PREDICTION OF SWELLING IN EXPANSIVE CLAYS

by

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Study of Expansive Clays in
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PREFACE

This report is the fourth in a series from Research Project 3-8-68-118, entitled "Study of Expansive Clays in Roadway Structural Systems." The report uses the theoretical results presented in Research Report 118-1 and the moisture distribution computer programs in Research Report 118-3 to arrive at a method for predicting vertical swelling in one and two-dimensional soil regions. Such prediction is possible through use of a three-dimensional graph of the pressure vs. total volume vs. water volume relationship for any soil of interest. Results of computer-predicted swelling are compared with field measurements made by University of Wyoming personnel. The accuracy of the method is considered to be excellent.

This project is a part of the cooperative highway research program of the Center for Highway Research, The University of Texas at Austin with the Texas Highway Department and the U. S. Department of Transportation Federal Highway Administration. The Texas Highway Department contact representative is Larry J. Buttler.

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LIST OF REPORTS

Report No. 118-1, "Theory of Moisture Movement in Expansive Clay" by Robert L. Lytton, presents a theoretical discussion of moisture movement in clay soil.

Report No. 118-2, "Continuum Theory of Moisture Movement and Swell in Expansive Clays" by R. Ray Nachlinger and Robert L. Lytton, presents a theoretical study of the phenomenon of expansive clay.

Report No. 118-3, "Prediction of Moisture Movement in Expansive Clay" by Robert L. Lytton and Ramesh K. Kher, uses the theoretical results of Research Reports 118-1 and 118-2 in developing one and two-dimensional computer programs for solving the concentration-dependent partial differential equation for moisture movement in expansive clay.

Report No. 118-4, "Prediction of Swelling in Expansive Clay" by Robert L. Lytton and W. Gordon Watt, uses the theoretical results presented in Research Report 118-1 and the moisture distribution computer programs of Research Report 118-3 to arrive at a method for predicting vertical swelling in one and two-dimensional soil regions.

Report No. 118-5, "An Examination of Expansive Clay Problems in Texas" by John R. Wise and W. Ronald Hudson, examines the problems of expansive clays related to highway pavements and describes a field test in progress to study the moisture-swell relationships in an expansive clay.

ABSTRACT

This report presents a method of predicting vertical swell in one and two-dimensional soil regions. The method is based on the assumption that volume change at a point can be determined when a change in moisture content is found for that point. Under certain conditions, discussed in Research Report 118-2, this assumption is strictly valid for the one-dimensional soil region. It is very nearly valid in a two-dimensional case if the shear "modulus" of the soil remains small.

The concentration-dependent parabolic partial differential equation for moisture change is solved for each time step by means of the computer programs discussed in Research Report 118-3. The change of moisture content, together with the overburden and surcharge pressure at a point, are used in the pressure vs. total specific volume vs. specific water volume relationship for the soil at that point to predict a local change of volume. Incremental vertical components of volume change are added in each vertical column to predict the total heave at the surface.

Predicted values of swell are compared with field measurements made at the University of Wyoming, and the results are considered excellent.

KEY WORDS: moisture movement, expansive clays, discrete-element analysis, computers, permeability, suction, ponding, Crank-Nicolson method, unsaturated permeability, compressibility, swelling.

SUMMARY

This report outlines a method of predicting the amount and rate of heave in a clay subgrade, based on a knowledge of the physical relationships among the soil, water, and air. This knowledge includes permeability of the unsaturated soil in both the vertical and horizontal direction; the relationship between water content, soil suction, and total volume change; the degree of saturation; and the swelling pressure.

A total of 30 experimentally determined parameters must be input into either of two computer programs for numerical solutions of estimated heave. Given the initial water contents or suctions at points within the subgrade and setting certain changes internally or at the boundaries of the specific region, the programs will print out the pattern of water movement and volume changes with time. Changes can be made in the boundary and internal conditions at any time to simulate natural variations in the field.

The computer programs are not yet documented because controlled experimental results which are sufficient to check the programs must still be obtained.

The programs can be used in the meantime to determine the effect of the measurement precision of each input parameter on the estimate of heave. The parameters which are not significant can then be given estimated values and the gathering of input data can be simplified. A reassessment of priorities in listing factors which cause heave and perhaps modification of laboratory tests and design procedures are indicated.

IMPLEMENTATION STATEMENT

Computer programs GCHPIP7 and SWELL1 provide the only known tool for predicting the amount and rate of differential heave in a nonsaturated clay soil. Most methods of predicting heave are empirical and attempt to provide the designer with a probably value of total heave only.

However, not all of the input data required for these programs are presently available. The relationships for permeability and suction come from soil-science literature, but measurements of suction in the field are still in the experimental stage, and accurate field measurements of small changes in water content, degree of saturation, and density have not been developed. Further development of these laboratory and field tests is the next major objective.

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CHAPTER 1. INTRODUCTION

There is a substantial difference between the change of moisture in a soil and the consequent change of soil volume. Research Report 118-1 (Ref 6) presented the theory and Research Report 118-3 (Ref 7) the methods of computing moisture diffusion in clay soil. These reports form an essential background to this report, which is concerned with translating the change of moisture into a change of volume by use of a relationship among pressure, total specific volume, and specific water volume. This relationship is assumed to be a single-valued surface in this report, although there is experimental evidence which demonstrates that under diverse compaction conditions a certain density of soil may develop either a high or low swelling pressure.

The method of computing swell used in this report is termed "simple volume change" and is based on a summation of percentages of total volume change at each point in a vertical column, with allowance for the volume-change reducing effect characteristic of overburden and surcharge pressure. The approach is not strictly correct, however, because lateral elasticity boundary conditions and stress distributions are not considered. Because incremental changes of volume and total stress are likely to be small, the "simple volume change" technique of this report is considered to be adequate and useful for many situations.

Simple volume change is computed from the p vs. V_T vs. V relationship discussed in Chapter 2 of this report and developed at some length in Chapter 4 of Research Report 118-1. Chapter 3 gives details of the input and output information for the two-dimensional computer program, and Chapter 4 shows in what manner the one-dimensional computer program differs from these. These last two chapters are similar in most respects to Chapters 4 and 5 of Research Report 118-3. They are included in this report in the interest of clarity and integrity of presentation. Chapter 5 of this report includes example problems worked with the one and two-dimensional computer programs.

Field measurements of moisture distribution and swell made by University of Wyoming personnel are compared with data calculated with the two computer programs presented in this report. The extended list of soil data that had to be assumed to permit the working of the problems illustrates two important points:

(1) Not enough useful soil data are measured with current investigation procedures.

(2) Computer experience with soil parameters can indicate which properties may be assumed without significantly affecting the final result.

Chapter 6 of this report presents conclusions drawn from the computer study of expansive clay soils and shale and from the development of the computer programs.

Separation of material contained in Research Reports 118-3 and 118-4 is intentional. Although moisture distribution computation is dependably based on diffusion theory, the idea of simple volume change is not strictly founded in theory. Consistency of approach would require that the coupled equations be solved simultaneously. The present approach "uncouples" the two equations and assumes that swelling can be determined when moisture distribution is known. In Research Report 118-2, this assumption was shown to be correct for a one-dimensional problem in which the "diffusion" and "elasticity" constitutive functions are constant. This is true in swelling clay, but if small changes are considered in the one-dimensional case, fairly accurate predictions can be achieved.

Thus, even from the theoretical point of view, the computer programs presented in this report should be expected to give acceptable and useful answers only, although occasionally, when changes are small, very accurate predictions can be expected. In view of these considerations, the answers obtained by the approximate methods of this report are judged to be excellent.

CHAPTER 2. SWELL PRESSURE VS. SPECIFIC VOLUME RELATIONSHIPS

Theoretical aspects of the relationships among swell pressure, total specific volume, and specific water volume were discussed in Chapter 4 of Research Report 118-1. The present chapter presents the computer programs that use these concepts to predict swell. The chapter is divided roughly into four parts: fundamental relationships, equations for the soil curves, limitations of the assumed equations, and Subroutine GULCH, which uses the equations in predicting total volume change.

Fundamental Relationships

There are several observations that are known from experience and experiment to be generally true of volume change in swelling clay. A few of these are given below:

(1) If it is unrestrained while water is being added, a dry soil can increase in volume by a larger percentage than it can when wet.

(2) If completely restrained from increasing its volume, a dry natural soil can develop greater swell pressure than it can if it starts swelling from a wet condition.

(3) For a given change of moisture content, a soil that is more lightly restrained will increase in volume by a greater percentage than the same soil starting from the same moisture condition but subjected to a higher confining pressure.

(4) Under the same restraining conditions, a soil which is initially more dense (i.e., has lower total specific volume) may increase in volume more than the same soil when initially less dense.

(5) Under complete restraint, an initially more dense soil may develop a higher swelling pressure.

(6) Statements (4) and (5) may be incorrect for soils compacted on the dry side of optimum. Higher swelling pressures and perhaps smaller percentages of change in volume occur in these types of compacted clay.

McDowell (Ref 8) uses statements 1, 2, and 3 in devising the method for determining potential vertical rise. The use of the word "potential" indicates that the predicted swell is based on a volume change of soil that is given access to as much water as it can absorb under a certain pressure condition. Of course, under field conditions, not all soil is provided with as much water as it can absorb. Indeed, a particular element of soil that is farther from a source of water will receive less than an identical element that is closer to the source because of the diffusion characteristic of moisture movement in soil.

The swelling prediction technique of this report uses statements 1 through 5 and a computed moisture change to calculate a volume strain due to swelling. The maximum possible percentage of swell is computed from the swell pressure vs. total specific volume curve and the sum of overburden and surcharge pressures. This maximum possible percentage of swell corresponds to the potential volume change predicted by the McDowell method. The fraction of this maximum swell that is expected to occur is computed from the predicted change of moisture content.

The change of total volume corresponding to a change of water volume can be represented on a two-dimensional graph such as the one shown in Fig 1. Statement 1, concerning unrestrained swelling of soils, is illustrated by Curve abcd. Soil at Point a is drier and swells more in reaching Point d than does the soil starting at Point b. Statement 3, concerning greater swell with less restraint, is indicated by the three swell arrows starting from Point e. All have the same change of moisture content, but the soil under greater pressure exhibits a slighter slope. Statement 4, regarding greater percentage of total volume change for denser materials, is shown by the two broken lines meeting at Point f. In this example, the final moisture contents are identical, but the volume of the soil swelling from Point b changed by a greater amount.

A horizontal line, such as ae in Fig 1, describes a soil that is restrained from changing in volume as its water content increases. Swelling pressure is obtained by conducting a test in which a soil is restrained while its water content is increased. Generally, the soil is 90 to 95 percent saturated at the end of the test. Statements 2 and 5 are drawn from observations of such swelling tests.

A natural soil which has been subjected to drying is denser rather than a soil of the same water content subjected to mechanical compaction. This is true of the individual pieces and crumbs of soil although certainly not of the friable collection of crumbs on the surface of dry ground.

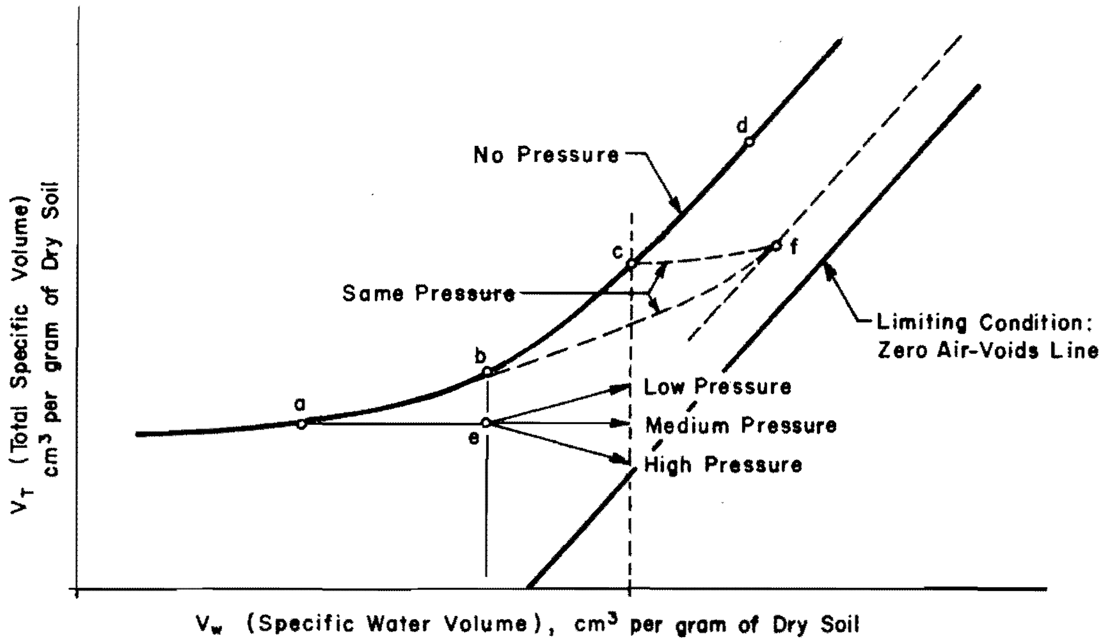


Fig 1. Relationships on the V_T vs. V_W plane.

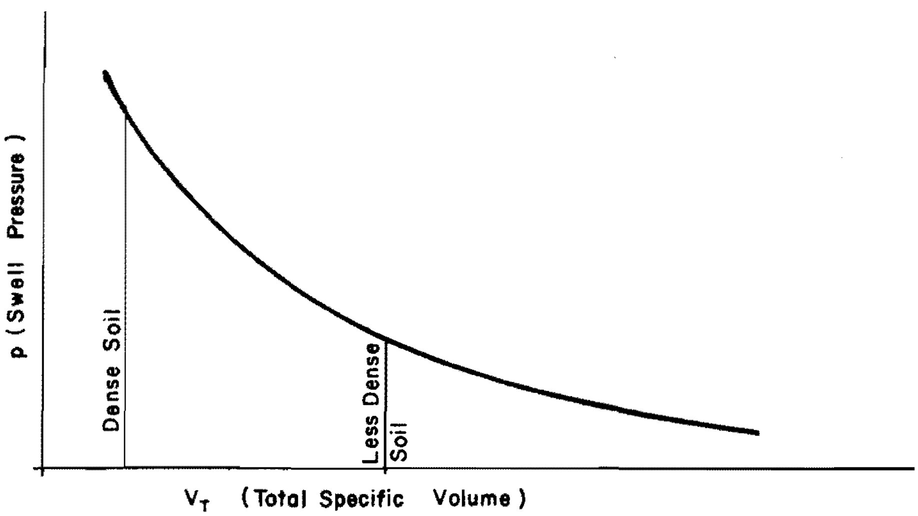


Fig 2. Relationships on the p vs. V_T plane.

Statement 2, which concerns the greater swelling pressure of a drier soil, is illustrated in Fig 2. Statement 5 is normally an analogous alternative of statement 2, but neither statement is correct for a compacted soil.

Equations for Soil Curves

Soil in its natural state has a total specific volume vs. specific water volume relationship that resembles the shrinkage curve. That is, if a sample of soil is taken from a boring and its specific water volume and total specific volume are found, then these data will plot a point on a curve (such as Curve abcd of Fig 1.). The problem of predicting volume change requires that the initial state from which changes occur be known. The equations for soil curves developed in this section are a convenient way of specifying these initial conditions with the minimum input of data.

Three curves are considered:

(1) initial total specific volume vs. specific water volume (Curve 1, Fig 3),

(2) swell pressure vs. total specific volume (Fig 2), and

(3) 90 to 95 percent saturation (Curve 3, Fig 3).

The point at which the initial moisture content intersects Curve 1 automatically yields the initial total specific volume of the soil (e.g., point 1 in Fig 3). The curve from Fig 2 combined with the total vertical pressure at a point in a soil region yields the maximum total specific volume to which the soil may swell at that pressure. The maximum total specific volume line is drawn to intersect the 90 to 95 percent saturation line (Curve 3, Fig 3) to yield Point 2 in Fig 3. Points 1 and 2 are the end points of the desired soil-swell curve (Curve 2, Fig 3). This curve takes into account the amount of vertical pressure that acts on the soil at any depth. The equation for the soil-swell curve is assumed to be of the same exponential form as the initial total specific volume vs. specific water volume curve (Curve 1). The equations for Curve 1, the swell pressure vs. total specific volume curve, and the soil swell curve are discussed below.

Initial Total Specific Volume vs. Specific Water Volume Curve (Curve 1, Fig 3). The form of this curve is assumed to be the same shape as the shrinkage curve. It is divided into two distinct parts:

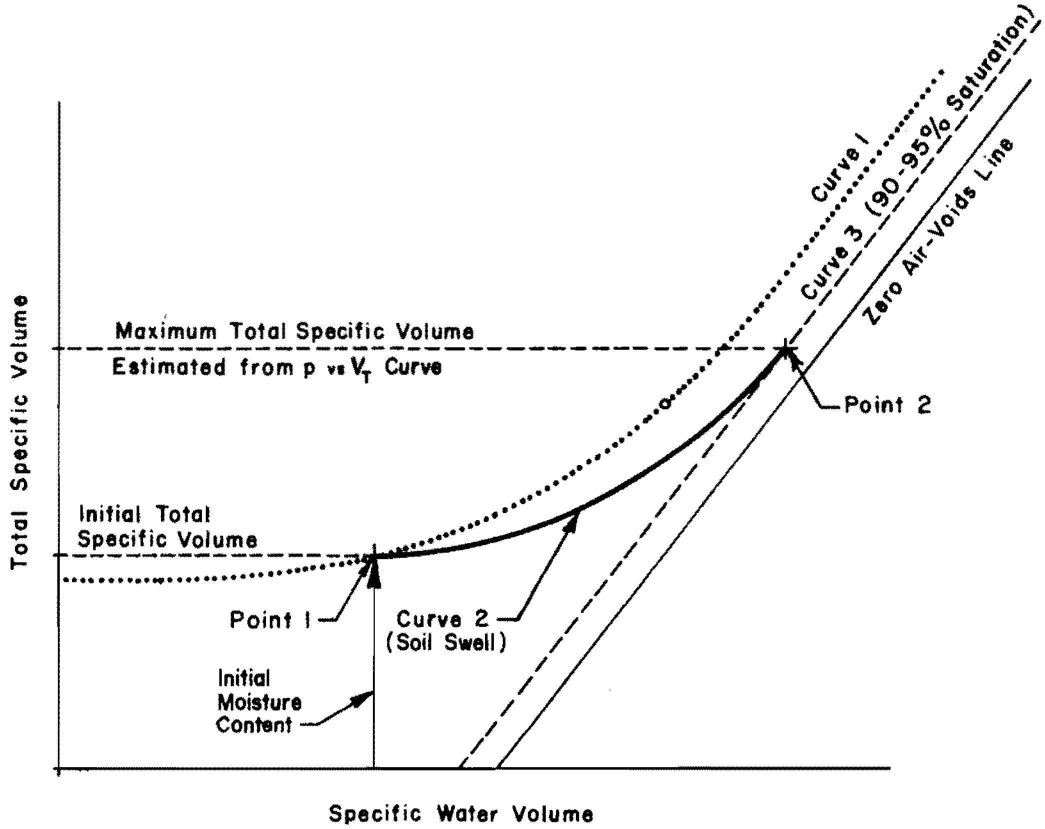


Fig 3. Relationship between total specific volume and specific water volume for a soil swelling under pressure.

(1) the effectively unsaturated and

(2) the effectively saturated,

which are separated from each other by an air entry point. This curve is not necessarily identical with the shrinkage curve for the following two possible reasons:

(1) the swelling curve exhibits a hysteresis effect, and

(2) some swelling may have occurred before the soil reached the condition considered to be the initial condition. However, even in this case the initial total specific volume vs. specific water volume curve will probably have the same general shape as the shrinkage curve.

The effectively unsaturated branch of the V_T vs. V_W curve is described by the following equation:

$$V_T = V_{TO} + \alpha_o V_W + \frac{(1 - \alpha_o)}{Q} \left(\frac{V_W}{V_{WA}} \right)^Q V_{WA} \qquad (2.1)$$

where

V_T = total specific volume,

V_{TO} = total dry specific volume,

V_W = specific water volume,

V_{WA} = specific water volume at air entry,

α_o = slope of the V_T vs. V_W curve at zero water content,

Q = an exponent.

The effectively saturated branch of the curve starts at the air entry point and has a positive slope of 1.0. At each point within a soil region, an initial V_T vs. V_W condition may be calculated; these initial values will be referred to as V_{TI} and V_{WI} in subsequent discussion.

The data for Fig 4 were taken from a paper by Kassiff, et al (Ref 3), in which moisture vs. density relationships for natural and compacted Israel clay were presented. The density data have been converted to the specific volumes used in the present report. Several significant items can be noted on this graph.

First, the natural soil in its effectively saturated state is considerably more unsaturated (60 to 70 percent) than the same soil which has been remolded and compacted. Secondly, the limit of structural integrity is clearly shown here to occur at a total specific volume of 0.813. Thirdly, the smallest total specific volume was developed by soil in its natural state. This densest natural condition was measured from soil samples taken at the end of autumn after the dry season. Thus, the fourth significant factor of note is that, in its natural conditions, this clay (and perhaps most clay) remains in the effectively saturated region of soil behavior, even in its driest condition. Fifth, the natural soil air entry point is much drier than the optimum moisture content in the compacted clay, even when the high compactive effort of the modified AASHO procedure is used.

Measurements of the entire V_T vs. V_W curve of samples of natural Houston Black Clay and natural Oasis silt loam have been reported by Lauritzen (Ref 5). Data extracted from his findings are given in Fig 5. The zero air-voids curve is for an assumed specific gravity of solids of 2.70. Not shown in this report, but of potential interest to the user of computer programs GCHPIP7 and FLOPIP1, are the curves Lauritzen shows for mixtures of these clayey soils with alfalfa. These curves show the effect of organic matter mixed with an expansive soil.

Swell Pressure vs. Total Specific Volume Curve. The equation for this curve is in the same form as a gas law; it applies to constant temperature conditions and involves a constant product of a pressure and a volume raised to some power. The form of this curve is discussed in detail on page 87 of Chapter 3, Research Report 118-1. It is assumed that there is some maximum total specific volume, V_{TF}, above which the soil will exhibit no swelling pressure. It is further assumed that the highest swelling pressure is developed by the soil in its densest condition, that of minimum total specific volume, V_{TO}. The equation used to describe this relationship is

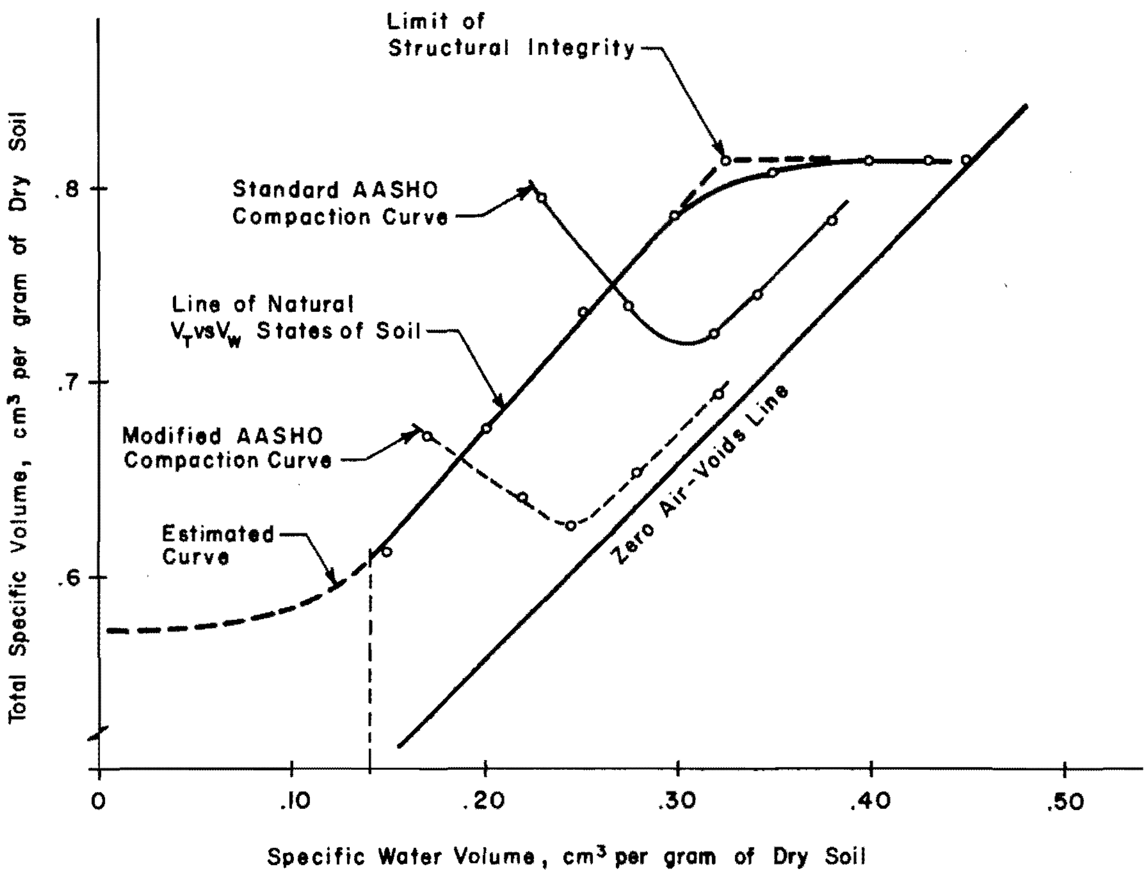
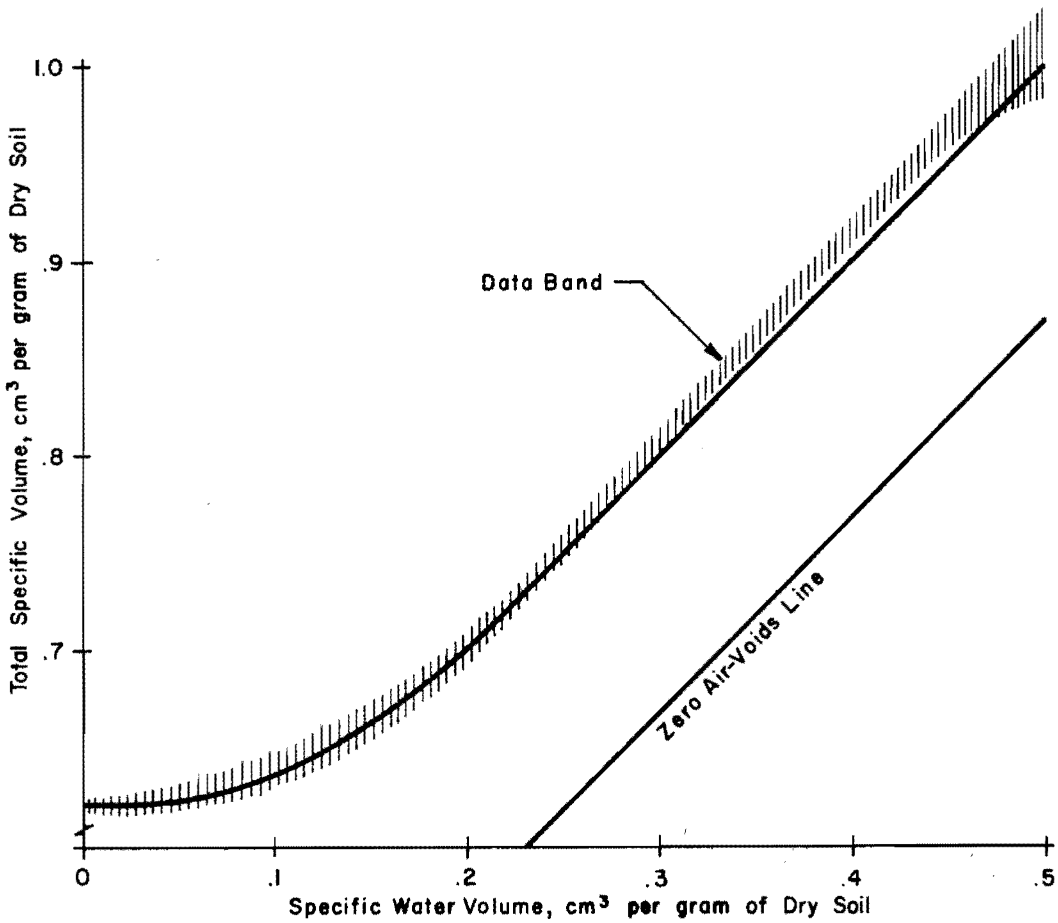
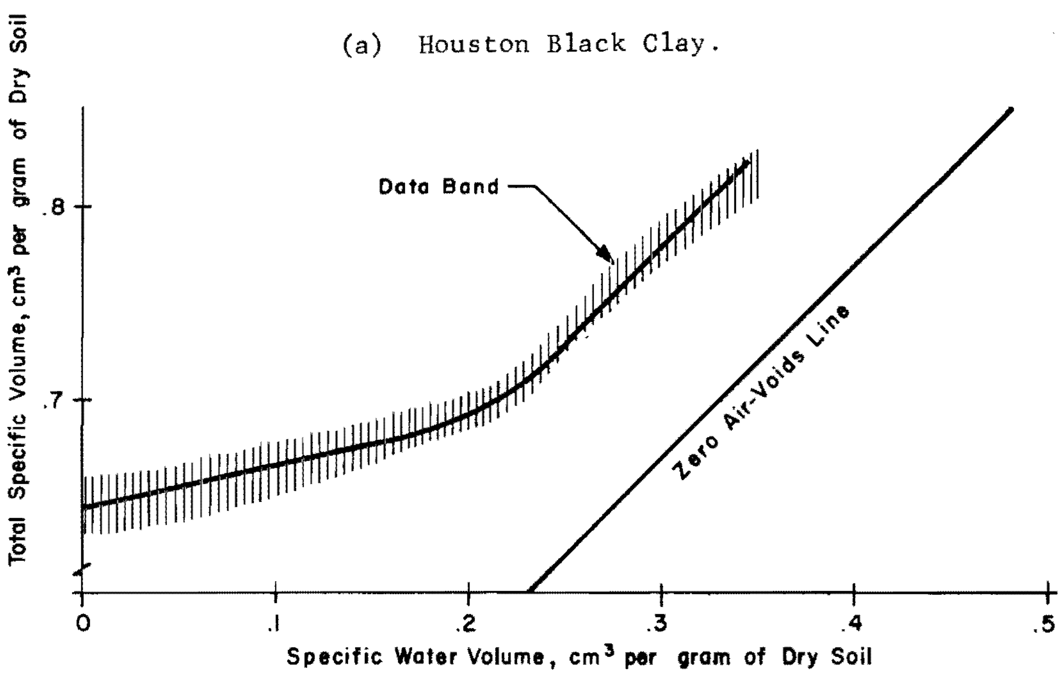


Fig 4. Comparison of V_T vs. V_W relationships for natural and compacted soil (data from Kassiff, et al, Ref 3).



(a) Houston Black Clay.



(b) Oasis silt loam.

Fig 5. V_T vs. V_W curves for natural soils (from Lauritzen, Ref 5).

$$p = p_o \left(\frac{V_{TF} - V_{TP}}{V_{TF} - V_{TO}} \right)^m \tag{2.2}$$

where

p = swelling pressure,

V_{TP} = total specific volume corresponding to p,

V_{TF} = maximum total specific volume (above this value, no swelling pressure is assumed to develop),

m = an exponent.

The general shape of these curves is observed in McDowell's (Ref 8) graph of pressure vs. percentage of volume change. In the present report, total specific volume has been used instead of percentage of volume change; consequently, exact correlation with McDowell's curves cannot be expected. The experimental shape of this p vs. V_T curve for a compacted clay from the Taylor formation is shown in Fig 31 of Research Report 118-1. Computer experience with this form of the p vs. V_T relationship indicates that the exponent m will normally be close to and perhaps slightly above 1.0.

If the total vertical pressure at a point in a soil region is known, then this can be equated to the maximum swell pressure that can develop at that point. With this swell pressure and Eq 2.2, it is possible to calculate the maximum total specific volume to which the soil may expand:

$$V_{TP} = V_{TF} - \left(\frac{p}{p_o} \right)^{\frac{1}{m}} (V_{TF} - V_{TO}) \tag{2.3}$$

where

V_{TP} = the maximum total specific volume for some pressure p.

This value of V_{TP} is used with a third curve to obtain the maximum specific water volume under pressure, V_{WP}.

The 90 to 95 Percent Saturation Line (Curve 3, Fig 3). Only one point is required to establish the location of this line. Its slope is assumed to be 1.0, and it is parallel to the zero air-voids line. The point chosen to locate the line is (V_{TF}, V_{WF}), a point which corresponds to the zero swell-pressure condition. The final total specific volume, V_{TF}, is used in the p vs. V_T curve as well. The value of the final specific water volume, V_{WF}, is used to specify the final condition of saturation to be expected in a swell-pressure test. The tests reported in Chapter 4 of Research Report 118-1 indicate that the maximum swell pressure is recorded at a degree of saturation of between 90 and 95 percent. Of course, there is no objection to specifying Curve 3 to be the zero air-voids line, except that this line is not normally reached under experimental or field conditions. Curve 3 is used to determine the maximum specific water volume under pressure, V_{WP}, in the following manner.

Point 2, with coordinates (V_{TP}, V_{WP}), is assumed to fall on Curve 3, which is a line with a slope of 1.0. If the difference of total specific volumes multiplied by this slope is subtracted from V_{WF}, then the value of V_{WP} is obtained:

$$V_{WP} = V_{WF} - 1.0(V_{TF} - V_{TP}) \tag{2.4}$$

The soil-swell curve may be generated once the coordinates of Point 1 (V_{TI}, V_{WI}) and Point 2 (V_{TP}, V_{WP}) are known.

Soil-Swell Curve (Curve 2, Fig 3). Despite whether the initial condition of a soil is above or below the air entry point, the same form of swell curve is assumed. Two such curves are shown in Fig 6 (Curves a and b). The slope of the curve at Point 1 is assumed to be zero, and at Point 2 it must be 1.0 or less. The equation of the curve is assumed to have the same exponent as that of Curve 1:

$$V_T = V_{TI} + (V_{TP} - V_{TI}) \left(\frac{V_W - V_{WI}}{V_{WP} - V_{WI}} \right)^Q \tag{2.5}$$

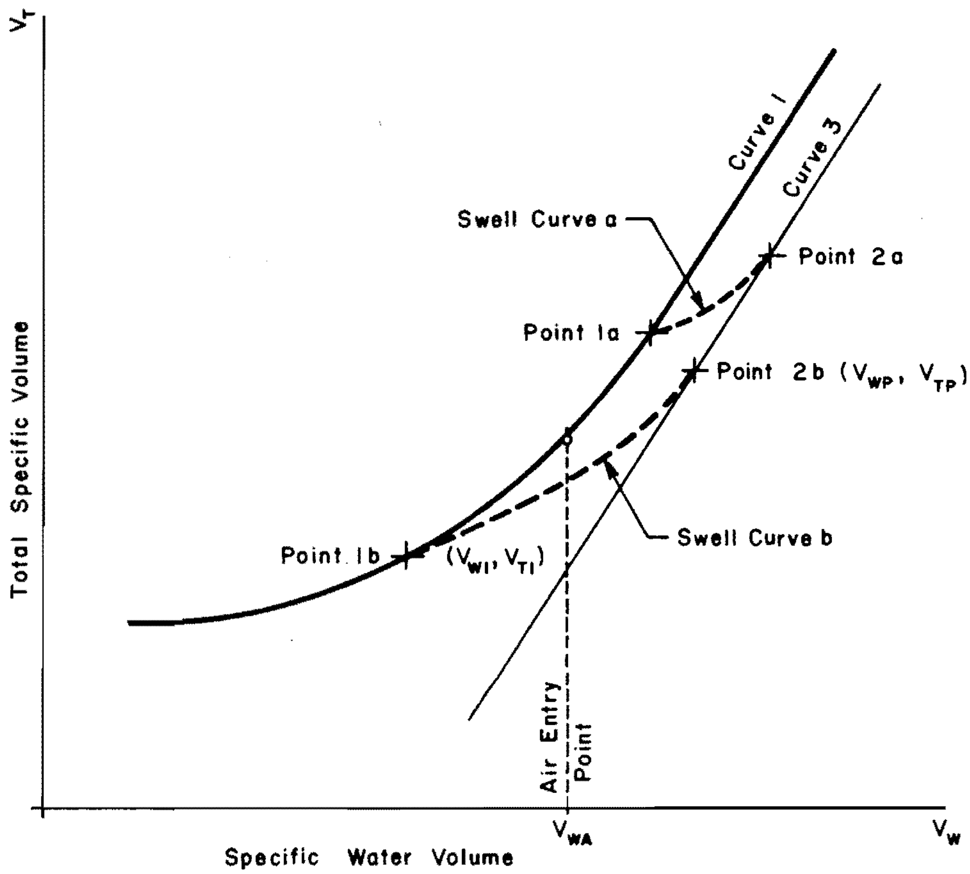


Fig 6. Soil-swell curves.

where

V_W = some new water content greater than the initial water content,

V_T = new total specific volume.

The volume strain corresponding to this change of total specific volume is computed as

$$\frac{\Delta V}{V} = \frac{V_T - V_{TI}}{V_{TI}} \tag{2.6}$$

This volume strain is used to compute the upward thrust of an element of soil. The method of calculating total and incremental upward movement is discussed later in this chapter.

There is one restriction on the equations for the swell curves: their slopes must be less than or equal to 1.0 at Point 2. The slope of the curve at that point is

$$\left[\frac{dV_T}{dV_W} \right]_2 = Q \frac{(V_{TP} - V_{TI})}{(V_{WP} - V_{WI})} \leq 1.0 \tag{2.7}$$

and thus a maximum Q of

$$Q_{max} = \frac{V_{WP} - V_{WI}}{V_{TP} - V_{TI}} \tag{2.8}$$

is used.

Volume strain is computed for every point in a soil region. In order to convert it to incremental and total upward movement, the following information is required:

(1) the size of the vertical increment and

(2) the percentage of volume strain that goes into vertical movement.

The size of the vertical increment is part of the data that are read into the computer program. Swelling is assumed to be uniform throughout the increment length, which is centered on the point at which change of water content is computed. Thus, only half of the increment length at the highest point in a vertical column is used to compute swelling. A full increment length is used everywhere else.

The percentage of volume strain that goes into upward movement depends heavily upon boundary conditions. It would be fairly safe to assume that, if a vertical column of soil is surrounded for its entire depth by other soil which is in the act of swelling, lateral confinement is complete and, consequently, the entire volume strain is directed upward. Only with very substantial evidence should it be assumed that the percentage of volume change that is directed upward is less than 100 percent. In most practical situations, the lower limit of this upward percentage of swell is 33-1/3 percent, which occurs only if it can be assumed that passive resistance does not develop in the surrounding soil to limit the lateral swell of soil in the given column.

It would actually be desirable to base the calculation of volume change on the mean stress at a point in a soil region. The three-dimensional average of vertical and horizontal pressures could be used to determine volume strain, and the strains could be parceled out in each direction in inverse proportion to the pressure acting in that direction. Horizontal soil pressures are not normally known, however, and the approach of this report is to avoid considering them except in the choice of the factor establishing the upward percent of volume change. Results of computer simulations of field data have indicated that 100 percent upward volume change is a reasonable assumption. These computer results will be discussed in Chapter 5 of this report.

Limitations of the Equations

The equations are derived and the computer program is arranged to predict increases in volume in a wetting situation. The assumption of one direction of volume change eliminates the need for including hysteresis, and it rules out consideration of consolidation problems.

Estimation of the initial total specific volume and specific water volume conditions of soil is a matter of conjecture in most practical situations. An approximate idea of the shape of the curve may be gained by determining the shrinkage curve for a small sample of natural soil. The shape of the curve can also be approximated by assuming a sharp break in the swell curve at the shrinkage limit and drawing a horizontal line to represent the drier soil and a line with a slope of 1.0 to represent the effectively saturated soil. In this case, a high value for the exponent Q should be used.

The swell pressure vs. specific total volume curve is not ordinarily known in detail for natural soils, and it must be estimated with limited information. The two most critical estimations are of

(1) the maximum swell pressure, p_o, and

(2) the maximum total specific volume, V_{TF}.

The value exponent m must also be estimated, but usually it will not be greatly different from 1.0. Some experience with the number m is required before a definite delineation of its boundaries can be set.

The maximum swell pressure can be determined only by experience and experiment. The maximum total specific volume, V_{TF}, will occur when the soil has reached its limit of structural integrity, when it will have virtually no more tendency to take on water. In this condition, corresponding roughly to a pF of 0.0, the soil can be considered to have no swell pressure.

Accuracy of the swell pressure curve is limited. Because it is single-valued, it cannot represent the experimentally determined curves shown in Chapter 4 of Research Report 118-1; such curves are for compacted materials and exhibit two swell pressures for a single total specific volume of soil. The higher swell pressure is from the drier soil. In addition, for compacted soil, even the V_T vs. V_W curve is double-valued: for a single total specific volume there are two specific water volumes, one on each side of optimum moisture. Consequently, these curves should not be considered adequate to deal with compacted soil with initial conditions on the dry side of optimum moisture. Because it is wise construction practice to compact swelling clay on the wet side of optimum, this limitation of these equations should not prove to be serious.

The exponential form of the curves gives enough latitude for virtually any experimental curve to be described rather accurately by these equations.

Subroutine GULCH

The flow chart of Subroutine GULCH is given in Appendix 2. The flow chart includes all of the equations given in this chapter.

The purpose of the subroutine is to use a change of water content and Curves 1, 2, and 3 to obtain a volume strain. The data used by the subroutine must be specified in certain units. Total specific volume and specific water volume should be given in units of centimeters and grams for ease of computation, as explained below.

Specific Water Volume. In the cgs units system, the specific water volume has the same number as the familiar gravimetric moisture content. The density of water in the cgs system is 1.0 and the specific water volume is

$$V_W = \frac{\text{(Vol. water)}}{\text{(Vol. solids) } \gamma_S} ; \frac{\text{(Vol. water) } \gamma_W}{\text{(Vol. solids) } \gamma_S} = w \qquad (2.9)$$

where

V_W = specific water volume, cm^3/g ,

γ_S = unit weight of solids, g/cm^3 ,

γ_W = unit weight of water, g/cm^3 ,

w = gravimetric moisture content, decimal ratio.

Because the input water content is gravimetric, there is no difficulty in computing the specific water volume because the specific water volume and the gravimetric moisture content have identical numbers.

CHAPTER 3. THE TWO-DIMENSIONAL COMPUTER PROGRAM

This chapter outlines the capabilities of the computer program developed for predicting transient moisture movement and for using moisture changes to estimate total volume change. The computer program is the seventh in a series of programs named GCHPIP (Grid-Cylindrical-Heavy Soil PIPe) but is the first which includes the capability to predict volume change. The capability is contained in Subroutine GULCH, discussed in Chapter 2. The entire computer program is written in FORTRAN language for the Control Data Corporation 6600 computer at The University of Texas at Austin Computation Center. An austere version of FORTRAN has been maintained to permit easy conversion to other types of machines.

Analysis of Program GCHPIP7

An overall view of the program is presented, optional portions are outlined, and some of the underlying relationships are discussed. A guide for data input is included as Appendix 3. In it are nine tables of input data, each of which is explained here.

The flow chart for the program is presented in Appendix 2, a glossary of notation in Appendix 1, and the program listing in Appendix 4. The listing is referenced in the following description of the program with statement numbers identifying the beginning and end of each part of the program.

Data Input

The initial portion of Program GCHPIP7 reads in the data entered in Tables 1 through 8. Options in Tables 1, 2, and 8 are discussed in more detail later. Detailed information regarding the permeability throughout the soil region and the relationships among suction, water content, and volume change for each soil type in the region must be supplied. These associations are discussed at the end of the chapter.

Table 1 sets switches which keep previous data and which control the subsequent input of data. Table 2 sets the boundaries of the region, the spacing of the grid, and the time increments. The program will determine soil and water movements within a block of soil over a period of time for both constant and variable boundary conditions. Table 2 also inputs information for the iterative process of solution, which is described later.

Since saturated soils are rarely found in clay subgrades, the input to Table 3 includes coefficients with which to operate on the saturated permeability to obtain unsaturated values. As in Report 118-3, the permeability may be anisotropic; also, the maximum value of permeability at any point can be in any direction in the vertical plane of the grid.

The input from Table 4 can set up unique suction vs. water content vs. volume change relationships for each grid point in the region. Thus, the non-homogeneity of the natural ground and the pavement substructures can be imitated.

The data entered into Table 5 are meant to duplicate conditions in the field as they exist now or as they will exist at the beginning of an experiment. The data entered into Table 6 imply a change in these conditions because of some external change in environment, e.g., a rainstorm, a drought, a rise or fall in a parched water table, ponding, covering with an impermeable membrane, or a change in the humidity or temperature. The body of the program computes the changes which take place in the soil due to the input of Table 6.

Table 7 inputs accelerators for the iteration process so that conditions at the end of each time step can be reached with minimal computer effort.

Information in Table 8A controls the input of subsequent changes in boundary conditions given in a Table 9 sequence. If a boundary condition change is not made at the end of a time interval, then the soil-moisture relationship continues to move toward an equilibrium condition to satisfy the previous boundary condition.

The initial input phase of the program ends at statement 2000 with the input of Table 8B.

Equivalence of Variables

Each time that a suction value is input or set for a point in the region, the program calls Subroutine DSUCT to calculate the water content and $\frac{\partial \tau}{\partial \theta}$, the change in suction with water content for that point. When the water content is known, then Subroutine SUCTION is called to calculate suction τ and $\frac{\partial \tau}{\partial \theta}$. If the humidity and temperature of a particular point is input, then

Specific Volume of Solids. This quantity is simple to compute in the cgs system:

$$V_S = \frac{(\text{Vol. solids})}{(\text{Vol. solids})\ \gamma_S} = \frac{1}{\gamma_S} \tag{2.10}$$

where

V_S = specific volume of solids, cm^3/g .

The use of the reciprocal of the unit weight of solids is a simple matter if γ_S is expressed in centimeters and grams. In this case, the unit weight is equal to the specific gravity of the solids.

