

where l is the length of slice measured along the base, ɑ is the angle of the line joining the centre of the failure circle to the mid-point of the base of the slice, W is the weight of the slice and u is the pore water pressure at the base of the slice. The above equation can be easily modified to accommodate the water within the tension crack.

Since this method does not involve iterative calculations, it permits a quick and direct computation of the factor of safety. Therefore this is considered advantages over the other methods.

3.3. Bishop's Method

Based on the assumption of circular slip surface (figure 2), Bishop derived the factor of safety as

$$F = \frac{\sum \left\{c'b + (W - ub + \Delta X)\tan\phi'\right\} \dfrac{\sec\alpha}{1 + \tan\alpha \tan\phi'/F}}{\sum W \sin\alpha}$$

where b is the width of the slice and ΔX is the difference between the interslice shear forces. Values of F, and of ΔX of every slice, that satisfy this equation, give a rigorous solution to this problem.

In Bishop's routine method, the resultant interslice shear force on each slice is neglected or in other words the resultant interslice force is considered to be horizontal. This method was found to give fairly accurate results because it satisfies the moment equilibrium.

3.4. Janbu's Method

Janbu's method was developed to find out the factor of safety of slides with any shape of slip surface. A problem when dealing with a slip surface of arbitrary shape is that the convenience of a single point through which a number of the force components act, and are therefore lost from a moment equilibrium equation based on that point, is no longer available. In Janbu's method, therefore, the force equilibrium rather than the moment equilibrium was chosen for the development of the method. The factor of safety is given by

$$F = \frac{\sum \left\{c'b + (W - ub + \Delta X)\tan\phi'\right\} \dfrac{\sec^2\alpha}{1 + \tan\alpha \tan\phi'/F}}{\sum W \tan\alpha}$$

Based on limited number of calculations, Janbu proposed an empirical correction to be applied to the results of a calculation made using his method. The correction should be applied to the converged factor of safety as follows

$$F_{corrected} = f_0 \cdot F$$

where f_0 is taken from the chart (Fig 3). In the Janbu's simplified method, the resultant interslice forces are considered to be horizontal. But the interslice forces are calculated for the Janbu's rigorous method.

3.5. Spencer's Method

Spencer's method is applicable to any shape of slip surfaces with or without a tension crack. The resultant of all the interslice forces (figure 4) on a single slice is

$$Z = \frac{c'b/F + (W \cos\alpha - ub\sec\alpha)\tan\phi'/F - W\sin\alpha}{\cos(\alpha - \theta)\left\{1 + \tan\phi' \tan(\alpha - \theta)/F\right\}}$$

where θ is the angle with respect to the horizontal of this resultant. For equilibrium of the whole sliding mass, the sum of the interslice forces and their moments about the centre of rotation must be zero. With the assumption, that the resultant interslice forces are at a constant slope through the sliding mass, the two unknowns F and θ can be determined. Furthermore this method satisfies the force equilibrium as well as the moment equilibrium.

3.6. Miscellaneous Other Methods

Many methods were reported in the past for determining the factor of safety, but only few of them are explained above.

An alternative procedure for analysing long slopes is presented by Duncan and Stark (1990). They developed equations shown in Fig 5 by analyzing a number of slides on long slopes using Bishop's routine method and relating the results to the expressions for factor of safety from infinite slope analyses. It was found that the factor of safety for rotational slides and for the infinite slope condition could be related through the adjustment factors C_1 and C_2 shown in Fig 5.

4. Techniques Used in Stability Analysis

Different techniques are used in stability analysis for critical surface and tension cracks etc.

4.1. Finding Critical Failure Surface

Searching for the most critical sliding surface in a slope can be made easier if slip circles are used. Total quantity of data required to set up a systematic search is relatively less. Different schemes have been used by various people for finding the critical failure surface.