Total Specific Volume. This quantity is the reciprocal of the dry density in the cgs system, and it must be established experimentally. The equation for determining V_T is as follows:

$$V_T = \frac{(\text{Total volume})}{(\text{Vol. solids})\ \gamma_S} \tag{2.11}$$

Some check points can aid in establishing a suitable value of V_T . The number 0.60 (cm^3/g) is a fairly common value of V_T when soil is in the dry condition and is obtained by dividing the volume of a sample of dry soil in cubic centimeters by its weight in grams. This number should always be greater than the sum of the specific water volume at the shrinkage limit and the specific volume of solids. For example, if a soil has the properties

shrinkage limit = 19 percent and
specific gravity of solids = 2.70,

then a lower limit of the total dry specific volume is numerically equal to

$$0.19 + \frac{1}{2.70} = 0.56 \tag{2.12}$$

Once this value is known, the remaining part of the curve may be assumed, as shown in the example problems of Chapter 5.

The method of computing volume change in the present chapter includes those soil properties that are the most important in estimating the expansion of clay. The following four soil curves are employed:

(1) the initial total specific volume vs. specific water volume relationships, which is assumed to be of the same form as the shrinkage curve;

(2) the swell pressure vs. total specific volume curve;

(3) the 90 to 95 percent saturated line for the final V_T vs. V_W swelling condition; and

(4) the soil swell curve, which extends between the initial and final swelling points and which is used to obtain volume change from moisture-content change.

The control points on these curves are not directly related to Atterberg limits, although it is obvious that the water content in the effectively saturated range between the air entry point and the limit of structural integrity is related to the shearing strength of the soil and, therefore, to the Atterberg limits. It is probable that there is a simple relationship between plasticity index and the change of water content between the limits given above. While this relation is not known, it may be the subject of a very worthwhile experimental investigation, because the majority of volume change takes place in this region.

The limitations of the equations used in this chapter include an inability to deal with the following peculiarities:

(1) hysteresis in shrink-swell activity and

(2) double-valued functions of total specific volume.

Although these limitations should be recognized, they probably will not be serious under most practical conditions.

Finally, the fact that much of the data for the three basic soil curves must, at present, be assumed emphasizes the need for a few well-conducted laboratory experiments on typical expansive clays to obtain meaningful data for the curves.

Subroutine HUMIDY is called to calculate the suction and, consequently, DSUCT calculates water content and $\frac{\partial\tau}{\partial\theta}$.

When either water content or suction is not input for a point, then the gradients of suction $\frac{\partial\tau}{\partial x}$ or $\frac{\partial\tau}{\partial y}$, or gradients of water content $\frac{\partial\theta}{\partial x}$ or $\frac{\partial\theta}{\partial y}$, will be used to set the corresponding suctions and water contents from known values at other grid points.

These manipulations are performed between statements 1522 and 1526, 1615 and 1690, 1915 and 1990, and in statement 2665.

Time Step

A large DO-loop starts at statement 1900 and continues to statement 9000 at the end of the program. Within the DO-loop, time is irrelevant. By comparing the input and output of each time step, however, one can sense the changes in suction, water content, and total volume at a point or in the whole region with the progress of time.

Changes in Boundary Conditions

At the beginning of each time step specified in Table 8, Table 9 inputs, values of suction, and water content are set at appropriate points in the soil. If no changes in boundary conditions are specified, the program skips directly to statement 1980 for the computation of permeability.

Permeability Calculations

The permeability input in Table 3 is to be entered as six separate variables for each station. In a DO-loop between 1983 and 2010, the unsaturated direct and cross permeabilities are calculated and set for each point in the region. Suction coefficients are then calculated between statements 2120 and 2130. The unsaturated permeability must be recalculated each time because the nonsaturation multiplier is dependent upon the soil suction.

Iterations to Determine Suction

The iterative process begins at statement 2196 and continues to statement 8000. The Crank-Nicolson method of numerical solution for a parabolic partial differential equation was discussed in Chapter 3, Research Report 118-3, and is used in this program.

The program is formulated such that flow is considered in the x-pipes and values of τ_x are calculated for each point. Then, beginning with statement 2370 and ending at 2570, flow is considered in the y-pipes. The coefficients used to calculate τ_y use the values of τ_x set from the previous half-iteration and vice versa.

In the first step of each half-iteration, the acceleration parameters for each station are set. For the first few iterations they are preset with parameters input in Table 7. Subsequent iterations generate their own parameters from suctions and other coefficients calculated in the previous half-iteration. This is accomplished in small DO-loops, such as the one ending at 2214.

The x-tube flow coefficients are calculated one level at a time; the previous values of suction at the station and surrounding stations for the latest half-iteration and the suction for the preceding time increment are used. The suction coefficients that are assumed not to vary with suction changes that take place during the iterative process are also used in the calculation.

The next portion of each half-iteration calculates the continuty coefficients. Considerable programming is required to set the proper values within, on, and outside the boundaries. The usual route is directly to statement 2350, unless the boundary conditions are set for the point. If suction is set for the point by the boundary condition, then the solution procedure goes to statement 2320, which merely maintains the value of suction at that point.

If a gradient in suction in the x-direction is set internally in the boundary conditions, then the usual path for the solution is to statement 2340. Other calculations in this section are for conditions at the boundaries of the region.

The recursion or continuity coefficients are calculated in statement 2350 as A_i and B_i for that particular jth level.

In a small DO-loop ending in statement 2360, the suction τ_x for each point is calculated using the recursion coefficients and working across the region from right to left at each jth level.

The last five paragraphs above are repeated for each level in turn, progressing from bottom to surface. This operation is governed by the DO-loop starting at 2196 and ending at 2370. The whole procedure is then repeated for a half-iteration in the y-direction (which is commonly vertical); this ends at 2570.

The numerical operation is then checked for convergence. If the difference between τ_x and τ_y is greater than a specified tolerance, a closure error is signaled. The number of stations in the grid that did not close is printed for that iteration. The values of τ_x and τ_y are printed for several monitor stations for each iteration. If all stations close within the tolerance, control is taken from the iteration DO-loop and the solution proceeds beyond statement 8000.

Output

A DO-loop starting at 2650 and proceeding to 2700 calculates the suction values τ for that time step and outputs these values.

For all stations where closure has been possible, which is the usual case, the suction at each station is calculated by means of weighted averages of τ_x and τ_y .

The closure signal printed at the successful conclusion of computations on a particular time step signifies one of the following:

(1) actual closure has been achieved at each point of a region, or

(2) the number of iterations allowed for each time step has been completed.

A glance at the monitor data will indicate which has occurred. If the second condition occurs, then an explicit forward-difference estimation of the new τ at each point not closed is made. This estimation uses both the values of τ for the previous time step and the most recently computed values of τ_x and τ_y . If many such closures occur, it may be desirable to shorten the time increment, h_t , to assure stability of the estimation process.

The suction and corresponding water content are output if such was specified in Table 8B for the particular time step.

Calculation of Heave

The final portion of the program consists of a DO-loop ranging from statement 2800 to 2820 in which the heave is calculated for each time step. Subroutine GULCH is called to calculate the change in volume due to the decrease in suction. The decrease in suction corresponds to an increase in water content. In Subroutine GULCH, the data input in Table 4 is used to determine the volumetric strain. A coefficient is used to relate the vertical strain to volumetric strain, and the vertical strain at each station is returned to the main program.

The vertical movement at the surface is calculated by multiplying the vertical strain at each level by the increment length and summing over the length of the column. For the surface level, however, the strain is only multiplied by one-half the increment length. The station and heave are output and the program returns to determine the suction, water content, and heave for subsequent time steps.

Details of Input

The formats for each input card are given in detail in Appendix 3. They are also discussed briefly below.

Units

Units of suction in this program are inches of water; water content is in percent, angles in degrees, permeability in inches per second, time in seconds, and increment lengths in inches.

Problem Identification Cards

In the card deck problem identification cards precede the data for any table. The first card is in an alphanumeric format that allows 80 columns of run information. The second card includes five spaces for alphanumeric characters to be used as the problem number. The last 70 spaces on the card are for problem identification.

Table 1. Program Control Switches

The program control card is divided into spaces five columns wide. In the first six of these spaces, the hold option for Tables 2 through 7, which directs the program to retain the data used in the preceding problem, may be exercised by placing 1 in the appropriate position.

The six five-column spaces between column 31 and column 60 specify the number of cards to be read in Tables 2 through 7. There is one exception: The number of cards in Table 4A is specified in the position reserved for Table 4.

In column 65, the switch KGRCL is set. This switch specifies whether the problem has rectangular or cylindrical coordinates. The number 1 specifies a rectangular grid, while 2 signals that the problem to be solved is in cylindrical coordinates.

In column 70, the switch KLH is specified. The number 1 in that column denotes a "light" soil. In this case, compressibility effects are disregarded. If a 2 is inserted, Subroutine HEAVY is called. It permits consideration of the soil-suction change as a function of overburden pressure, soil compressibility, and porosity.

The switch KTAPE is set in column 75. If the number 1 is set, this option is exercised; if zero is set, the option is ignored.

Table 2. Increment Lengths and Iteration Control

The region to be considered for Table 2 is divided into a horizontal-vertical rectangular pattern with the y-axis as the left border and the x-axis as the bottom of the region. The number of equal x-increments, which can also represent the radial increments of an axisymmetric problem, are input in the first five columns of the first card of data for Table 2. The increment lengths are input in inches, and the duration of each time step is given in seconds. The inside radius specified in the space between columns 41 and 50, must be a value other than zero if cylindrical coordinates have been specified. If KGRCL has been set at 1, however, this space may be left blank. The closure tolerance which is also specified on this card, is a relative one based on a fraction of the computed τ_y . That is, the error at each point must be within a specified fraction of the value of suction at that point.

The second card in Table 2 requires the specification of a list of four monitor stations. The values of τ_x and τ_y at these points for each iteration will be printed out at each time step for which output is desired.

The third card in Table 2 permits some experimentation with the form of the equation which is being solved. If a 1 is set, the transient-flow equation is specified. If a 2 is inserted, the time-derivative term is set to zero. In most circumstances, the transient-flow condition will be specified.

Table 3. Permeability

The tensor form of permeability has been programmed, and provision has been made for using unsaturated permeability. A different set of principal permeabilities, directions, and coefficients for determining unsaturated permeability may be read in at each point of a soil region. The card which specifies permeability contains three essential parts:

(1) the specified rectangular region,

(2) the two principal permeabilities and their directions, and

(3) the coefficients for determining unsaturated permeability.

Each of these will be discussed separately.

Specified Rectangular Region. The first four five-column spaces give the corner coordinates of the region within which the permeability data applies. The first two numbers specify the smallest x and y-coordinates and the next two specify the largest x and y-coordinates. Permeability is a property of a pipe increment between mesh points. Because of this, permeability should be specified for all pipe increments that extend one increment beyond each boundary point. Thus, if a region extends from coordinates (0,0) to coordinates (10,10) , the permeabilities should be specified for pipe increments (0,0) to (11,11) . This corresponds with the stationing system illustrated in Figs 2 and 3 in Chapter 2 of Research Report 118-3.

Principal Permeabilities and Their Directions. The principal permeabilities are given in the next three ten-column spaces in order, i.e., P1 , P2 , and ALFA . The quantity P1 is the principal permeability nearest the x-direction, and ALFA is the angle in degrees from P1 to the x-direction; counterclockwise angles are positive. The quantity P2 is the principal permeability at right angles to P1 . The permeabilities specified should be the saturated permeabilities in units of inches per second. They will be corrected downward by the three unsaturated coefficients found in the next part of the card if the water content of the soil drops below what has been termed in Research Report 118-1 as "final saturation."

Unsaturated Permeability Coefficients. The form of unsaturated permeability recommended by W. R. Gardner (Ref 2) has been programmed. This form is

$$k_{unsat} = \frac{k_{sat}}{\frac{\tau^n}{b} + 1} \tag{3.1}$$

where

k_{unsat} = unsaturated permeability,

k_{sat} = saturated permeability,

b = an empirical coefficient,

n = an exponent that varies with grain size.

Since much of the published data on unsaturated permeability are in units of centimeters, a conversion factor may be included to transform the inches of suction used in this program to the centimeters from which the constants b and n are derived. The expression programmed is

$$k_{unsat} = \frac{k_{sat}}{\frac{(a\tau)^n}{b} + 1} \tag{3.2}$$

where a is normally equal to 2.54 cm/in.

It is important to remember that the data read in at each point are added algebraically to the data already stored at that point. At the start of a problem in which previous data are not kept, permeability values at each point are set to zero. Either positive or negative values of permeability, angle, or unsaturated permeability may be read in at each point; but the computer will use the algebraic sum of all data furnished it for each point.

Table 4. Suction vs. Water Content Curves

Table 4 data consist of two parts. In the first part, numbered, single-valued suction vs. volumetric water content relationships and other pertinent soil data are specified. In the second part, the rectangular regions to which each numbered pF vs. water content curve is applied are established. No hysteresis effects are considered in these relationships. This limitation is not serious, however, because the pF vs. water content relationship that is specified for a point may be an approximation of a scanning curve. The greatest difficulty introduced by this limitation occurs when the trend of moisture change is reversed and a new pF vs. water content curve must be followed. When this situation arises, one problem is stopped, all previous data is held, and the appropriate pF vs. water content curves are changed to represent the new scanning curve. B. G. Richards (Ref 10) notes that the hysteresis effect can frequently be neglected because, in many cases, changes of moisture content are in one direction over a long period of time. Youngs' discussion of the infiltration problem gives an important exception to this rule (Ref 11). Scanning curves may be estimated from experimental data in the manner demonstrated in Research Report 118-1.

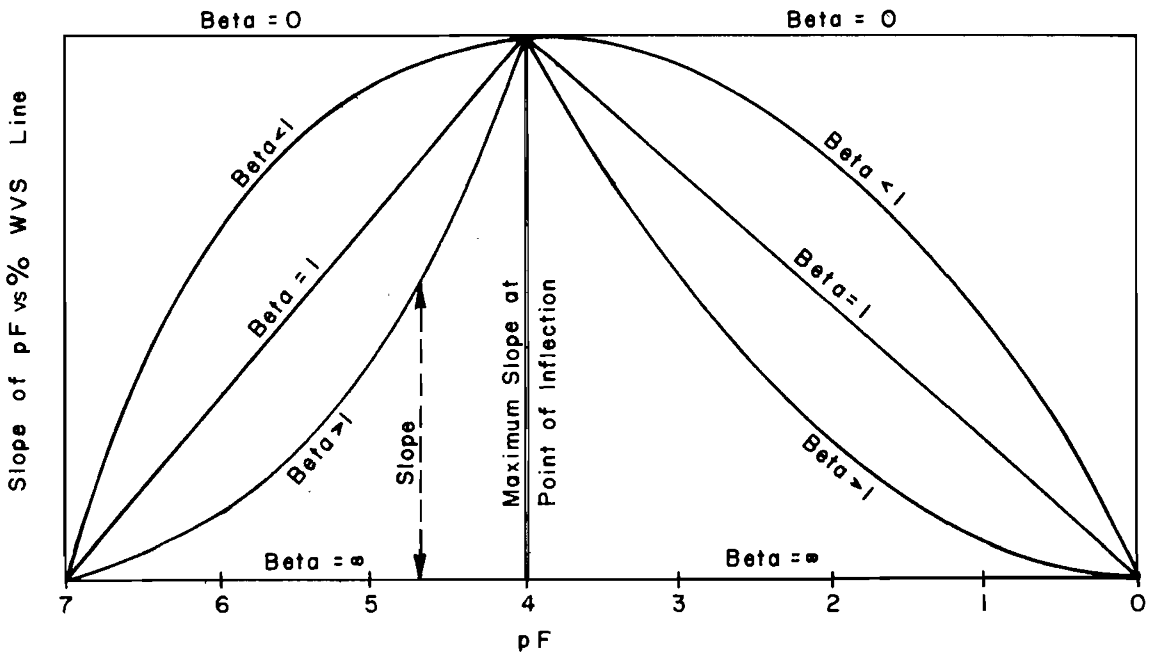
The pF vs. Water Content Relationship. The pF vs. water content relationship is assumed to be in the form of an exponential curve, the slope of which is the ordinate of a pF vs. slope curve. The cumulative area under the pF vs. slope curve is the percentage of final saturation. Both curves are needed to explain the assumed pF vs. water content relationships. The pF vs. slope curve is shown in Fig 7(a), and the pF vs. percentage of final saturation curve is shown in Fig 7(b). The pF vs. slope curve may be intuitively related to the pore-size distribution of the soil. The point of inflection of the pF vs. percentage of final saturation curve rests on the line between 100-percent final saturation and maximum pF . Any inflection point pF , maximum pF , and exponent for the pF curve (BETA) , may be specified to give the shape of pF vs. water content curve desired. The final-saturation water content must be specified as well.

Input Soil Data. Soil data for each type of soil are included on two consecutive cards. Each of the sets of two cards is assigned a number by the computer in the order in which the cards are read by the computer. The data on the first card of each set include the following:

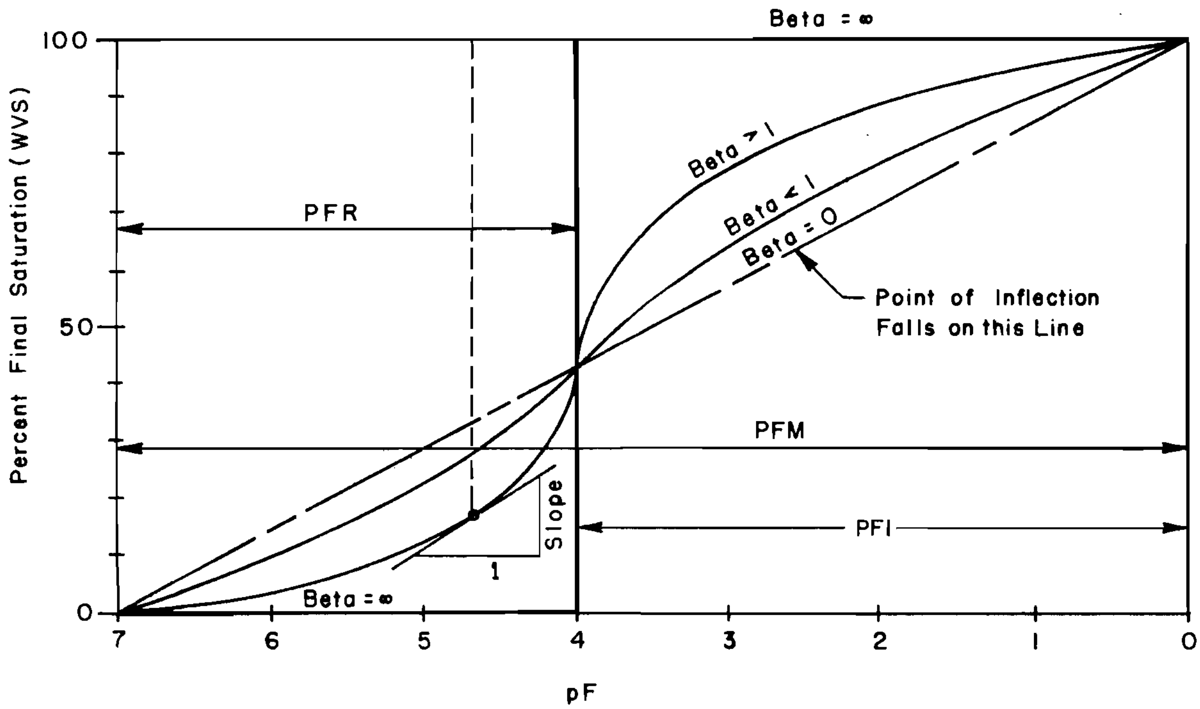
(1) number of separate rectangular regions to which the following data apply, LOC ;

(2) maximum pF ;

(3) pF at the inflection point, PFI ;



(a) Relationshipship of pF vs. slope.



(b) Relationship of pF vs. percentage of final saturation.

Fig 7. Suction vs. moisture relationships.

(4) exponent for pF curve, BETA ;

(5) air-entry gravimetric water content in percent, WVA ;

(6) exponent for the specific water volume vs. total specific volume relationship, Q (the shape of this curve could be assumed to be the same as that of the shrinkage curve);

(7) the slope of the specific water volume vs. total specific volume curve at zero water content, ALFO (it is probably safe to assume that this value will always be zero);

(8) porosity at air-entry point, a decimal ratio, PN ;

(9) slope of the void ratio vs. log pressure (e-log p) curve, AV ;

(10) saturation exponent relating the degree of saturation to the factor χ_E , which is assumed (perhaps erroneously in some cases) to range from zero to one, R ;

(11) the soil unit weight in pounds per cubic inch, GAM ; and

(12) the gravimetric water content in percent at final (or suction-free) saturation, WVS .

If the overburden pressure and compressibility of the soil are not to be considered, i.e., if the switch KLH has been set to 1, then only items 1, 2, 3, 4, and 12 need to be read in. The form of the assumed relationships among these soil variables has already been discussed.

Some of the soil data to be provided on the second card in Table 4 are in the cgs measurement system, primarily for convenience in computing them. Examples of this will be shown in Chapter 5. There are eight entries on the second card:

(1) the total specific volume of dry soil in cm^3 per gram of dry soil, VTO ;

(2) the total specific volume of soil at final saturation in cm^3 per gram of dry soil, VTF ;

(3) the specific water volume on the zero air-voids line corresponding to the final total specific volume in cm^3 per gram of dry soil, WVF (the number for this is identical to gravimetric water content expressed as a decimal ratio);

(4) the swell pressure corresponding to the dry total specific volume, PO ;

(5) the exponent of the swell pressure vs. total specific volume curve, ENP (an exponent greater than 1.0 will produce a curve that is concave upward);

(6) the surcharge pressure in pounds per square inch, SRCH ;

(7) the ratio between vertical expansion and volumetric expansion of the soil _in situ_, PCTUP , expressed as a decimal ratio (this ratio specifies how much of the total volume change goes into upward movement); and

(8) the specific gravity of solids, GAMS .

Items 1 through 4 are indicated in Fig 8.

Location of Soil Data. These cards in Table 4, which represent the different types of soils present in a soil region, specify the number of rectangular regions occupied by the soil of each type in space LOC . The sum of the values in LOC is called NLOC . The soil data cards must be followed by exactly the number of cards as are in the sum NLOC , which is the same as the total number of rectangular regions occupied by the different types of soils. These cards give the smallest x and y-coordinate and the largest x and y-coordinate of each region and specify the curve number which applies there. For example, when two soils are present in a soil region and one occupies two locations and the other occupies one location, the total number of curve location cards should be three.

The unit of suction used in this program is inches of water. The pF is the Briggs logarithm of suction in centimeters of water. Ordinary pF vs. water content curves should be furnished, however, since there is a programmed internal conversion from centimeters to inches for computed suction values.

Table 5. Initial Conditions

Each card put into the computer has a rectangular distribution scheme for either of two cases: water content (Case 1) or suction (Case 2). The value at the upper right-hand corner of the specified rectangular region is given along with the x and y-slopes of these quantities. If the value in the upper right-hand corner is smaller than any other in the region, both slopes should be positive. If no slopes are read in, the machine will assume them to be zero and distribute the same value of either water content or suction over the entire region.

The values input in this manner are added algebraically to the values already stored at each point. To avoid any complications, when a new problem is read in and the keep option is set to zero, all initial values of water content and suction are set at zero. Any subsequent additions will start from that datum.

Initial conditions are replaced in the computer memory with new values at each time step. For this reason, the exercise of the hold option for Table 5 means simply that the most recently computed values of suction and

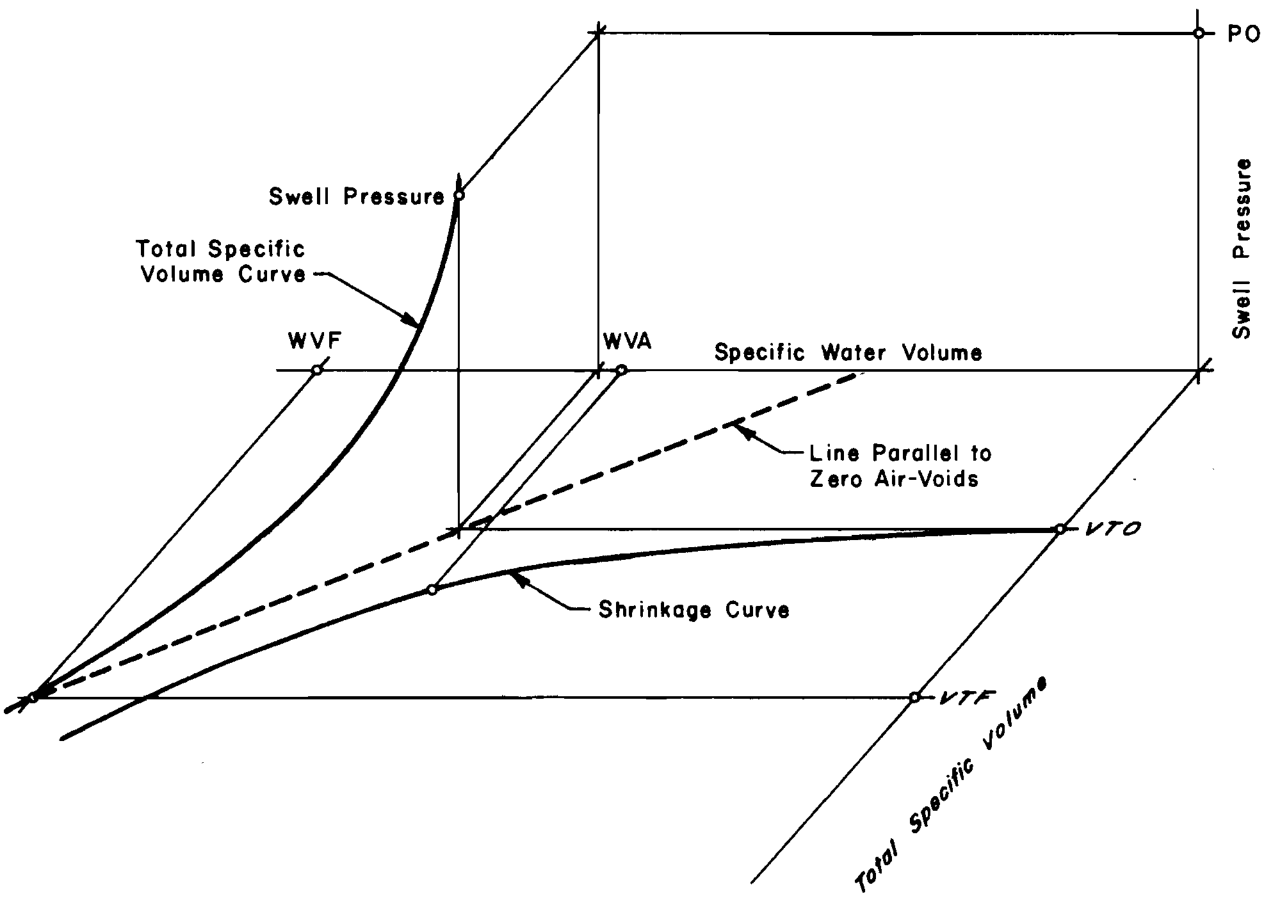


Fig 8. Three-dimensional representation of relationships among specific water volume, total specific volume, and swell pressure.

moisture content will be retained. A new set of initial conditions must be input if a new start is required.

Table 6. Boundary and Internal Conditions

Five cases are permitted as boundary and internal conditions:

(1) gravimetric water content,

(2) suction,

(3) suction gradient in the x-direction,

(4) suction gradient in the y-direction, and

(5) temperature and humidity of soil water.

A rectangular distribution scheme distributes the specified quantity uniformly over the region outlined by its smallest and largest x and y-coordinates and adds algebraically to values already stored at each point in the region. Cases 1, 2, and 5 result in computation of a value of suction and a final setting of the switch KAS(I,J) to 2. Boundary and internal conditions are computed differently based on the value of the switch KAS(I,J), which is set for each point. The computer recognizes the following values of this switch:

KAS(I,J) = 1 , water content is set,
= 2 , suction set,
= 3 , x-gradient set,
= 4 , y-gradient set, and
= 5 , temperature and soil-water humidity is set.

A discussion of these conditions and the way they are computed is given in Research Report 118-3. The method of converting each of the five input conditions is discussed in the succeeding paragraphs.

Gravimetric Water Content Set. When this quantity is specified, Subroutine SUCTION is called. It converts water content to suction according to the pF vs. water content relationships read in as Table 4. Values of pF and $\frac{\partial \tau}{\partial \theta}$ are also computed. Water content may be set at any point of a region.

Suction Set. The setting of this quantity requires that Subroutine DSUCT be called to compute volumetric water content pF and $\frac{\partial \tau}{\partial \theta}$ from the appropriate input soil data. Suction may be set at any point of a region.

x-Gradient Set. The x-gradient must not be set at any point on the upper or lower boundary of the soil region. When a suction gradient is set on the right or left boundary (excluding the corner points), a line starting at the value of suction that is one station inside the boundary is projected outward to the boundary along the gradient that has been set. In this manner, a value of suction is set at the boundary point. Then Subroutine DSUCT is called to provide information on water content, pF , and $\frac{\partial \tau}{\partial \theta}$. An x-gradient may be set at any interior pipe increment.

y-Gradient Set. The y-gradient may be set at any point along the upper and lower boundaries of the region including the corner. The same projection scheme is used as explained above, and Subroutine DSUCT is called into operation. A y-gradient may be set along any interior pipe increment.

Temperature and Soil-Water Humidity Set. This option may be used at any point where these data are known. The option was intended for use primarily along the upper boundary where infiltration and evaporation rates may be used to establish a soil-moisture humidity, but the condition is valid at any point of the region. Subroutine HUMIDY is used to compute suction according to the relative humidity formula presented in Chapter 3 of Research Report 118-1.

The switch KAS(I,J) will be set automatically to 1, and suction gradients will be set to zero at every station in the region where boundary conditions have not been specified.

Table 7. Closure Acceleration Data

A different number of closure valve settings for the x and the y-directions may be read into the computer. The number of each is specified on the first card of Table 7.

The cards immediately following list the x-closure valve settings and the cards after that list the y-closure valve settings. A maximum of ten of each may be used. The computation of these values is described in Chapter 3 of Research Report 118-3.

Table 8A. Time Steps for Boundary-Condition Change

The options that are permitted are based on the value of KEY , which is input on the first card of Table 8A. The values of KEY and their meanings are given below:

KEY = 1 , discontinuous boundary-condition change (a list of time steps is read in for boundary condition changes),
= 2 , continuous boundary-condition change (new boundary condition must be read in at each time step), and
= 3 , no boundary-condition change.

If KEY is set at 1, then the same card should specify the number of time steps at which boundary conditions will change. This first card should then be followed by cards listing the time steps at which boundary conditions will change. The maximum number of time steps at which boundary conditions change should not be greater than the number of time steps in the problem nor greater than the dimensioned storage of KLOC , the array which tells the program when to read a new set of boundary conditions.

Table 8B. Time Steps for Output

This table is included to decrease the amount of output that is produced by the computer. The first card of Table 8B specifies a value of KEYB . Values of KEYB and their explanations are given below:

KEYB = 1 , discontinuous output (a list of time steps at which output is desired is read in), and
= 2 , continuous output.

If KEYB is 1, then the same card should specify the number of time steps for output (NOUT) . Additional cards listing these time steps should follow.

If KEYB is 2, no other cards should be added. The maximum number of time steps for output should not exceed the maximum number of time steps for the problem or the dimensioned storage of array KPUT .

Table 9. Subsequent Boundary Conditions

This table is used only if KEY from Table 8A is set at 1 or 2. At the beginning of the specified time step, at least two cards are read in: (1) the time-step identifier and (2) the boundary-condition card.

Time-Step Identifier. This card has two entries: (1) the time step and (2) the number of cards to be input at this time step.

Boundary-Condition Cards. These cards follow the same format as those used in Table 6. The same subroutines are called, and all other explanations for Table 6 data apply to the data to be read in as Table 9.

This completes the outline of input procedures. All data that is fed into the machine is echo printed by the computer to afford a check on the information actually being used in the computer.

Output

Output generated before each time step includes the station, suction, water content, $\frac{\partial \tau}{\partial \theta}$, and the elements of the unsaturated permeability tensor (P11 , P12 , and P22) at each point of the region.

Output generated after each time step includes the station, suction, water content, pF , and closure valve settings.

Major Options Available in Program

Retention of Data from Previous Program

If the numeral 1 is punched in any of the keep options of Table 1, the computer will retain the data that are in the computer for the variables specified in Tables 2 through 7. At the end of the initial program, the variables listed in Table 2, 3, 4, 7, and 8 for input will be the values in the computer memory. However, the values given for suction and water content in Table 5 will be the most recent computations. The boundary conditions existing at the end of the last problem will be retained. These will be values input in Table 6, amended by additions input in Table 9.

For the third problem and additional problems, the keep options will retain the sum of the imputs for previous problems for Table 3. There is no way, however, to amend values in Tables 2A, 8A, and 8B in the present program. Information for Tables 2B and 2C must be read in anew for each problem, even if the keep option is used for Table 2.

Variation in Response to Boundary Condition Changes with Time

Table 8B allows three options to be used regarding subsequent boundary-condition changes: intermittent change, continuous change, and no change.

With intermittent change, the programmer can follow natural occurrences such as precipitation, drought, temperature, and humidity. By varying the number of time steps between boundary-conditon changes, the effect of a long drought in comparison with a short dry period can be determined.

With continuous change, a ponding project, daily fluctuations in temperature and humidity, or the reaction of the subgrade to a rainfall or drought of variable intensity can be simulated.

With no boundary-condition changes, the effect of a membrane on a subgrade can be simulated. This option also allows the soil to reach a stable equilibrium with its environment.

Rectangular or Cylindrical Coordinate Grid Systems

The rectangular coordinate system can be used to calculate heave when the region being considered is a vertical plane. The cylindrical coordinates, on the other hand, are useful for studies around piles, sand drains, drilled holes, and other axisymmetric systems. The switch for this option is in Table 1.

Transient or Steady State

Table 2C is a switch by which the initial and boundary conditions can set the constant suction for each station. With respect to time, the problem then becomes one of determining flow under constant potentials.

Ordinarily, this switch would be set to the numeral 1, which permits transient flow. With this option, the soil can be initially saturated and the effect of drying at the edges can be observed by proper input into Table 6 or Table 9.

Variable Output

Output can be obtained for all or any of the time steps by setting the switch in Table 8B.

KTAPE Switch

Setting this switch to any non-zero integer causes the program to include the KTAPE option at each time step. This option was built into the program to provide data for use in a two-dimensional, finite-element, elastic-continuum computer program devised by Dr. Eric B. Becker, Professor of Aerospace Engineering, The University of Texas at Austin. Unless the user intends to treat the soil as a continuum and to calculate the strains and displacements from the stress release values supplied by this option, the KTAPE switch should be set equal to zero.

HEAVY Option

A soil at some depth below the surface will be subject to a total vertical pressure equal to the weight of overburden per unit of horizontal area. This pressure can be distributed through the particle contacts as effective stress and through the water phase as pore pressure. If the water pressures are positive, then the effective stresses are less than the total stresses. If there is a suction in the pore water, the effective stresses will be greater than the overburden pressure.

The addition of a surcharge on the soil surface will increase the total stress and, thereby, permit a less negative value of pore pressure, i.e., a reduced suction. The applied stress can be considered to push the particles into closer contact, push the air-water interfaces further into the larger voids, and generally increase the volume of water per unit of total volume of soil and water. Thus, the density, water content, and degree of saturation will be increased. If the soil is saturated before application of the surcharge, any tensile stresses in the water will be reduced by the increase in total stress. The effective stress may be increased or decreased, but at all times it will be equal to the total pressure minus the pore-water pressure. When dealing with partially saturated soils, it is easier to treat the effective stress as the total overburden pressure plus a portion of the absolute value of the soil suction. Intuitively then, the weight of the overburden can be expected to reduce the suction from a high negative value to a low negative value.

At any depth below the surface of the clay, effective stress can decrease and the soil can become more saturated without a change in total overburden pressure; this is due to a reduction in suction from a high negative value to a low negative value. This change in effective stress may or may not be accompanied by a change in soil volume, depending on how much energy must be expended by the suction against the surrounding total pressure in increasing the soil volume.

The volume-change process can be viewed as taking place in two parts. In the first part, suction change expends enough energy to overcome the surrounding pressure and brings the soil to a point of imminent volume change, without changing volume. In the second part, the magnitude of suction is further reduced, and, consequently, volume changes.

The optional Subroutine HEAVY is included to enable modification of the soil suction at depth. Such modification would be influenced by the weight of the overburden and the compressibility characteristics of the soil structure and is an attempt to account for the energy expended to overcome pressure, even when no volume change occurs. Subroutine HEAVY is used throughout the program if the number 2 is placed in column 70 of the input of Table 1. Input of the numeral 1 ignores the weight of the overburden in calculating the suction. If the HEAVY option is not used, there is no need to input the e-log p compressibility coefficient, AV ; the chi-factor exponent, R ; or the exponent of the swell pressure vs. total specific volume curve, ENP . AV and ENP are alternate inputs. If a value of ENP other than zero is input, the subroutine calculates the volume change using this value. If a value of zero is input for ENP , a value of AV must be input for use in calculating the soil compressibility.

The relationships used in Subroutine HEAVY are discussed below.

Water Pressure vs. Total Pressure Relationship. This relationship is discussed in some detail in Chapter 4 of Research Report 118-1. The term α_{po} is defined in that report as follows:

$$\alpha_{po} = \left(\frac{\partial u}{\partial p} \right)_t \qquad (3.3)$$

where

u = excess pore pressure,

p = total pressure,

t = time after the initial change of water pressure.

Also defined in Chapter 4 of Research Report 118-1 is the relationship between total specific volume and the specific water volume in a free-swell test. This relationship is

$$\alpha_{FS} = \frac{\dfrac{\Delta V_T}{V_S \gamma_S}}{\dfrac{\Delta V_W}{V_S \gamma_S}} = \frac{\Delta V_T}{\Delta V_W} \tag{3.4}$$

where

α_{FS} = slope of the total specific volume vs. specific water volume curve,

ΔV_T = change in total specific volume,

ΔV_W = change in specific water volume,

V_S = volume of the soil solids,

γ_S = unit weight of the soil solids.

Equation 2.1 has been formulated in Chapter 2 of the present report as

$$V_T = V_{TO} + \alpha_o V_W + \frac{1 - \alpha_o}{Q} \left(\frac{V_W}{V_{WA}} \right)^Q V_{WA}$$

If this equation is differentiated to find the slope, then

$$\alpha_{FS} = \frac{dV_T}{dV_W} = \alpha_o + (1 - \alpha_o) \left(\frac{V_W}{V_{WA}} \right)^{Q-1} \tag{3.5}$$

The expansion of the soil from an initial specific water volume, V_{WI}, to some intermediate value, V_W, as the soil approaches an equilibrium value with time follows the swell curve (Eq 2.5)

$$V_T = V_{TI} + (V_{TP} - V_{TI}) \left(\frac{V_W - V_{WI}}{V_{WP} - V_{WI}}\right)^Q$$

That is, it is of the same general shape as the free-swell curve, but the swell will always be less than if the soil were allowed to swell under no external restraint. The soil has swelled from some initial value of suction when the specific water volume was V_{WI} to some lower equilibrium value when the specific water volume is increased to V_{WP}. The change in total volume as a function of change in specific water volume can be denoted by the secant α_B :

$$\alpha_B = \frac{V_T - V_{TI}}{V_W - V_{WI}} \tag{3.6}$$

The term α_{po} is estimated by assuming an initial value equal to α_B and a final value equal to zero. That is, the change in the suction, $d\tau$, and the rate of change in suction with change in specific water volume due to overburden effects, $\left(\frac{d\tau}{d\theta}\right)_p$, will approach zero as the suction, swell, and specific water volume reach equilibrium values. Referring to Fig 9, the decay with time can be represented by

$$\alpha_{po} = \alpha_B \left[\frac{(V_{TP} - V_{TI}) - \Delta V_T}{(V_{TP} - V_{TI})} \right] \tag{3.7}$$

$$\alpha_{po} = \alpha_B \left[1 - \frac{\alpha_B (V_W - V_{WI})}{(V_{TP} - V_{TI})} \right] \tag{3.8}$$

<u>Chi-Saturation Curve</u>. The limitations on the relationship between the unsaturated stress parameter, χ_E, and the degree of saturation, S, are discussed in Chapter 4 of Research Report 118-1. The assumed form of the

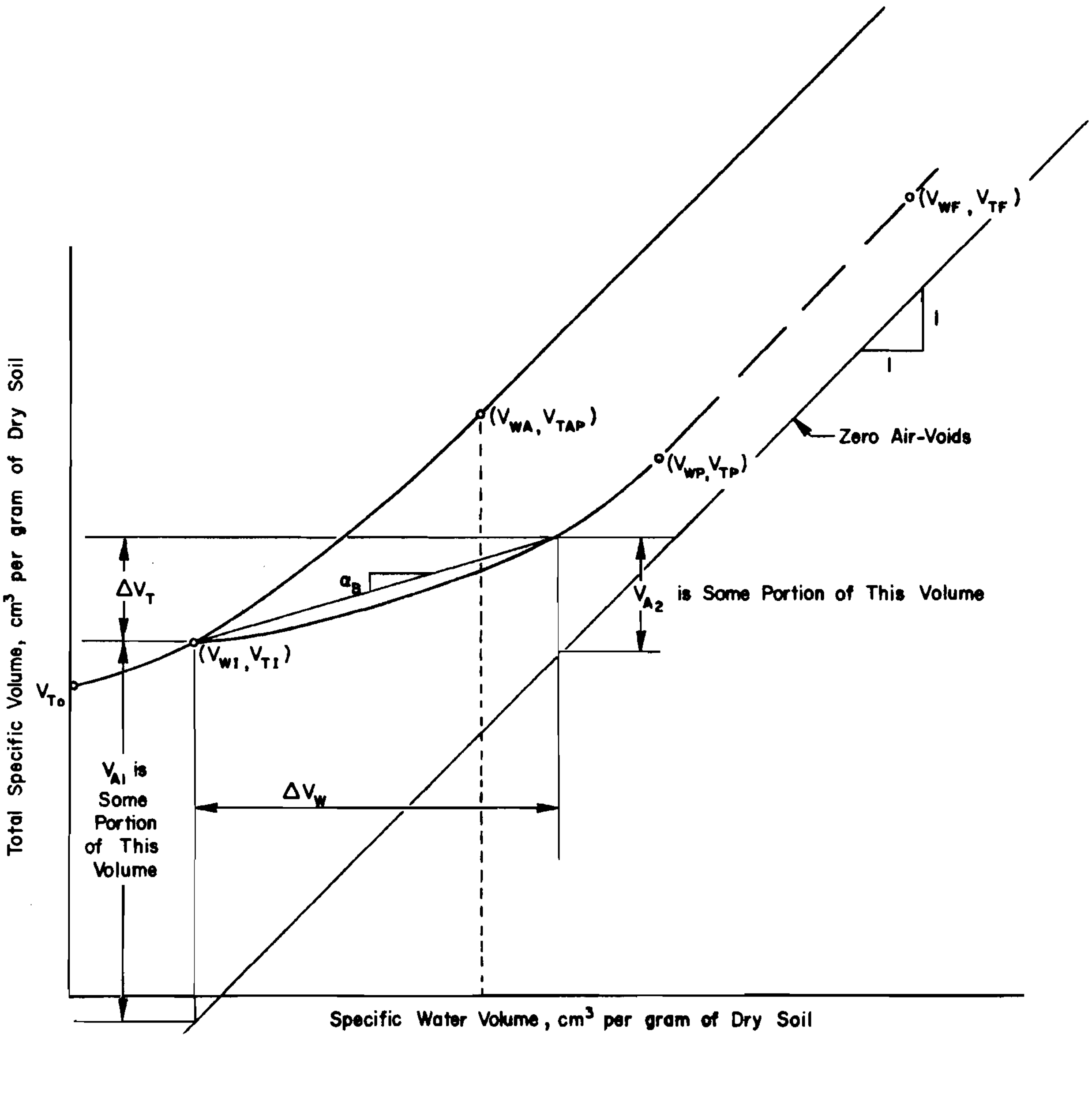


Fig 9. Expulsion or compression of air as swelling takes place.

relationship is undoubtedly too simple to include all cases, but it is programmed as the exponential function given below:

$$\chi_E = S^R = \left(\frac{V_W}{V_T - V_W}\right)^R = \left(\frac{\theta}{n}\right)$$

$$= \left[\frac{(V_W \cdot 1)(1-n)(G)}{n}\right]^R \qquad (3.9)$$

where

χ_E = equilibrium unsaturated stress parameter;

S = degree of saturation, a decimal ratio;

R = an exponent;

V_W = specific water volume;

V_T = total specific volume;

$\theta = \frac{V_W}{V_T}$ = volumetric water content, a decimal ratio;

n = soil porosity, a decimal ratio;

$V_W \cdot 1$ = gravimetric water content, a decimal ratio;

G = specific gravity of the soil solids.

This calculation is made only if the water content is less than air-entry water content. Although in error, the porosity is assumed to remain constant once the water content falls below the air entry point. Above the air-entry water content, $\chi_E = 1$, and the porosity is assumed to have the form

$$n = \left(\frac{n_A + \Delta\theta}{1 + \Delta\theta} \right) \tag{3.10}$$

where

$$\Delta\theta = (V_W - V_{WA}) \ (1 - n)G \tag{3.11}$$

and

n_A = the porosity at air entry, a decimal ratio;

V_{WA} = the specific water volume at air entry.

An appropriate value of the exponent R should be determined after consulting experimental results, but a value between 0.5 and 2.0 would cover many cases reported in the literature. In all of these computations, the term $(1 - n)G$ is used to convert gravimetric into volumetric water content, where G is the specific gravity of the soil solids.

Compressibility Relationship. The basic relationship used in this computation is Eq 4.106 of Research Report 118-1. Some other equations will be considered first. The plot of void ratio and the logarithm of pressure gives a straight line over a fairly wide range of pressures, as long as soils are either preconsolidated or normally consolidated and not in an intermediate pressure range. The relationship normally used is

$$e - e_o = -C_c \log_{10} \frac{p}{p_o} = -0.435 \ C_c \log e \frac{p}{p_o} \tag{3.12}$$

where

e = void ratio,

p = pressure,

C_c = slope of the e-log p curve.

The derivative of this expression yields

$$\frac{de}{dp} = -0.435 \frac{C_c}{p} \tag{3.13}$$

In Chapter 4 of Research Report 118-1, reference was made to Blight's compressibility coefficient, c, as defined in the following equation (Ref 1):

$$\frac{\Delta V_T}{V_T} = c\Delta p \tag{3.14}$$

where

V_T = total specific volume after the volume change ΔV_T has been completed,

Δp = change in total pressure,

c = a negative number indicating a decrease in volume with an increase in pressure.

If it is assumed that the change of total volume is equal to the change of void volume, the equation can be rewritten as

$$(1 - n)\Delta e = c\Delta p \tag{3.15}$$

and thus

$$\frac{\Delta e}{\Delta p} = \frac{c}{1 - n} \tag{3.16}$$

Equations 3.13 and 3.16 may be combined to give an expression for Blight's compressibility, c, in terms of the slope of the e-log p curve:

$$c = \frac{C_c(n - 1)}{p} \tag{3.17}$$

This relationship and one other, which will be developed below, will be included in the compressibility correction term for the slope of the pressure vs. free suction vs. moisture curve, which is discussed in Chapter 4 of Research Report 118-1.

The second relationship deals with the ratio of air volume, V_A, to water volume, V_W.

$$\frac{V_A}{V_W} = \frac{V_V - V_W}{V_W} = \frac{\frac{V_V}{V_T} - \frac{V_W}{V_T}}{\frac{V_W}{V_T}} \tag{3.18}$$

$$\frac{V_A}{V_W} = \frac{n - \theta}{\theta} \tag{3.19}$$

where

n = porosity,

θ = volumetric water content.

Equations 3.17 and 3.19 are to be used subsequently. As explained in detail in Chapter 4 of Research Report 118-1, the rate of change of suction with respect to water content varies with the compressibility of the soil. This is expressed in Research Report 118-1 by the following relationship:

$$\frac{\partial\tau}{\partial\theta} = \left(\frac{\partial\tau}{\partial\theta}\right)_o + \left(\frac{\partial\tau}{\partial\theta}\right)_p \tag{3.20}$$

where the o subscript represents the pressure-free relationship and the p subscript denotes the contribution of the compressibility of the soil. This latter term uses Eq 3.19 and is expressed in the following fashion for saturated soil:

$$\left(\frac{\partial \tau}{\partial \theta} \right)_p = - \frac{\alpha_{po}}{c(1 - \theta)\chi_E} \cdot \frac{1}{\gamma_W} \tag{3.21}$$

where

χ_E = equilibrium effective stress factor, which is equal to 1 for saturation;

γ_W = unit weight of water which is independent of pressure if soil is saturated;

θ = volumetric water content, the ratio of specific water volume to total specific volume;

c = a coefficient of compressibility, a negative number.

This equation is used to adjust the value of $\frac{\partial \tau}{\partial \theta}$ computed from the pF vs. water content curves. The value of p is taken as the total overburden and surcharge pressure and is computed from the values of GAM and SRCH read into the computer.

The net effect of the negative sign in Eq 3.21 and the negative value of compressibility coefficient c will be a positive addition to the $\frac{d\tau}{d\theta}$ relationship because the weight of the overburden is considered. That is, the suction will be less negative with an increase in water content when the compressibility effects are taken into account.

For the partially saturated case, Eq 4.106 of Research Report 118-1 is in error. Equation 4.106 reads as Eq 3.22:

$$\left(\frac{\partial \tau}{\partial \theta} \right)_P = \frac{-n}{c\theta \chi_E} \frac{\left[1 + F(\alpha_{FS} - 1) \right]}{\left(1 - n + \frac{V_a}{V_W} \right)} \frac{1}{P_o} \frac{RT_e}{mg} e^{\frac{-\tau mg}{RT_e}} \tag{3.22}$$

This equation should have read as

$$\left(\frac{\partial \tau}{\partial \theta} \right)_P = \frac{-\left[1 + F(\alpha_{FS} - 1) \right]}{c\left(\frac{\theta}{n} \right) \chi_E \left(1 - n + \frac{V_a}{V_W} \right)} \frac{1}{\gamma} \tag{3.23}$$

$$\left(\frac{\partial \tau}{\partial \theta} \right)_P = \frac{-\left[1 + F(\alpha_{FS} - 1) \right]}{c\chi_E (S - \theta + 1 - S)} \frac{1}{\gamma} \tag{3.24}$$

$$\left(\frac{\partial \tau}{\partial \theta} \right)_P = - \frac{1}{c(1 - \theta)\chi_E} \left[1 + F\ (\alpha_{FS} - 1) \right] \frac{1}{\gamma_W} \tag{3.25}$$

where

γ_W = unit weight of water,

α_{FS} = ratio of total volume to water-volume change, and

F = a factor which includes air compressibility and solubility.

The presumption that γ_W depended on the vapor pressure should not have been made, since $1/\gamma_W$ was simply a constant included to convert psi (pressure) into inches of suction. Combining Eqs 3.17 and 3.25 gives an expression for suction change when the compressibility characteristics are known from consolidation tests.

$$\left(\frac{\partial \tau}{\partial \theta} \right)_P = + \frac{\left[1 + F(\alpha_{FS} - 1) \right] p}{0.435 C_c (1 - n)(1 - \theta)\chi_E} \cdot \frac{1}{\gamma_W} \tag{3.26}$$

The expression $F(\alpha_{FS} - 1)$ is derived in Research Report 118-1 to represent the changes in the air volume that occur with changes of suction in a soil that is swelling against the overburden pressure. Figure 9 will aid in the derivations which follow.

When there is a small additional increase in total volume and water volume, the volume of the soil can be pictured as three distinct volumes: volume of soil particles, V_S ; volume of water, V_W ; and volume of air, V_A . An increase in the water volume is accompanied by an increase in the total volume and a decrease in the air volume. The air volume is decreased because the 1:1 slope of the zero air-voids curve is steeper than the total specific volume vs. specific water volume curve. Thus, the change in air volume is air volume 2 minus air volume 1 equals $-\Delta V_W \cdot 1 + \alpha_B(\Delta V_W)$, or under an ambient pressure is the free-swell value reduced by the factor F :

$$\frac{\Delta V_A}{\Delta V_W} = F(\alpha_{FS} - 1) = -1 + \alpha_B \tag{3.27}$$

and

$$1 + F(\alpha_{FS} - 1) = \alpha_B \tag{3.28}$$

The relationship between α_B and α_{po} has been shown in Eq 3.8. In the present report, the α factor is removed from the expression for the suction change expressed by Eqs 3.25 and 3.26 so that

$$\left(\frac{\partial \tau}{\partial \theta} \right)_p = \alpha_{po} dp \tag{3.29}$$

and

$$dp = - \frac{1}{c(1 - \theta)\chi_E \gamma_W} \tag{3.30}$$

or

$$dp = \frac{p}{0.435C_c(1 - n)(1 - \theta)\chi_E} \cdot \frac{1}{\gamma_W} \qquad (3.31)$$

The factor α_{po} is now described more precisely by Eq 3.8 than by the factor α_B used in Research Report 118-1.

Alternate Form of Blight's Compressibility Coefficient. If data from the swell pressure vs. total specific volume curve are provided, Subroutine HEAVY uses these data instead of the slope of the e-log p curve, C_c.

As discussed in Chapter 2 of this report, the p vs. V_T curve is expressed by Eq 2.2

$$p = p_o \left(\frac{V_{TF} - V_{TP}}{V_{TF} - V_{TO}} \right)^m$$

where

p_o = swell pressure of dry soil,

p = swell pressure or, in this case, a pressure calculated as the sum of overburden and surcharge pressures,

V_{TP} = a total specific volume corresponding to p,

V_{TO} = total dry specific volume,

V_{TF} = maximum total specific volume,

m = an exponent (referred to in computer programs GCHPIP7 and SWELL1 as ENP).

Differentiation of this expression leads to the alternate form of Blight's compressibility coefficient:

$$\frac{dV_T}{V_{TP}} = \left[- \frac{(V_{TF} - V_{TP})}{mpV_{TP}} \right] dp \tag{3.32}$$

which gives the form of c .

$$c = - \left(\frac{V_{TF} - V_{TP}}{mpV_{TP}} \right) \tag{3.33}$$

A switch in Subroutine HEAVY is set to use this expression if a value for the exponent m is part of the soil data supplied. The exponent m is expected to be near and slightly above 1.0.

CHAPTER 4. THE ONE-DIMENSIONAL COMPUTER PROGRAM

This chapter describes the differences between the capabilities of the two-dimensional computer program GCHPIP7 and the one-dimensional computer program SWELL1. The latter was developed from the two-dimensional program by extracting two important features, changing another, and adding one more feature. The extractions are:

(1) the computation of suction change in the y-direction and

(2) the alternating-direction implicit iteration procedure at each time step.

The doubly-dimensioned arrays are changed to single-dimensioned. The added feature is a switch to allow the choice of vertical- or horizontal-flow problems.

Familiarity with the contents of Chapter 3 of the present report is essential to an understanding of the discussion presented in this chapter. Input format is discussed in the same order as in the previous chapter, and only the differences are noted.

Problem Identification Cards

Three cards are used for problem and run identification; the first two of these have 80 columns of alphanumeric run information, and the third has five spaces for the problem number and 70 spaces for problem identification. Only two cards are used in computer program GCHPIP7.

Table 1. Program Control Switches

Only six table switches are provided for input. Table 7 in GCHPIP7 is not included in SWELL1. One additional switch is provided, KVERT. This switch allows the choice between vertical flow (KVERT = 1) and horizontal flow (KVERT = 2). The initial conditions read into the computer in Table 4 are not stored. The most recently computed values of suction and moisture content are retained if the keep switch for Table 4 is set to 1.

Table 2. Increment Lengths

This table is substantially different from Table 2 in computer program GCHPIP7. Tables 2B and 2C have been eliminated entirely, and Table 2A has been changed to include a smaller amount of input information. The only information input in the SWELL1 Table 2 includes the number of increments and time steps, the magnitudes of each, and the inside radius if a horizontal cylindrical-flow problem is being worked.

Table 3. Permeability

The one-dimensional problem permits a change of saturated permeability in several different regions along the length being considered. No direction of principal permeability is considered in this program. The constants a , b , and n have the same meaning as in computer program GCHPIP7.

Table 4. Suction-Water Content Curves

The information on Table 4 given in Chapter 3 is identical for SWELL1 with one exception. In SWELL1, Table 4 specifies the linear location of the places where each of the pF vs. water content curves apply.

Table 5. Initial Conditions

Several changes have been made in Table 5. Each card input in Table 5 has a linear distribution scheme for either of two cases: gravimetric water content (Case 1) or suction (Case 2). If the value at the right-hand (or up-station) side of the distribution is smaller than any other, the slope specified should be positive. If no slope is read in, the machine will assume a zero slope and distribute the same value over the entire linear region.

All input values are added algebraically to those already stored at each point. New problems start with zero suction and water-content values at each point along the line.

Table 6. Boundary and Internal Conditions

Boundary and internal conditions that may be specified are as follows:

(1) gravimetric water content,

(2) suction,

(3) suction gradient, and

(4) temperature and humidity of soil water.

The specified quantity is distributed uniformly over the linear region determined by the smallest and largest increment numbers.

In this program, a specified boundary or internal condition replaces any previously stored value. Otherwise, the discussion of Table 6 in Chapter 3 is applicable.

Tables 8 and 9 for SWELL1

The discussions of Tables 8A, 8B, and 9 in Chapter 3 are also applicable for computer program SWELL1. There is no Table 7 for this computer program because Table 7 applies only to two-dimensional problems.

Output. Output before each time step includes the station, suction, water content, $\frac{\partial\tau}{\partial\theta}$, and the unsaturated permeability at each point along the line being considered.

Output after each time step includes the station, suction, water content, and pF .

Computer program SWELL1 is similar to the two-dimensional program in many respects, but the differences in input are such that use of a separate input format, as shown in Appendix 8, may be required.

The flow chart is identical with that of GCHPIP7, except for the fact that computations are made in only one direction and no iteration is required for solution at a particular time step.

CHAPTER 5. EXAMPLE PROBLEMS

This chapter presents example problems worked with both the one-dimensional and the two-dimensional computer programs for predicting swell.

It is not surprising that there is no known set of field and laboratory data sufficient to provide information for Curves 1, 2, and 3 and to give field measurements by which to validate predicted results. Thus, typical soil curves are assumed in this chapter, and swell predictions are compared with field measurements made by personnel of the Natural Resources Research Institute at the University of Wyoming under the direction of Professor Donald R. Lamb (Ref 4). Details of the field test are given in Chapter 6 of Research Report 118-3, but some of the salient points will be repeated here.

Over a period of 80 days, measurements of vertical swell and moisture content were made on a 40-foot-square area of expansive clay. Water was supplied on a 4-foot grid by pipes fed by 55-gallon drums. Elevations were measured on set plates with a level, and moisture contents were determined using nuclear-moisture-density depth probes and access tubes. Both the elevation plates and the access tubes were placed on 8-foot grids. Moisture from the atmosphere was sealed out by a polyethylene membrane. The soil at the site has a liquid limit of 61 percent and a plastic limit of 26.

Swell-pressure and free-swell tests were made on compacted samples of the soil. No maximum swell pressure was reported although pressures of 1500 psf (10.4 psi) were developed within ten hours after the start of the test; in no case did the pressure seem to be approaching a limit. Volume changes of 6 percent occurred within ten hours when the soil swelled from a moisture condition slightly above the natural soil water content. No natural densities were reported. A standard AASHO optimum moisture content of 23.5 percent and a maximum dry density of 99 lb/cu ft were determined, however. This dry density corresponds to a total specific volume of (62.4/99) = 0.63 cm^3/gm dry soil.

Determination of Assumed Soil Curves

The first essential soil curve is the suction vs. moisture relationship and the second is the permeability vs. suction relationship. Both of these curves have been treated extensively in Chapter 6 of Research Report 118-3. The data determined for the West Laramie clay in that report and assumed for the present report are given in the following table.

TABLE 1. ASSUMED SOIL DATA FOR WEST LARAMIE CLAY

Factor	Value
Final saturated water content, percent	40.0
Maximum pF	6.5
Inflection pF	3.0
Suction vs. moisture curve exponent	3.0
Saturated permeability, in./sec	1.0×10^{-6}
Unsaturated factor b	1.0×10^{9}
Unsaturated exponent n	3.0

With this information given, it is possible to compute an inflection-point water content of around 21.5 percent, which is lower than the plastic limit and the reported optimum moisture content. The complete suction-moisture curve is shown in Fig 10.

The data given in Table 1 above are used in all example problems, with some minor variations for the purpose of accuracy in the numerical results of the two-dimensional problem. There are two reasons for varying these data slightly in the two-dimensional problem.

(1) Initial conditions are not described accurately in the idealized soil medium used in the computer. An approximation of the inaccuracy of initial conditions is shown in Fig 11, which compares initial field measurements with computer input data.

(2) Too high a permeability is assumed. In such a case, computed suction becomes positive, and the computer treats the soil as completely saturated. The difficulty is avoided by decreasing the magnitude of maximum permeability by 5 or 10 percent in many cases.

In the remainder of this section, the assumed values which determine Curves 1, 2, and 3, are discussed.

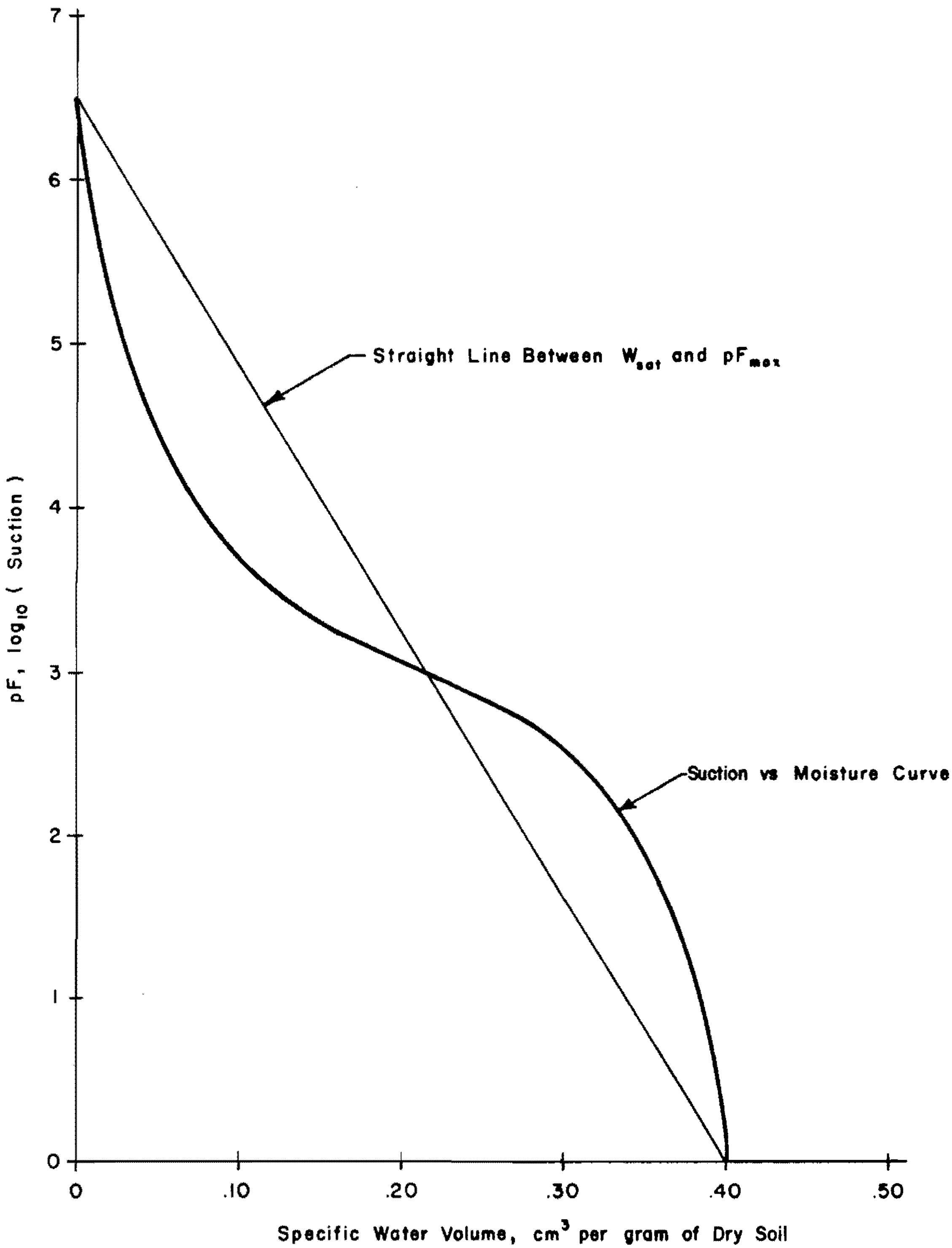


Fig 10. Suction vs. moisture curve used in swell prediction problems.

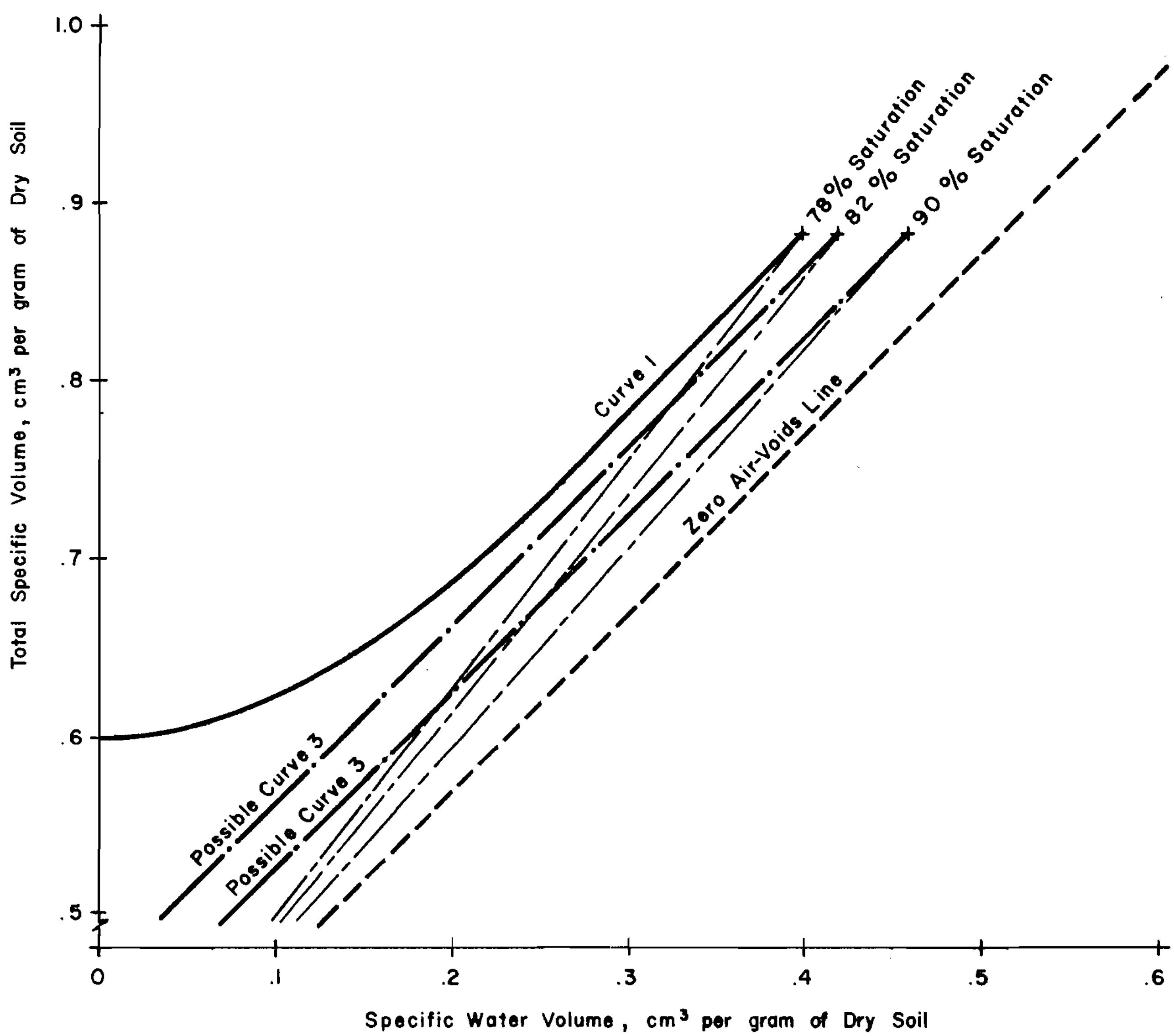


Fig 11. Assumed V_T vs. V_W curve for West Laramie clay.

<u>Assumed Curve 1</u>. Three points are used to determine this curve: zero water content, air entry, and maximum total specific volume. The general shape of the curve is taken from Lauritzen's data (Ref 5) for natural Houston Black Clay given in Chapter 2 of the present report. The assumed curve is shown in Fig 11.

At zero water content, a total specific volume of 0.60 is assumed. The initial slope of the total specific volume vs. specific water volume curve is assumed to be zero.

At air entry, the reported value of optimum moisture content seems to fall within the same range as the air-entry moisture content for Houston Black Clay. The unsaturated V_T vs. V_W curve to that point is assumed to be parabolic, with an exponent of 2.0. Given the above information, it is possible to calculate from Eq 2.1 the total specific volume at air entry:

$$V_{TA} = V_{TO} + \alpha_o V_{WA} + \frac{(1 - \alpha_o)}{Q} \left(\frac{V_{WA}}{V_{WA}} \right)^Q V_{WA} \tag{5.1}$$

Since

$$\alpha_o = 0.0$$

Eq 5.1 becomes

$$V_{TA} = V_{TO} + \frac{V_{WA}}{Q} \tag{5.2}$$

$$= 0.60 + \frac{.235}{2.0} \tag{5.3}$$

$$= 0.7175 \text{ cm}^3/\text{g} \tag{5.4}$$

The print for maximum total specific volume is established in just as simple a manner. The final saturation water content from Table 1 is 40.0 percent. Because Curve 1 has a slope of 1:1 in the effectively saturated part, the final total specific volume is given as

$$V_{TF} = V_{TA} + (V_{WS} - V_{WA}) \quad (5.5)$$

$$= 0.7175 + (0.40 - .235) \quad (5.6)$$

$$= 0.8825 \text{ cm}^3/\text{g} \quad (5.7)$$

The soil becomes progressively more saturated along Curve 1 from the air entry point to the point of final saturation. The degree of saturation at each end point is computed below:

	Air Entry	Final
Specific volume of voids $(V_T - V_S)$	.3475	.5125
Specific water volume	.235	.40
Degree of saturation, fraction	$\frac{.235}{.3475}$	$\frac{.40}{.5125}$
Degree of saturation, percent	67.6	78.0

The lines of equal saturation shown in Fig 11 illustrate the manner in which saturation changes along either Curve 1 or Curve 3.

Assumed Curve 3. Only one point needs to be specified for Curve 3, which is given by the intersection of the maximum total specific volume and the maximum specific water volume. Because there is little experimental data to indicate the degree of saturation at the maximum specific water volume, two values are tried. The results of each are shown as results of the example problems. Final degrees of saturation of 82 and 90 percent are chosen arbitrarily, these correspond to the 42 and 46 percent water contents shown in Fig 11.

Assumed Curve 2. The following two questions about curves, the swell pressure vs. total specific volume curve, remain to be resolved by experiment:

(1) What is its maximum swell pressure?

(2) What is the shape of the curve?

Neither of these questions were answered in the data reported by the University of Wyoming because the primary emphasis in that study was on measuring swell and pressure that had been reduced by the addition of stabilizing agents.

Because the swell pressure vs. total specific volume curve is unknown in this case, the following procedure is adopted. Two probable but disparate values of swell pressure, 40 and 90 psi, are assumed and several problem solutions are attempted with different exponents for the swell pressure curve. The problem results are then compared with measured field results. An exponent of 10 to 20 gives all negative volume change. An exponent less than 1.0 gives too great a volume change. Because experimental data discussed in Chapter 4 of Research Report 118-1 indicate an increasingly higher swell pressure with decreasing total specific volume, the exponent is assumed to be greater than 1.0.

As an additional check, McDowell's (Ref 8) curves of percentage of volumetric swell versus pressure are used. The curves of the present report use total volume rather than percentage of swell; thus, McDowell's curves are not strictly applicable to this discussion, except under the following conditions:

(1) All free swell is assumed to arrive at the same final total specific volume.

(2) Each of McDowell's family curves, rated by percentage of free swell (e.g., 5 percent, 10 percent, etc.), can be developed in the same soil by changing the initial water content. The higher percentage of free swell would, of course, come from the drier soil.

(3) Zero volume-change swell pressures for each family curve may be found at the intersection of that curve with the zero-percent swell axis.

Table 2 shows the calculations required to arrive at the continuous curve shown in Fig 12.

The top part of the curve in Fig 12 shows a slight concavity; this indicates a p vs. V_T curve exponent slightly greater than 1.0. An exponent of 1.2 was chosen arbitrarily and is used throughout the example problems.

One-Dimensional Swell Prediction

The location chosen for the tests of the one-dimensional swell prediction program was nuclear-moisture-density access tube No. 11 of the West Laramie,

TABLE 2. CALCULATION OF AN APPROXIMATE SWELL PRESSURE VS. TOTAL SPECIFIC VOLUME CURVE

Percentage Of Free Swell	$\frac{\text{Final Vol.}}{\text{Initial Vol.}}$, f	Relative Total Specific Volume, 1/f	Total Specific Volume	Zero Volume-Change Swell Pressure, psi
0	1.00	1.000	.8825	0
5	1.05	.952	.840	9
10	1.10	.909	.802	21
15	1.15	.870	.767	31
20	1.20	.833	.735	43
25	1.25	.800	.706	52
30	1.30	.770	.679	62
35	1.35	.742	.653	--

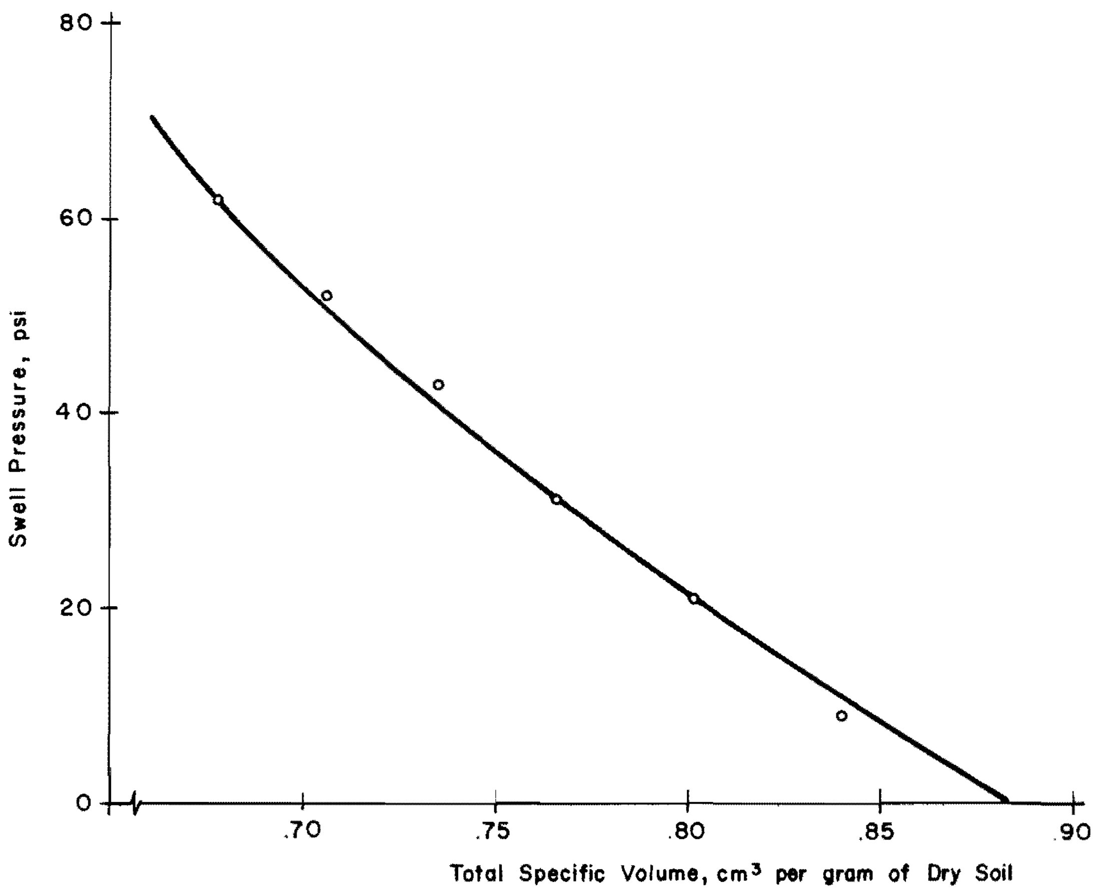


Fig 12. An approximate p vs. V_T curve based on McDowell's p vs. $\%\Delta V$ relationships (Ref 8).

Wyoming, test site. Layout and description of the test site are given in Chapter 6 of Research Report 118-3 and will not be repeated here, except for the vicinity of the location at which swell is to be predicted.

Figure 13 shows the access tube chosen for the one-dimensional study and its relation to water supply points and elevation plates.

As mentioned above, uncertainty about the location of Curve 3 and about the maximum swell pressure suggested a series of four problems from the combinations of two swelling pressures, 40 and 90 psi, and two locations of maximum water content, 42 and 46 percent.

The average of the total swell measured at elevation plates Nos. 4, 6, 7, and 9 is compared with that predicted by each of the four combinations of swell pressure and maximum water content in Table 3.

On the basis of these results, it was judged that the combination of 40 psi swelling pressure and 46 percent maximum water content gives the best results. Consequently, these results are presented in more detail in Table 4.

Several pertinent facts should be mentioned at this point.

(1) The initial and final moisture conditions are those described in Chapter 6 of Research Report 118-3. Initial values were taken from the measured field data, and the predicted final values are within 0.1 percent over the entire 13.5-foot depth considered in this problem.

(2) The total swell occurred in the immediate vicinity of the water supply. In this case, all swell occurred in the upper two feet of clay.

(3) Because swell takes place in the upper few feet, the difference in swelling pressures is not significant in the predicted results.

(4) Although all three soil curves had to be assumed, the predicted results are considered excellent.

Example Problem: Two-Dimensional Swell

The problem of predicting two-dimensional swelling is two steps more complicated than that of predicting one-dimensional swell. The complications arise in establishing

(1) initial conditions that roughly approximate the actual initial conditions of the soil and

(2) proper boundary conditions along each side of an area.

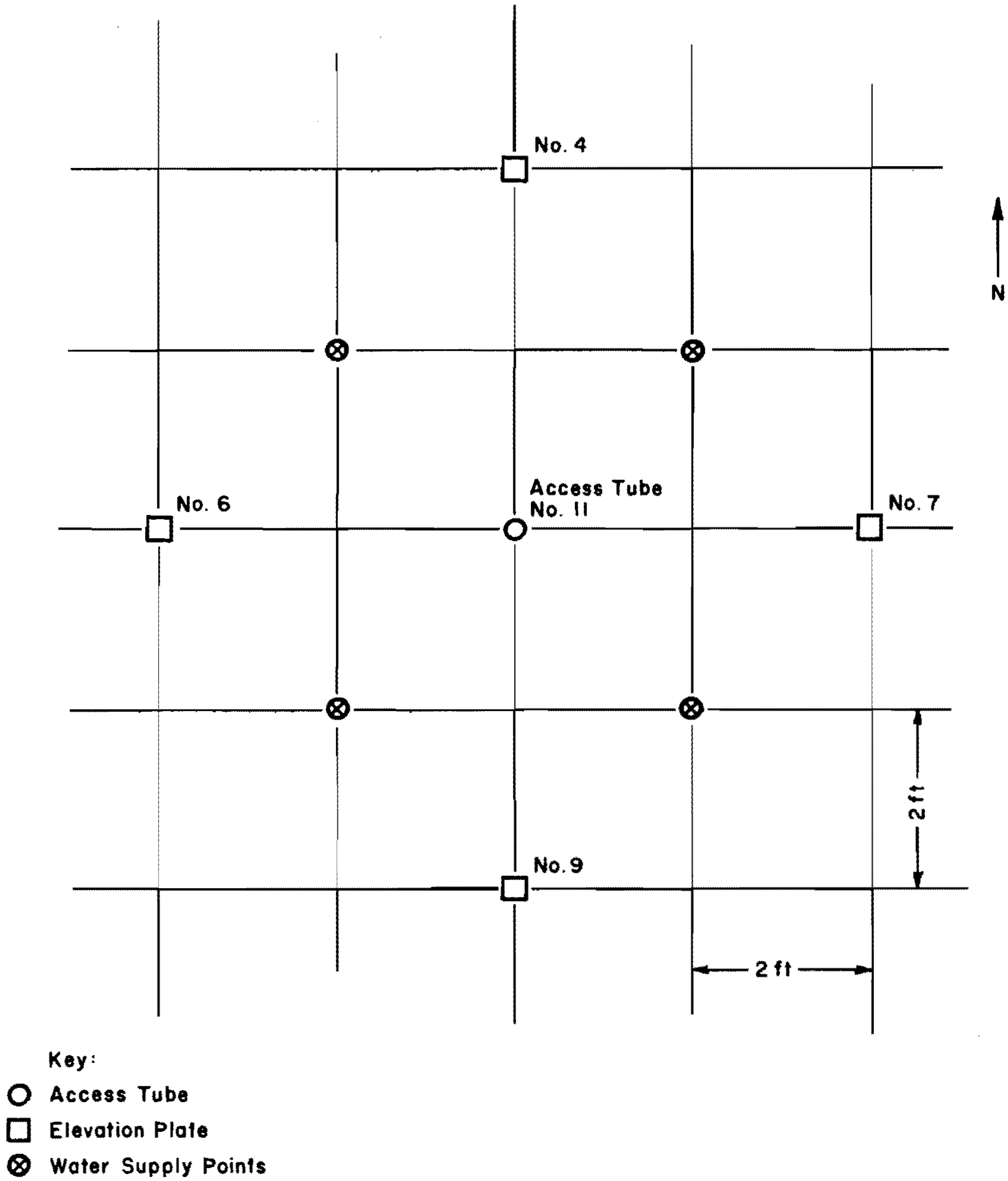


Fig 13. Layout of field test apparatus in vicinity of access tube No. 11.

TABLE 3. COMPARISON OF MEASURED AND PREDICTED TOTAL SWELL

Time After Start of Field Test, days	Average Swell, feet	Computed Simulated Time, days	Predicted Swell (ft) at			
			40 psi		90 psi	
			V_{WF} = 42%	V_{WF} = 46%	V_{WF} = 42%	V_{WF} = 46%
0	0.00	0	0.000	0.000	0.000	0.000
21	0.07	24	0.102	0.076	0.101	0.076
51	0.11	56	0.129	0.097	0.128	0.096
80	0.12	80	0.147	0.111	0.146	0.110

TABLE 4. COMPUTER PREDICTION OF SWELL

Distance from Top of Soil, ft	Predicted Total Swell After Days Indicated, inches			
	8	24	56	80
0.0	0.79	0.91	1.16	1.33
0.5	0.11	0.24	0.49	0.65
1.0	0.00	0.03	0.15	0.25
1.5	--	0.00	0.03	0.08
2.0	--	--	0.00	0.01
2.5	--	--	--	0.00
3.0	--	--	--	--
13.5	--	--	--	--

Initial Conditions. The difficulty in establishing an appropriate set of initial conditions is illustrated in Figs 14 and 15. In Fig 14, moisture conditions are known (or measured) only in vertical columns 6 and 8 feet apart, and moisture contours are drawn to show a possible initial distribution of moisture. Figure 15 shows the initial moisture data as supplied to computer program GCHPIP7. These input data require the use of 21 cards. Instead of using these data cards, it would be possible to interpolate values at each grid point from the moisture contours shown in Fig 14. This latter procedure would require 720 input cards; this effort is deemed speculative, in view of the wide spacing between columns where moisture conditions are presumably known. The same problem will face anyone attempting to predict two-dimensional swell. The initial conditions are important; the final results depend on them. The inaccuracies noted in the two-dimensional solution presented in this report may be explained largely in terms of inaccurate initial conditions.

There is one distinct difference between the actual and simulated initial moisture conditions. In the simulated moisture regime, a constant moisture content of 13.7 percent below a depth of 3 feet is assumed. This arbitrary value, while not far from the measured water content, is not considered important in the prediction of volume change because most of the swell is expected to occur in the upper 2 feet. The only consideration in establishing the value of this constant moisture content is to ensure that the soil will not draw water out of the upper few feet and thus limit swell.

Boundary Conditions. Five separate boundary conditions had to be determined before this two-dimensional swell problem could be worked. These boundaries were

(1) at the top in the wetted area;
(2) at the top in the area not subjected to wetting;
(3) on the right side, 18 feet away from the closest water supply;
(4) on the bottom, 10 feet from the wetted surface; and
(5) on the left side along the vertical column occupied by access tube No. 11.

At the outset, it was decided that the wetted area would be all of the ground surface within 2 feet of water line. Thus, there were no discrete points of water supply. Instead, it was assumed that the entire surface between access tube No. 11 and 2 feet beyond the outside water line would be completely wet at the start of the test.

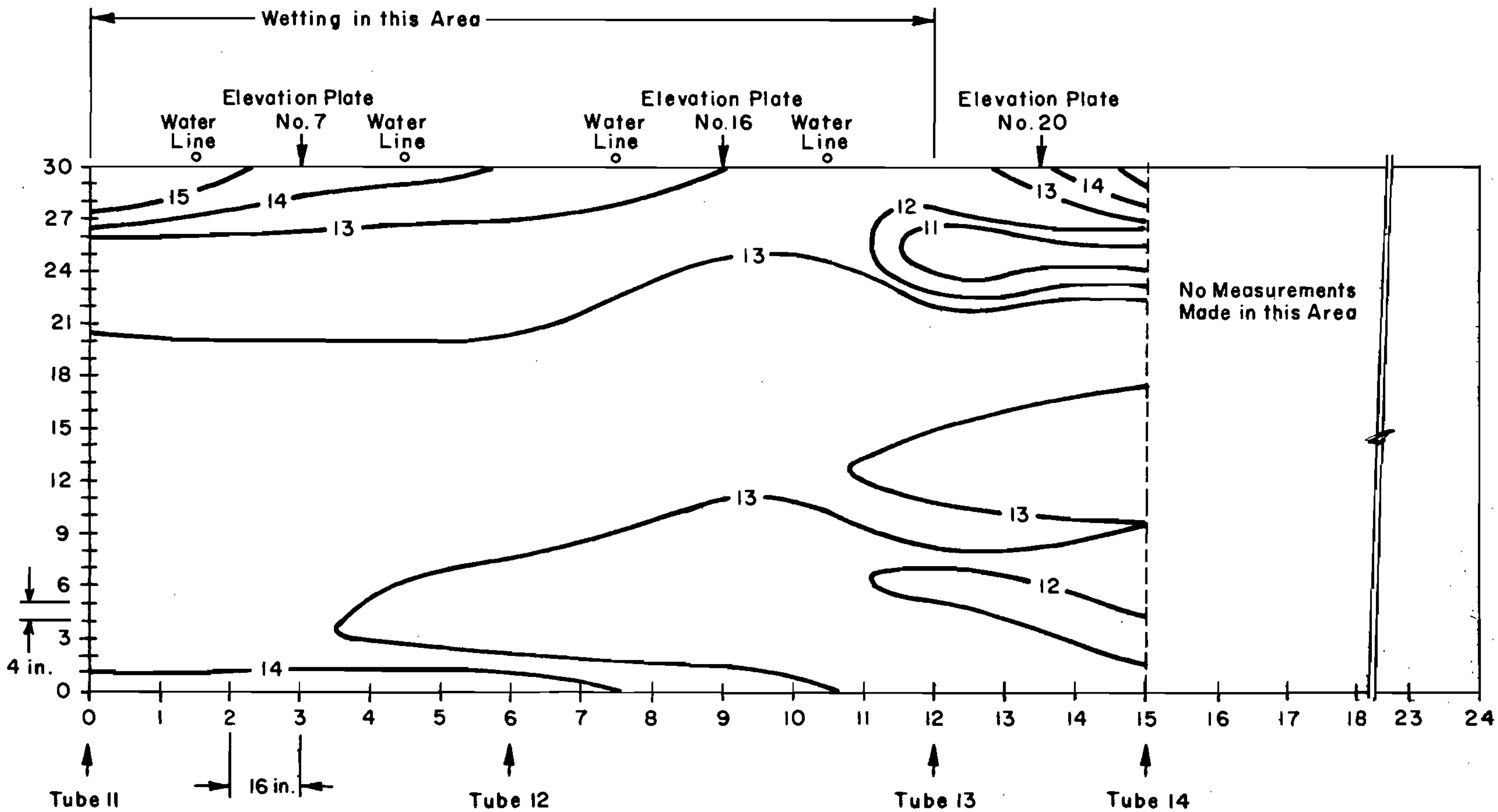


Fig 14. Initial moisture conditions at West Laramie test site.

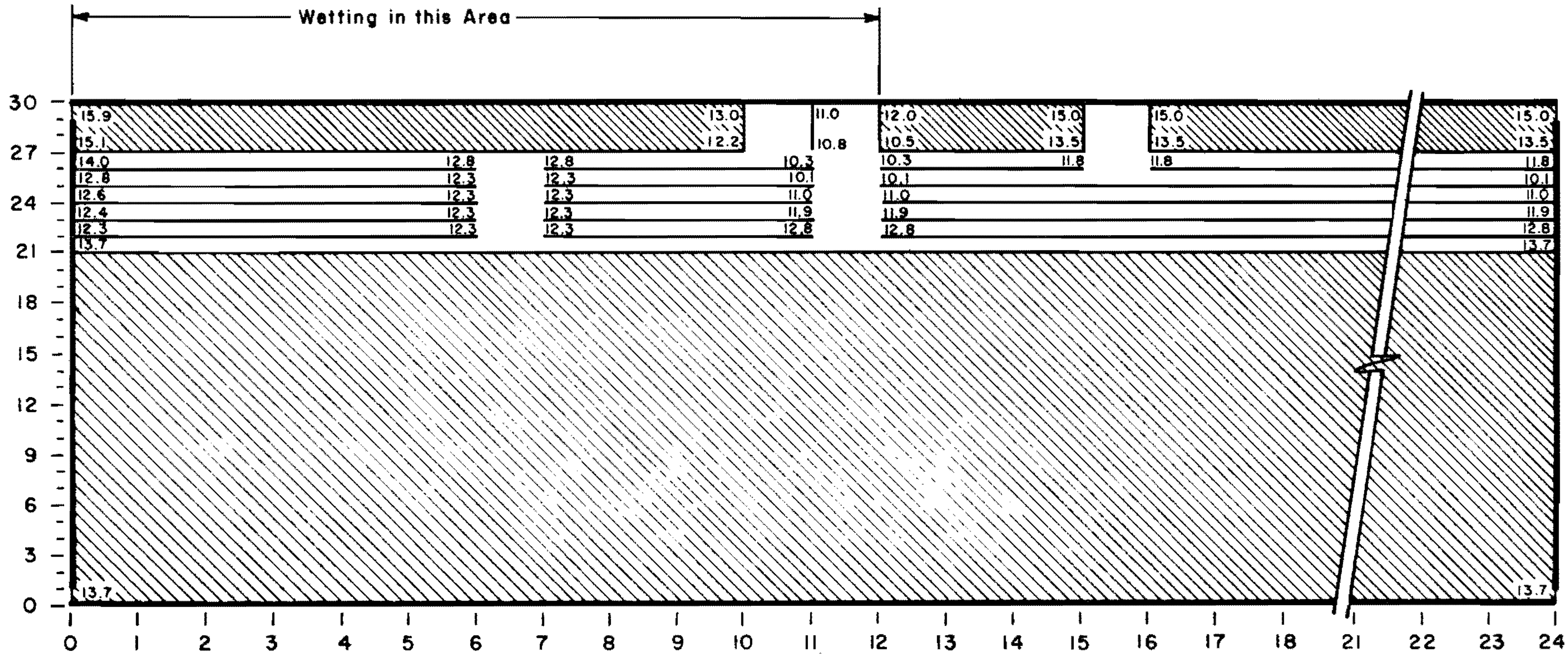


Fig 15. Initial moisture conditions at West Laramie test site as used in a computer simulation of the problem.

The ground surface area beyond the wetted portion was assumed to remain at its initial moisture condition. Thus, any swell noticed outside the wetted area would be due to horizontal transfer of water under the ground surface.

The right side boundary was set sufficiently far away from the water source to be considered safe to assume that water content would not change during the test.

The bottom boundary was set at 10 feet below the ground surface, because the experimental data indicated that virtually no moisture change would occur below about 3 feet, and the bottom boundary condition was assumed to be zero water-content change during the course of the test.

The boundary conditions at the left side changed with time. These conditions were known at certain intervals of time because of the nuclear moisture-density readings made. The water content at each discrete time step was also determined by the one-dimensional computer program. As noted in Research Report 118-3, the computer-predicted moisture contents matched the measured moisture contents very closely at all times when comparisons could be made. Because it is desirable to have the boundary conditions change with time as closely matched with natural changes as possible, computer-predicted moisture contents were used for all time steps. New boundary conditions were read into the computer 8, 16, 40, 48, 64, and 72 days after the beginning of the test. Field-measured moisture data were available only for 51 and 80 days after the beginning of the test.

Soil Properties. With two exceptions, the soil properties used in this problem are identical with those used in the one-dimentional swell prediction example problems. The two exceptions are the values of saturated permeability and the shape of the suction vs. moisture curve. Comparison of the values used in the one-dimensional and two-dimensional problems is given in Table 5.

The reason for the change is evident from Fig 14, which shows the initial distribution of moisture. There is a very dry lens of soil about 1 foot below the surface between Stations 11 and 15. The one-dimensional suction vs. moisture curve would require that the suction in the dry area be -1581 inches, whereas, in the 13 percent moisture content soil just 4 to 8 inches away, the suction is -1024 inches. This difference gives a high suction gradient, and the difference of gradients is used to calculate the change in suction from

TABLE 5. COMPARISON OF SOIL PARAMETERS USED IN EXAMPLE PROBLEMS

Parameter	One-Dimensional	Two-Dimensional
Saturated permeability, in/sec	1.0×10^{-6}	0.5×10^{-6}
Maximum pF	6.5	5.0
Inflection pF	3.0	3.0
Suction vs. moisture curve exponent	3.0	4.0

one time step to the next. In these high ranges of suction, inaccuracies in computing the proper value of suction curvature can easily occur. This inaccuracy is termed truncation.

Truncation in the numerical process is discussed in Chapter 6 of Research Report 118-3. Truncation is important to this study because it can be the direct cause of unreasonable results, such as positive suction values, which are considered impossible in the example problems of the present report.

There are two ways of dealing with the problem of suction-gradient truncation.

(1) Reduction of the permeability. Sometimes only a small reduction is required, although in this problem a reduction of saturated permeability from 1 X 10^{-6} in/sec to 0.9 X 10^{-6} in/sec did not correct the problem.

(2) Reduction of the slope of the suction vs. moisture curve in the vicinity of the inflection point. Changing the exponent from 3.0 to 4.0 was the only action required in this case.

The suction vs. moisture curve used in the two-dimensional problem is shown as Curve b in Fig 16 and Curve a is the suction vs. moisture relationship used in the one-dimensional problems. Along Curve b, the dry soil has a suction of -590 inches, and the 13 percent moisture content soil has a suction of -475 inches. The difference of 115 inches, as opposed to the difference of 557 inches obtained in the earlier problem, illustrates the source of the truncation problem.

To reduce further the size of suction gradients used in computations, the suction at the wetted ground surface was set at -20 inches, which corresponds to a moisture content of 38.6 percent.

Results of Computation. The results of the two-dimensional computations are given in Tables 6 and 7 and Fig 17. The tables compare predicted and measured final moisture contents and changes in moisture content. Figure 17 compares the predicted ground surface profile with changes of elevation measured at points along the profile.

As shown in Table 6, the final moisture contents predicted by the computer are lower than the field-measured values at all points 8 inches or more below the ground surface. The predicted changes in moisture content are lower than those measured in the field; this point is illustrated in Table 7.

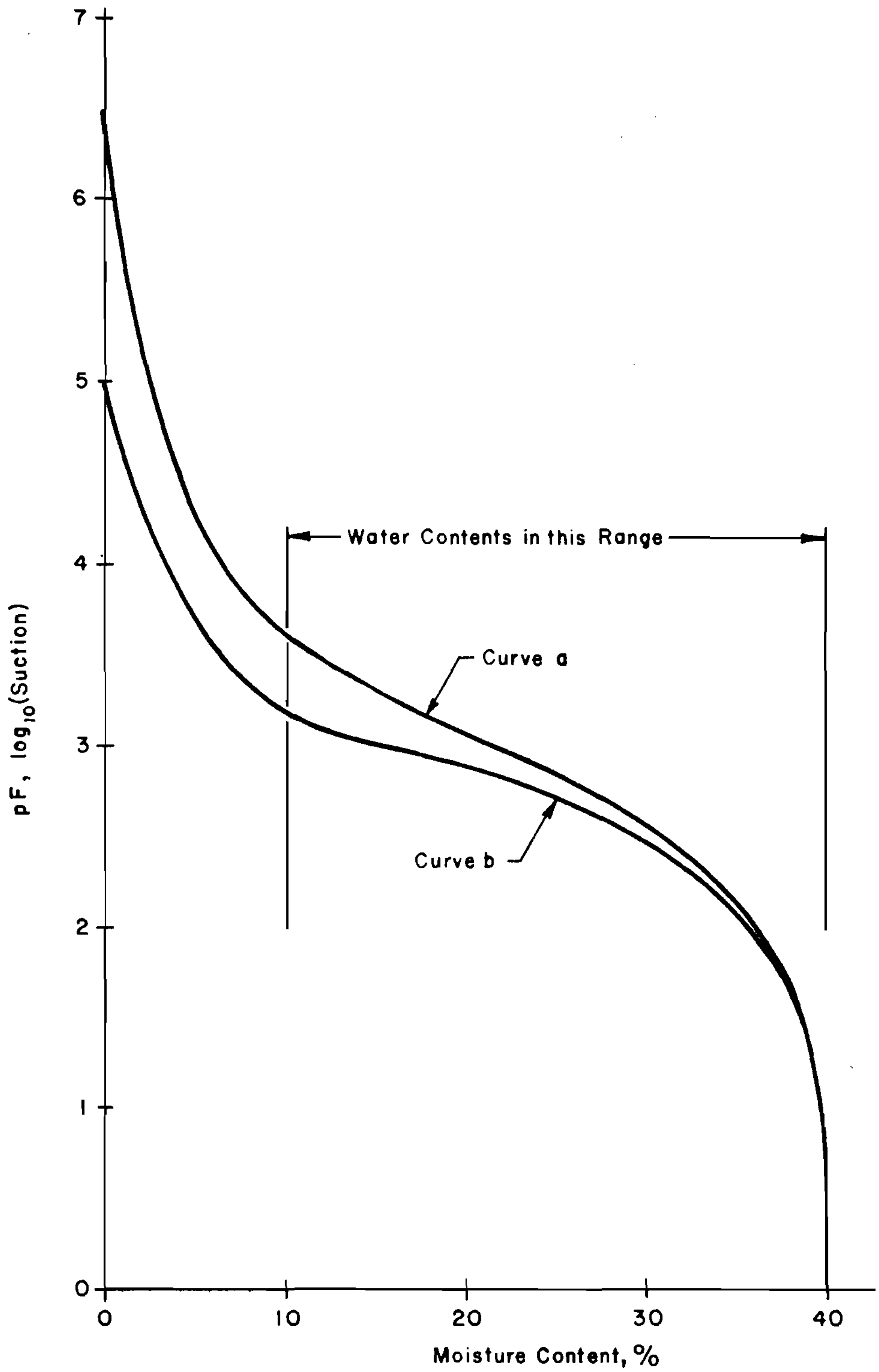


Fig 16. Comparison of suction vs. moisture curves used in one-dimensional (Curve a) and two-dimensional (Curve b) swelling prediction problems.

TABLE 6. COMPARISON OF FINAL MOISTURE CONTENTS

	Tube No. 11		Tube No. 12		Tube No. 13		Tube No. 14	
Depth, ft	Field Measurements	Computer Prediction (Station 0)	Field Measurements	Computer Prediction (Station 6)	Field Measurements	Computer Prediction (Station 12)	Field Measurements	Computer Prediction (Station 15)
0.00	--	38.6	--	38.6	--	38.6	--	15.0
0.67	28.6	27.1	28.3	22.5	26.0	21.2	23.5	13.6
1.67	20.7	17.3	21.6	13.2	18.1	11.6	10.1	11.8
2.67	12.6	13.2	19.3	12.9	12.9	12.4	13.1	12.4
3.67	14.0	n.c.*	13.8	n.c.	13.4	13.5	13.5	13.5
4.67	13.8	n.c.	13.8	n.c.	12.6	n.c.	13.1	n.c.
5.67	13.8	n.c.	13.3	n.c.	12.4	n.c.	12.4	n.c.
7.00	13.2	n.c.	13.0	n.c.	13.0	n.c.	12.8	n.c.
8.00	13.8	n.c.	12.4	n.c.	11.8	n.c.	12.0	n.c.
9.00	13.0	n.c.	12.8	n.c.	12.4	n.c.	11.6	n.c.
10.00	14.3	n.c.	14.9	n.c.	11.7	n.c.	12.6	n.c.

* n.c. = no change

TABLE 7. COMPARISON OF CHANGES IN MOISTURE CONTENT

Depth, ft	Tube No. 11		Tube No. 12		Tube No. 13		Tube No. 14	
	Field Measurements	Computer Prediction (Station 0)	Field Measurements	Computer Prediction (Station 6)	Field Measurements	Computer Prediction (Station 12)	Field Measurements	Computer Prediction (Station 15)
0.00	--	25.6	--	25.6	--	26.6	--	0.0
0.67	13.3	14.1	14.4	9.5	13.9	10.2	8.5	-0.4
1.67	7.9	5.5	9.3	0.9	7.7	1.5	n.c.	1.7
2.67	0.3	0.9	7.0	0.6	-0.3	-0.4	n.c.	-0.4
3.67	n.c.*	n.c.	n.c.	n.c.	-0.5	-0.2	n.c.	-0.2
4.67	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
5.67	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
7.00	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
8.00	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
9.00	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
10.00	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.

* n.c. = no change

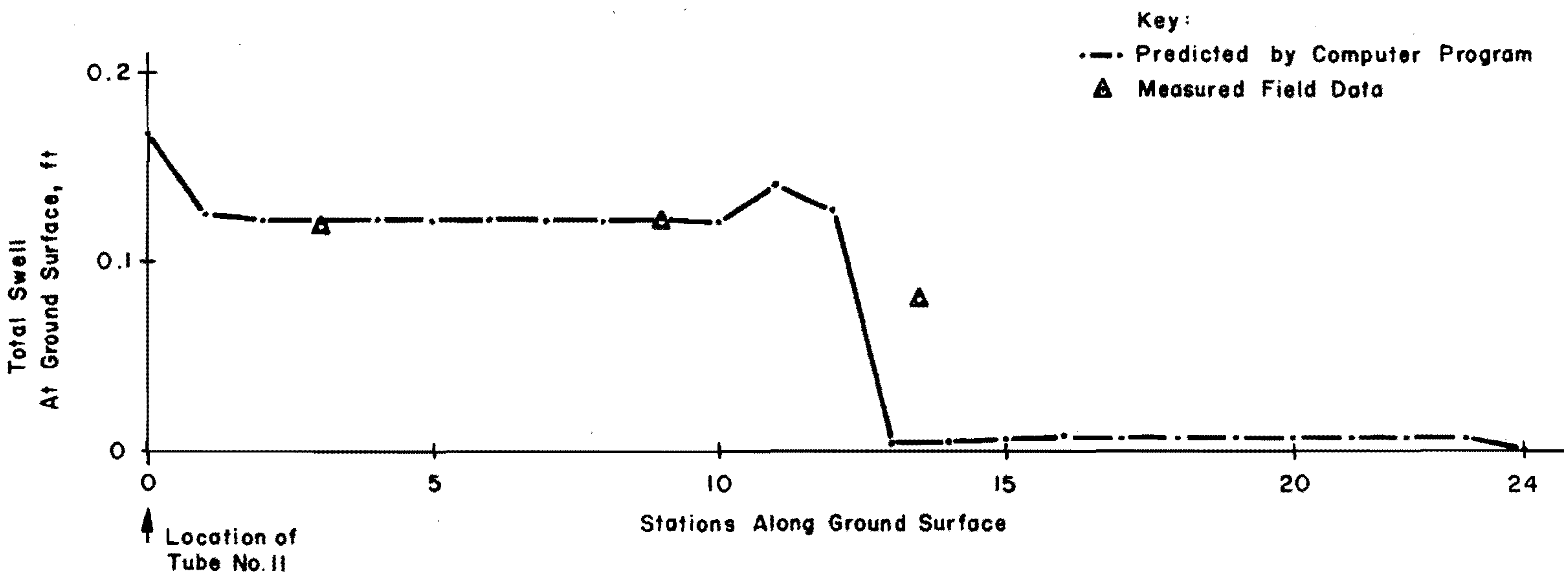


Fig 17. Comparison of predicted and field-measured swell after 80 days.

However, in the field test, moisture content was not measured at the ground surface. Consequently, it is conceivable that the moisture contents and changes of moisture content were predicted too high. Also, the nuclear moisture-density method of measuring moisture content gives a reading based on conditions within a spherical volume within its zone of influence, and the computer-predicted value is taken from a single point. Thus the moisture contents obtained by these two methods would be expected to be somewhat different in a region of high moisture gradient.

The computer prediction of the swell profile gives results which, in the light of the many assumptions made, are much closer to those measured than would reasonably be expected. The tables of moisture distribution and moisture change indicate that the major portion of the swell originates from the upper 2 feet of soil and that a large portion of the swelling is in the upper 8 inches, a condition which is somewhat different than would be expected from the field measurements. The total measured swell in the wetted area averaged 0.12 feet, and the predicted swell was 0.122 feet in the same area. The additional swell in the vicinity of station 12 occurred because of the wetting of the unusually dry soil lens in that area.

Between stations 13 and 14, where supposedly no wetting occurred, a swell of 0.08 feet was measured, compared with an average of 0.004 inches predicted by the computer. There are two reasons for this discrepancy:

(1) Some wetting must have occurred outside of the wetted area in order for field-measured soil moisture at 8 inches below the ground surface to increase 8.5 percent over the period of the test. This unknown source of wetting was not considered in the example problem.

(2) Shear strength of the soil is not considered in the simple volume change technique used in this report. If one vertical column of soil rises relative to another, the shear stresses and strains that develop between them are not considered. If the shear stiffness of the soil had been considered, the swell would gradually reduce to its lower value outside the wetted area.

Actually, the second effect may not be of major importance, although its magnitude may be significant. At present, it is judged that if moisture conditions can be predicted properly, the predicted swell profile will be reasonably close to the swell that actually occurs. This question is not considered settled, however. Certainly, the results of the continuum theory developed in Research Report 118-2 indicate that the moisture diffusion problem can be worked separately from the swelling problem only in one-dimensional problems. Also, as discussed in Chapter 3 of the present report, provision is made for reading the equivalent stress release $(\gamma\chi\Delta\tau)$ onto tape in the two-dimensional computer program for use in a finite-element elasticity computer program designed to study the way changes in suction and moisture affect a continuum.

The example problems presented in the present chapter are the results of computer prediction of a time-dependent process of moisture diffusion and prediction of swelling. The overall results match field measurements very well. Certain discrepancies were expected and occurred, but were surprisingly small in their effects on the overall results.

CHAPTER 6. CONCLUSIONS

This report presents three important developments which have been treated separately as the subjects of Chapters 2, 3, and 4. The entire report is concerned with using a computer-predicted change of moisture content to calculate the consequent change of soil volume. Chapter 2 presents a way of using the relationships among pressure, water volume, and total volume to compute a soil-volume change. Chapter 3 gives a detailed description of the input and output capabilities of the two-dimensional computer program GCHPIP7. Chapter 4 describes the ways in which input and output of the one-dimensional computer program SWELL1 are different.

The example problems presented in Chapter 5 indicate the accuracy that can be achieved with the method of prediction used in this report and also point up its limitations which, on the basis of the results, do not appear to be serious.

This method of predicting total swell is termed "simple volume change" because it does not consider elasticity-type boundary conditions of lateral restraint, except indirectly by use of a factor which specifies how much of the total volume change is directed upward. Shearing strain is not considered in transferring movement from one vertical soil column to another or in distorting the shape of individual elements of a soil medium. There are three reasons for using the "simple volume change" concept:

(1) Most long-term experimental data available to engineers are for tests of the soil in one dimension only. These tests can measure only total change of volume and can give no indication of the long-term shear "modulus" of the soil.

(2) The results of the simple volume change procedure indicate that very accurate predictions can be achieved without consideration of the soil as a continuum. The simplicity of the technique and of the required input data combined with the demonstrated accuracy recommend the approach for practical use.

(3) In Research Report 118-2, it was shown theoretically that the total heave can be computed directly in one-dimensional problems when the moisture distribution is known. Extension of this idea to two dimensions is theoretically invalid, but in view of the

possibly low value of the long-term shear-modulus function, the assumption that two-dimensional moisture distribution determines two-dimensional swell may approximate reality well enough to permit consistently good predicted values of swell profile.

The simple volume change method uses the following three curves in establishing the swell curve of a soil under any pressure:

(1) Curve 1, the natural soil V_T vs. V_W curve, which is similar to the free-swell curve;

(2) Curve 2, the swell pressure vs. total specific volume curve; and

(3) Curve 3, the final V_T vs. V_W curve corresponding to a state of saturation that is less than 100 percent.

These three curves are used with the initial moisture condition of the soil and the pressure acting on the soil to determine Points 1 and 2, the end points of the soil-swell curve along which change of volume and water content are assumed to occur. Moisture diffusion computations give a predicted change of moisture content from which a change of volume can be predicted.

The computer programs of this report are analytical tools with broad ranges of capabilities for studying problems in swelling clays. On the one hand, the soil properties required as inputs are largely unknown for many soils at the time of this writing thus indicating a need for experimental determination of these simple properties. On the other hand, the computer can now be used to study the effect of change of soil properties on the accuracy of prediction. These computer studies will be valuable as indications of the range of precision required of instruments to measure these soil properties. Parameter studies of a sort were reported in Chapter 6 of Research Report 118-3 and in Chapter 5 of the present report, in which the saturated permeability used in the one-dimensional problems was cut in half in the two-dimensional problem, and a significant change in the suction vs. moisture curve was made. In spite of these changes, the predicted total heave differed by approximately 8 percent.

Thus, although it would be satisfying from a theoretical standpoint to describe the suction vs. moisture relationship and the permeability vs. suction relationship precisely, it may neither be possible nor necessary from a practical standpoint.

Changes of soil properties which can and, in many cases, should be studied include the effects of ponding and chemical treatment on the probable swell of the soil. Study of these properties can be made with confidence with the computer programs of this report, which are founded on a sound theoretical basis and which are sufficiently general to permit the solution of a broad range of problems associated with the movement of water through a porous material.

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APPENDIX 1

GLOSSARY OF COMPUTER NOMENCLATURE

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FORTRAN Term	Description
A(,)	Coefficient of suction at point T(I,J-1) . A(,), B(,), CX(,), CY(,), D(,), E(,), and F(,) are coefficients of the finite-difference equation representing change of suction with time.
AA( )	Continuity coefficient for constant A . In the linear equation $$T_i = A_i + B_i T_{i+1}$$ A_i and B_i (AA and BB , respectively) are continuity (recursion) coefficients and the denominator used to solve these coefficients is CC . See BB( ) and CC( ).
AK( )	Unsaturated permeability coefficient a in Eq 3.1: $$k_{unsat} = \frac{k_{sat}}{1 + \frac{a\tau^n}{b}} = k_{sat}\left(\frac{b}{b + a\tau^n}\right)$$ Equal to either ±2.54 centimeters per inch or 1 inch per inch. AK and BK are stored values of constants a and b , respectively. Their values can be changed by inputting constant values AK1 and BK1 , respectively, in Table 3 to add to values already stored. AK and BK are made zero at the beginning of each problem.

FORTRAN Term	Description
AK1	See AK( ) .
AL( )	Tube-flow matrix coefficient of TX or TY at I-1 . AL( ) , BL( ) , and CL( ) are coefficients for a one-pass, alternate-direction implicit method of solution for the finite-difference equation.
ALF	Input in Table 3 to set ALFA( ) or to change the value of ALFA( ) . Units in degrees.
ALFA( )	Angle between principal permeability P1 and the x-direction. Units in degrees. This angle is set or changed by adding ALF to the previous value of ALFA( ) .
ALFB	Secant of total specific volume versus specific water volume curve beginning at the initial water content. Used in Subroutine HEAVY and calculated in Subroutine GULCH as the ratio of the amount of swell DELV to the change in water content DELW . A vector describing swell under constant overburden pressure as water content is increased. Where water content decreases, ALFB = 1 .
ALFO( )	Value of ALF at specific water volume of zero. Input in Table 4A. Used in main program and Subroutine GULCH.
ALFP	Rate of change in suction with change in overburden pressure at some time after the initial change in water content. Used in Subroutines SUCTION, DSUCT, and HEAVY. Termed α_{po} in Research Report 118-1.
AN1	Alphanumeric identifiers on first two cards.
AN2	Alphanumeric identifiers on problem card.

FORTRAN Term	Description
AT	Percent of saturation based on gravimetric water contents. Used in Subroutines SUCTION and DSUCT.
AT(,)	The equivalent stress release $$\chi P_{sat}\left(e^{\frac{\tau_1 RT}{mg}} - e^{\frac{\tau RT}{mg}}\right)$$ Computed at the end of the program and put on tape for input to a future program. Units in pounds per square inch.
ATEMP	Temporary storage for calculated AA values.
AV( )	Slope on e-log p consolidated curve; can represent C_c or the slope on the overconsolidation branch of curve.
A1	Final value of J minus initial value of J , i.e., number of stations from surface. See A3 .
A1	Value of ALFA in radians. See A3 .
A1	Temporary storage for AK values. See A3 .
A1	Counter in calculating permeability in cylindrical coordinates. Represents stations from lowest depth. Sum of CX and CY . See A3 .
A2	y-Slope gives variation in water content or suction with depth in Table 5. Units in percent per inch for water content and inches per inch for suction. See A3 .
A2	$(90^{\circ}$ - ALFA) in radians. See A3 .
A2	Has values of 0.5 or CX/(CX + CY) in calculating new values of suction by weighted average methods. See A3 .
A3	Temporary storage, as are A1 and A2 , used in DO - loops throughout the main program.

FORTRAN Term	Description
A4	A4 = 1.1 : switch to steady-state flow. A4 = 0.0 : switch to transient-state flow (used in statements 2215 and 2450).
B	Equals BETA(L) . Used in Subroutines SUCTION and DSUCT.
B(,)	Suction coefficient for T(I-1,J) . See A(,) .
BB( )	Continuity coefficient for constant B . See AA( ) .
BE	Value of EN(I,J) used as exponent n in calculating permeability in Eq 3.1. See AK( ) .
BETA( )	Exponent of pF versus water content relationship (see Fig 7). Input in Table 4.
BK( )	Unsaturated permeability coefficient b . See AK( ) .
BK1	See AK1 .
BL( )	Tube-flow matrix coefficient of TX at I . See AL( ) .
BTEMP	Temporary storage for calculated BB values.
C	Coefficient to transform log to base 10 to log to base e . Used in Subroutines SUCTION AND DSUCT.
CC( )	Continuity coefficient for constant C . See AA( ) .
CHI	Represents χ_E , the equilibrium unsaturated stress parameter (see Eq 3.7).
CL( )	Tube-flow matrix coefficient of TY at J+1 . See AL( ) .
CONST	A common factor $\left[\left(\frac{h_t}{2}\right)\left(\frac{d\tau}{d\theta}\right) \right]$ used in calculation of suction coefficients.
CTEMP	Temporary storage for calculated CC values.
CX(,)	Suction coefficient for T(I,J) . See A(,) .
CY(,)	Suction coefficient for T(I,J) . See A(,) .
C1	Number of x-stations before last station. See C3 .

FORTRAN Term	Description
C1	Set to 1.0 if ALFA = 0 ; otherwise, set to cos A1 . See C3 .
C1	Set to BK(I,J) for solution of Gardner's equation. See C3 .
C2	x-Slope (see A2) input in Table 5. See C3 .
C2	Set to 0.0 if ALFA = 0 ; otherwise, set to cos A2 . See C3 .
C2	Reciprocal of the unsaturated permeability coefficient, UNSAT . See C3 .
C3	Set to 0.0 if ALFA = 0 ; otherwise, set to cos A3 . C1 , C2 , and C3 are temporary storages used in DO loops throughout the main program.
D	Equals PFM( ) minus pF at the inflection point. Used in Subroutines SUCTION and DSUCT. See PF1 .
D(,)	Suction coefficient for T(I+1,J) . See A(,) .
DELT	Change in water content necessary for equilibrium to be established between the overburden pressure and the swelling pressure. Used in Subroutine GULCH.
DELV	The amount of swell that can take place at constant applied pressure given a water content change of DELW . Used in Subroutine GULCH.
DELW	Change in water content from some initial state, WVI(,) , on the free-swell curve to some intermediate value, WV(,) . Values range from zero to DELT. Used in Subroutine GULCH.
DL( )	Tube-flow constant.

FORTRAN Term	Description
DP	Rate of change of the overburden pressure with respect to the volumetric water content, TH . Used in Subroutines SUCTION, DSUCT, and HEAVY.
DTDW(,)	Change in suction with volumetric water content. Units in inches. Computed in Subroutine DSUCT.
DTDX(,)	Suction gradient in x-direction. Units in inches of water per inch.
DTDY(,)	Suction gradient in y-direction. Units in inches of water per inch.
DTH	Increase in volumetric water content, which, in a saturated soil, is equal to the increase in the porosity. Used in Subroutine HEAVY.
DTX1	Initial suction gradient in x-direction. DTX1 and DTY1 , in inches of water per inch, are input in Table 6.
DTY1	Initial suction gradient in y-direction. See DTX1 .
DV(,)	Vertical strain in soil column. Calculated by Subroutine GULCH and used in main program. As output from GULCH, DV is the vertical strain for a particular station resulting from a change in water content at that station.
DVERT( )	Upward movement, in inches, at any depth.
E(,)	Suction coefficient for T(I,J+1) . See A(,) .
ECL	Allowable error in suction calculation at any point.
EM	Molecular weight of fluid. In the case of water, 18.02 grams per mole.
EN	Exponent used in Eq 3.1 to calculate unsaturated permeability coefficient. EN1 is value input in Table 3. See AK( ) .

FORTRAN Term	Description
ENP( )	Exponent of swelling pressure versus total specific volume curve. Input into Table 4B. ENP(L) is used in Subroutine HEAVY to calculate corrections for computed values of suction and water content. Used in Subroutine GULCH to calculate change in volume (see Fig 7).
ENP(L)	See ENP( ) .
ENRT	Represents $\frac{RT}{mg}$, the isothermal constant for pressure versus volume relationships used in calculating the equivalent stress release. See AT(,) .
EN1	See EN .
EPS	Closure tolerance. Used to calculate ECL . Input in Table 2A. No units.
ERR	Difference between calculated suctions at a point for each half-iteration.
F(,)	Gravity-potential component of permeability. See A(,) .
FACT	Differentiation of the gravimetric water content (a decimal fraction) as a function of the volumetric water content, i.e., $dw/d\theta$. Used in Subroutines SUCTION and DSUCT.
FAC1	Next suction previous to FAC2 divided by ENRT . FAC1 and FAC2 are exponents used in calculation of AT(,) . See FAC2 .
FAC2	Final suction divided by ENRT .
G	Acceleration due to gravity: 981 cm/sec^2 .
GAM	Wet unit weight of soil in pounds per cubic inch. Input in Table 4A. Used in main program and Subroutines HEAVY and GULCH.

FORTRAN Term	Description
GAMS( )	Specific gravity of soil solids. Input in Table 4B. Used in main program and Subroutines SUCTION, DSUCT, and HEAVY.
HT	Time increment (time step) in seconds. Input in Table 2A.
HX	Increment length (in inches) in horizontal x-direction. HX and HY are input in Table 2A.
HY	Increment length (in inches) in vertical y-direction. See HX .
H1	Relative humidity input in Table 6.
I	Integer counter for stations in x-direction. Used in main program and Subroutine HEAVY.
I	Integer counter for stations in x-direction. Used in Subroutines SUCTION and DSUCT. Equals I2 .
IM1	x-Coordinate of monitor Station 1. Input in Table 2B.
IM2	x-Coordinate of monitor Station 2. Input in Table 2B.
IM3	x-Coordinate of monitor Station 3. Input in Table 2B.
IM4	x-Coordinate of monitor Station 4. Input in Table 2B.
IN1	Switch input in Table 2C. IN1 = 1 for transient flow; IN1 = 2 for steady-state flow.
IN1	x-Coordinate of left boundary of region. See JN2 .
IN2	x-Coordinate of right boundary of region. See JN2 .
IR	Integer counting stations in reverse order in the x-direction.
IT	Counter for iterations.
ITEST	A check built in to insure problem will not run unless a problem number is input. Thus, successive problems can run on same job number, and a blank card inserted after data input will end the job.

FORTRAN Term	Description
ITIME	Total number of time steps input into Table 2A.
ITMAX	Maximum allowable iterations per time step. Input into Table 2A. No units.
IV	Larger value of IX or IY .
IX	Number of fictitious closure settings in x-direction. See IY .
IY	Number of fictitious closure settings in y-direction. IX and IY are input in first card of Table 7.
I1	x-Coordinate of monitor Station 1 used in output.
I2	x-Coordinate of monitor Station 2 used in output.
I2	Value of I used to enter all subroutines.
I3	x-Coordinate of monitor Station 3 used in output.
I4	x-Coordinate of monitor Station 4 used in output.
J	Integer counter for stations in y-direction. Used in main program and Subroutines HEAVY and GULCH.
J	Integer counter for stations in y-direction used in Subroutines SUCTION and DSUCT. Equals J2 .
JM1	y-Coordinate of monitor Station 1.
JM2	y-Coordinate of monitor Station 2.
JM3	y-Coordinate of monitor Station 3.
JM4	y-Coordinate of monitor Station 4.
JN1	y-Coordinate of lower boundary of region. See JN2 .
JN2	y-Coordinate of upper boundary of region. IN1 , IN2 , and JN2 are input in Table 3 to outline regions of constant permeability. IN1 , IN2 , JN1 , and JN2 are input in Table 4 to outline regions where swell pressure versus total

FORTRAN Term	Description
	volume relationships are constant. IN1 , IN2 , JN1 , and JN2 are input in Table 5 to outline regions where initial conditions are constant. IN1 , IN2 , JN1 , and JN2 are input in Table 6 to outline regions where boundary and internal conditions are constant. IN1 , IN2 , JN1 , and JN2 are input into Table 9 to outline regions where boundary condition changes are alike.
JR	Integer counting stations in reverse order in y-direction. See IR .
J1	y-Coordinate of monitor Station 1 used in output.
J1	y-Coordinate of station for output of closure.
J2	y-Coordinate of monitor Station 2 used in output.
J2	Value of J used to enter all subroutines.
J3	x-Coordinate of monitor Station 3 used in output.
J4	y-Coordinate of monitor Station 4 used in output.
K	Integer counter for time steps. Used in main program and Subroutines SUCTION and DSUCT.
K	Counter for input of cards in Table 3.
KAS(,)	Indicator of type of water content versus suction data held at each station.
KASE	Indicator of type of boundary conditions input in Tables 6 and 9. For stations where boundary conditions are set, KAS(I,J) equals KASE .
KAT	Curve number will call all data input in Table 4 and referenced by that number, i.e., PFM(M) , BETA(M) , WVA(M) , Q(M) , ALFO(M) , PN(M) , AV(M) , R(M) , WN(M) , VTO(M) ,

FORTRAN Term	Description
	VTF(M) , WVF(M) , PO(M) , ENP(M) , GAMS(M) , PRF(M) . KAT is input in Table 4 to show locations where each curve number applies.
KAT	Case number. When water contents and slopes relating to water contents are input in Table 5, KAT = 1 . If suctions and slopes relating to suctions are input in Table 5, KAT = 2 . Value of KAT is then used as a switch.
KAT	Switch to accept input from Table 9. If KAT = 1 , Table 9 is input for that time step. If KAT = 2 , there are no changes in boundary conditions for that time step.
KAT	Four-way switch to compute continuity coefficients. In this case, KAT = KAS(I,J) .
KAT	Two-way switch. Equals KLOS(I,J) . When KAT = 1 , the closure error at that station is within the tolerable error. When KAT = 2 , the closure error is greater than the tolerable error. If KAT = 2 , a new suction is calculated for KAS(I,J) = 1 for that station using the calculated suction values of adjoining stations. KAT can be used in various contexts because it is a nonsubscripted integer variable which is defined immediately before each use.
KEEP2	Signal to keep input data from previous problem for Table 2A.
KEEP3	Signal to keep input data from previous problem for Table 3.
KEEP4	Signal to keep input data from previous problem for Table 4.
KEEP5	Signal to keep input data from previous problem for variables designated in Table 5.

FORTRAN Term	Description
KEEP6	Signal to keep data from previous problem for variables designated in Tables 6 and 9.
KEEP7	Signal to keep input data from previous problem for Tables 7 and 8.
KEY	Time-step option switch. When KEY = 1 , list of time steps read in. New boundary conditions for each time step: KEY = 2 . No boundary changes: KEY = 3 . KEY is input in Table 8A.
KEYB	Switch for time steps for output. Input into Table 8B. Read in list of time steps: KEYB = 1 . Continuous output: KEYB = 2 .
KGRCL	Coordinate switch for calculating permeabilities input into Table 1. KGRCL = 1 for rectangular coordinates; KGRCL = 2 for cylindrical coordinates.
KLH	Switch to consider compressibility of soil input into Table 1. When KLH = 1 , the overburden pressure is not considered in calculating the suction changes with a change in volumetric water content. When KLH = 2 , the overburden pressure is considered. Used in main program and Subroutines SUCTION and DSUCT.
KLOC( )	Switch set for each time step. When KLOC( ) = 1 , new boundary conditions read in. When KLOC( ) = 2 , no change in boundary conditions.
KLOS( )	Closure switch set for each station. If closure of iterative method of calculating suction is within tolerable error, KLOS( ) = 1 . If tolerable limit is exceeded, KLOS = 2 .

FORTRAN Term	Description
KOUNT	Counter for the number of stations where error of closure exceeds tolerance for each time step. If KOUNT = 0 , computer prints word CLOSURE .
KOUT	Equals KPUT( ) for each time step.
KPUT( )	Switch to determine output for each time step. Print output: KPUT( ) = 1 . Do not print: KPUT( ) = 2 .
KT( )	Storage for time steps at which output is desired. Values are input in Table 8B.
KTAPE	Switch to calculate and store AT(,) . If KTAPE = 1 , calculate AT(,) . If KTAPE = 0 , skip this operation.
KTIME	A time step at which boundary conditions are changed. Input on a header card in Table 9.
KURV(,)	Equals KAT in main program. Applicable curve number set for each station within the region outlined by input card in Table 4. Also used in subroutines.
L	Last station less one, e.g., L = MYP3 - 1 .
L	KURV(,) in integer form. Subscript relating to suction versus total specific volume versus psecific water volume curves.
LOC	Counter of the number of stations for which a set of data input in Table 4 is applicable. Value of LOC is input on the first card of each set representing a suction versus water content curve. See NLOC , KAT , and KURV(,) .
M	Counter for number of sets of data representing suction versus water content curves. Used to control input of Table 4. The integer M is the curve number for that set

FORTRAN Term	Description
	of input. See KAT and KURV(,) . NCD4 is the final value of M .
M	Counter in DO-loop for readings in additional cards in Table 4 to outline regions in which suction versus water content curves are applicable. NLOC is the final value of M .
M	Counter to input Table 5. NCD5 is the final value of M .
M	Counter to input Tables 6 and 9. NCD6 is the final value of M .
M	Counter in DO-loop used to calculate vertical heave at various depths in the soil.
MMAX	Largest positive value of either MXP5 or MYP5 .
MX	Number of x-increments input into Table 2A.
MXP2	Equals MX + 2 . MXP2 , MXP3 , MXP4 , and MXP5 are calculated for use as end points in computation processes.
MXP3	Equals MX + 3 . See MXP2 .
MXP4	Equals MX + 4 . See MXP2 .
MXP5	Equals MX + 5 . See MXP2 .
MY	Total number of y-increments used in Subroutine HEAVY.
MY	Number of y-increments input into Table 2A.
MYP2	Equals MY + 2 . MYP2 , MYP3 , MYP4 , and MYP5 are calculated for use as end points in computation processes.
MYP3	Equals MY + 3 . See MYP2 .
MYP4	Equals MY + 4 . See MYP2 .
MYP5	Equals MY + 5 . See MYP2 .

FORTRAN Term	Description
N	Counter to read in value of KT( ) for Table 8A. Final value of N is NSTEP .
N	Number of time steps for which KLOC( ) is set to 1 when boundary condition changes are intermittent.
N	Counter to output values of KT( ) . Final value of N is NOUT .
N	Number of time steps for which KPUT( ) = 1 when output is intermittent.
NCD2	Number of cards related to Table 2. NCD2 is never used by the computer; therefore, input is optional.
NCD3	Number of additional cards for input of data in Table 3.
NCD4	Number of sets of data (2 cards per set) which represent different suction versus water content relationships. When KEEP4 = 1 , previous data are kept and no new data can be read into Table 4. If new data are to be added to the problem, all of the previous data sets must be input anew and KEEP4 = 0 . NCD4 is not the number of data cards in Table 4; total data cards would be equal to NLOC plus twice NCD4 .
NCD5	Number of additional cards for input of data in Table 5. The data from this input are added to the data already stored for each station. The stored datum is the last calculated value and not necessarily the previous input.
NCD6	Number of cards of additional data read in for Tables 6 or 9. Data are added to values already stored at that location. NCD6 is input into Table 1 for Table 6 and into Table 9 to

FORTRAN Term	Description
	input boundary condition changes for pertinent time steps. The input value for NCD6 should count the data cards but not the header cards, which contain KTIME and NCD6 .
NCD7	Number of data cards input in Table 7.
NLOC	Total number of cards in Table 4 which specify the regions over which particular suction versus water content relationships would apply. NLOC is the sum of the various LOC values input in the data sets of Table 4. See NCD4 .
NOUT	Total number of time steps where output is required. The input into Table 8B is not recognized by computer if continuous output is called for. See KEYB .
NPROB	Problem number, read from second card in program and first card in subsequent problems. Used to identify problem and subproblem. Problems may be entered one after another and various portions can be reused (see KEEP2 through KEEP7). A blank card is inserted after the end of all data. The computer reads this as NPROB = 5H . The comparison with ITEST ends the compilation of data and starts execution of the problems.
NSTEP	Total number of time steps at which boundary conditions change. NSTEP is input in header card of Table 8A and value is used only if KEY = 1 .
P	Overburden pressure, inches of water, in Subroutines SUCTION, DSUCT, and HEAVY.
P	Overburden pressure, pounds per square inch, in Subroutine GULCH.

FORTRAN Term	Description
PCTUP	Ratio between the vertical expansion and volumetric expansion of the soil *in situ*. Value must be input in Table 4. The same value is used for all soils in one problem. Value is used in Subroutine GULCH.
PF	Equals PFM - PF1 . Used in Subroutines SUCTION and DSUCT.
PFM( )	Maximum pF value. Must be chosen arbitrarily as the dry end point of each suction versus water content curve and input in Table 4.
PFR( )	Equals PFM( ) - PF1 .
PF1	The pF at the inflection point. Determined from each suction versus water content curve and input in Table 4.
PF1	Equals pF , the log of suction to base 10. Calculated in Subroutine SUCTION for each time step and printed when output when called for. PF1 will be zero for all positive values of suction and will not exceed PFM . PF1 is set to zero for a steady-state case in which A4 = 0 .
PL	Principal permeability at right angles to PB . Input into Table 3 in units of inches per second. PL is added to any previous stored value of P2 .
PN( )	Porosity at air entry. Input into Table 4. Used in programs as POR(I,J) .
PO( )	Swell pressure corresponding to the total dry specific volume. Input into Table 4 in units of pounds per square inch. Used in Subroutine GULCH.
POR(,)	Porosity at air entry for each station. Used to calculate CHI in Subroutines SUCTION, DSUCT, and HEAVY.

FORTRAN Term	Description
PSAT	Saturated vapor pressure in centimeters of water.
P1	Overburden pressure in psi. Used in Subroutine HEAVY.
P1(,)	Principal permeability nearest to the x-direction for each station. See PB . Units of inches per second.
P11(,)	Direct permeability in x-direction. The portion of the x-component of velocity contributed by a change in suction in the x-direction. Units in inches per second.
P12(,)	Cross permeability in either the x or y-direction. For example, it is the portion of the x-component of velocity contributed by a change in suction in the y-direction. Units in inches per second.
P2(,)	Principal permeability at right angles to P1 . See PL . Units in inches per second.
P22(,)	Direct permeability in y-direction. See P11 and P12 . Units in inches per second.
Q( )	Exponent of the specific water volume versus total specific volume curve. Describes swell under zero total pressure. Input in Table 4 and used in Subroutines HEAVY and GULCH. Equals QMO in HEAVY.
QMO	Equals Q( ) in Subroutines HEAVY and GULCH.
QM1	Equals Q( ) + 1 . Used in Subroutine GULCH.
R	Radius of station being considered in axisymmetric case for calculation of suction coefficients A(,) , B(,) , CX(,) , CY(,) , D(,) , E(,) , and F(,) . Units in inches.

FORTRAN Term	Description
R( )	Saturation exponent relating the degree of saturation to CHI . Input in Table 4 for each suction versus water content curve and used at end of program to calculate CHI .
RECB	Reciprocal of (BETA( ) + 1.0) . Used in Subroutines SUCTION and DSUCT.
RENP	Reciprocal of ENP(L) . Used in Subroutine GULCH.
RG	Gas constant. Equals 8.314×10^7 ergs per degree centigrade per mole.
RO	Inside radius. A finite number must be input in Table 3 to represent radius of source or sink in cylindrical seepage problems. Units in inches.
RPO	Equals R( ) for calculation of CHI . Used in main program and Subroutine HEAVY.
S	Used in Subroutine GULCH. Reciprocal of ALFB when DELW equals DELT . Must be greater than or equal to Q( ) so that the swell cannot exceed the free-swell value.
SAT	Used in Subroutine HEAVY. Equals χ_E , the equilibrium unsaturated stress parameter.
SRCH	Surcharge pressure (pounds per square inch) exerted externally on the upper boundary of the region. Only one value for each value of KURV(I,J) input into Table 4. Used in Subroutines HEAVY and GULCH.
T(,)	Suction (inches of water) set or calculated for each station. See TL . Used in Subroutines SUCTION, DSUCT, and HEAVY.
TA	Absolute value of T(I,J) . Used in computing permeability.

FORTRAN Term	Description
TAT	Used in Subroutines SUCTION and DSUCT. Value of AT which corresponds to the inflection point on the degree of saturated versus pF curve.
TE	Soil temperature (degrees F) input into Tables 6 and 9 and used in Subroutine HUMIDY to calculate suction.
TE	Pressure-free suction expressed as positive number. Used in Subroutines SUCTION and DSUCT.
TEM	Absolute temperature (degrees Kelvin) used to calculate AT(,) .
TERM	Used in Subroutine HEAVY. Factor to convert gravimetric water content (decimal fraction) to volumetric water content (decimal fraction).
TH	Volumetric water content expressed as a decimal fraction. Used in Subroutine HEAVY.
TI(,)	Initial value of T(I,J) used in computing AT(,) .
TX(,)	The computed value for suction at a station at the end of a time step, i.e., T^{k+1}(,) . The suction at the beginning of the time step is T(,) or T^{k}(,) . TX(,) is the suction computed during the first half of each iteration for stations considered in sequence in the x-direction. See TY(,) .
TY(,)	The computed value for suction at a station at the end of a time step. TY(,) is the suction computed during the last half of each iteration for stations considered in sequence in the y-direction. See TX(,) .

FORTRAN Term	Description
T1	Variance to input changes in suction in Tables 5, 6, and 9. These values are added to whatever value is stored in T(,) . Units in inches of water.
UNSAT	Unsaturated permeability coefficient K(unsaturated) = K(saturated)UNSAT . See AK( ) and BK( ) .
UP	Numerator of valve-setting terms VSX(,) and VSY( ) .
VSX(,)	Valve setting for solution of flow in the y-direction. One of the acceleration parameters in the Crank-Nicolson method of solution. Set for each station. See VX( ) .
VSY( )	Valve setting for solution of flow in the x-direction. See VSX(,) and VY( ) . Set for each station.
VTAP	Used in Subroutine GULCH. Total specific volume on the free-swell curve corresponding to the air-entry water content, WVA(L) .
VTF( )	Total specific volume of zero swell pressure. Used in Subroutines HEAVY and GULCH.
VTI	Used in Subroutine GULCH. Initial total specific volume of the free-swell curve corresponding to WVI(,) . Volume changes start from VTI and work toward VTP .
VTO( )	Total specific volume of dry soil. Used in Subroutine GULCH. Input into Table 4 for each suction versus water content curve. Units in cubic centimeters per gram of oven-dried soil.
VTP	Total specific volume when soil is in static equilibrium with weight of overburden. Used in Subroutines HEAVY and GULCH.

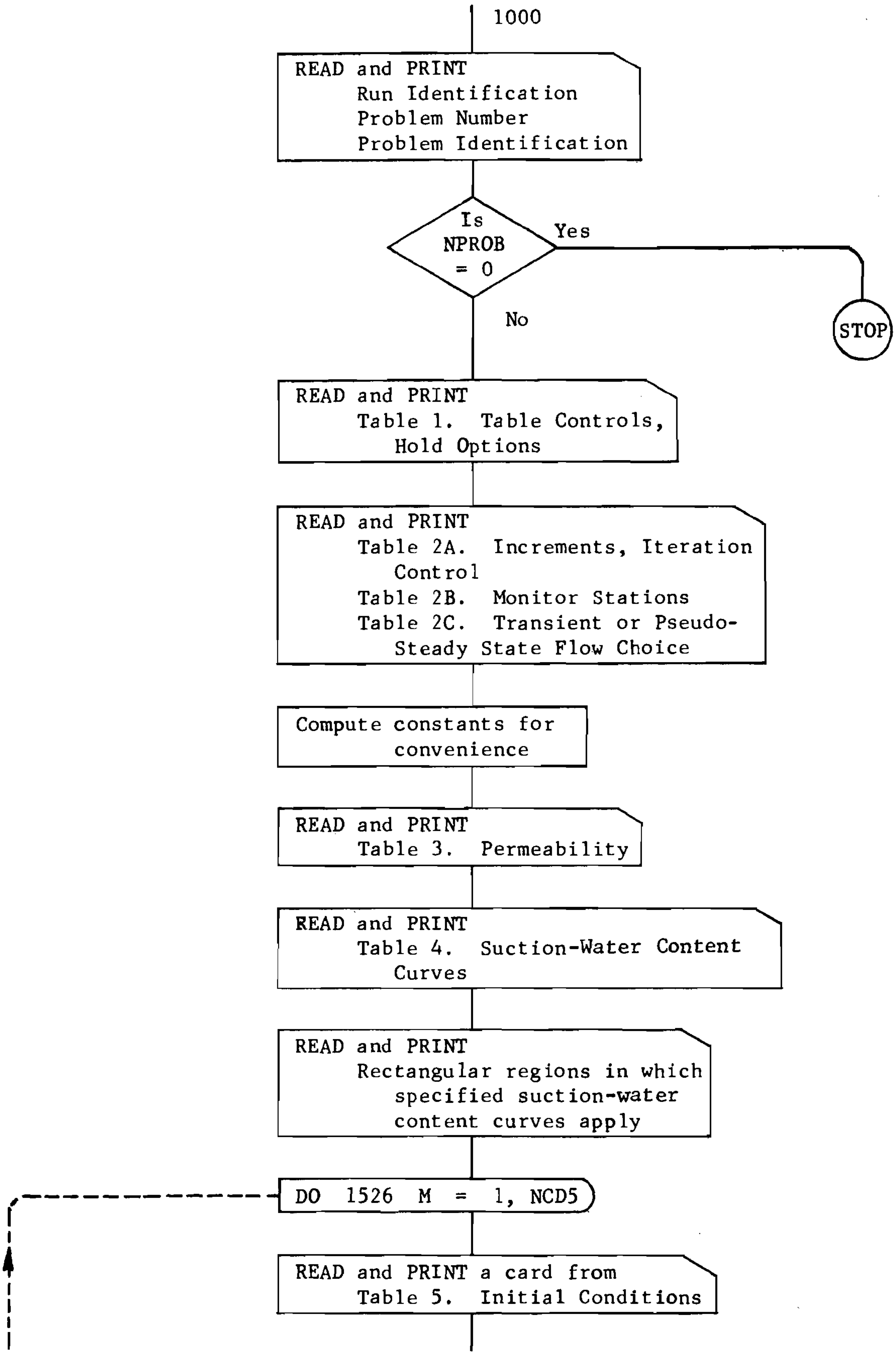
FORTRAN Term	Description
VX( )	Fictitious closure valve-setting input to be applied at each station as VSX(,) until solution generates values internally. Input into Table 7. See IX .
VY( )	Fictitious closure valve-setting input to be applied at each station as VSY(,) until solution generates values internally. Input into Table 7. See IY .
WN( )	Gravimetric water content at final saturation (suction equals zero). Input in Table 4 in percent for each suction versus water content curve. Set as WVS(,) for each station within applicable region.
WV(,)	Gravimetric water content in percent at each station in a region. Has same numeric coefficient as specific water volume. Used in main program and all subroutines.
WVA( )	Air-entry water content for each free-swell curve of total specific volume versus specific water volume.
WVF( )	Specific water volume at zero swell pressure corresponding to final total specific volume. Units in cubic centimeters per gram. Input into Table 4 for each suction versus water content curve and used in Subroutine GULCH.
WVI(,)	Initial specific water volume for each station in a region. Expressed as percent and set equal to WV(,) at time equal to zero. Used in Subroutines HEAVY and GULCH.
WVP	Used in Subroutine GULCH. Specific water volume corresponding to VTP .
WVS(,)	Gravimetric water content in percent at saturation (suction equals zero) for each station in region. Set equal to

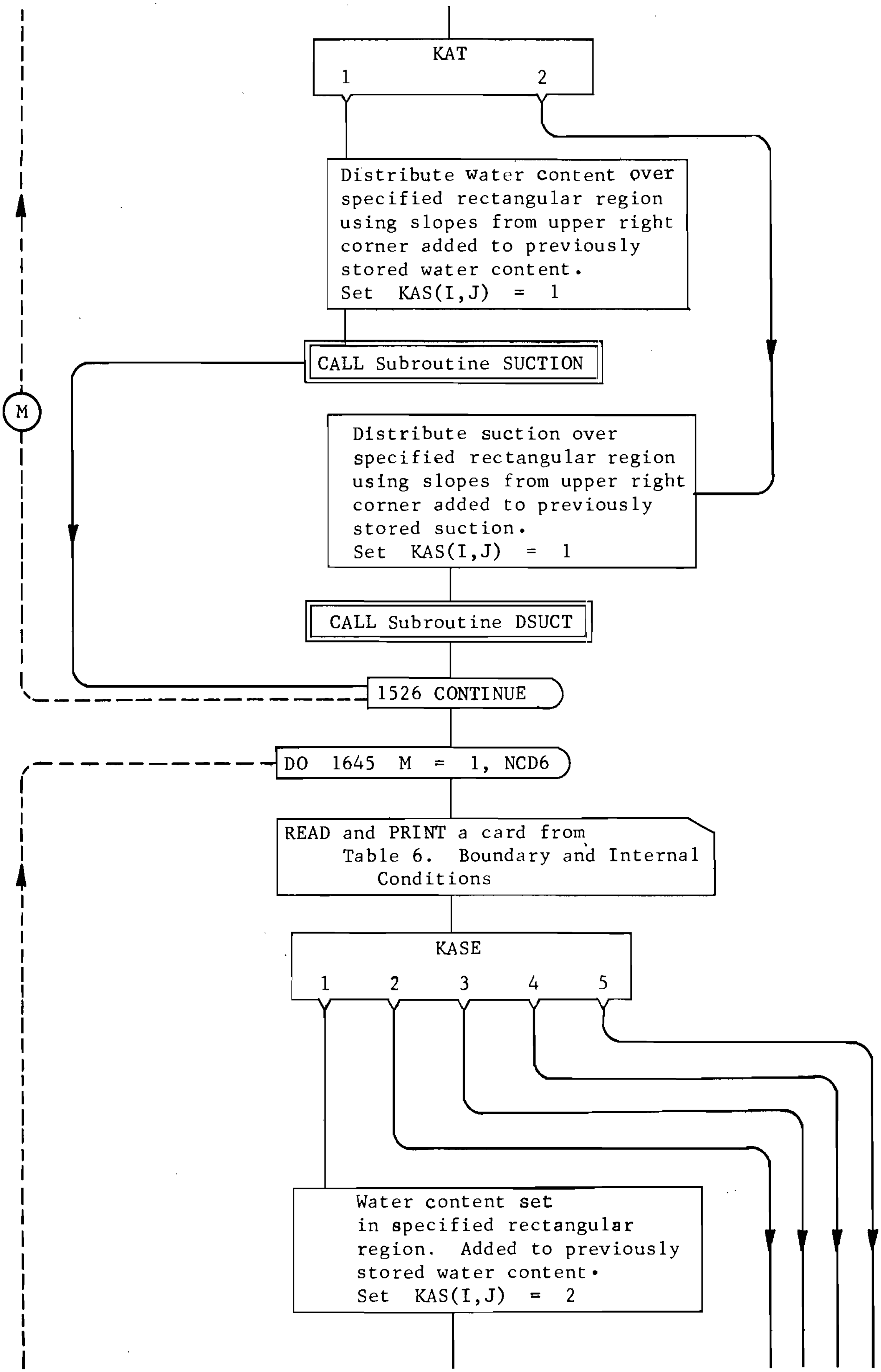
FORTRAN Term	Description
	WN( ) and used in Subroutines SUCTION and DSUCT.
WVI	Input in Tables 5, 6, and 9 for gravimetric water content in percent. The value is added to previously stored values of WV(,) at each station.
XM	A collection of terms used in Subroutines SUCTION and DSUCT obtained when suction T(I,J) is differentiated with respect to the volumetric water content, TH .

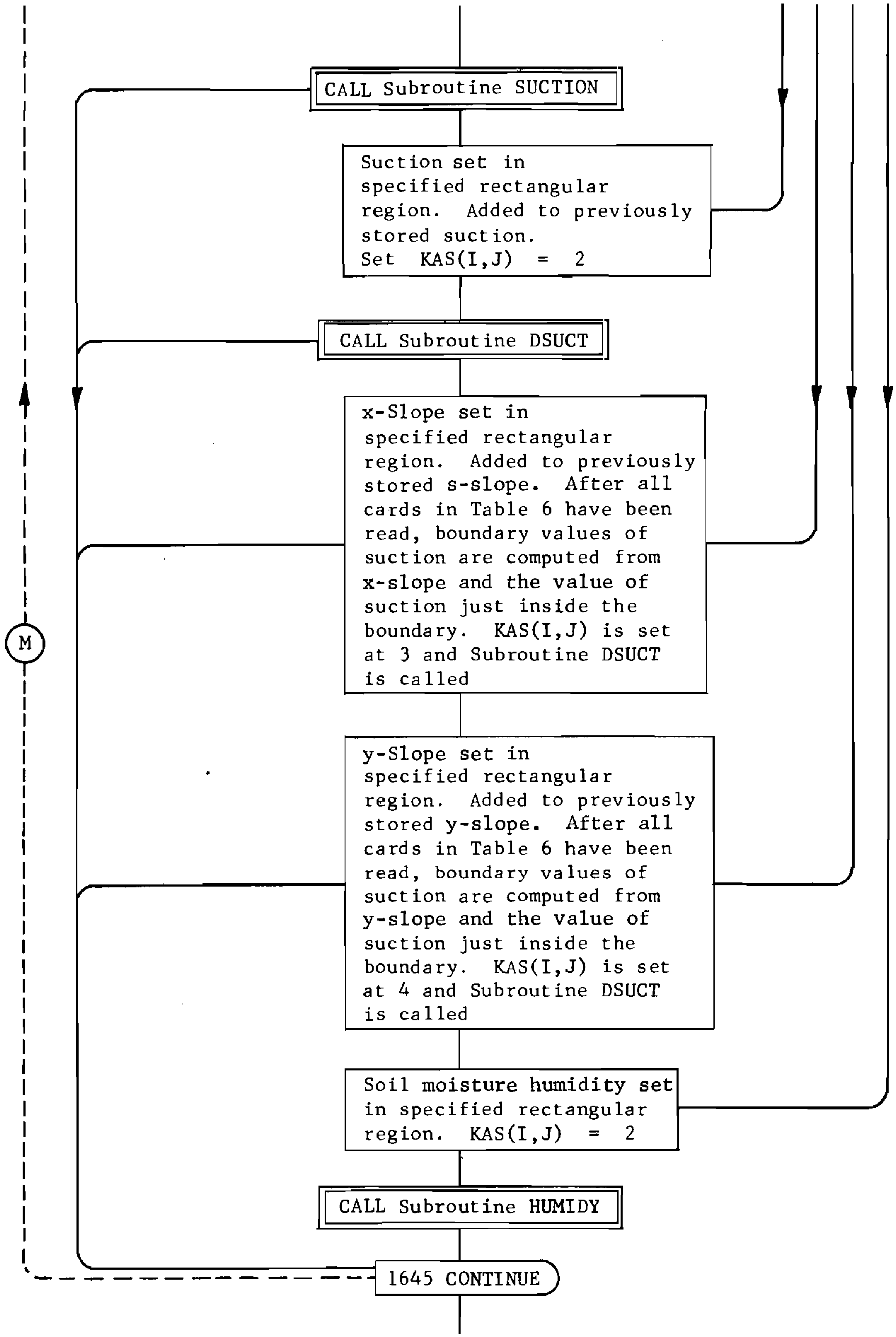
APPENDIX 2

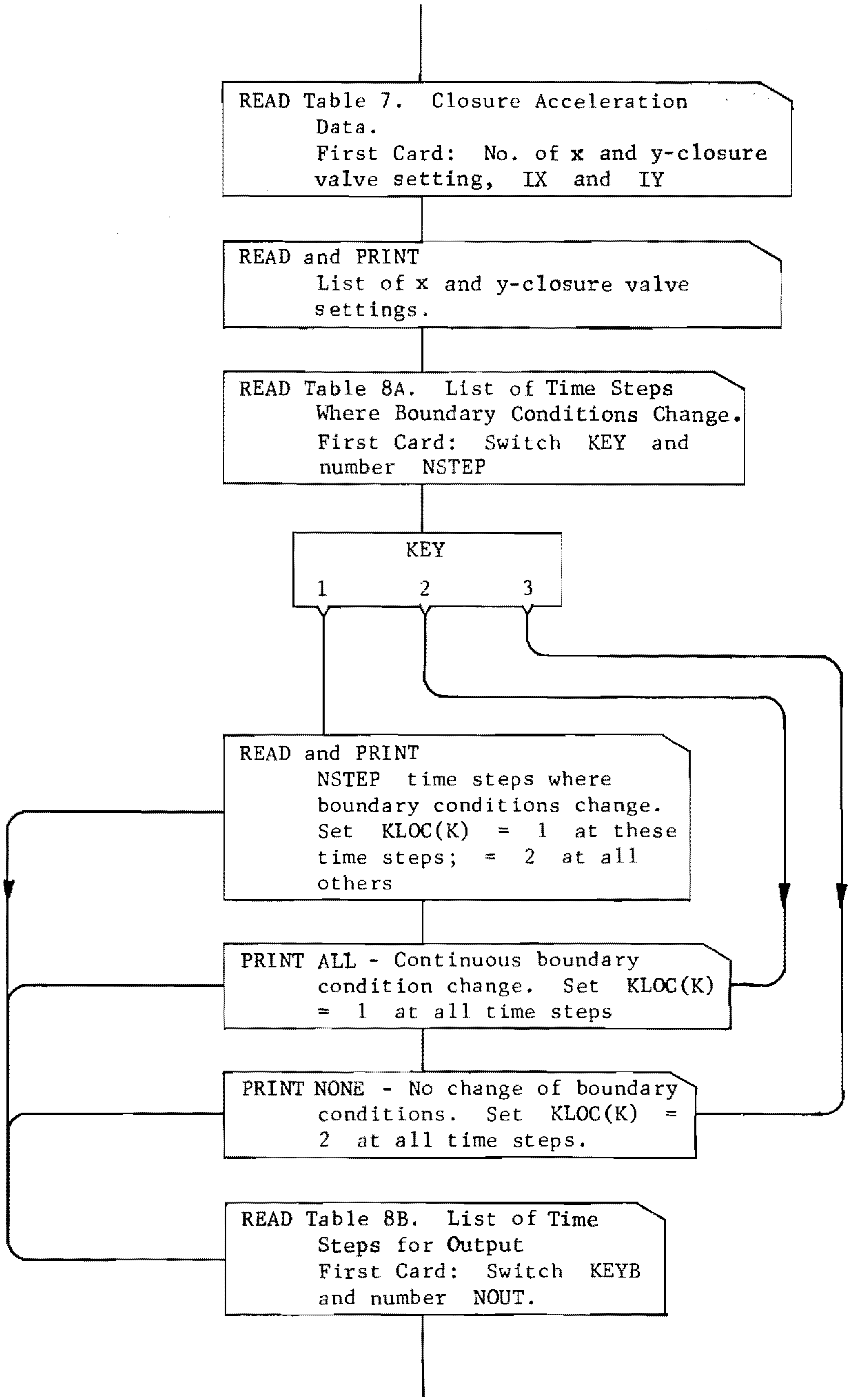
PROGRAM GCHPIP7 FLOW CHARTS

PROGRAM GCHPIP7

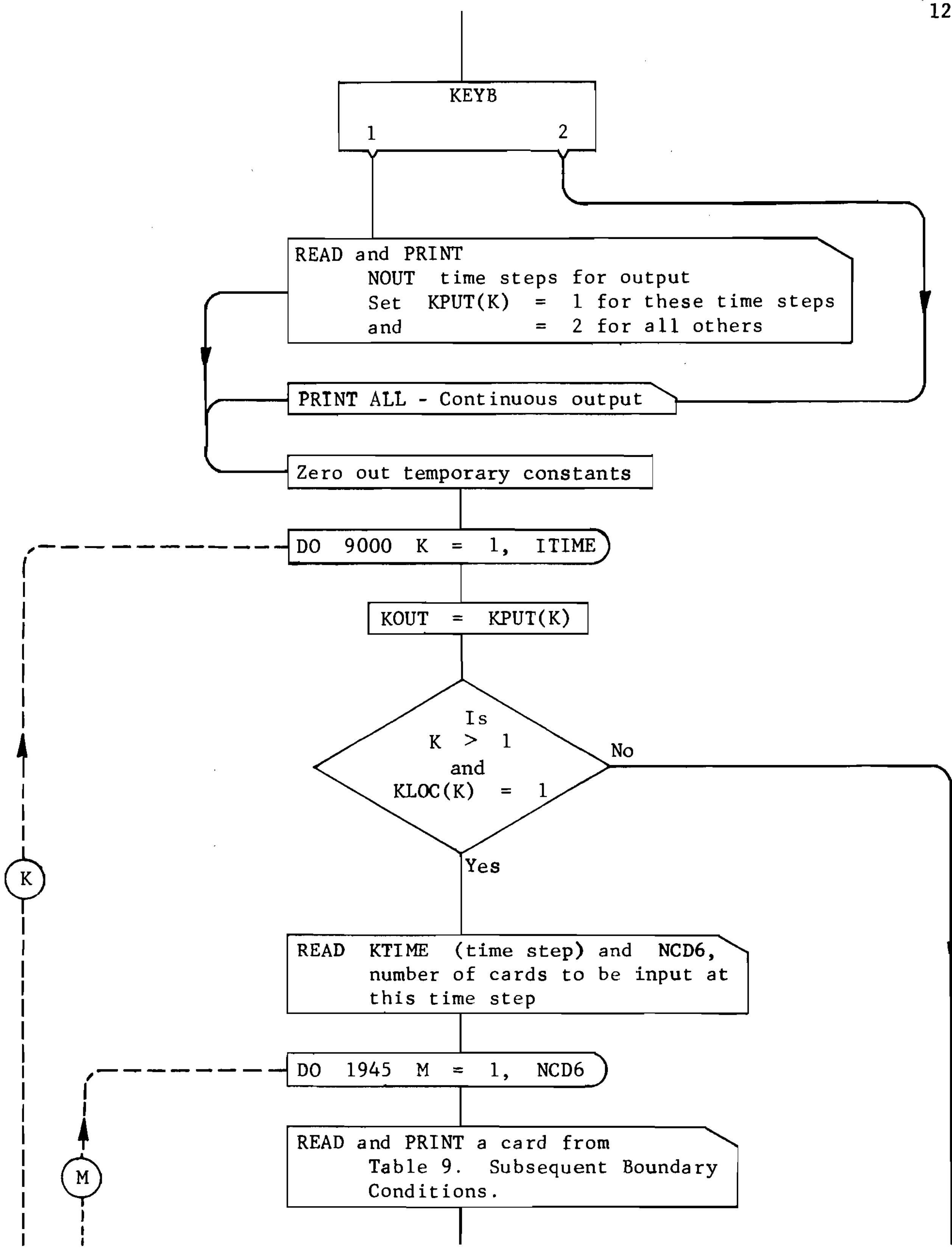


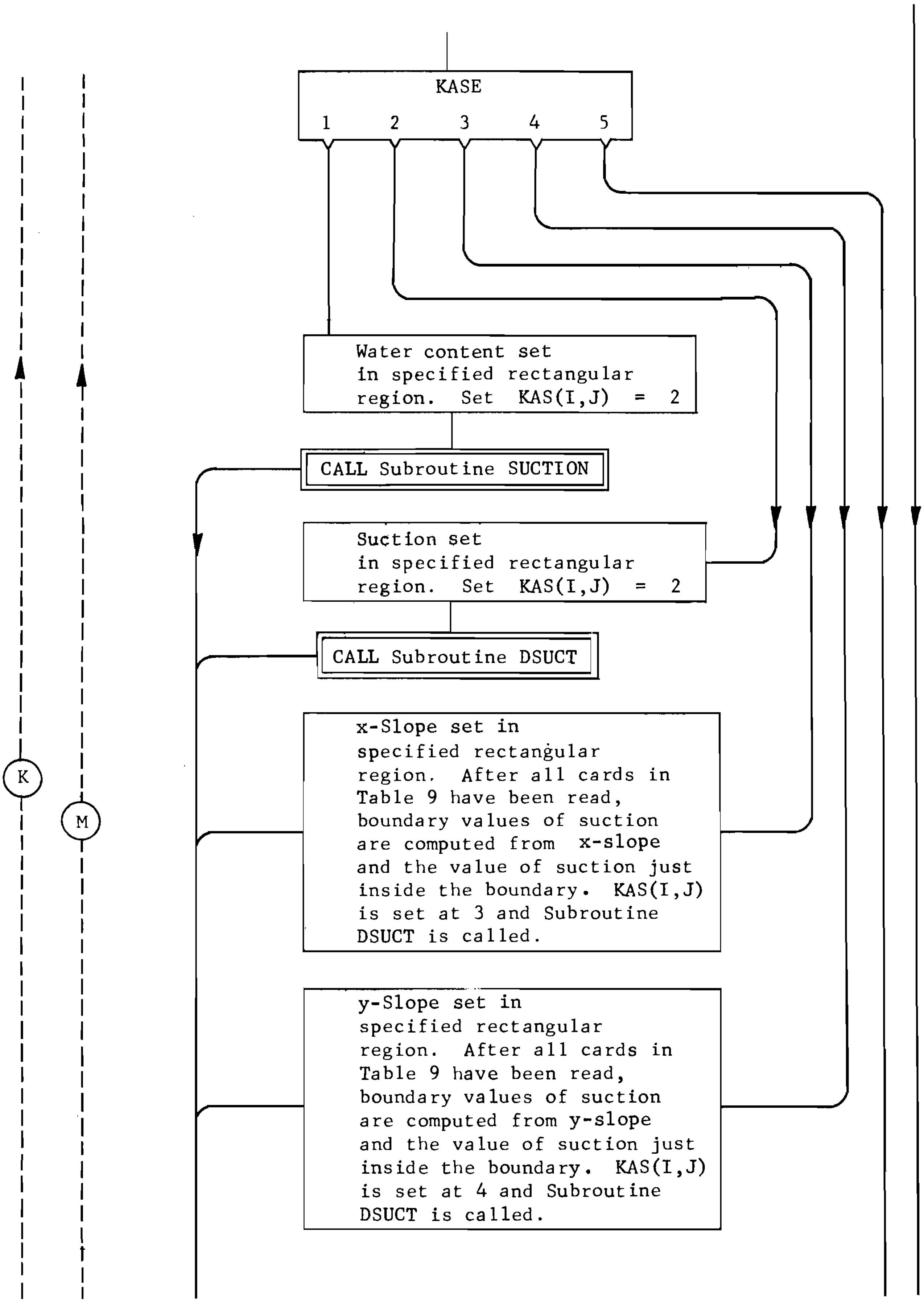

KAT
1
2
Distribute water content over specified rectangular region using slopes from upper right corner added to previously stored water content.
Set KAS(I,J) = 1
CALL Subroutine SUCTION
M
Distribute suction over specified rectangular region using slopes from upper right corner added to previously stored suction.
Set KAS(I,J) = 1
CALL Subroutine DSUCT
1526 CONTINUE
DO 1645 M = 1, NCD6
READ and PRINT a card from Table 6. Boundary and Internal Conditions
KASE
1
2
3
4
5
Water content set in specified rectangular region. Added to previously stored water content.
Set KAS(I,J) = 2

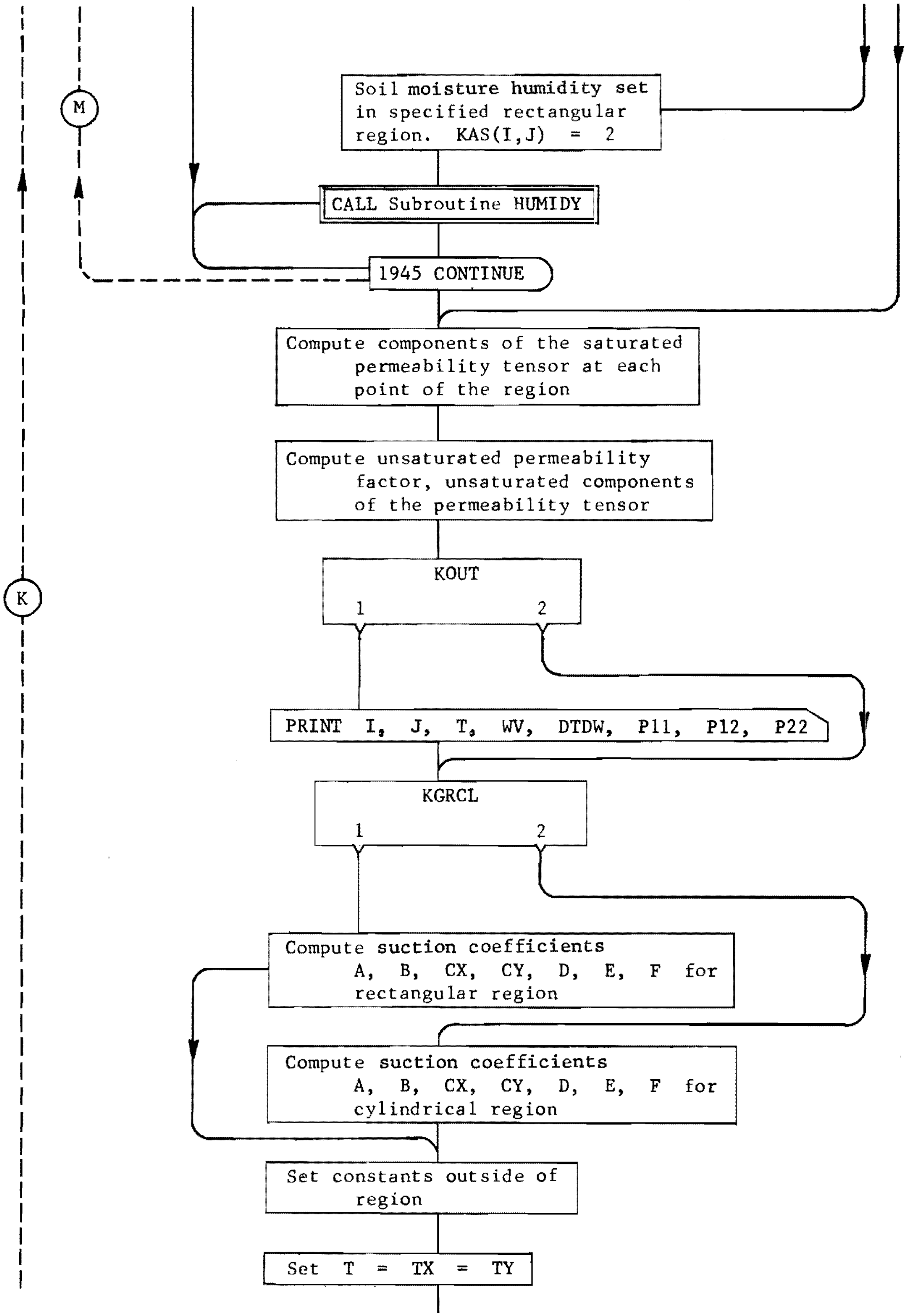

CALL Subroutine SUCTION
Suction set in specified rectangular region. Added to previously stored suction. Set KAS(I,J) = 2
CALL Subroutine DSUCT
x-Slope set in specified rectangular region. Added to previously stored s-slope. After all cards in Table 6 have been read, boundary values of suction are computed from x-slope and the value of suction just inside the boundary. KAS(I,J) is set at 3 and Subroutine DSUCT is called
y-Slope set in specified rectangular region. Added to previously stored y-slope. After all cards in Table 6 have been read, boundary values of suction are computed from y-slope and the value of suction just inside the boundary. KAS(I,J) is set at 4 and Subroutine DSUCT is called
Soil moisture humidity set in specified rectangular region. KAS(I,J) = 2
CALL Subroutine HUMIDY
M
1645 CONTINUE



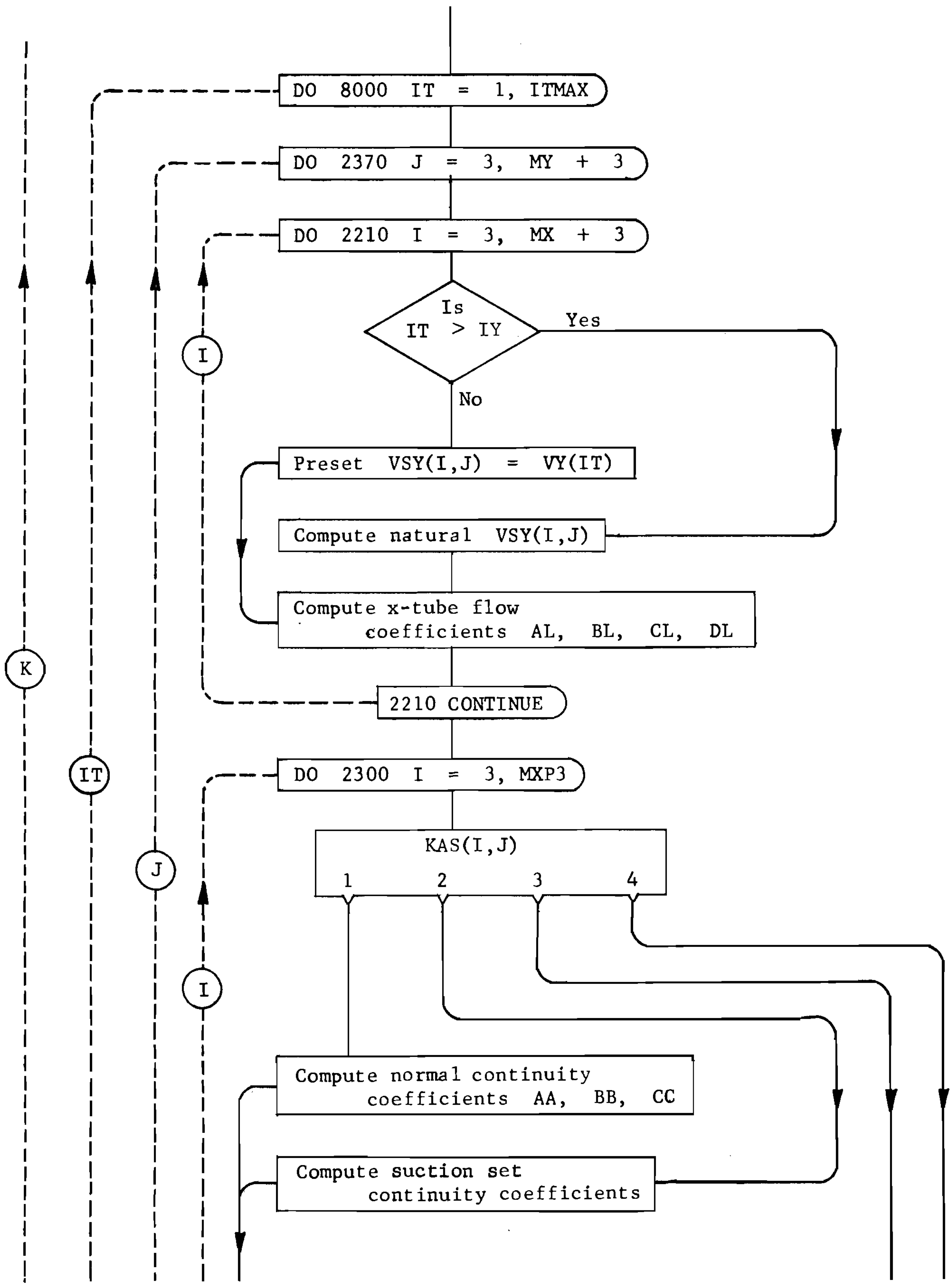
READ Table 7. Closure Acceleration Data.
First Card: No. of x and y-closure valve setting, IX and IY
READ and PRINT
List of x and y-closure valve settings.
READ Table 8A. List of Time Steps Where Boundary Conditions Change.
First Card: Switch KEY and number NSTEP
KEY
1
2
3
READ and PRINT
NSTEP time steps where boundary conditions change.
Set KLOC(K) = 1 at these time steps; = 2 at all others
PRINT ALL - Continuous boundary condition change. Set KLOC(K) = 1 at all time steps
PRINT NONE - No change of boundary conditions. Set KLOC(K) = 2 at all time steps.
READ Table 8B. List of Time Steps for Output
First Card: Switch KEYB and number NOUT.

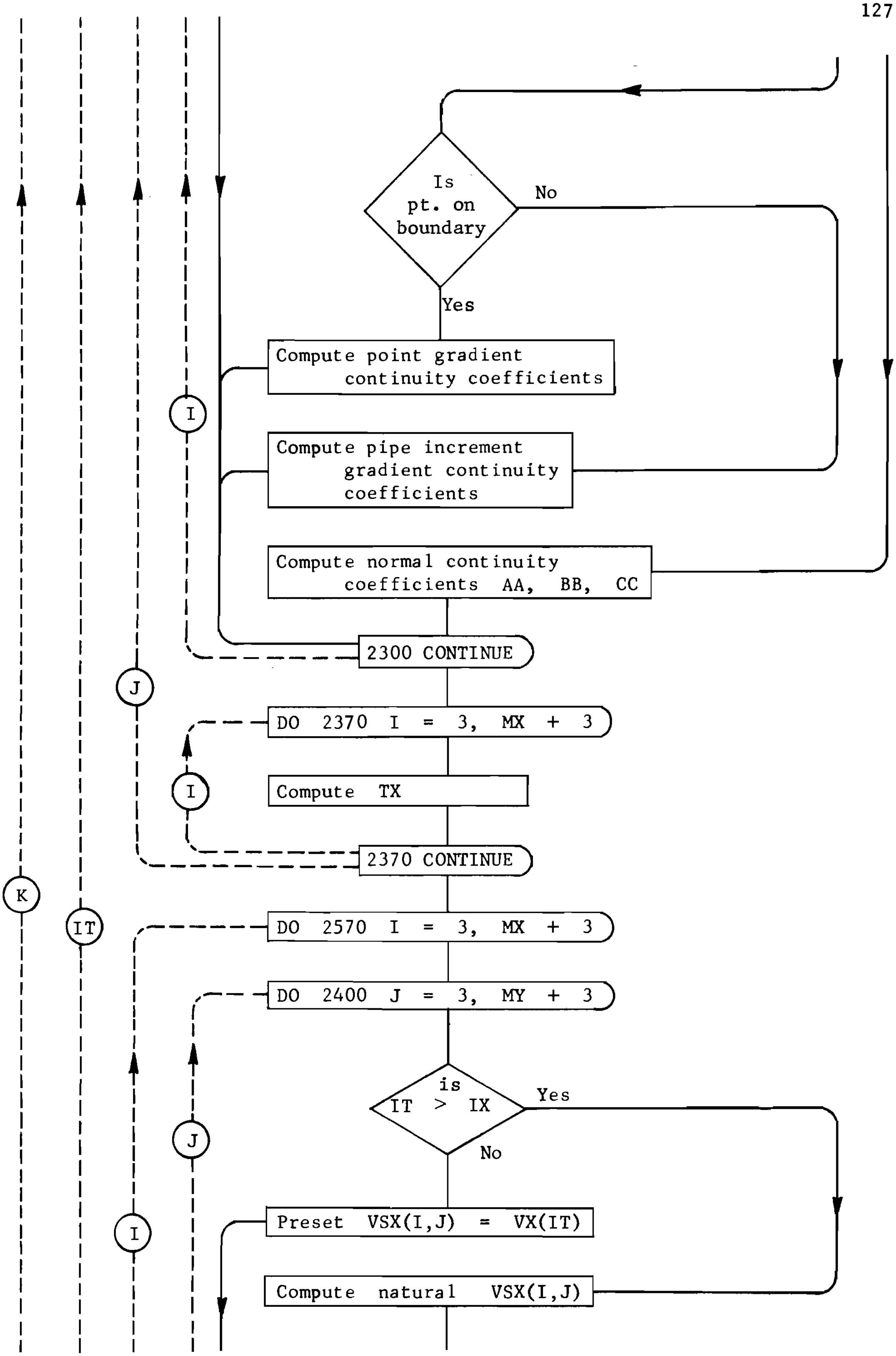

KEYB
1
2
READ and PRINT
NOUT time steps for output
Set KPUT(K) = 1 for these time steps
and = 2 for all others
PRINT ALL - Continuous output
Zero out temporary constants
DO 9000 K = 1, ITIME
KOUT = KPUT(K)
Is
K > 1
and
KLOC(K) = 1
No
Yes
K
READ KTIME (time step) and NCD6,
number of cards to be input at
this time step
DO 1945 M = 1, NCD6
M
READ and PRINT a card from
Table 9. Subsequent Boundary
Conditions.


KASE
1
2
3
4
5
Water content set in specified rectangular region. Set KAS(I,J) = 2
CALL Subroutine SUCTION
Suction set in specified rectangular region. Set KAS(I,J) = 2
CALL Subroutine DSUCT
x-Slope set in specified rectangular region. After all cards in Table 9 have been read, boundary values of suction are computed from x-slope and the value of suction just inside the boundary. KAS(I,J) is set at 3 and Subroutine DSUCT is called.
y-Slope set in specified rectangular region. After all cards in Table 9 have been read, boundary values of suction are computed from y-slope and the value of suction just inside the boundary. KAS(I,J) is set at 4 and Subroutine DSUCT is called.
K
M

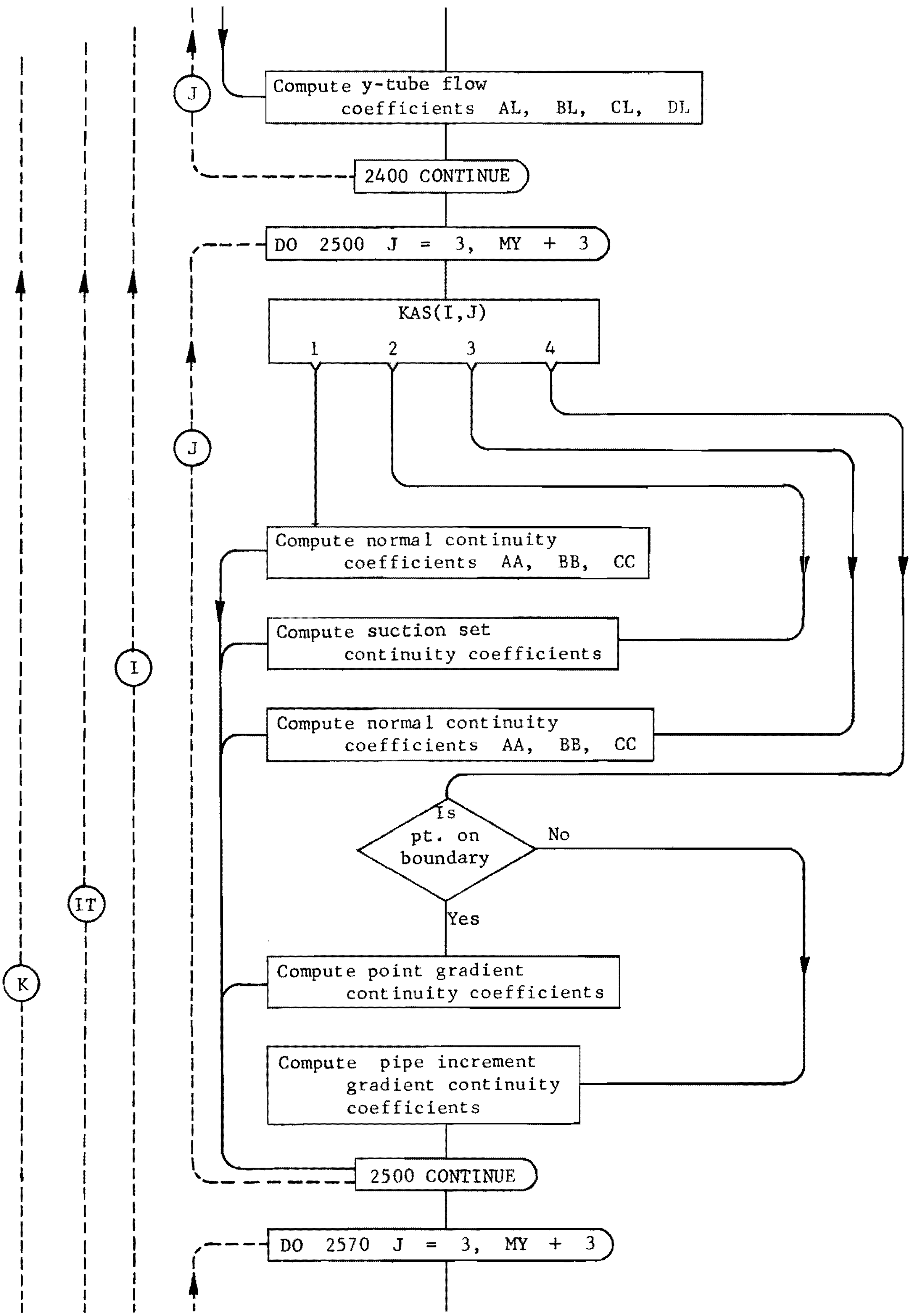


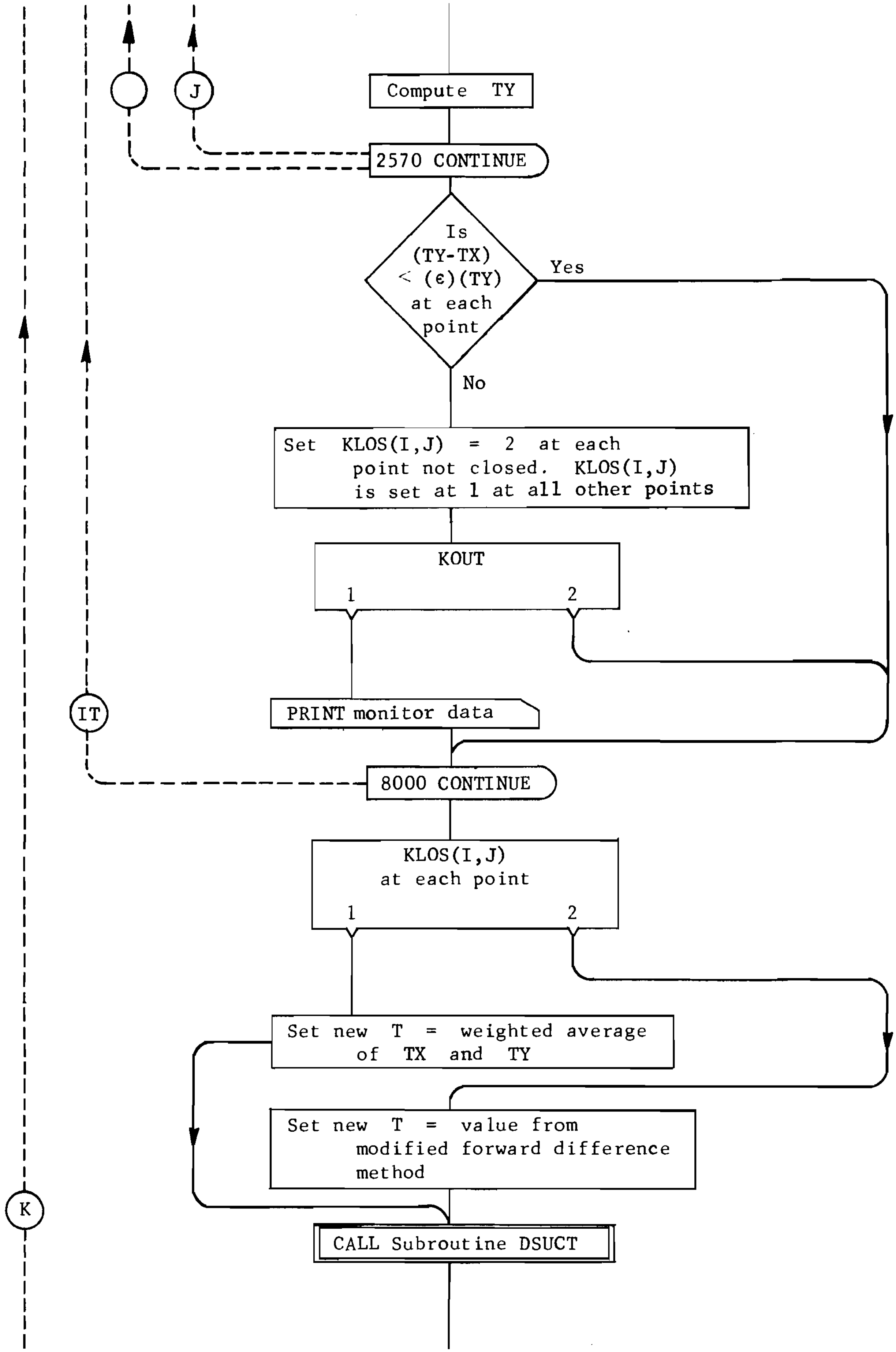
M
Soil moisture humidity set in specified rectangular region. KAS(I,J) = 2
CALL Subroutine HUMIDY
1945 CONTINUE
Compute components of the saturated permeability tensor at each point of the region
Compute unsaturated permeability factor, unsaturated components of the permeability tensor
K
KOUT
1
2
PRINT I, J, T, WV, DTDW, P11, P12, P22
KGRCL
1
2
Compute suction coefficients A, B, CX, CY, D, E, F for rectangular region
Compute suction coefficients A, B, CX, CY, D, E, F for cylindrical region
Set constants outside of region
Set T = TX = TY


DO 8000 IT = 1, ITMAX
DO 2370 J = 3, MY + 3
DO 2210 I = 3, MX + 3
Is IT > IY
Yes
No
Preset VSY(I,J) = VY(IT)
Compute natural VSY(I,J)
Compute x-tube flow coefficients AL, BL, CL, DL
2210 CONTINUE
DO 2300 I = 3, MXP3
KAS(I,J)
1
2
3
4
Compute normal continuity coefficients AA, BB, CC
Compute suction set continuity coefficients
K
IT
J
I

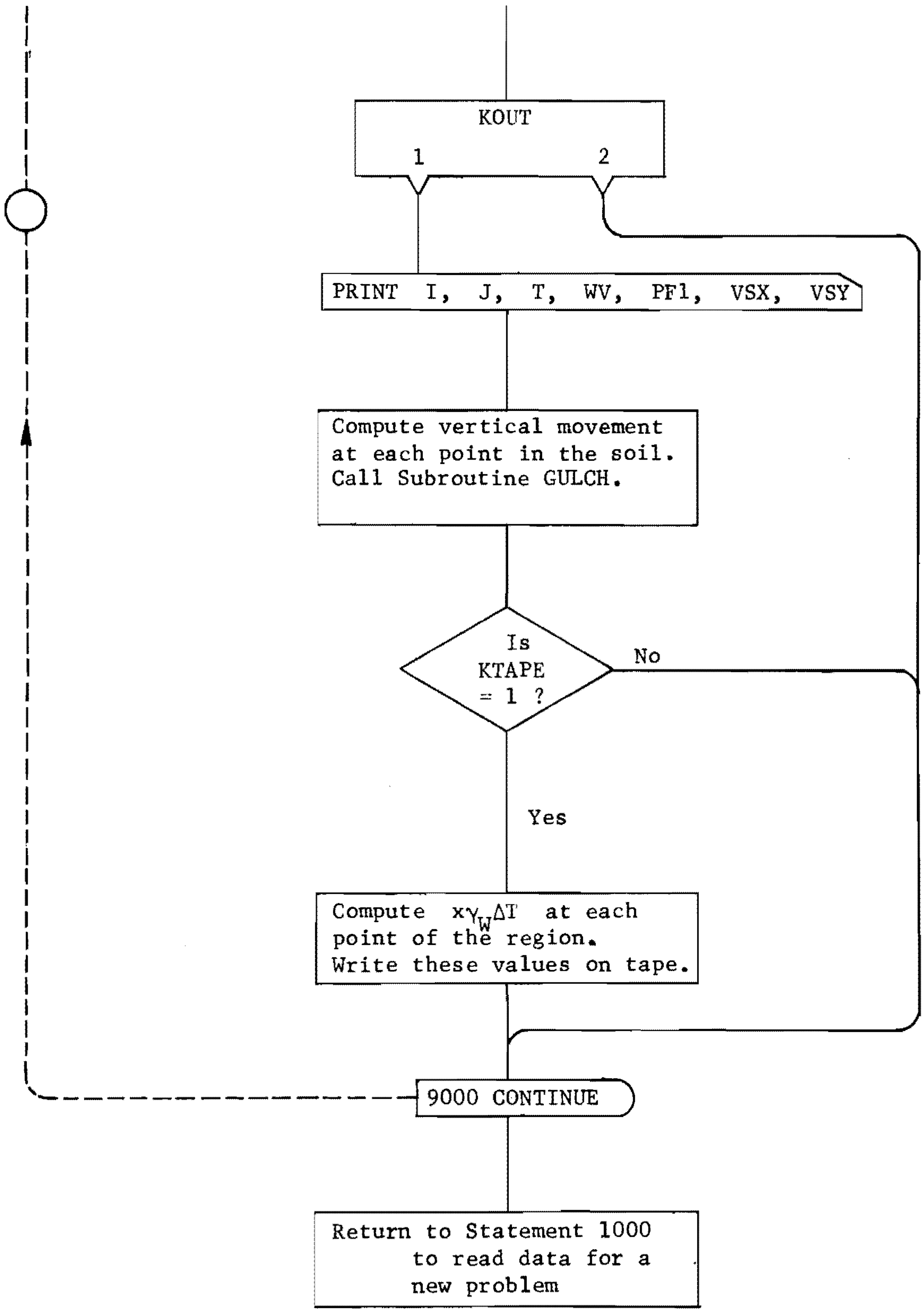


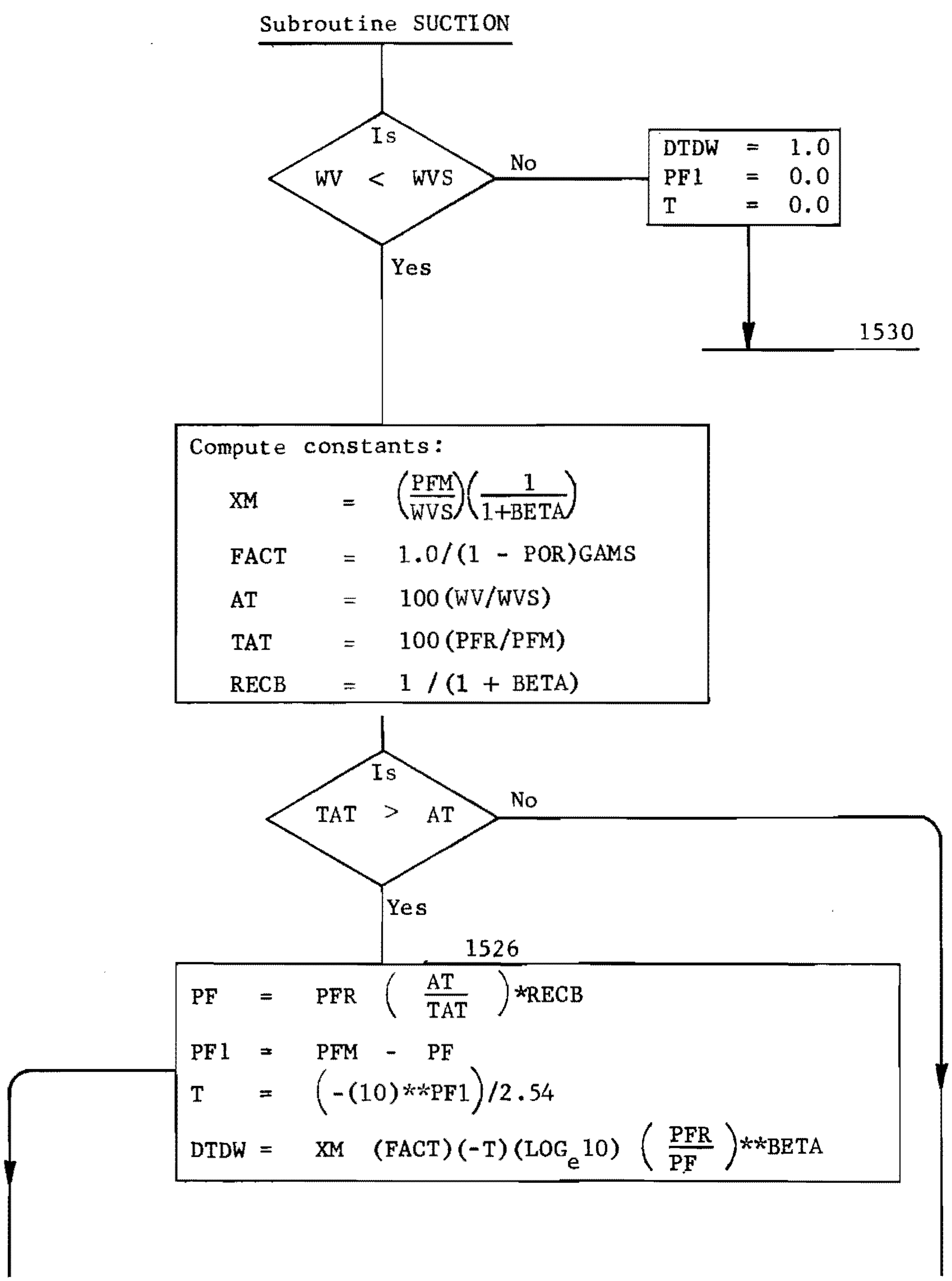
Is pt. on boundary
No
Yes
Compute point gradient continuity coefficients
I
Compute pipe increment gradient continuity coefficients
Compute normal continuity coefficients AA, BB, CC
2300 CONTINUE
J
DO 2370 I = 3, MX + 3
I
Compute TX
2370 CONTINUE
K
IT
DO 2570 I = 3, MX + 3
DO 2400 J = 3, MY + 3
is IT > IX
Yes
No
J
I
Preset VSX(I,J) = VX(IT)
Compute natural VSX(I,J)

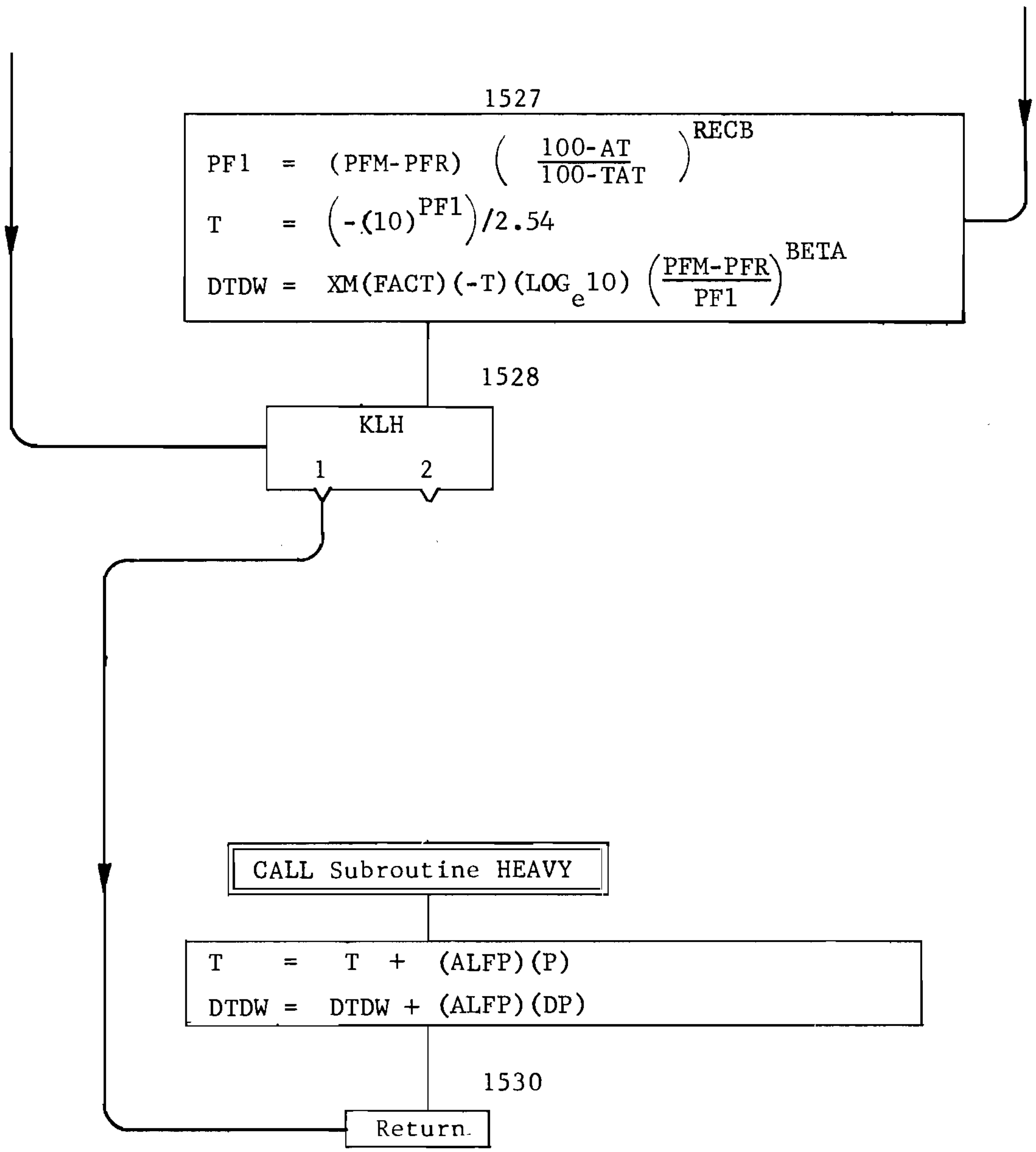

Compute y-tube flow coefficients AL, BL, CL, DL
J
2400 CONTINUE
DO 2500 J = 3, MY + 3
KAS(I,J)
1
2
3
4
J
Compute normal continuity coefficients AA, BB, CC
Compute suction set continuity coefficients
I
Compute normal continuity coefficients AA, BB, CC
Is pt. on boundary
No
Yes
IT
K
Compute point gradient continuity coefficients
Compute pipe increment gradient continuity coefficients
2500 CONTINUE
DO 2570 J = 3, MY + 3



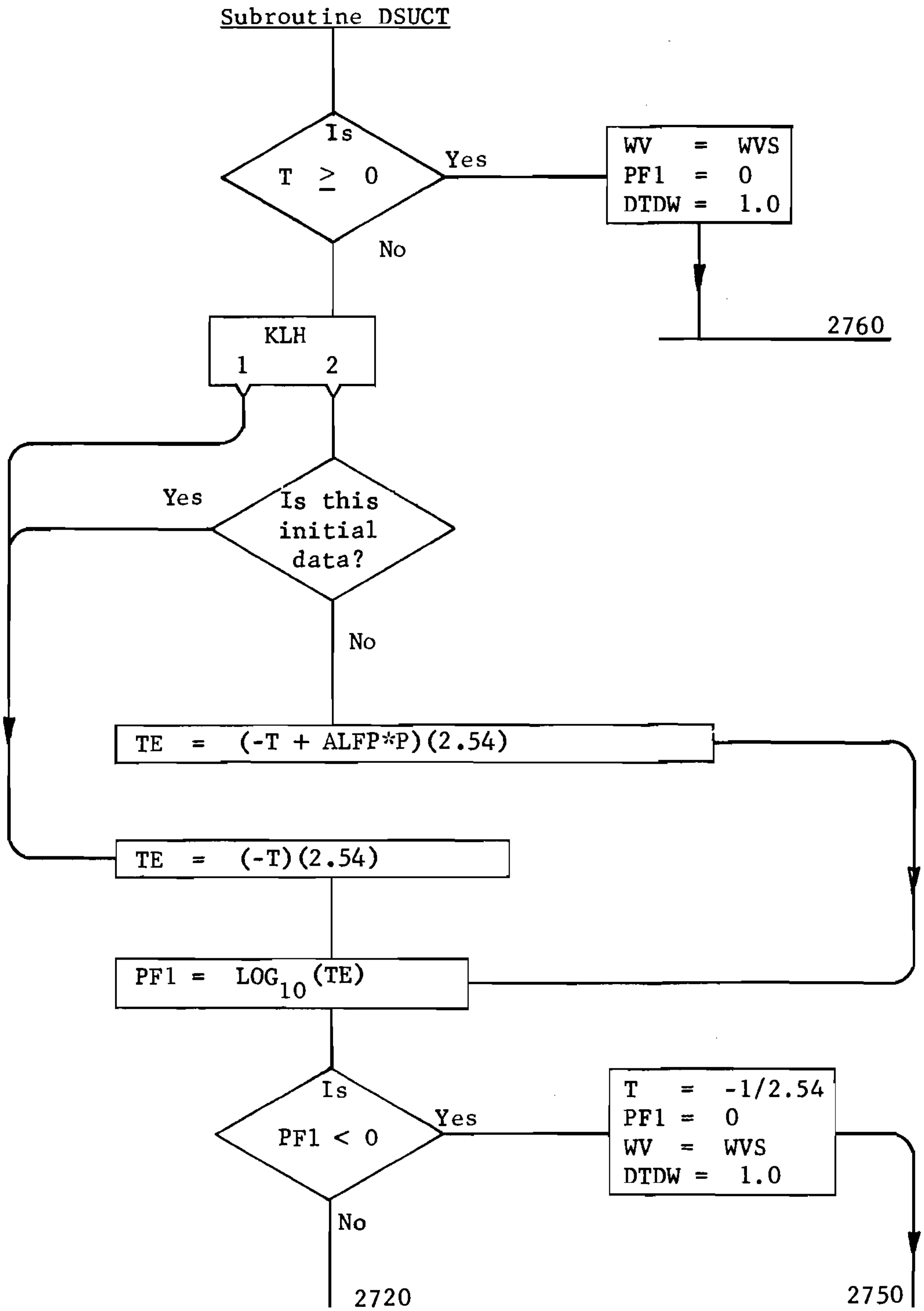
J
Compute TY
2570 CONTINUE
Is (TY-TX) < (ε)(TY) at each point
Yes
No
Set KLOS(I,J) = 2 at each point not closed. KLOS(I,J) is set at 1 at all other points
KOUT
1
2
IT
PRINT monitor data
8000 CONTINUE
KLOS(I,J) at each point
1
2
Set new T = weighted average of TX and TY
Set new T = value from modified forward difference method
K
CALL Subroutine DSUCT

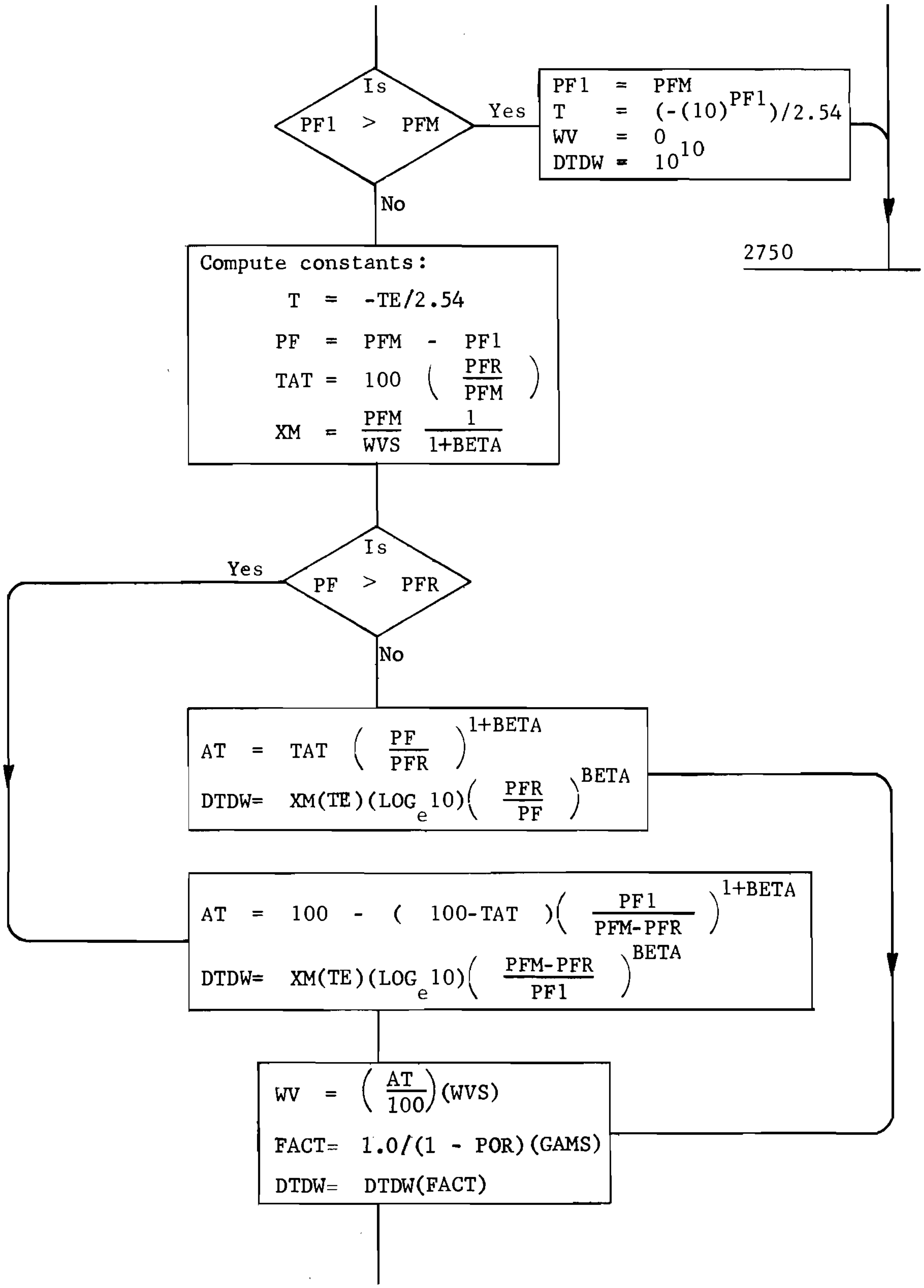

KOUT
1
2
PRINT I, J, T, WV, PF1, VSX, VSY
Compute vertical movement at each point in the soil. Call Subroutine GULCH.
Is KTAPE = 1 ?
No
Yes
Compute $x\gamma_W \Delta T$ at each point of the region. Write these values on tape.
9000 CONTINUE
Return to Statement 1000 to read data for a new problem

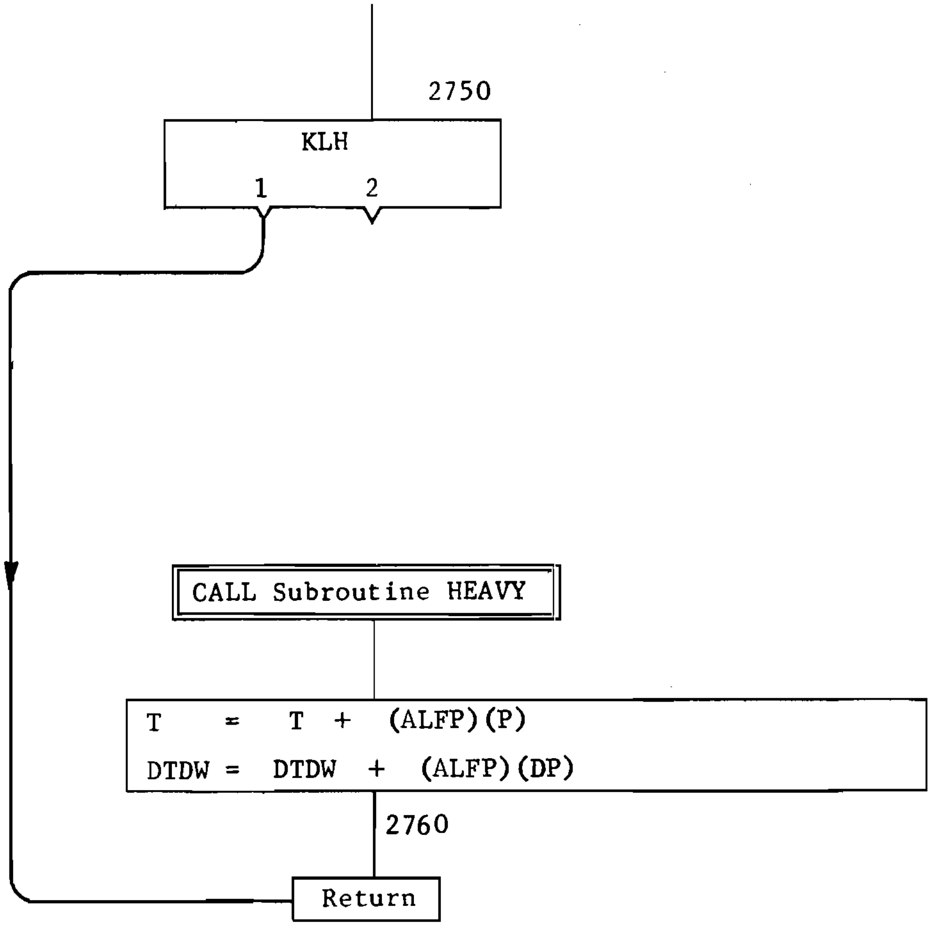

Subroutine SUCTION
Is WV < WVS
No
DTDW = 1.0
PF1 = 0.0
T = 0.0
1530
Yes
Compute constants:
XM = $\left(\frac{PFM}{WVS}\right)\left(\frac{1}{1+BETA}\right)$
FACT = 1.0/(1 - POR)GAMS
AT = 100(WV/WVS)
TAT = 100(PFR/PFM)
RECB = 1 / (1 + BETA)
Is TAT > AT
No
Yes
1526
PF = PFR $\left(\frac{AT}{TAT}\right)$*RECB
PF1 = PFM - PF
T = $\left(-(10)**PF1\right)$/2.54
DTDW = XM (FACT)(-T)(LOG_e10) $\left(\frac{PFR}{PF}\right)$**BETA



1527
PF1 = (PFM-PFR) $\left(\frac{100\text{-}AT}{100\text{-}TAT}\right)^{RECB}$
T = $\left(-(10)^{PF1}\right)/2.54$
DTDW = XM(FACT)(-T)(LOG_e10) $\left(\frac{PFM\text{-}PFR}{PF1}\right)^{BETA}$
1528
KLH
1
2
CALL Subroutine HEAVY
T = T + (ALFP)(P)
DTDW = DTDW + (ALFP)(DP)
1530
Return


Subroutine DSUCT
Is T ≥ 0
Yes
No
WV = WVS
PF1 = 0
DTDW = 1.0
2760
KLH
1 2
Yes
Is this initial data?
No
TE = (-T + ALFP*P)(2.54)
TE = (-T)(2.54)
PF1 = LOG10 (TE)
Is PF1 < 0
Yes
No
T = -1/2.54
PF1 = 0
WV = WVS
DTDW = 1.0
2720
2750


Is
PF1 > PFM
Yes
PF1 = PFM
T = (-(10)^PF1)/2.54
WV = 0
DTDW = 10^10
2750
No
Compute constants:
T = -TE/2.54
PF = PFM - PF1
TAT = 100 (PFR/PFM)
XM = PFM/WVS 1/(1+BETA)
Is
PF > PFR
Yes
No
AT = TAT (PF/PFR)^1+BETA
DTDW= XM(TE)(LOG_e 10)(PFR/PF)^BETA
AT = 100 - (100-TAT)(PF1/(PFM-PFR))^1+BETA
DTDW= XM(TE)(LOG_e 10)((PFM-PFR)/PF1)^BETA
WV = (AT/100)(WVS)
FACT= 1.0/(1 - POR)(GAMS)
DTDW= DTDW(FACT)


2750
KLH
1
2
CALL Subroutine HEAVY
T = T + (ALFP)(P)
DTDW = DTDW + (ALFP)(DP)
2760
Return

Subroutine GULCH

Compute overburden plus surcharge pressure

Is total pressure > maximum swelling Pressure ?

Yes

$DV = 0.0$

1770

No

$$VTP = VTF - \left(\frac{P}{PO} \right)^{\frac{1}{ENP}} (VTF - VTO)$$

$$WVP = WVF - (VTF - VTP) \; 100$$

Is Initial WV > WVA (air entry)

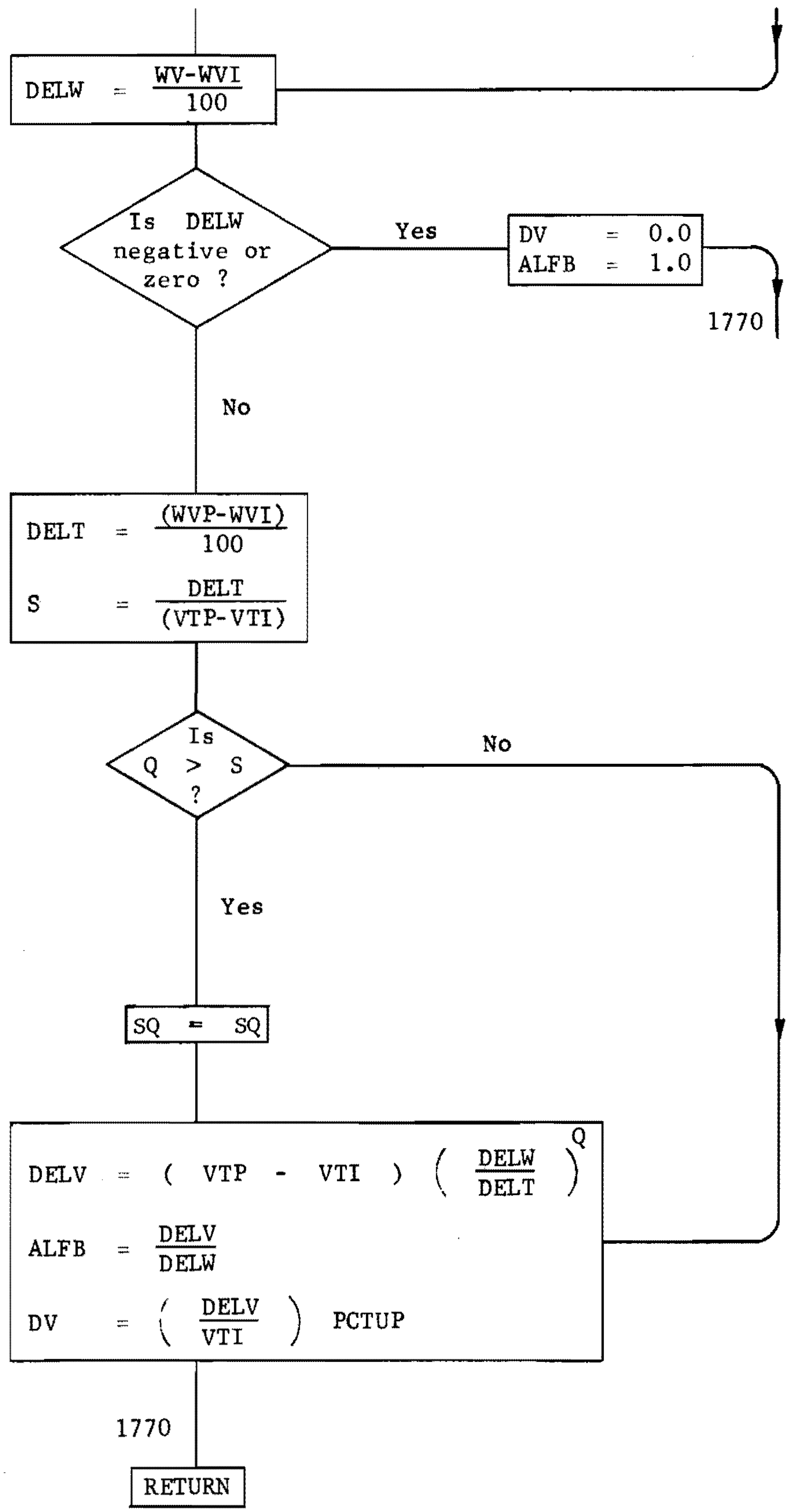
Yes

No

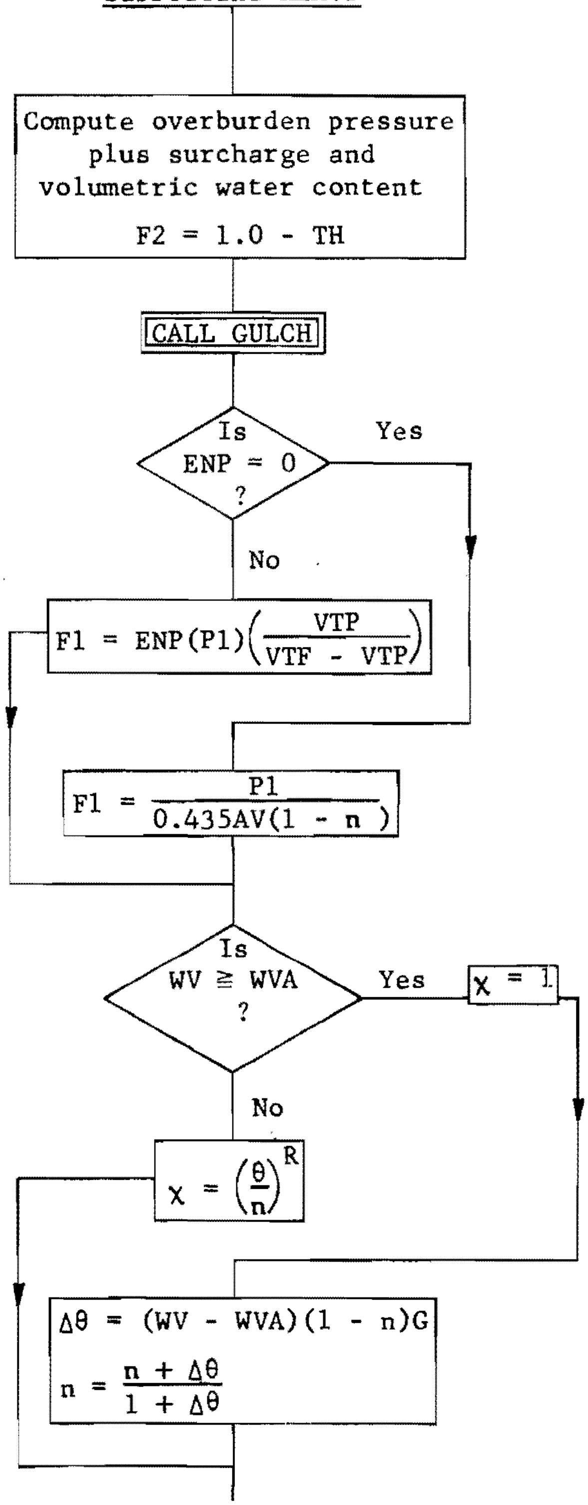
$$VTI = VTO + \frac{WVI}{100} \left[ALFO + \frac{(1-ALFO)}{Q} \left(\frac{WVI}{WVA} \right)^{Q-1} \right]$$

$$VTAP = VTO + \frac{WVA}{100} \left[ALFO + \frac{(1-ALFO)}{Q} \right]$$

$$VTI = VTAP + \left(\frac{WVI-WVA}{100} \right)$$


DELW = WV-WVI / 100
Is DELW negative or zero ?
Yes
DV = 0.0
ALFB = 1.0
1770
No
DELT = (WVP-WVI) / 100
S = DELT / (VTP-VTI)
Is Q > S ?
No
Yes
SQ = SQ
DELV = (VTP - VTI) (DELW / DELT)^Q
ALFB = DELV / DELW
DV = (DELV / VTI) PCTUP
1770
RETURN

Subroutine HEAVY



$$\boxed{dP = F1/[F2(\chi)(0.0361)]}$$

$$\boxed{\alpha_p = \alpha_B\left[1 = \alpha_B\left(\frac{WV - WVI}{VTP - VTI}\right)\right]}$$

RETURN

APPENDIX 3

GUIDE FOR DATA INPUT GCHPIP7

GENERAL PROGRAM NOTES

A detailed discussion of all input data is given in Chapter 3

All words not marked E or F are understood to be input as integers, the last number of which is in the farthest right space in the box . . . . `22`

All words marked E or F are for decimal numbers, which may be input at any position in the box with the decimal point in the proper position . . . . `-19.36`

`0.0013`

`72.`

The words marked E have been provided for those numbers which may require an exponential expression. The last number of the exponent should appear in the farthest right space in the box . . . . `-3.142E-06`

The program is arranged to compute quantities in terms of pounds, inches, and seconds. All dimensional input should be in these units.

GCHPIP7 GUIDE FOR DATA INPUT -- Card forms

IDENTIFICATION OF PROGRAM AND RUN (one alphanumeric card per problem)

1	80

1	80

IDENTIFICATION OF PROBLEM (one card per problem; program stops if NPROB is left blank)

NPROB (1–5)		DESCRIPTION OF PROBLEM (alphanumeric) (11–80)

TABLE 1. TABLE CONTROLS, HOLD OPTIONS

ENTER 1 TO HOLD PRIOR TABLE						NUM CARDS ADDED FOR TABLE						SWITCH KGRCL	SWITCH KLH	SWITCH KTAPE
2	3	4	5	6	7	2	3	4A	5	6	7	1 or 2	1 or 2	1 or 0
5	10	15	20	25	30	35	40	45	50	55	60	65	70	75

IF KGRCL IS
- 1 Grid Coordinates
- 2 Cylindrical Coordinates

IF KLH IS
- 1 Light - overburden pressure and compressibility not considered
- 2 Heavy - overburden pressure and compressibility considered

IF KTAPE IS
- 1 Calculate and store equivalent stress release
- 0 Skip this section of program

TABLE 2A. INCREMENTS ITERATION CONTROL

NUM OF X-INCRS	NUM OF Y-INCRS	MAX ITERS PER TIME STEP	NUM TIME STEPS	X-INCR LENGTH	Y-INCR LENGTH	INSIDE RADIUS	TIME STEP	CLOSURE TOLERANCE
				E	E	E	E	E
1 5	10	15	20	30	40	50	60	70

TABLE 2B. MONITOR STATIONS

COORDINATES OF MONITOR POINTS

I	J	I	J	I	J	I	J
1 5	10	15	20	25	30	35	40

TABLE 2C. CHOICE OF TRANSIENT OR PSEUDO STEADY-STATE FLOW

1 : TRANSIENT FLOW 2 : PSEUDO STEADY-STATE FLOW

5

TABLE 3. PERMEABILITY

FROM		TO					UNSATURATED PERMEABILITY COEFFICIENTS		
I	J	I	J	PERMEABILITY B P1	PERMEABILITY H P2	ANGLE FROM P1 TO HORIZ.	AK	BK	EN
				E	E	E	E	E	E
1 5	10	15	20	30	40	50	60	70	80

TABLE 4. SUCTION-MOISTURE-COMPRESSIBILITY

NUMBER LOCATIONS	MAX PF	INTL PF	PF VERSUS CURVE EXPONENT	AIR ENTRY WATER CONTENT	ALFA EXPONENT	ALFA AT ZERO WATER CONTENT	POROSITY AT AIR ENTRY	E-LOG P COMPRESSIBILITY COEFFICIENT	X EXPONENT	UNIT WEIGHT OF SOIL	FINAL SATURATION WATER CONTENT
	F	F	F	F	F	E	E	E	F	F	E
1 5	10	15	20	25	30	40	50	60	65	70	80

DRY SPECIFIC TOTAL VOLUME	FINAL SPECIFIC TOTAL VOLUME	FINAL ZERO AIR WATER CONTENT	SWELL PRESSURE, psi	EXPONENT OF P-V CURVE	SURCHARGE PRESSURE, psi	RATIO VOLUME CHANGE VERTICAL	SPECIFIC GRAVITY OF SOLIDS
E	E	E	E	E	E	E	E
1 10	20	30	40	50	60	70	80

FROM I	FROM J	TO I	TO J	CURVE NUM KAT
1 5	10	15	20	25

TABLE 5. INITIAL CONDITIONS

FROM I	FROM J	TO I	TO J	KAT 1 OR 2	WATER CONTENT	SUCTION	Y-SLOPE A2	X-SLOPE C2
					E	E	E	E
1 5	10	15	20	25	31 40	50	60	70

TABLE 6. BOUNDARY AND INTERNAL CONDITIONS

FROM I	FROM J	TO I	TO J	KASE 1 TO 5	WATER CONTENT	SUCTION	X-GRADIENT OF SUCTION	Y-GRADIENT OF SUCTION	SOIL-MOISTURE HUMIDITY	TEMP
					E	E	E	E	F	F
1 5	10	15	20	25	31 40	50	60	70	75	77 80

TABLE 7. CLOSURE ACCELERATION DATA

NUM VX	NUM VY
5	10

VX and VY are externally specified x and y-closure valve settings which are all used before natural closure valve settings are computed.

X-CLOSURE VALVE SETTINGS (maximum number is 10)

E	E	E	E	E	E	E	E
1–10	20	30	40	50	60	70	80

E	E
1–10	20

Y-CLOSURE VALVE SETTINGS (maximum number is 10)

E	E	E	E	E	E	E	E
1–10	20	30	40	50	60	70	80

E	E
1–10	20

TABLE 8A. TIME STEPS FOR BOUNDARY-CONDITION CHANGE

KEY	NSTEP
5	8–10

IF KEY IS 1 Read in a list of time steps for boundary-condition change NSTEP is the number of these steps.

2 Continuous boundary-condition change. Read in a new boundary condition at each time step. NSTEP is left blank.

3 No boundary-condition change. NSTEP is left blank.

LIST OF TIME STEPS (if KEY = 1 , maximum is 50)

1–5	10	15	20	25	30	35	40	45	50	55	60	65	70

1–5	10	15	20	25	30	~~35~~

TABLE 8B. LIST OF TIME STEPS FOR OUTPUT

KEYB	NOUT
5	8 – 10

IF KEYB IS
1 Read in a list of output time steps. NOUT is the number of these time steps.
2 Continuous output. Value of NOUT not used.

LIST OF TIME STEPS (if KEYB = 1 , maximum is 50)

1–5	10	15	20	25	30	35	40	45	50	55	60	65	70

1–5	10	15	20

TABLE 9. SUBSEQUENT BOUNDARY CONDITIONS (if KEY = 1 or 2)

TIME STEP	NUMBER CARDS
1–5	10

FROM I	FROM J	TO I	TO J	KASE 1 TO 5	WATER CONTENT	SUCTION	X-GRADIENT OF SUCTION	Y-GRADIENT OF SUCTION	SOIL-MOISTURE HUMIDITY	TEMP
					E	E	E	E	F	F
1–5	10	15	20	25	31–40	50	60	70	75	77–80
					KASE = 1	KASE = 2	KASE = 3	KASE = 4	KASE = 5	

APPENDIX 4

PROGRAM LISTING GCHPIP7

```
      PROGRAM GCHPIP7 (INPUT,OUTPUT)                                     25MAY70
C     NOTATION
C     T          SUCTION
C     TX         TRIAL SUCTION  IN  X - PIPES
C     TY         TRIAL SUCTION IN  Y - PIPES
C     P11        PERMEABILITY IN X-DIRECTION  AFFECTED BY  X- HEAD CHANGE
C     P12        PERMEABILITY IN X-DIRECTION  AFFECTED BY  Y- HEAD CHANGE
C     P21        PERMEABILITY IN Y-DIRECTION  AFFECTED BY  X- HEAD CHANGE
C     P22        PERMEABILITY IN Y-DIRECTION  AFFECTED BY  Y- HEAD CHANGE
C     P1         PRINCIPAL  PERMEABILITY NEAREST  X-DIRECTION
C     P2         PRINCIPAL  PERMEABILITY NEAREST  Y-DIRECTION
C     A          SUCTION              COEFFICIENT  OF  T( I,J-1)
C     B          SUCTION              COEFFICIENT  OF  T( I-1,J)
C     C          SUCTION              COEFFICIENT  OF  T( I , J)
C     D          SUCTION              COEFFICIENT  OF  T( I+1,J)
C     E          SUCTION              COEFFICIENT  OF  T(I,J+1)
C     F          GRAVITY  POTENTIAL COMPONENT  OF  PERMEABILITY
C     DTDW       RATE OF CHANGE OF SUCTION  WITH WATER  CONTENT
C     AL         TUBE  FLOW  MATRIX COEFFICIENT  OF    TX  OR  TY AT I -1
C     BL         TUBE  FLOW  MATRIX COEFFICIENT  OF    TX  OR  TO AT I
C     CL         TUBE  FLOW  MATRIX COEFFICIENT  OF    TX  OR  TY AT I +1
C     DL         TUBE  FLOW     CONSTANT
C     HX         INCREMENT  LENGTH  IN  THE  X-DIRECTION
C     HY         INCREMENT  LENGTH  IN  THE  Y-DIRECTION
C     HT         INCREMENT  LENGTH  IN  THE  TIME- DIRECTION
C     AA         CONTINUITY  COEFFICIENT  - A  CONSTANT
C     BB         CONTINUITY  COEFFICIENT  - B  CONSTANT
C     CC         CONTINUITY  COEFFICIENT  - C  CONSTANT
C     DD         CONTINUITY  COEFFICIENT  - A  DENOMINATOR
C     ALPHA      ANGLE BETWEEN  P1 AND  THE  X- DIRECTION
C     EPS        CLOSURE  TOLERANCE  ON  DIFFERENCE  IN TX AND  TY
C     WV         VOLUMETRIC WATER  CONTENT
C     WVS        SATURATED WATER CONTENT
C     VSX        CLOSURE  PARAMETER  FOR  THE   X-DIRECTION
C     VSY        CLOSURE  PARAMETER  FOR  THE   Y-DIRECTION
      DIMENSION P1(29,35),P2(29,35),ALFA(29,35),AK(29,35),BK(29,35),
     1EN(29,35),WV(29,35),T(29,35),P11(29,35),P12(29,35),P22(29,35),
     2DTDW(29,35),VSX(29,35),VSY(29,35),A(29,35),B(29,35),CX(29,35),
     3CY(29,35),D(29,35),E(29,35),F(29,35),AL(35),BL(35),CL(35),DL(35),
     4AA(35),BB(35),CC(35),TX(29,35),TY(29,35),KURV(29,35),
     5KLOC(1000),AN1(16),AN2(7),WVS(29,35),DTDX(29,35),DTDY(29,35),
     6KAS(29,35),VX(10),VY(10),PFM(10),PFR(10),BETA(10),WVA(10),Q(10),
     7ALFO(10),R(10),AV(10),PN(10),POR(29,35),KT(50),WN(10),KPUT(1000),
     8KLOS(29,35),WVI(29,35),VTO(10),VTF(10),WVF(10),PO(10),E-P(10),
     9GAMS(10),DVERT(35),DV(29,35),TI(29,35),AT(29,35)
      COMMON/ONE/PFM,PFR,BETA,DTDW,PF1
     1/TWO/T,I2,J2
     2/THREE/WVS,KLH,K
     3/FOUR/WVA,Q,ALFO,R,AV,POR,KURV,WV,GAM,ALF,P,DP,DALF,MY,+Y,PN
     4/FIVE/WVI,VTO,VTF,WVF,PO,ENP,GAMS,SRCH,PCTUP,DV,ALFB,VTP,ALFP      25MAY70
    1 FORMAT (// 50H  PROGRAM GCHPIP7   R.L.LYTTON  REVISION DATE
     1           12H25 MAY, 1970,  //)
   11 FORMAT(      5H1     ,80X ,10HI-----TRIM )
   12 FORMAT (  8A10)
   14 FORMAT ( A5,5X,7A10)
   15 FORMAT (///10H      PROB , /5X, A5, 5X, 7A10)
   20 FORMAT (16I5)
   21 FORMAT ( 4I5,5E10.3)
   22 FORMAT ( 4I5,6E10.3)
   23 FORMAT ( I5,5F5.2,3E10.3,2F5.1,E10.3)
   24 FORMAT (5I5,5X,4E10.3)
   25 FORMAT ( 5I5,5X,4E10.3,F5.3,1X,F4.1)
   26 FORMAT( 8E10.3)
   27 FORMAT ( 5X,I5,2(5X,E10.3))
   28 FORMAT( 2I4,2X,6(E10.3,2X))
   29 FORMAT (// 50H   I    J     T(I,J)        WV(I,J)     DTDW(I,J)    P11
     1             30H(I,J)     P12(I,J)     P22(I,J)      )
  100 FORMAT (///40H  TABLE 1. PROGRAM CONTROL SWITCHES.
     1 / 50X,      25H             TABLES NUMBER
     2 / 50X,      35H      2      3     4A    5     6     7
     3        //   40H             PRIOR  DATA OPTIONS (1 = HOLD),11X ,6I5,
     4          /  41H             NUMBER CARDS INPUT THIS PROBLEM, 10X,6I5,
     5   //        41H             GRID = 1, CYLINDER = 2 SWITCH   , 10X,I5,
     6    //       41H             LIGHT = 1, HEAVY = 2  SWITCH    Y 10X,I5,
     7    //       41H             TAPE WRITE  YES = 1               = 10X,I5 )
  200 FORMAT (///50H  TABLE 2. INCREMENT LENGTHS. ITERATION C-NTROL     )
  201 FORMAT (// 35H             NUM OF X-INCREMENTS     = , 5X,I5,
     1      /    , 35H           X-INCREMENT LENGTH      = , E10.3,5H IN. ,
     2      /    , 35H           NUM OF  Y-INCREMENTS    = , 5X,I5 ,
     3      /    , 35H           Y-INCREMENT LENGTH      = , E10.3,5H IN. ,
     4      /    , 35H           NUM OF TIME INCREMENTS = , 5X, I5,
     5      /    , 35H           TIME INCREMENT LENGTH  = , E10.3,5H SECS,
     6      /    , 35H           ITERATIONS / TIME STEP = , 5X,I5,
     7      /    , 35H           INSIDE RADIUS           = ,E10.3,5H IN    ,
     8      /    , 35H           TOLERANCE               = ,E10.3)
  202 FORMAT (// 30H             MONITOR STATIONS I,J ,5X, 4(I7,+3I))
  203 FORMAT (// 25H    TRANSIENT  FLOW        )
  204 FORMAT (// 35H     PSEUDO-STEADY STATE FLOW        )
  300 FORMAT (///30H  TABLE  3.  PERMEABILITY       )
  301 FORMAT (// 50H   FROM        TO          P1          P2   ALFA(DEG.)
     1           30H    AK          BK    EXPONENT    )
  400 FORMAT (///45H  TABLE  4. SUCTION - WATER CONTENT CURVES    )
  401 FORMAT (// 35H             CURVE NUMBER                 ,I5,
     1     /,    35H             NUM  LOCATIONS          =  , I5,
     2     /,    35H             MAXIMUM  PF             =  ,5X,F5.2,
     3     /,    35H             PF  AT  INFLECTION      =  ,5X,F5.2,
     4     /,    35H             EXPONENT  FOR  PF       =  ,5X,F5.2,
     5     /,    35H             AIR ENTRY WATER CONT    =  ,5X,F5.2,
     6     /,    35H             DRYING CURVE EXPONENT =  ,5X,F5.2,
     7     /,    35H             ALFA AT 0 WATER CONT    =  , E10.3,
     8     /,    35H             INITIAL  POROSITY       =  , E10.3,
     9     /,    35H             REFERENCE  AV           =  , E10.3    )
  402 FORMAT (    35H            SATURATION EXPONENT     =  ,5X,F5.2,
     1     /,    35H             SOIL UNIT WT  PCI       =  , E10.3 ,
     2     /,    35H             SATURATED WATER CONT. =  , E10.3,// )
  403 FORMAT (// 25H   NO.       FROM     TO       )
  404 FORMAT (///35H             CURVE NUMBER               , I5,
     1          /35H             INITIAL TOTAL VOLUME  =  , E10. ,
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    2           /35H           FINAL TOTAL VOLUME    =  , E10.3,
    3           /35H           FINAL WATER CONTENT   =  , E10.3,
    4           /35H           SWELL PRESSURE, PSI   =  , E10.3,
    5           /35H           EXPONENT OF P-V CURVE =  , 5X,F5.2,
    6           /35H           SURCHARGE PRESS, PSI  =  , E10.3,
    7           /35H           PCT VOL CHG VERTICAL  =  , E10.3,
    8           /35H           SPEC.GRAV.SOLIDS      =  , E10.3, // )
  500 FORMAT (///30H  TABLE 5. INITIAL CONDITIONS  )
  501 FORMAT (// 50H     FROM       TO      CASE      VOL. W.    PORE PR.
    1           20H  SLOPE Y   SLOPE X    )
  600 FORMAT (///45H  TABLE 6. BOUNDARY AND INTERNAL CONDITIONS  )
  601 FORMAT (// 50H  FROM STA    TO STA  CASE          WV          T
    1           40H  DT/DX        DT/DY       H  TEMP            )
  700 FORMAT (///40H  TABLE 7.  CLOSURE ACCELERATION DATA    )
  701 FORMAT (// 40H     FICTITIOUS CLOSURE VALVE SETTINGS  ,//,
    1           40H       NO.        VSX           VSY          )
  800 FORMAT (///40H  TABLE 8A. TIME STEPS FOR B.C. CHANGE    )
  801 FORMAT (// 50H  ITERATION  PTS.NOT CLOSED               MONITOR
    1           10H STATIONS ,//,32X, 4(2I3,6X)  )
  802 FORMAT ( 2(5X,I5),10H    TX       ,4(E10.3,2X)  )
  803 FORMAT (    20X,  10H    TY       , 4(E10.3,2X),/ )
  804 FORMAT (// 50H  STATION      T(I,J)       WV(I,J)       PF(I,J)
    1             30HVSX(I,J)     VSY(I,J)               )
  805 FORMAT ( 2I4,5X,5(E10.3,2X)    )
  806 FORMAT (// 10H     ALL    )
  807 FORMAT (// 10H    NONE     )
  808 FORMAT (///40H  TABLE 8B. TIME STEPS FOR OUTPUT.       )
  809 FORMAT (// 15H    TIME STEP  =   , I5,//)
  810 FORMAT (// 20H    ***CLOSURE***      ,//)
  811 FORMAT (///40H     HEAVE PROFILE FOR SOIL AT J-LEVEL  ,I3,
    1          // 30H      I-STA    VERTICAL MOVEMENT , // )
  900 FORMAT (// 50H  TABLE 9. SUBSEQUENT BOUNDARY CONDITIONS          )
  905 FORMAT (// 40H    USING DATA FROM PREVIOUS PROBLEM     )
  906 FORMAT (// 45H    USING DATA FROM PREVIOUS PROBLEM PLUS     )
  907 FORMAT (// 25H     ERROR IN DATA         )
                ITEST   =   5H
 1000 READ 12,(AN1(N), N =1, 16)
 1010 READ 14, NPROB, ( AN2(N), N =1,7)
         IF (NPROB - ITEST) 1020, 9999, 1020
 1020 PRINT 11
      PRINT 1
      PRINT 12, (AN1(N), N = 1,16)
      PRINT 15, NPROB, (AN2(N), N =1,7)
C     INPUT  OF  TABLE 1 . TABLE CONTROLS,  HOLD OPTIONS,
 1100 READ 20, KEEP2,KEEP3,KEEP4,KEEP5,KEEP6,KEEP7,NCD2,NCD3,NCD4,NCD5,
     1NCD6,NCD7,KGRCL,KLH,KTAPE
      PRINT 100,KEEP2,KEEP3,KEEP4,KEEP5,KEEP6,KEEP7,NCD2,NCD3,NCD4,
     1NCD5,NCD6,NCD7,KGRCL,KLH,KTAPE
C     INPUT OF  TABLE 2A  INCREMENTS, ITERATION CONTROL
 1200 PRINT 200
         IF(KEEP2)9980, 1210, 1230
 1210 READ 21, MX,MY,ITMAX,ITIME,HX,HY,RO,HT,EPS
      PRINT 201, MX,HX,MY,HY,ITIME,HT,ITMAX,RO,EPS
         GO TO 1240
 1230 PRINT 905
C     COMPUTE  CONSTANTS TO BE USED IN THE PROGRAM
 1240          MXP5   =  MX + 5
               MYP5   =  MY + 5
               MXP4   =  MX + 4
               MYP4   =  MY + 4
               MXP3   =  MX + 3
               MYP3   =  MY + 3
                MXP2      =  MX + 2
                MYP2      =  MY + 2
C     READ IN THE TABLE  2B  MONITOR STATIONS
      READ 20, IM1,JM1,IM2,JM2,IM3,JM3,IM4,JM4
      PRINT 202,IM1,JM1,IM2,JM2, IM3, JM3, IM4, JM4
               IM1    =  IM1 + 3
               JM1    =  JM1 + 3
               IM2    =  IM2 + 3
               JM2    =  JM2 + 3
               IM3    =  IM3 + 3
               JM3    =  JM3 + 3
               IM4    =  IM4 + 3
               JM4    =  JM4 + 3
C     TABLE  2C.  CHOICE  OF  TRANSIENT OR  STEADY  STATE  FL W
      READ 20,IN1
         GO TO (1250,1260) IN1
 1250 PRINT 203
               A4           =  1.0
         GO TO 1300
 1260 PRINT 204
               A4           =  0.0
C     INPUT  TABLE  3,  PERMEABILITY
 1300 PRINT 300
          IF(KEEP3) 9980,1310,1317
 1310     DO 1315  I = 1, MXP5
          DO 1315  J = 1, MYP5
               P1(I,J)    =   0.0
               P2(I,J)    =   0.0
               ALFA(I,J)  =   0.0
               AK (I,J)   =   0.0
               BK (I,J)   =   0.0
               EN (I,J)   =   0.0
               WVS(I,J)   =   0.0
 1315    CONTINUE
         GO TO 1319
 1317     IF (NCD3)9980,1330,1318
 1318 PRINT 906
 1319 PRINT 301
         DO 1320  K = 1, NCD3
      READ 22, IN1,JN1,IN2,JN2,PB,PL,ALF,AK1,BK1,EN1
      PRINT 22,IN1,JN1,IN2,JN2,PB,PL,ALF,AK1,BK1,EN1
               IN1    =  IN1 + 3
               JN1    =  JN1 + 3
               IN2    =  IN2 + 3
               JN2    =  JN2 + 3
          DO 1320  I  = IN1,IN2
          DO 1320  J  = JN1,JN2
               P1(I,J)    =   P1(I,J) +  PB
               P2(I,J)    =   P2(I,J) + PL
               ALFA(I,J)  =   ALFA(I,J)+ ALF
```

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            AK (I,J)  =   AK  (I,J)+  AK1
            BK (I,J)  =   BK  (I,J)+  BK1
            EN(I,J)   =   EN(I,J)  +  EN1
 1320     CONTINUE
         GO TO 1400
 1330 PRINT 905
C     INPUT OF TABLE  4. SUCTION - WATER CONTENT CURVE
C     AT PRESENT,  THIS IS AN EXPONENTIAL SINGLE - VALUED CUROE.   IT
C    1SHOULD BE REPLACED BY NUMERICAL CURVES  FOR WETTING, DRYING, AND
C    2SCANNING BETWEEN THE TWO.
 1400 PRINT 400
          IF (KEEP4) 9980,1410,1430
 1410          NLOC  = 0
          DO 1415 M  =  1,NCD4
      READ 23,LOC,PFM(M), PF1  ,BETA(M),WVA(M),Q(M),ALFO(M),PN(M),AV(M),
     1R(M),GAM,WN(M)
      PRINT 401,M,LOC,PFM(M), PF1  ,BETA(M),WVA(M),Q(M),ALFO(M),
     1PN(M),AV(M)
      PRINT 402,R(M),GAM,WN(M)
      READ 26, VTO(M), VTF(M), WVF(M), PO(M), ENP(M), SRCH, PCTUP,
     1         GAMS(M)
      PRINT 404, M, VTO(M), VTF(M), WVF(M), PO(M), ENP(M), SRCH,
     1            PCTUP, GAMS(M)
               PFR(M)    =  PFM(M) - PF1
               NLOC  =  NLOC + LOC
 1415     CONTINUE
      PRINT 403
          DO 1420 M  =  1,NLOC
      READ 20, IN1,JN1,IN2,JN2,KAT
      PRINT 20, KAT,IN1,JN1,IN2,JN2
               IN1  =  IN1 + 3
               JN1  =  JN1 + 3
               IN2  =  IN2 + 3
               JN2  =  JN2 + 3
          DO 1420 I  = IN1,IN2
          DO 1420 J  = JN1,JN2
               KURV(I,J)  =  KAT
              POR(I,J)   =   PN(KAT)
               WVS(I,J)  =  WN(KAT)
 1420     CONTINUE
          GO TO 1500
 1430 PRINT 905
C     INPUT OF TABLE 5. INITIAL CONDITIONS
 1500 PRINT 500
          IF(KEEP5)9980,1510,1505
 1505     IF(NCD5) 9980,1506,1507
 1506 PRINT 905
          GO TO 1600
 1507 PRINT 906
          GO TO  1520
 1510     DO 1515 I = 1,MXP5
          DO 1515 J = 1,MYP5
               WV(I,J) =  0.0
               WVI(I,J)  =  0.0
               T(I,J)      =  0.0
               TI(I,J)   =   0.0
```

```
 1515     CONTINUE
 1520 PRINT  501
          DO 1526 M =  1,NCD5
               K           =  0
      READ 24 , IN1,JN1,IN2,JN2,KAT,WV1,T1,A2 , C2
      PRINT 24, IN1,JN1,IN2,JN2,KAT,WV1,T1,A2 , C2
               IN1  = IN1 + 3
               JN1 = JN1 + 3
               IN2 = IN2 + 3
               JN2 = JN2 + 3
         GO TO (1522,1523), KAT
 1522     DO 1525 I = IN1,IN2
          DO 1525 J  = JN1,JN2
               A1          =  JN2 - J
               C1          =  IN2 - I
               WV(I,J)     =  WV(I,J) + WV1 + A1*A2*HY + C1*C2*HX
               WVI(I,J)    =  WV(I,J)
               KAS(I,J) = 1
               I2    =  I
               J2    =  J
      CALL SUCTION
               TI(I,J)     =   T(I,J)
 1525     CONTINUE
          GO TO 1526
 1523    DO 1524 I  =  IN1,IN2
         DO 1524 J  =  JN1,JN2
               A1          =  JN2 - J
               C1          =  IN2 - I
               KAS(I,J)    =  1
               T(I,J)      =  A1*A2*HY  +  C1*C2*HX  +  T1 +  T(I,J)
               TI(I,J)     =   T(I,J)
         IF (A4) 1528,1527
 1527          WV(I,J)     =  WVS(I,J)
               WVI(I,J)    =  WV(I,J)
               DTDW(I,J) =  1.0
               PF1         =  0.0
          GO TO 1524
 1528          I2          =  I
               J2          =  J
      CALL DSUCT
               WVI(I,J)    =  WV(I,J)
 1524    CONTINUE
 1526     CONTINUE
C     INPUT OF TABLE 6. BOUNDARY AND INTERNAL CONDITIONS
 1600 PRINT 600
          IF(KEEP6) 9980,1610,1605
 1605     IF(NCD6) 9980,1606,1607
 1606 PRINT 905
          GO TO 1700
 1607 PRINT 906
          GO TO 1612
 1610 PRINT 601
          DO 1611 I  = 1, MXP5
          DO 1611 J  = 1, MYP5
               KAS(I,J) =  1
               DTDX(I,J)  =  0.0
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            DTDY(I,J)  =  0.0
1611     CONTINUE
1612     DO 1645 M  =  1,NCD6
            K          =  -1                                      21MAR70
      READ 25, IN1,JN1,IN2,JN2,KASE, WV1, T1, DTX1, DTY1,H1,TE
      PRINT 25,IN1,JN1,IN2,JN2,KASE, WV1, T1, DTX1, DTY1,H1,TE
            IN1     =  IN1 + 3
            JN1     =  JN1 + 3
            IN2     =  IN2 + 3
            JN2     =  JN2 + 3
         DO 1645 I  =  IN1,IN2
         DO 1645 J  =  JN1,JN2
            I2      =  I
            J2      =  J
            KAS(I,J) =  KASE
         GO TO (1615,1620,1625,1630,1635) KASE
1615        WV(I,J)   =  WV(I,J) + WV1
            WVI(I,J)  =  WV(I,J)
      CALL SUCTION
            TI(I,J)    =   T(I,J)
            KAS(I,J)    =  2
         GO TO 1645
1620        T(I,J)    =  T1  +  T(I,J)
            TI(I,J)    =   T(I,J)
      CALL DSUCT
            WVI(I,J)   =  WV(I,J)
         GO TO 1645
1625        DTDX(I,J)=  DTDX(I,J) +  DTX1
         GO TO 1645
1630        DTDY(I,J)=  DTDY(I,J) +  DTY1
         GO TO 1645
1635  CALL HUMIDY (TE,H1)
            TI(I,J)    =   T(I,J)
      CALL DSUCT
            WVI(I,J)   =  WV(I,J)
            KAS(I,J)   =  2
1645     CONTINUE
            K          =  -1                                      21MAR70
        DO 1670 J         = 4,MYP2
         IF ( 3 - KAS(3,J)) 1655, 1650, 1655
1650        T(3,J)     =    T(4,J)   - HX* DTDX(3,J)
            TI(3,J)    =    T(3,J)
            I2         =  3
            J2         =  J
      CALL DSUCT
           WVI(3,J)    =    WV(3,J)
1655     IF ( 3 - KAS(MXP3,J)) 1670,1660,1670
1660        L          =    MXP3  -  1
            T(MXP3,J) =    T(L,J) +  HX *DTDX( MXP3,J)
            TI(MXP3,J)=    T(MXP3,J)
            I2         =  MXP3
            J2         =  J
      CALL DSUCT
           WVI(MXP3,J) =  WV(MXP3,J)
1670     CONTINUE
         DO 1690 I   =    3, MXP3
         IF( 4  - KAS(I,3)) 1680, 1675, 1680
1675        T(I,3)     =    T(I,4)  -  HY* DTDY(I,3)
            TI(I,3)    =    T(I,3)
            I2         =  I
            J2         =  3
      CALL DSUCT
           WVI(I,3)    =    WV(I,3)
1680     IF (4  -  KAS(I,MYP3)) 1690, 1685, 1690
1685        L          =    MYP3  -  1
            T(I,MYP3) =    T(I,L) +  HY * DTDY(I,MYP3)
            TI(I,MYP3)=    T(I,MYP3)
            I2         =  I
            J2         =  MYP3
      CALL DSUCT
           WVI(I,MYP3) = WV(I,MYP3)
1690     CONTINUE
C     INPUT OF TABLE 7. CLOSURE ACCELERATION DATA
1700  PRINT 700
      IF(KEEP7)9980,1710,1706                                     01DE9
1705     IF(NCD7) 9980,1706,1707
1706  PRINT 905
      GO TO 1800                                                  01DE9
1707  PRINT 906
1710  PRINT 701
      READ 20, IX,IY
         IF(IX - IY) 1711,1712,1712
1711        IV     =  IY
         GO TO 1715
1712        IV     =  IX
1715     DO 1720 I   = 1,IV
            VX(I)  =  0.0
            VY(I)  =  0.0
1720     CONTINUE
      READ 26,( VX(N),N = 1,IX)
      READ 26,( VY(N),N = 1,IY)
         DO 1725 I   = 1,IV
      PRINT 27, I,  VX(I),  VY(I)
1725     CONTINUE
1800  PRINT 800
      READ 20, KEY    , NSTEP
         GO TO (1805,1840,1860) KEY
C     LIST OF TIME-STEPS WHERE B.C. CHANGE
1805  READ 20, (KT(N), N = 1,NSTEP)
      PRINT 20, (KT(N), N  =  1,NSTEP)
            N    =  1
         DO 1830 K =  1, ITIME
      IF (K-KT(N))1820,1815,1820                                  01DE9
1815        KLOC(K)  =     1
            N        =     N + 1
         GO TO 1830
1820        KLOC(K)  =     2
1830     CONTINUE
         GO TO 1871
C     CONTINUOUS B.C. CHANGE (READ IN NEW B.C. FOR EACH TIME STEP)
1840     DO 1850 K  =  1,ITIME
           KLOC(K) =  1
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 1850     CONTINUE
      PRINT 806
          GO TO 1871
 1860 PRINT 807
          DO 1870 K   =  1, ITIME
               KLOC(K)   =  2
 1870     CONTINUE
 1871 PRINT 808
      READ 20,KEYB,NOUT
          GO TO ( 1872,1882) KEYB
C     LIST OF TIME STEPS FOR OUTPUT READ IN
 1872 READ 20,(KT(N),N = 1,NOUT )
      PRINT 20,(KT(N), N = 1,NOUT)
               N          =  1
          DO 1875 K  =  1, ITIME
      IF (K-KT(N))1874,1873,1874
 1873          KPUT(K)    =  1
               N          =  N + 1
          GO TO 1875
 1874          KPUT(K)    =  2
 1875     CONTINUE
          GO TO 2000
C     CONTINUOUS OUTPUT
 1882     DO 1883 K  =  1,ITIME
               KPUT(K)   =  1
 1883     CONTINUE
      PRINT 806
C     ZERO-OUT OF ALL TEMPORARY CONSTANTS
 2000     DO 2005 I  = 1,MXP5
          DO 2005 J  = 1,MYP5
               A(I,J)     =   0.0
               B(I,J)   =   0.0
               CX(I,J)  =   0.0
               CY(I,J)  =   0.0
               D(I,J)   =   0.0
               E(I,J)   =   0.0
               F(I,J)   =   0.0
               TX(I,J)  =   0.0
               TY(I,J)  =   0.0
               VSX(I,J) =   0.0
               VSY(I,J) =   0.0
 2005     CONTINUE
          IF(MYP5 - MXP5) 2006,2006,2007
 2006          MMAX     =    MXP5
          GO TO 2008
 2007          MMAX     =    MYP5
 2008     DO 2009 I  =  1, MMAX
               AL(I)    =   0.0
               BL(I)    =   0.0
               CL(I)    =   0.0
               DL(I)    =   0.0
 2009     CONTINUE
C     START OF TIME STEP
          DO 9000 K  =  1, ITIME
               KOUT       =  KPUT(K)
          IF (K - 1) 9980, 1980, 1900
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01DE9

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 1900          KAT    =    KLOC(K)
          GO TO (1910,1980)  KAT
 1910 READ 20, KTIME, NCD6
      PRINT 900
      PRINT 906
      PRINT 601
          DO 1945 M  =  1, NCD6
      READ 25, IN1,JN1,IN2,JN2,KASE, WV1, T1, DTX1, DTY1, H1, TE
      PRINT 25,IN1,JN1,IN2,JN2,KASE, WV1, T1, DTX1, DTY1, H1, TE
               IN1    =   IN1 + 3
               JN1    =   JN1 + 3
               IN2    =   IN2 + 3
               JN2    =   JN2 + 3
          DO 1945 I   =   IN1,IN2
          DO 1945 J   =   JN1,JN2
               I2     =   I
               J2     =   J
               KAS(I,J) =  KASE
          GO TO (1915,1920,1925,1930,1935) KASE
 1915          WV(I,J)    =  WV1
      CALL SUCTION
               KAS(I,J)    =  2
          GO TO 1945
 1920          T(I,J)     =  T1
      CALL DSUCT
          GO TO 1945
 1925          DTDX(I,J) =  DTX1
          GO TO 1945
 1930          DTDY(I,J) =  DTY1
         GO TO 1945
 1935 CALL HUMIDY (TE,H1)
      CALL DSUCT
               KAS(I,J)  =  2
 1945     CONTINUE
         DO 1970 J         =  4,MYP2
          IF   ( 3  -  KAS(3,J)) 1955, 1950, 1955
 1950          T(3,J)     =   T(4,J)   - HX* DTDX(3,J)
               I2         =  3
               J2         =  J
      CALL DSUCT
 1955     IF ( 3   - KAS(MXP3,J)) 1970, 1960, 1970
 1960          L          =   MXP3  -  1
               T(MXP3,J) =   T(L,J) +  HX*DTDX(MXP3,J)
               I2         =  MXP3
               J2         =  J
      CALL DSUCT
 1970     CONTINUE
          ?O 1990 I  =  3, MXP3
          IF( 4  - KAS(I,3)) 1975, 1965, 1975
 1965          T(I,3)     = T(I,4)   - HY* DTDY(I,3)
               I2         =  I
               J2         =  3
      CALL DSUCT
 1975     IF (4 -  KAS(I,MYP3)) 1990, 1985, 1990
 1985          L          =  MYP3 - 1
               T(I,MYP3) =  T(I,L) +  HY* DTDY(I,MYP3)
```

```
            I2          =  1
            J2          =  MYP3
      CALL DSUCT
 1990     CONTINUE
C     ROTATION,COMPUTATION OF UNSATURATED PERMEABILITY
 1980     DO  2010 I  = 3, MXP4
          GO TO ( 1982,1983) KOUT
 1982 PRINT 809,K
      PRINT 29
 1983     DO  2010 J  =  3,MYP4
          IF (ALFA(I,J))2014,2013,2014
 2013           C1          =  1.0
                C2          =  0.0
                C3          =  0.0
          GO TO 2017
 2014           A1          =  ALFA(I,J)/57.2957795
                C1      =  COS(A1)
                A2      =  (90.0 - ALFA(I,J))/57.2957795
                C2      =  COS(A2)
                A3      =  (90.0 + ALFA(I,J))/57.2957795
                C3      =  COS(A3)
 2017           P11(I,J)   =  P1(I,J)*C1*C1 + P2(I,J)*C2*C2
                P22(I,J)   =  P1(I,J)*C3*C3 + P2(I,J)*C1*C1
                P12(I,J)   =  P1(I,J)*C1*C3 + P2(I,J)*C1*C2
 2015 TA   = ABS(T(I,J))                                                01DE9
                BE           =  EN(I,J)
                A1          =  AK(I,J)
                C1          =  BK(I,J)
      C2   = 1. + ((TA*A1)**BE)/C1                                      01DE9
                UNSAT       =  1.0 / C2
                P11(I,J)     =  P11(I,J)* UNSAT
                P22(I,J)     =  P22(I,J)* UNSAT
                P12(I,J)     =  P12(I,J)* UNSAT
 2020     GO TO (2025,2010)KOUT
 2025           I1          =  I - 3
                J1          =  J - 3
      PRINT 28,I1,J1,T(I,J),WV(I,J),DTDW(I,J),P11(I,J),P12(I,J),P22(I,J)
 2010     CONTINUE
          GO TO (2120,2140) KGRCL
 2120     DO 2130 I  =  3, MXP3
          DO 2130 J  =  3, MYP3
                CONST      =  HT * DTDW(I,J) / (2.0)
                A(I,J)     = (( P12(I,J)/ HX  + P22(I,J)/HY )/HY) * CONST
                B(I,J)     = (( P11(I,J)/ HX  + P12(I,J)/HY )/HX) * CONST
                CX(I,J)    = (( P11(I,J)/ HX  + P11(I+1,J)/HX + P12(I,J)/HY
     1                      + P12(I+1,J)/HY )/HX)* CONST
                CY(I,J)    = ((P12(I,J)/HX + P12(I,J+1)/HX + P22(I,J)/HY
     1                      + P22(I,J+1)/HY)/HY )* CONST
                D(I,J)   =  (( P11(I+1,J)/HX + P12(I,J+1)/HY)/HX)*CONST
                E(I,J)    = (( P12(I+1,J)/HX + P22(I,J+1)/HY)/HO)*CONST
                F(I,J)     =-(( P12(I,J) - P12(I+1,J))/(HX)
     1                      + (P22(I,J) - P22(I,J+1))/(HY))* CONST
 2130     CONTINUE
          GO TO 2155
 2140     DO 2150 I  =  3,MXP3
                A1          =  I - 3
                R           =  RO + A1*HX
          DO 2150 J  =  3,MYP3
                CONST      =  HT*DTDW(I,J)*(0.5)
                A(I,J)     =  (( -P12(I,J)/R  +  P12(I,J)/HX
     1                         + P22(I,J)/HY)/HY)*CONST
                B(I,J)     =  (( -P11(I,J)/R  +  P11(I,J)/HX
     1                         + P12(I,J)/HY)/HX)*CONST
                CX(I,J)    =  (( -P11(I,J)/R  +  P11(I,J)/HX
     1                         + P11(I+1,J)/HX  +  P12(I,J)/HY
     2                         - P12(I+1,J)/HY)/HX
     3                         - P12(I,J)/(HY*R))*CONST
                CY(I,J)    =  (( P12(I,J)/HX  +  P12(I,J+1)/HX
     1                         + P22(I,J)/HY  +  P22(I,J+1)/HY)/HY)
     2                         *CONST
                D(I,J)     =  (( P11(I+1,J)/HX  +  P12(I,J+1)/HY)/HX)
     1                         *CONST
                E(I,J)     =  (( P12(I+1,J)/HX  +  P22(I,J+1)/HY)/HY)
     1                         *CONST
                F(I,J)     =- (  - P12(I,J)/R  +  P12(I,J)/HX
     1                         - P12(I+1,J)/HX  +  P22(I,J)/HY
     2                         - P22(I,J+1)/HY  )*CONST
 2150     CONTINUE
 2155     DO 2195 I  =  1,MXP5
          DO 2195 J  =  1,MYP5
                TX(I,J)    =  T(I,J)
                TY(I,J)    =  T(I,J)
       IF (A4) 2195,2181,2195                                           01DE9
 2181           T(I,J)     =  0.0
 2195     CONTINUE
                I1          =    IM1 - 3
                J1          =    JM1 - 3
                I2          =    IM2 - 3
                J2          =    JM2 - 3
                I3          =    IM3 - 3
                J3          =    JM3 - 3
                I4          =    IM4 - 3
                J4          =    JM4 - 3
       PRINT 801, I1,J1,I2,J2,I3,J3,I4,J4
          DO 8000 IT  =  1, ITMAX
           DO 2370  J  =  3, MYP3
C      CLOSURE  PARAMETER  CHOICE
          IF ( IT - IY) 2197,2197,2212
C      PRESET PARAMETERS
 2197     DO 2210  I  =  3, MXP3
                VSY(I,J)   =  VY(IT)
 2210     CONTINUE
          GO TO 2215
C      SELF-DETERMINING PARAMETERS
 2212     DO 2214  I  =  3, MXP3
                UP          = - A(I,J)* TY(I,J-1) + CY(I,J)* TY(I,J)
     1                        - E(I,J)* TY(I,J+1)
          IF (TY(I,J))2216,2217,2216
 2217           VSY(I,J)   =  VY(1)
          GO TO 2214
 2216           VSY(I,J)   =  UP/TY(I,J)
         IF(VSY(I,J))2213,2214,2214
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```
 2213          VSY(I,J)   =  0.0
 2214     CONTINUE
 2215     DO 2200  I  =  3, MXP3
               AL(I)          = -B(I,J)
               BL(I)          =  CX(I,J) +  A4 + VSY(I,J)
               CL(I)          = -D(I,J)
               DL(I)       =  A(I,J)*T(I,J-1) + B(I,J)*T(I-1,J)
     1              - (CX(I,J)+ CY(I,J)-  A4)* T(I,J) + D(I,J)* T(I+1,J)
     2                       + E(I,J)* T(I,J+1) + 2.0 * F(I,J)
     3                      + A(I,J)* TY(I,J-1) + ( VSY(I,J) - CY(I,J))*
     4                        TY(I,J)  +  E(I,J)* TY(I,J+1)
 2200     CONTINUE
C      COMPUTE CONTINUITY COEFFICIENTS
          DO 2300 I  =  3, MXP3
       IF (3 - KAS(3,J)) 2305,2304,2305                                  01DE9
 2304  IF (I - 4) 2305,2300,2305                                         01DE9
 2305          KAT          =  KAS(I,J)
          GO TO ( 2350,2320,2330,2350) KAT
C      SUCTION SET
 2320          CC(I)       =  1.0
               BB(I)       =  0.0
               AA(I)       =  T(I,J)
       IF (I - 3) 2324,2322,2324                                         01DE9
 2322          BB(2)       =  1.0
               AA(2)       =  0.0
          GO TO 2300
 2324  IF (I -MXP3)2300,2326,2300                                        01DE9
 2326          BB(I+1)     =  0.0
               AA(I+1)     =  T(I,J)
          GO TO 2300
C      SLOPE SET
 2330  IF (2 -KAS(I-1,J))2334,2332,2334                                  01DE9
 2332          CC(I)       =  1.0
               BB(I)       =  0.0
               AA(I)       =  T(I-1,J) + DTDX(I,J)*HX
          GO TO 2300
 2334  IF ( I- 3) 2336 ,2338 ,2336                                       01DE9
 2336  IF (I-MXP3)2340,2338,2340                                         01DE9
 2338          AA(I-1)     =  -DTDX(I,J)*HX
               BB(I-1)     =  1.0
               BB(I)       =  0.0
               AA(I)       =  TY(I,J)
               CC(I+1)     =  1.0
               BB(I+1)     =  0.0
               AA(I+1)     =  AA(I)*BB(I-1) + HX*DTDX(I,J)
          GO TO 2300
C      PIPE INCREMENT SLOPE SET
 2340          CC(I)       =  BL(I) + AL(I)*BB(I-1)
               BB(I)       =  -CL(I) / (CC(I))
               AA(I)       =  (DL(I) - AL(I)*AA(I-1))/(CC(I))
               CTEMP       =  1.0  +  CC(I-1)*(1.0 - BB(I-1))/(CC(I))
               BTEMP       =  BB(I)/CTEMP
               ATEMP       =  (AA(I) + CC(I-1)*(AA(I-1) + HX*DTDX(I,J))
     1                          /(CC(I)))/CTEMP
               AA(I-1)     =  -DTDX(I,J)*HX
               BB(I-1)     =  1.0
               AA(I)       =  ATEMP
               BB(I)       =  BTEMP
               CC(I)       =  CTEMP
          GO TO 2300
 2350          CC(I)    =  BL(I) + AL(I)* BB(I-1)
               BB(I)    =  -CL(I)/ CC(I)
               AA(I)    =  (DL(I) - AL(I)* AA(I-1))/ CC(I)
 2300     CONTINUE
          DO  2360  IR =  2, MXP4
               I    =  MXP4  + 2  - IR
               TX(I,J)   =  AA(I) +  BB(I) * TX (I+1,J)
 2360     CONTINUE
 2370     CONTINUE
C      SOLUTION OF FLOW IN Y-PIPES
          DO 2570  I  =  3,MXP3
C      CLOSURE PARAMETER CHOICE
          IF (IT - IX) 2365,2365,2375
C      PRESET PARAMETERS
 2365     DO  2367 J   =  3, MYP3
               VSX(I,J)   =  VX(IT)
 2367     CONTINUE
          GO TO 2450
C      SELF-DETERMINING  PARAMETERS
 2375     DO 2385  J  =   3, MYP3
               UP          =  -B(I,J)* TX(I-1,J) + CX(I,J)*TX(I,J)
     1                        -D(I,J)* TX(I+1,J)
          IF (TX(I,J))2379,2376,2379
 2376          VSX(I,J)   =  VX(I)
          GO TO 2385
 2379          VSX(I,J)   =  UP/TX(I,J)
         IF (VSX(I,J))2380,2385,2385
 2380          VSX(I,J)   =  0.0
 2385     CONTINUE
 2450     DO 2400  J  =   3, MYP3
               AL(J)  =  - A(I,J)
               BL(J)  =  CY(I,J) +    A4   + VSX(I,J)
               CL(J)  =  - E(I,J)
               DL(J)  =  A(I,J)* T(I,J-1) + B(I,J)* T(I-1,J)
     1                - (CX(I,J) + CY(I,J) -   A4)* T(I,J) + D(I J)*
     2                  T(I+1,J)   +   E(I,J)* T(I,J+1) +  2.0* FYI,J)
     3                + B (I,J)* TX(I-1,J) +.   ( VSX(I,J) - CX( ,J))*
     4                TX(I,J)  +  D(I,J)*TX(I+1,J)
 2400     CONTINUE
C      COMPUTE CONTINUITY COEFFICIENTS
          DO 2500 J  =  3, MYP3
       IF (4 - KAS(I,3))2505,2504,2505                                   01DE9
 2504  IF (J -4) 2505,2500,2505                                          01DE9
 2505          KAT          =  KAS(I,J)
          GO TO ( 2550,2520,2550,2530) KAT
C      SUCTION SET
 2520          CC(J)       =  1.0
               BB(J)       =  0.0
               AA(J)       =  T(I,J)
       IF (J-3 ) 2524,2522,2524                                          01DE9
 2522          BB(2)       =  1.0
               AA(2)       =  0.0
```

```
      GO TO 2500
 2524 IF (J -MYP3) 2500,2526,2500                                   01DE9
 2526         BB(J+1)   =  0.0
              AA(J+1)   =  T(I,J)
      GO TO 2500
C     SLOPE SET
 2530 IF ( 2 - KAS(I,J-1)) 2534,2532,2534                           01DE9
 2532         CC(J)     =  1.0
              BB(J)     =  0.0
              AA(J)     =  T(I,J-1) + DTDY(I,J)*HY
      GO TO 2500
 2534 IF ( J -3) 2536,2538,2536                                     01DE9
 2536 IF ( J -MYP3) 2540,2538,2540                                  01DE9
 2538         AA(J-1)   =  -DTDY(I,J)*HY
              BB(J-1)   =  1.0
              BB(J)     =  0.0
              AA(J)     =  TX(I,J)
              CC(J+1)   =  1.0
              BB(J+1)   =  0.0
              AA(J+1)   =  AA(J)*BB(J-1) + HY*DTDY(I,J)
      GO TO 2500
C     PIPE INCREMENT SLOPE SET
 2540         CC(J)     =  BL(J) + AL(J) *BB(J-1)
              BB(J)     =  -CL(J) / (CC(J))
              AA(J)     =  (DL(J) - AL(J)*AA(J-1))/(CC(J))
             CTEMP      =  1.0 + CC(J-1)*(1.0 - BB(J-1))/(CCOJ))
             BTEMP      =  BB(J)/CTEMP
             ATEMP      =  (AA(J) + CC(J-1)*(AA(J-1) + HY*DT+Y(I,J))
     1                       /(CC(J)))/CTEMP
              AA(J-1)   =  -DTDY(I,J)*HY
              BB(J-1)   =  1.0
              AA(J)     =  ATEMP
              BB(J)     =  BTEMP
              CC(J)     =  CTEMP
      GO TO 2500
 2550         CC(J)    =  BL(J) +  AL(J) *BB(J-1)
              BB(J)    = - CL(J)/ CC(J)
              AA(J)    = (DL(J) -  AL(J)* AA(J-1))/ CC(J)
 2500 CONTINUE
      DO 2560 JR  =  2,MYP4
              J  =  MYP4  + 2  - JR
              TY(I,J)  =  AA(J) + BB(J) *TY(I,J+1)
 2560 CONTINUE
 2570 CONTINUE
C     CHECK CLOSURE TOLERANCE
              KOUNT    =  0
      DO 2600 I   =  3,MXP3
      DO 2600 J   =  3,MYP3
              KLOS(I,J) =  1
              ECL       =  ABS(EPS*TY(I,J))
              ERR       =  ABS(TY(I,J) - TX(I,J))
      IF( ECL - ERR) 2605,2600,2600
 2605         KOUNT =KOUNT + 1
              KLOS(I,J) =  2
 2600 CONTINUE
      IF(KOUNT)9980,2650,2608
 2608     GO TO (2610,8000)KOUT
 2610 PRINT 802, IT,KOUNT,TX(IM1,JM1),TX(IM2,JM2),TX(IM3,JM3)T
     1 TX(IM4,JM4)
      PRINT 803, TY(IM1,JM1),TY(IM2,JM2),TY(IM3,JM3),TY(IM4,JM4)
 8000     CONTINUE
C     OUTPUT OF TIME STEP RESULTS
 2650 PRINT 810
         DO 2700 I  =  3,MXP3
          GO TO (2625,2630)KOUT
 2625 PRINT 809, K
      PRINT 804
 2630     DO 2700 J  =  3,MYP3
               I2     =  I
               J2     =  J
               KAT      =  KLOS(I,J)
         GO TO (2653,2680) KAT
 2680          KAT      =  KAS(I,J)
          GO TO (2685,2653,2653,2653) KAT
 2685          T(I,J)     =  T(I,J) + A(I,J)*( T(I,J-1) + TY(I,J-1))
     1                      +  B(I,J)*( T(I-1,J) + TX(I-1,J))
     2                      -  CX(I,J)*( T(I,J) + TX(I,J))
     3                      -  CY(I,J)*( T(I,J) + TY(I,J))
     4                      +  D(I,J)*( T(I+1,J) + TX(I+1,J))
     5                      +  E(I,J)*( T(I,J+1) + TY(I,J+1))
     6                      +  2.0*F(I,J)
          GO TO 2665
 2653          A1         =  CX(I,J) + CY(I,J)
          IF(A1)2652,2651,2652
 2651          A2         =  0.5
               A3         =  0.5
          GO TO 2660
 2652          A2         =  CX(I,J)/A1
               A3         =  CY(I,J)/A1
 2660          T(I,J)     =  A2*TX(I,J)   +  A3*TY(I,J)
 2665 CALL DSUCT
          GO TO (2670,2700) KOUT
 2670          I1         =  I - 3
               J1       =  J - 3
      PRINT 805,I1,J1,T(I,J),WV(I,J),PF1,VSX(I,J),VSY(I,J)
 2700     CONTINUE
          GO TO (2800, 9000) KOUT
C     COMPUTATION OF VERTICAL MOVEMENT AT EACH POINT
 2800          MYP        =  MY - 1
          DO  2830  J  =  MYP,MYP3
               JN1        =  J - 3
      PRINT 811,JN1
          DO 2830 I  =  3, MXP3
               DVERT(I)  =   0.0
          DO 2820 M  =  3, J
               I2 = I
               J2 = M
      CALL GULCH
               L   =  KURV(I,M)
      IF (I-MXP3) 2815,2810,2815                                    01DE9
 2810          DV(I,M)    =   DV(I,M) * 0.5
 2815          DVERT(I)   =   DVERT(I)  +  HY*DV(I,M)
```

```
2820     CONTINUE
      PRINT 27 , I,DVERT(I)
2830     CONTINUE
         IF (KTAPE) 2900,9000,2900
2900  WRITE(1)  AN2
      WRITE(1)  MX,MY,HX,HY
             G           =    981.0
             EM          =    18.02
            RG = 8.814E+07                                          12DE9
             TEM         =    298.0
             PSAT        =    32.6 / 2.54
             ENRT        =   RG*TEM/( G*EM )                        12DE9
         DO 2950 I  =  3,MXP3
         DO 2950 J  =  3,MYP3
             L           =    KURV(I,J)
             RPO         =    R(L)
             CHI         =    (WV(I,J)/(100.0 *POR(I,J)))**RPO
         IF( WV(I,J) - WVA(L)) 2920,2910,2910
2910         AT(I,J)     =    - CHI*0.0361*( TI(I,J) - T(I,J))
         GO TO 2950
2920         FAC2        =    T(I,J)*2.54 / ENRT
             FAC1        =    TI(I,J)*2.54 / ENRT
             AT(I,J)     =    - CHI* PSAT*( EXP(FAC1) - EXP(FA 2))
2950     CONTINUE
      WRITE(1) ((AT(I,J),I= 3,MXP3),J= 3,MYP3)
      REWIND 1
9000     CONTINUE
         GO TO 1010
9980  PRINT 907
9999     CONTINUE
      END
```

```
      SUBROUTINE SUCTION
      COMMON/ONE/PFM(10),PFR(10),BETA(10),DTDW(29,35),PF1
     1/TWO/T(29,35),I2,J2
     2/THREE/WVS(29,35),KLH,K
     3/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(29,35),
     4KURV(29,35),WV(29,35),GAM,ALF,P,DP,DALF,MY,HY,PN(10)
     5/FIVE/WVI(29,35),VTO(10),VTF(10),WVF(10),PO(10),ENP(10)TGAMS(10),
     6SRCH,PCTUP,DV(29,35),ALFB,VTP,ALFP                            25MAY70
             I           =   I2
             J           =   J2
             L           =   KURV(I,J)
         IF( WV(I,J) - WVS(I,J) ) 1525,1524,1524
1524         DTDW(I,J) =     1.0
             PF1         =   0.0
             T(I,J)      =   0.0
         GO TO 1530
1525         AT          =   (100.0*WV(I,J))/(WVS(I,J))
             TAT         =   (100.0*PFR(L))/(PFM(L))
             B           =   BETA(L)
             RECB        =   1.0/(1.0 + B )
             C           =   2.302585
             D           =   PFM(L) - PFR(L)
             XM          =   PFM(L) / ( WVS(I,J)*(1.0 + BETA(L )))
             FACT        =    1.0 / (( 1.0 - POR(I,J))*GAMS(L))
         IF(TAT - AT) 1527,1526,1526
1526         PF          =   PFR(L)*(AT/TAT)**RECB
             PF1         =   PFM(L) - PF
             T(I,J)      =   (-(10.0)**PF1)/(2.54)
             TE          =   ABS(T(I,J))
             DTDW(I,J) = (TE*XM*C*(PFR(L)/PF)**B) * FACT
         GO TO 1528
1527         PF1         =   D*((100.0 - AT)/(100.0 - TAT))**RECB
             T(I,J)      =   (-(10.0)**PF1)/(2.54)
             TE          =   ABS(T(I,J))
             DTDW(I,J) = (XM*TE*C*(D/PF1)**B) * FACT
1528     GO TO (1530,1523) KLH                                      26MAY70
1523  CALL HEAVY
             T(I,J)      =    T(I,J) + ALFP*P                       26MAY70
             DTDW(I,J) =      DTDW(I,J) + ALFP*DP                   26MAY70
1530  RETURN
      END
```

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      SUBROUTINE DSUCT
      COMMON/ONE/PFM(10),PFR(10),BETA(10),DTDW(29,35),PF1
     1/TWO/T(29,35),I2,J2
     2/THREE/WVS(29,35),KLH,K
     3/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(29,35),
     4KURV(29,35),WV(29,35),GAM,ALF,P,DP,DALF,MY,HY,PN(10)
     5/FIVE/WVI(29,35),VTO(10),VTF(10),WVF(10),PO(10),ENP(10)TGAMS(10),
     6SRCH,PCTUP,DV(29,35),ALFB,VTP,ALFP                                25MAY70
            I          =  I2
            J          =  J2
            L          =  KURV(I,J)
      IF(T(I,J))2710,2705,2705
 2705       WV(I,J)    =  WVS(I,J)
            DTDW(I,J)  =  1.0
            PF1        =  0.0
      GO TO 2760                                                        25MAY70
 2710 GO TO (2713,2711)KLH
 2711 IF (K)2712,2713,2712                                              01DE9
 2712 CALL HEAVY
            TE         =   -T(I,J)*2.54 + ALFP*P*2.54                   26MAY70
      GO TO 2714
 2713       TE         =  - T(I,J)*(2.54)
 2714       PF1        =  ALOG10(TE)
      IF(PF1)2715,2720,2720
 2715       PF1        =  0.0
            T(I,J)     =  -1.0/(2.54)
            WV(I,J)    =  WVS(I,J)
            DTDW(I,J)  =   1.0
      GO TO 2750
 2720 IF ( PF1 - PFM(L)) 2724,2724,2722
 2722       PF1        =  PFM(L)
            T(I,J)     =  (-(10.0)**PF1)/2.54
            WV(I,J)    =  0.0
            DTDW(I,J)  =  1.0E+10
      GO TO 2750
 2724       PF         =  PFM(L) - PF1
            B          =  BETA(L)
            BP         =  1.0 + BETA(L)
            C          =  2.302585/2.54                                 25MAY70
            D          =  PFM(L) - PFR(L)
            TAT        =  (PFR(L)*100.0)/(PFM(L))
            XM         =  PFM(L) / ( WVS(I,J)*(1.0 + BETA(L)))
            T(I,J)     =    -TE / 2.54                                  25MAY70
      IF (PF - PFR(L))2725,2725,2730
 2725       AT         =  TAT*(PF/PFR(L))**BP
            DTDW(I,J)  =  TE*C*XM*(PFR(L)/PF)**B
      GO TO 2735
 2730       AT         =  100.0 - (100.0 - TAT)*(PF1/D)**BP
            DTDW(I,J)  =  TE*C*XM*(D/PF1)**B
 2735       WV(I,J)    =  AT*WVS(I,J)/(100.0)
            FACT       =   1.0 / (( 1.0 - POR(I,J))*GAMS(L)
            DTDW(I,J) = DTDW(I,J) * FACT
 2750 GO TO (2760,2756) KLH                                             26MAY70
 2756 CALL HEAVY
            T(I,J)     =  T(I,J)   +   ALFP*P                           26MAY70
            DTDW(I,J)  =     DTDW(I,J) + ALFP*DP                        26MAY70
 2760 RETURN
      END
```

```
      SUBROUTINE HEAVY
      COMMON/TWO/T(29,35),I2,J2
     1/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(29,35),
     2KURV(29,35),WV(29,35),GAM,ALF,P,DP,DALF,MY,HY,PN(10)
     3/FIVE/WVI(29,35),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
     4SRCH,PCTUP,DV(29,35),ALFB,VTP,ALFP                                25MAY70
            I          =  I2
            J          =  J2
            L          =  KURV(I,J)
C     DETERMINE OVERBURDEN PLUS SURCHARGE PRESSURE AND HEAD
            P1         =   ( MY + 3 - J)*GAM*HY + SRCH
            P          =  P1/ (0.0361)
            TERM       =   ( 1.0 - POR(I,J))*GAMS(L)
            TH         =  WV(I,J)*TERM / 100.0
            F2         =    1.0 - TH                                    26MAY70
         CALL GULCH                                                     26MAY70
      IF  (ENP(L)) 1542,1541,1542                                       01DE9
 1541       F1         =    P1 / ( .435 * AV(L) * ( 1.0 - POR(I,J)))    01DEC69
         GO TO 1543
 1542       F1         =     ENP(L)*P1*VTP/(VTF(L)-VTP)                 26MAY70
 1543    IF (WV(I,J) - WVA(L)) 1540,1556,1556                           26MAY70
 1540       RPO        =  R(L)
            SAT        =   (TH/POR(I,J))**RPO
         GO TO 1554                                                     21MAR70
 1556       DTH        =   (WV(I,J)- WVA(L) )* TERM / 100.0             21MAR70
            SAT        =    1.0                                         26MAY70
            POR(I,J)   =  ( PN(L) + DTH)/(1.0 + DTH)
 1554       DP         =   F1        / ( F2 * SAT * 0.0361 )            25MAY70
            ALFP       =     ALFB*(1.0 - ALFB*(WV(I,J)-WVI(I,J))/(VTP-  26MAY70
     1VTI))                                                             26MAY70
 1560  RETURN                                                           TEM
      END
```

```
      SUBROUTINE HUMIDY (TE,H1)
      COMMON/TWO/T(29,35),I2,J2
            I      =  I2
            J      =  J2
            R          =  8.314E+07
            G          =  981.0
            EM         =  18.02
            AN         =  ALOG(H1)
            TM         =  (TE - 32.0)*5.0/(9.0)   +  273.0
            T(I,J)     =    R*TM*AN/(G*EM*2.54)
      RETURN
      END
```

```
      SUBROUTINE GULCH
      COMMON/TWO/T(29,35),I2,J2
     1/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(29,35),
     2KURV(29,35),WV(29,35),GAM,ALF,P,DP,DALF,MY,HY,PN(10)
     3/FIVE/WVI(29,35),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
     4SRCH,PCTUP,DV(29,35),ALFB,VTP,ALFP                                25MAY70
              I           =   I2
              J           =   J2
              L           =   KURV(I,J)
C     DETERMINE OVERBURDEN PRESSURE  PLUS  SURCHARGE
              P           =   (MY + 3  - J)*GAM*HY + SRCH
         IF ( P  - PO(L))  1725,1720,1720
 1720         DV(I,J)     =   0.0
         GO TO 1770
 1725         RENP        =   1.0/ ENP(L)
C     ALL CALCULATIONS IN THIS SUBROUTINE ARE DONE USING TOTAL
C     VOLUME AND WATER CONTENTS IN THE C.G.S. SYSTEM.
C     TO CONVERT VT TO CU. IN. / LB., MPY BY 27.7.
C     GRAVIMETRIC WATER CONTENT EQUALS SPECIFIC VOLUME OF WATER
C     IN THIS SYSTEM.
              VTP         =   VTF(L)  -  ((P/PO(L))**RENP)*( VTF(L) -
     1                           VTO(L))
              WVP         =   WVF(L) - ( VTF (L) - VTP )*100.0
         IF( WVI(I,J) -WVA(L)) 1730,1750,1750
 1730         QM1         =   Q(L) - 1.0
              QMO         =   Q(L)
              VTI         =   VTO(L) + WVI(I,J)*( ALFO(L) + (1=0 -
     1                         ALFO(L))*(( WVI(I,J)/WVA(L))**QM1)/QMO )
     2                              / 100.0
         GO TO 1760
 1750         VTAP        =   VTO(L) + WVA(L)*( ALFO(L) + (1.0 - ALFO(L))
     1                         /Q(L)) / 100.0
              VTI         =   VTAP  + (WVI(I,J) - WVA(L)) / 10.0
 1760         DELW        =   ( WV(I,J) - WVI(I,J)) / 100.0
         IF (DELW) 1731,1731,1735
 1731         DV(I,J)     =   0.0
              ALFB        =   1.0
         GO TO 1770
 1735         DELT        =   ( WVP - WVI(I,J)) / 100.0
              S           =   DELT / ( VTP - VTI )
         IF ( Q(L) - S ) 1737,1737,1736
 1736         QMO         =    S                                        26MAY70
 1737         DELV        =    (VTP - VTI)*(DELW/DELT)**QMO             26MAY70
              ALFB        =   DELV/DELW
C       DV  IS  A  VOLUME  STRAIN
              DV(I,J)     =   DELV*PCTUP / VTI
 1770 RETURN
      END
```

APPENDIX 5

SAMPLE DATA GCHPIP7

```
TRIAL PROBLEM FOR PREDICTING TWO-DIMENSIONAL SWELL USING PROGRAM GCHPTP7 AND
THE THERMO-ELASTICITY FINITE ELEMENT COMPUTER PROGRAM DEVISED BY ERIC BECKER
TRY 1     UNIVERSITY OF WYOMING SWELL TEST DATA      SEPT 10,1968
                                   3     1     1   21    4     3     1     2
  24    30    10    11    16.0       4.0         0.0       691200.0    .001
   1     1     1     2     1     3     2     2
   1
   0     0    25    31   5.00E-09  5.00E-09   0.0         2.54       1.00E+09   3.0
   1 5.0   3.0   4.0   23.5 2.0    0.0        .485        .08        .0 .0695   40.0
  .60         .8825       46.0       90.0      1.20        0.1         1.0        2.70
   0     0    24    30     1
   0    27    10    30     1         13.0
  11    27    11    30     1         11.0                 - .01667
  12    27    15    30     1         15.0                 - .125        .0625
  16    27    24    30     1         15.0                 - .125
   0    26     6    26     1         12.8                              .0125
   7    26    11    26     1         10.3                             +0234
  12    26    15    26     1         11.8                             -.0312
  16    26    24    26     1         11.8
   0    25     6    25     1         12.3                             -.0052
   7    25    11    25     1         10.1                              .0344
  12    25    24    25     1         10.1
   0    24     6    24     1         12.3                             C00312
   7    24    11    24     1         11.0                               .0203
  12    24    24    24     1         11.0
   0    23     6    23     1         12.3                             .00104
   7    23    11    23     1         11.9                             .00625
  12    23    24    23     1         11.0
   0    22     6    22     1         12.3
   7    22    11    22     1         12.8                             -.0078
  12    22    24    22     1         12.8
   0     0    24    21     1         13.7
   0     0    24     0     1          0.0
   0     1     0    29     2                     0.0
  24     1    24    29     2                    0.0
   0    30    24    30     1         0.0
   3     3
  .001        .01         .001
  .001        .01         .001
   3
   1     3
   1     2    11
```

APPENDIX 6

SAMPLE OUTPUT GCHPIP7

PROGRAM GCHPIP7 R.L.LYTTON REVISION DATE 25 MAY, 1970

TRIAL PROBLEM FOR PREDICTING TWO-DIMENSIONAL SWELL USING PROGRAM GCHPIP7 AND
THE THERMO-ELASTICITY FINITE ELEMENT COMPUTER PROGRAM DEVISED BY ERIC BECKER

PROB
TRY 1 UNIVERSITY OF WYOMING SWELL TEST DATA SEPT 10,1968

TABLE 1. PROGRAM CONTROL SWITCHES.

	TABLES NUMBER 2	3	4A	5	6	7
PRIOR DATA OPTIONS (1 = HOLD)	-0	-0	-0	-0	-0	-0
NUMBER CARDS INPUT THIS PROBLEM	3	1	1	21	4	3
GRID = 1, CYLINDER = 2 SWITCH	1					
LIGHT = 1, HEAVY = 2 SWITCH	2					
TAPE WRITE YES = 1	-0					

TABLE 2. INCREMENT LENGTHS, ITERATION CONTROL

NUM OF X-INCREMENTS	=	24
X-INCREMENT LENGTH	=	1.600E+01 IN.
NUM OF Y-INCREMENTS	=	30
Y-INCREMENT LENGTH	=	4.000E+00 IN.
NUM OF TIME INCREMENTS	=	11
TIME INCREMENT LENGTH	=	6.912E+05 SECS
ITERATIONS / TIME STEP	=	10
INSIDE RADIUS	=	0. IN
TOLERANCE	=	1.000E-03

MONITOR STATIONS I,J 1 1 1 2 1 3 2 2

TRANSIENT FLOW

TABLE 3. PERMEABILITY

FROM		TO		P1	P2	ALFA(DEG.)	AK	BK	EXPONENT
0	0	25	31	5.000E-09	5.000E-09	0.	2.540E+00	1.000E+09	3.000E+00

TABLE 4. SUCTION - WATER CONTENT CURVES

CURVE NUMBER		1
NUM LOCATIONS	=	1
MAXIMUM PF	=	5.00
PF AT INFLECTION	=	3.00
EXPONENT FOR PF	=	4.00
AIR ENTRY WATER CONT	=	23.50
DRYING CURVE EXPONENT	=	2.00
ALFA AT 0 WATER CONT	=	0.
INITIAL POROSITY	=	4.850E-01
REFERENCE AV	=	8.000E-02
SATURATION EXPONENT	=	2.00
SOIL UNIT WT PCI	=	6.950E-02
SATURATED WATER CONT.	=	4.000E+01

CURVE NUMBER		1
INITIAL TOTAL VOLUME	=	6.000E-01
FINAL TOTAL VOLUME	=	8.825E-01
FINAL WATER CONTENT	=	4.600E+01
SWELL PRESSURE, PSI	=	9.000E+01
EXPONENT OF P-V CURVE	=	1.20
SURCHARGE PRESS, PSI	=	1.000E-01
PCT VOL CHG VERTICAL	=	1.000E+00
SPEC.GRAV.SOLIDS	=	2.700E+00

NO.	FROM		TO	
1	0	0	24	30

TABLE 5. INITIAL CONDITIONS

FROM		TO		CASE	VOL. W.	PORE PR.	SLOPE Y	SLOPE X
0	27	10	30	1	1.300E+01	-0.	-0.	-0.
11	27	11	30	1	1.100E+01	-0.	-1.667E-02	-0.
12	27	15	30	1	1.500E+01	-0.	-1.250E-01	-6.250E-02
16	27	24	30	1	1.500E+01	-0.	-1.250E-01	-0.
0	26	6	26	1	1.280E+01	-0.	-0.	1.250E-02
7	26	11	26	1	1.030E+01	-0.	-0.	2.340E-02
12	26	15	26	1	1.180E+01	-0.	-0.	-3.120E-02
16	26	24	26	1	1.180E+01	-0.	-0.	-0.
0	25	6	25	1	1.230E+01	-0.	-0.	-5.200E-03
7	25	11	25	1	1.010E+01	-0.	-0.	-3.440E-02
12	25	24	25	1	1.010E+01	-0.	-0.	-0.
0	24	6	24	1	1.230E+01	-0.	-0.	3.120E-03
7	24	11	24	1	1.100E+01	-0.	-0.	2.030E-02
12	24	24	24	1	1.100E+01	-0.	-0.	-0.
0	23	6	23	1	1.230E+01	-0.	-0.	1.040E-03
7	23	11	23	1	1.190E+01	-0.	-0.	6.250E-03
12	23	24	23	1	1.100E+01	-0.	-0.	-0.
0	22	6	22	1	1.230E+01	-0.	-0.	-0.
7	22	11	22	1	1.280E+01	-0.	-0.	-7.800E-03
12	22	24	22	1	1.280E+01	-0.	-0.	-0.
0	0	24	21	1	1.370E+01	-0.	-0.	-0.

TABLE 6. BOUNDARY AND INTERNAL CONDITIONS

FROM STA		TO STA		CASE	WV	T	DT/DX	DT/DY	H	TEMP
0	0	24	0	1	0.	-0.	-0.	-0.	*.000	-0.0
0	1	0	29	2	-0.	0.	-0.	-0.	*.000	-0.0
24	1	24	29	2	-0.	0.	-0.	-0.	*.000	-0.0
0	30	24	30	1	0.	-0.	-0.	-0.	*.000	-0.0

TABLE 7. CLOSURE ACCELERATION DATA

FICTITIOUS CLOSURE VALVE SETTINGS

NO.	VSX	VSY
1	1.000E-03	1.000E-03
2	1.000E-02	1.000E-02
3	1.000E-03	1.000E-03

TABLE 8A. TIME STEPS FOR B.C. CHANGE

NONE

TABLE 8B. TIME STEPS FOR OUTPUT.

1 2 11

TIME STEP = 1

I	J	T(I,J)	WV(I,J)	DTDW(I,J)	P11(I,J)	P12(I,J)	P22(I,J)
0	0	-4.448E+02	1.370E+01	4.822E+04	2.048E-09	0.	2.048E-09
0	1	-4.532E+02	1.370E+01	2.136E+01	1.980E-09	0.	1.980E-09
0	2	-4.532E+02	1.370E+01	2.137E+01	1.980E-09	0.	1.980E-09
0	3	-4.532E+02	1.370E+01	2.138E+01	1.980E-09	0.	1.980E-09
0	4	-4.532E+02	1.370E+01	2.139E+01	1.980E-09	0.	1.980E-09
0	5	-4.532E+02	1.370E+01	2.140E+01	1.980E-09	0.	1.980E-09
0	6	-4.532E+02	1.370E+01	2.141E+01	1.980E-09	0.	1.980E-09
0	7	-4.532E+02	1.370E+01	2.142E+01	1.980E-09	0.	1.980E-09
0	8	-4.532E+02	1.370E+01	2.143E+01	1.980E-09	0.	1.980E-09
0	9	-4.532E+02	1.370E+01	2.144E+01	1.980E-09	0.	1.980E-09
0	10	-4.532E+02	1.370E+01	2.145E+01	1.980E-09	0.	1.980E-09
0	11	-4.532E+02	1.370E+01	2.146E+01	1.980E-09	0.	1.980E-09
0	12	-4.532E+02	1.370E+01	2.147E+01	1.980E-09	0.	1.980E-09
0	13	-4.532E+02	1.370E+01	2.149E+01	1.980E-09	0.	1.980E-09
0	14	-4.532E+02	1.370E+01	2.150E+01	1.980E-09	0.	1.980E-09
0	15	-4.532E+02	1.370E+01	2.152E+01	1.980E-09	0.	1.980E-09
0	16	-4.532E+02	1.370E+01	2.153E+01	1.980E-09	0.	1.980E-09
0	17	-4.532E+02	1.370E+01	2.155E+01	1.980E-09	0.	1.980E-09
0	18	-4.532E+02	1.370E+01	2.157E+01	1.980E-09	0.	1.980E-09
0	19	-4.532E+02	1.370E+01	2.158E+01	1.980E-09	0.	1.980E-09
0	20	-4.532E+02	1.370E+01	2.160E+01	1.980E-09	0.	1.980E-09
0	21	-4.532E+02	1.370E+01	2.162E+01	1.980E-09	0.	1.980E-09
0	22	-4.985E+02	1.230E+01	2.572E+01	1.650E-09	0.	1.650E-09
0	23	-4.950E+02	1.240E+01	2.540E+01	1.674E-09	0.	1.674E-09
0	24	-4.863E+02	1.260E+01	4.458E+04	1.733E-09	0.	1.733E-09
0	25	-5.168E+02	1.180E+01	2.760E+01	1.533E-09	0.	1.533E-09
0	26	-4.445E+02	1.400E+01	2.099E+01	2.050E-09	0.	2.050E-09
0	27	-4.739E+02	1.300E+01	3.810E+04	1.822E-09	0.	1.822E-09
0	28	-4.742E+02	1.300E+01	3.599E+04	1.820E-09	0.	1.820E-09
0	29	-4.744E+02	1.300E+01	3.290E+04	1.818E-09	0.	1.818E-09
0	30	-4.747E+02	1.300E+01	2.642E+04	1.816E-09	0.	1.816E-09
0	31	0.	0.	-5.605+173	5.000E-09	0.	5.000E-09

ITERATION PTS.NOT CLOSED MONITOR STATIONS

ITERATION	PTS.NOT CLOSED		1 1	1 2	1 3	2 2
1	324	TX	-4.468E+02	-4.470E+02	-4.472E+02	-4.455E+02
		TY	-4.459E+02	-4.465E+02	-4.470E+02	-4.455E+02
2	85	TX	-4.460E+02	-4.466E+02	-4.470E+02	-4.454E+02
		TY	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02
3	40	TX	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02
		TY	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02
4	9	TX	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02
		TY	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02
5	1	TX	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02
		TY	-4.459E+02	-4.466E+02	-4.470E+02	-4.454E+02

CLOSURE

TIME STEP = 2

I	J	T(I,J)	WV(I,J)	DTDW(I,J)	P11(I,J)	P12(I,J)	P22(I,J)
0	0	-4.532E+02	1.370E+01	2.136E+01	1.980E-09	0.	1.980E-09
0	1	-4.532E+02	1.343E+01	4.974E+04	1.980E-09	0.	1.980E-09
0	2	-4.532E+02	1.344E+01	4.946E+04	1.980E-09	0.	1.980E-09
0	3	-4.532E+02	1.345E+01	4.917E+04	1.980E-09	0.	1.980E-09
0	4	-4.532E+02	1.346E+01	4.887E+04	1.980E-09	0.	1.980E-09
0	5	-4.532E+02	1.346E+01	4.856E+04	1.980E-09	0.	1.980E-09
0	6	-4.532E+02	1.347E+01	4.824E+04	1.980E-09	0.	1.980E-09
0	7	-4.532E+02	1.348E+01	4.791E+04	1.980E-09	0.	1.980E-09
0	8	-4.532E+02	1.349E+01	4.757E+04	1.980E-09	0.	1.980E-09
0	9	-4.532E+02	1.350E+01	4.721E+04	1.980E-09	0.	1.980E-09
0	10	-4.532E+02	1.351E+01	4.684E+04	1.980E-09	0.	1.980E-09
0	11	-4.532E+02	1.352E+01	4.646E+04	1.980E-09	0.	1.980E-09
0	12	-4.532E+02	1.353E+01	4.606E+04	1.980E-09	0.	1.980E-09

18	9.640E-02
19	1.016E-01
20	1.022E-01
21	1.022E-01
22	1.022E-01
23	1.022E-01
24	1.022E-01
25	1.014E-01
26	9.123E-02
27	2.938E-20

HEAVE PROFILE FOR SOIL AT J-LEVEL 27

I-STA	VERTICAL MOVEMENT
3	5.875E-20
4	3.061E-02
5	3.196E-02
6	3.033E-02
7	2.849E-02
8	2.637E-02
9	2.301E-02
10	2.593E-01
11	1.409E-01
12	7.791E-02
13	7.681E-02
14	3.738E-02
15	5.182E-02
16	5.799E-02
17	7.949E-02
18	9.640E-02
19	1.021E-01
20	1.028E-01
21	1.028E-01
22	1.028E-01
23	1.028E-01
24	1.028E-01
25	1.019E-01
26	9.144E-02
27	2.938E-20

HEAVE PROFILE FOR SOIL AT J-LEVEL 28

I-STA	VERTICAL MOVEMENT
3	5.875E-20
4	3.070E-02
5	3.196E-02
6	3.033E-02
7	2.849E-02
8	2.637E-02
9	2.301E-02
10	2.593E-01
11	1.409E-01
12	7.791E-02

APPENDIX 7

PROGRAM SWELL1 FLOW CHART

APPENDIX 7. PROGRAM SWELL1 FLOW CHART

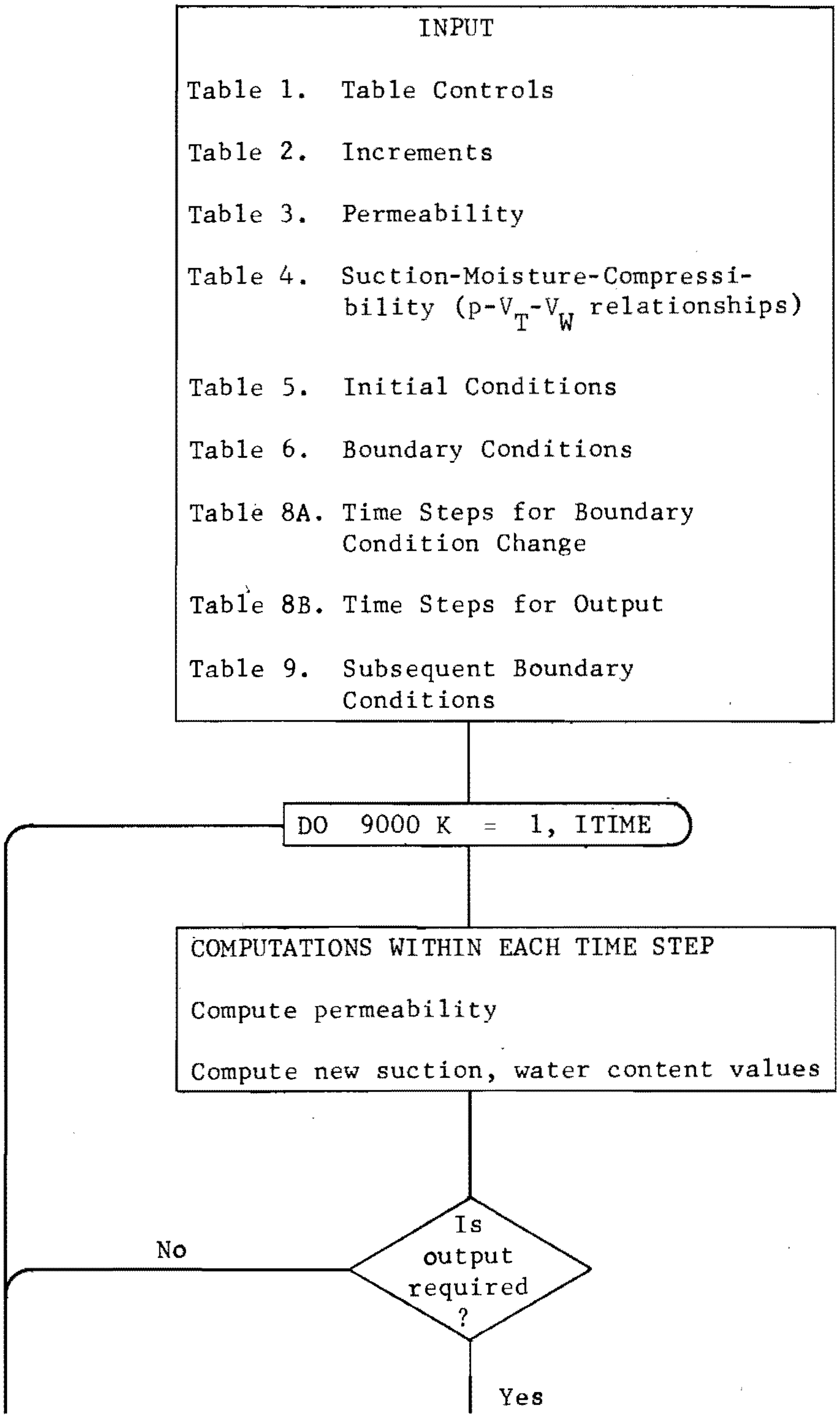
Commentary

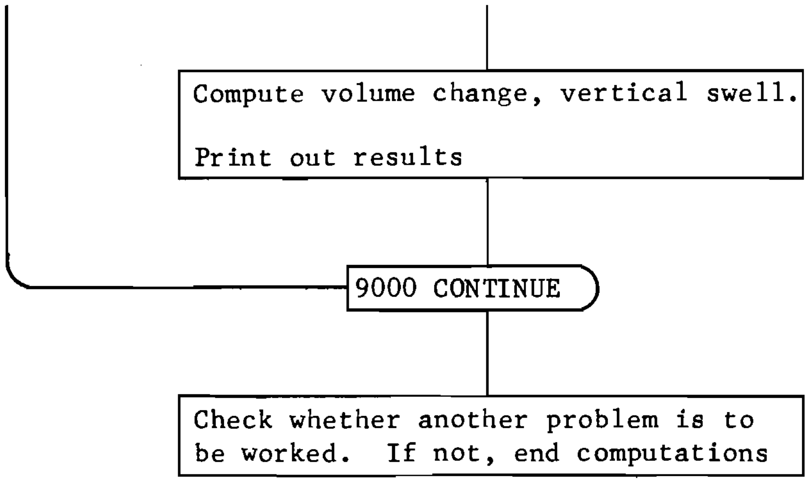
Although SWELL1 is a one-dimensional program, the input arrangement is identical in most respects with that of GCHPIP7. In addition, computation of new values of suction at each time step do not require iteration and closure. The computation procedure is identical with that for one direction in the two-dimensional computer program.

Because of the similarities, a detailed flow chart of SWELL1 is not presented here. Instead, a general flow diagram is included.

Flow charts of subroutines are not shown because of their similarity with those of GCHPIP7.

PROGRAM SWELL1




Compute volume change, vertical swell.
Print out results
9000 CONTINUE
Check whether another problem is to be worked. If not, end computations

APPENDIX 8

GUIDE FOR DATA INPUT, PROGRAM SWELL1

GENERAL PROGRAM NOTES

A detailed discussion of all input data is given in Chapter Seven.

All words not marked E or F are understood to be input as integers, the last number of which is in the farthest right space in the box 22

All words marked E or F are for decimal numbers which may be input at any position in the box with the decimal point in the proper position . . . . -19.36

0.0013

72.

The words marked E have been provided for those numbers which may require an exponential expression. The last number of the exponent should appear in the farthest right space in the box . . . . -3.142E-06

The program is arranged to compute quantities in terms of pounds, inches, and seconds. All dimensional input should be in these units.

SWELL1 GUIDE FOR DATA INPUT -- Card forms

IDENTIFICATION OF PROGRAM AND RUN (two alphanumeric cards per problem)

1	80

1	80

IDENTIFICATION OF PROBLEM (one card for each problem; program stops if NPROB is left blank)

NPROB (1–5)		DESCRIPTION OF PROBLEM (alphanumeric) (11–80)

TABLE 1. TABLE CONTROLS, HOLD OPTIONS

ENTER 1 TO HOLD PRIOR TABLE					NUM CARDS ADDED FOR TABLE					SWITCH KGRCL	SWITCH KLH	SWITCH KVERT
2	3	4	5	6	2	3	4	5	6	1 or 2	1 or 2	1 or 2
5	10	15	20	25	30	35	40	45	50	55	60	65

IF KGRCL IS
- 1 Grid Coordinates
- 2 Cylindrical Coordinates

IF KLH IS
- 1 Light - overburden pressure and soil compressibility not considered
- 2 Heavy - overburden pressure and soil compressibility considered

IF KVERT IS
- 1 Vertical Flow
- 2 Horizontal Flow

TABLE 2. INCREMENTS

NUM INCRS.	NUM TIME STEPS	INCREMENT LENGTH	INSIDE RADIUS	TIME STEP
		E	E	E
5	15	21 – 30	40	50

TABLE 3. PERMEABILITY

FROM I	TO I	SATURATED PERMEABILITY P	UNSATURATED PERMEABILITY COEFFICIENTS AK	BK	EN
		E	E	E	E
1 – 5	10	21 – 30	40	50	60

TABLE 4. SUCTION-MOISTURE-COMPRESSIBILITY

NUMBER LOCA-TIONS	MAX PF	INTL PF	PF VERSUS CURVE EXPONENT	AIR ENTRY WATER CON-TENT	ALFA EXPONENT	ALFA AT ZERO WATER CONTENT	POROSITY AT AIR ENTRY	E-LOG P COMPRESSIBILITY COEFFICIENT	χ EXPONENT	UNIT WEIGHT OF SOIL	FINAL SATURATION WATER CONTENT
	F	F	F	F	F	E	E	E	F	F	E
1 – 5	10	15	20	25	30	40	50	60	65	70	80

DRY SPECIFIC TOTAL VOLUME	FINAL SPECIFIC TOTAL VOLUME	FINAL ZERO AIR WATER CONTENT	SWELL PRESSURE	EXPONENT OF P-V CURVE	SURCHARGE PRESSURE	RATIO VOLUME CHANGE VERTICAL	SPECIFIC GRAVITY OF SOLIDS
E	E	E	E	E	E	E	E
1 – 10	20	30	40	50	60	70	80

FROM I	TO I	CURVE NUM
1 – 5	10	15

TABLE 5. INITIAL CONDITIONS

FROM I	TO I	KAS 1 or 2	WATER CONTENT	SUCTION	SLOPE C2
			E	E	E
1–5	10	15	21–30	40	50
			KAS = 1	KAS = 2	

TABLE 6. BOUNDARY CONDITIONS

I	I	KASE 1 to 4	WATER CONTENT	SUCTION	SUCTION GRADIENT	SOIL-MOISTURE HUMIDITY	TEMP
			E	E	E	F	F
1–5	10	15	21–30	40	50	55	62–65
			KASE = 1	KASE = 2	KASE = 3	KASE = 4	

TABLE 8A. TIME STEPS FOR BOUNDARY CONDITION CHANGE

KEY	NSTEP
5	8–10

IF KEY IS

1 Read in a list of time steps for boundary condition change. NSTEP is the number of these steps.

2 Continuous boundary condition change. Read in a new boundary condition at each time step. NSTEP is left blank

3 No boundary condition change. NSTEP is left blank.

LIST OF TIME STEPS (if KEY = 1 , maximum is 50)

1–5	10	15	20	25	30	35	40	45	50	55	60	65	70

1–5	10	15	20	25	30

TABLE 8B. LIST OF TIME STEPS FOR OUTPUT

IF KEYB IS
1 Read in a list of output time steps. NOUT is the number of these time steps.
2 Continuous output

KEYB	NOUT
5	8–10

LIST OF TIME STEPS (if KEYB = 1 , maximum is 50)

1–5	10	15	20	25	30	35	40	45	50	55	60	65	70

1–5	10	15	20

TABLE 9. SUBSEQUENT BOUNDARY CONDITIONS (if KEY = 1 or 2)

TIME STEP	NUMBER CARDS
1–5	10

FROM I	TO I	KASE 1 to 4	WATER CONTENT	SUCTION	SUCTION GRADIENT	SOIL-MOISTURE HUMIDITY	TEMP
1–5	10	15	21–30	40	50	55	62–65
			KASE = 1	KASE = 2	KASE = 3	KASE = 4	

STOP CARD (one blank card to end run)

1 80

APPENDIX 9

PROGRAM LISTING SWELL1

```
      PROGRAM SWELL1 ( INPUT,OUTPUT )
C     NOTATION
C     T           SUCTION
C     TX          TRIAL SUCTION  IN  X - PIPES
C     P1          PRINCIPAL PERMEABILITY IN X-DIRECTION
C     B           SUCTION COEFFICIENT OF T(I-1)
C     C           SUCTION COEFFICIENT OF T(I)
C     D           SUCTION COEFFICIENT OF T(I+1)
C     F           GRAVITY  POTENTIAL COMPONENT  OF  PERMEABILITY
C     DTDW        RATE OF CHANGE OF SUCTION  WITH WATER  CONTENT
C     AL          TUBE FLOW MATRIX COEFFICIENT OF TX AT I-1
C     BL          TUBE FLOW MATRIX COEFFICIENT OF TX AT I
C     CL          TUBE FLOW MATRIX COEFFICIENT OF TX AT I+1
C     DL          TUBE  FLOW     CONSTANT
C     HX          INCREMENT  LENGTH  IN  THE  X-DIRECTION
C     HT          INCREMENT  LENGTH  IN  THE  TIME- DIRECTION
C     AA          CONTINUITY  COEFFICIENT  - A  CONSTANT
C     BB          CONTINUITY  COEFFICIENT  - B  CONSTANT
C     CC          CONTINUITY  COEFFICIENT  - C  CONSTANT
C     DD          CONTINUITY  COEFFICIENT  - A  DENOMINATOR
C     ALPHA       ANGLE BETWEEN  P1 AND  THE  X- DIRECTION
C     WV          VOLUMETRIC WATER  CONTENT
C     WVS         SATURATED WATER CONTENT
      DIMENSION P1(40), P2(40),    AK(40), BK(40), EN(40), WV(40), T(40),
     1    DTDW(40), B(40), CX(40), D(40), F(40), AL(40), BL(40), CL(40),
     2    DL(40), AA(40), BB(40), CC(40), TX(40), KURV(40), KLOC(1000),
     3    AN1(16), AN2(7), WVS(40), DTDX(40), KAS(40), PFM(10), PFR(10),
     4    BETA(10), WVA(10), Q(10), ALFO(10), R(10), AV(10), PN(10),
     5    POR(40), KT(50), WN(10), KPUT(1000), KLOS(40),
     6    WVI(40),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
     7 .  DV(40),TI(40),AT(40)
      COMMON/ONE/PFM,PFR,BETA,DTDW,PF1
     1/TWO/T,I2
     2/THREE/WVS,KLH,K
     3/FOUR/WVA,Q,ALFO,R,AV,POR,KURV,WV,GAM,ALF,P,DP,DALF,MX,HX,PN
     4/FIVE/WV1,VTO,VTF,WVF,PO,ENP,GAMS,SRCH,PCTUP,DV,ALFB,VTP
    1 FORMAT (// 50H PROGRAM SWELL1   R.L.LYTTON    REVISION DATE
     1            15H  DEC 04, 1968  ,//)
   11 FORMAT(      5H1     ,80X ,10H1-----TRIM )
   12 FORMAT (  8A10)
   14 FORMAT ( A5,5X,7A10)
   15 FORMAT (///10H       PROB , /5X, A5, 5X, 7A10)
   20 FORMAT (16I5)
   21 FORMAT ( 2(I5,5X), 3E10.3 )
   22 FORMAT (2I5 , 10X, 4E10.3)
   23 FORMAT (I5, 5F5.2, 3E10.3, 2F5.1, E10.3 )
   24 FORMAT (3I5, 5X, 3E10.3)
   25 FORMAT (3I5, 5X, 3E10.3, F5.0, 6X, F4.1)
   26 FORMAT ( 8E10.3 )
   27 FORMAT ( 5X,I5,2E12.3 )
   28 FORMAT (I4, 2X, 4(E10.3, 2X))
   29 FORMAT (// 40H    I      T(I)         WV(I)         DTDW(I)
     1            15H     P1(I)        / )
  100 FORMAT (///40H  TABLE 1. PROGRAM CONTROL SWITCHES.
     1 / 50X,     25H           TABLES NUMBER
     2 / 50X,     35H    2      3    4A    5    6
     3          // 40H           PRIOR DATA OPTIONS (1 = HOLD) , 11X, 5I5,
     4           / 41H           NUMBER CARDS INPUT THIS PROBLEM, 10X, 5I5,
     5    //      41H           GRID = 1, CYLINDER = 2 SWITCH  , 10X,I5,
     6     //     41H           LIGHT = 1, HEAVY = 2  SWITCH   , 10X,I5,
     7     //     41H           VERT = 1, HORIZ = 2 SWITCH     , 10X, I5 )
  200 FORMAT (///50H  TABLE 2. INCREMENT LENGTHS, ITERATION CONTROL    )
  201 FORMAT (// 35H           NUM OF INCREMENTS       = , 5X,I5,
     1      /    , 35H           INCREMENT LENGTH        = , E10.3,5H IN  ,
     4      /    , 35H           NUM OF TIME INCREMENTS = , 5X, I5,
     5      /    , 35H           TIME INCREMENT LENGTH  = , E10.3,5H SECS,
     6      /    , 35H           INSIDE RADIUS           = , E10.3, 3H IN )
  202 FORMAT (// 30H           MONITOR STATIONS    , 5X, 4I7 )
  203 FORMAT (// 25H    TRANSIENT FLOW         )
  204 FORMAT (// 35H    PSEUDO-STEADY STATE FLOW         )
  300 FORMAT (///30H  TABLE  3. PERMEABILITY         )
  301 FORMAT (// 50H  FROM  TO                 P1          AK          BK    ,
     1            10H EXPONENT )
  400 FORMAT (///45H  TABLE  4. SUCTION - WATER CONTENT CURVES    )
  401 FORMAT (// 35H           CURVE NUMBER              ,I7,
     1      /,    35H           NUM  LOCATIONS          =  ,I7,
     2      /,    35H           MAXIMUM  PF              =  ,5X,F5C2,
     3      /,    35H           PF  AT  INFLECTION      =  ,5X,F5.2,
     4      /,    35H           EXPONENT  FOR  PF       =  ,5X,F5.2,
     5      /,    35H           AIR ENTRY WATER CONT    =  ,5X,F5.2,
     6      /,    35H           DRYING CURVE EXPONENT  =  ,5X,F5.2,
     7      /,    35H           ALFA AT 0 WATER CONT    =  ,5X,E10.3,
     8      /,    35H           INITIAL  POROSITY       =  ,5X,E10.3,
     9      /,    35H           REFERENCE  AV           =  ,5X,E10.3 )
  402 FORMAT (    35H           SATURATION EXPONENT     =  ,5X,F5.2,
     1      /,    35H           SOIL UNIT WT  PCI       =  ,5X,E10.3,
     2      /,    35H           SATURATED WATER CONT. =  ,5X,E10.3,// )
  403 FORMAT (// 15H   NO. FROM  TO )
  404 FORMAT (///35H           CURVE NUMBER              , I5,
     1           /35H           INITIAL TOTAL VOLUME   =  , E10.3,
     2           /35H           FINAL TOTAL VOLUME     =  , E10.3,
     3           /35H           FINAL WATER CONTENT    =  , E10.3,
     4           /35H           SWELL PRESSURE, PSI    =  , E10.3,
     5           /35H           EXPONENT OF P-V CURVE =  , 5X,F5.2,
     6           /35H           SURCHARGE PRESS, PSI   =  , E10.3,
     7           /35H           PCT VOL CHG VERTICAL   =  , E10.3,
     8           /35H           SPEC.GRAV.SOLIDS       =  , E10.3, // )
  500 FORMAT (///30H  TABLE 5. INITIAL CONDITIONS  )
  501 FORMAT (// 50H  FROM  TO   CASE    VOL. W.    PORE PR.  SLOPE X  )
  600 FORMAT (///45H  TABLE 6. BOUNDARY AND INTERNAL CONDITIONS  )
  601 FORMAT (// 50H  FROM  TO   CASE      WV          T         DT/DX    ,
     1            15H     H      TEMP )
  800 FORMAT (///40H  TABLE 8A. TIME STEPS FOR B.C. CHANGE    )
  804 FORMAT (// 45H   I         T(I)          WV(I)          PF(I)       / )
  805 FORMAT (I4, 5X, 3(E10.3,2X) )
  806 FORMAT (// 10H    ALL    )
  807 FORMAT (// 10H    NONE    )
  808 FORMAT (///40H  TABLE 8B. TIME STEPS FOR OUTPUT        )
```

```
  809 FORMAT (// 15H   TIME STEP  =   , I5,//)
  811 FORMAT (// 35H STATION    TOTAL MVMT     INCR MVMT  )
  900 FORMAT (// 50H  TABLE 9. SUBSEQUENT BOUNDARY CONDITIONS          )
  901 FORMAT (///30H  TABLE  10. OUTPUT OF RESULTS )
  905 FORMAT (// 40H     USING DATA FROM PREVIOUS PROBLEM    )
  906 FORMAT (// 45H     USING DATA FROM PREVIOUS PROBLEM PLUS     )
  907 FORMAT (// 25H      ERROR IN DATA          )
                ITEST  =  5H
 1000 READ 12,(AN1(N), N =1,16)
 1010 READ 14, NPROB, ( AN2(N), N =1,7)
           IF (NPROB - ITEST) 1020, 9999, 1020
 1020 PRINT 11
      PRINT 1
      PRINT 12, (AN1(N), N = 1,16)
      PRINT 15, NPROB, (AN2(N), N =1,7)
C     INPUT  OF  TABLE I , TABLE CONTROLS,  HOLD OPTIONS,
 1100 READ 20, KEEP2, KEEP3, KEEP4, KEEP5, KEEP6, NCD2, NCD3, NCD4,
     1          NCD5, NCD6, KGRCL, KLH, KVERT
      PRINT 100, KEEP2, KEEP3, KEEP4, KEEP5, KEEP6, NCD2, NCD3, NCD4,
     1            NCD5, NCD6, KGRCL, KLH, KVERT
C     INPUT OF  TABLE 2A  INCREMENTS, ITERATION CONTROL
 1200 PRINT 200
           IF(KEEP2)9980, 1210, 1300
 1210 READ 21, MX, ITIME, HX, RO, HT
      PRINT 201, MX, HX, ITIME, HT, RO
           GO TO 1240
 1230 PRINT 905
C     COMPUTE  CONSTANTS TO BE USED IN THE PROGRAM
 1240           MXP5   =  MX + 5
                MXP4   =  MX + 4
                MXP3   =  MX + 3
                 MXP2      =  MX + 2
                HXE2  = HX * HX
                A4          =  1.0
          GO TO 1300
 1260 PRINT 204
                A4          =  0.0
C     INPUT  TABLE  3.  PERMEABILITY
 1300 PRINT 300
           IF(KEEP3) 9980,1310,1317
 1310      DO 1315  I = 1, MXP5
                P2(I)   = 0.0
                AK(I)   = 0.0
                BK(I)   = 0.0
                EN(I)   = 0.0
                WVS(I)  = 0.0
 1315      CONTINUE
          GO TO 1319
 1317      IF (NCD3)9980,1330,1318
 1318 PRINT 906
 1319 PRINT 301
           DO 1320  K = 1, NCD3
      READ  22, IN1, IN2, PB,        AK1, BK1, EN1
      PRINT 22, IN1, IN2, PB,        AK1, BK1, EN1
                IN1   =  IN1 + 3
                IN2   =  IN2 + 3
           DO 1320  I   = IN1,IN2
                P2(I)    = P2(I) + PB    $    P1(I) = P2(I)
                AK(I)    = AK(I) + AK1
                BK(I)    = BK(I) + BK1
                EN(I)    = EN(I) + EN1
 1320      CONTINUE
          GO TO 1400
 1330 PRINT 905
C     INPUT OF TABLE  4. SUCTION - WATER CONTENT CURVE
C     AT PRESENT.  THIS IS AN EXPONENTIAL SINGLE - VALUED CURVE.   IT
C    1SHOULD BE REPLACED BY NUMERICAL CURVES  FOR WETTING, DRYING, AND
C    2SCANNING BETWEEN THE TWO.
 1400 PRINT 400
           IF (KEEP4) 9980,1410,1430
 1410           NLOC  = 0
           DO 1415 M  =  1,NCD4
      READ 23,LOC,PFM(M), PF1   ,BETA(M),WVA(M),Q(M),ALFO(M),PN(M),AV(M),
     1R(M),GAM,WN(M)
      PRINT 401,M,LOC,PFM(M), PF1   ,BETA(M),WVA(M),Q(M),ALFO(M),
     1PN(M),AV(M)
      PRINT 402,R(M),GAM,WN(M)
      READ 26,VTO(M),VTF(M),WVF(M),PO(M),ENP(M),SRCH,PCTUP,GAMS(M)
      PRINT 404,M,VTO(M),VTF(M),WVF(M),PO(M),ENP(M),SRCH,PCTUP,GAMS(M)
                PFR(M)     =  PFM(M) - PF1
                NLOC   =  NLOC + LOC
 1415      CONTINUE
      PRINT 403
           DO 1420 M  =  1,NLOC
      READ 20, IN1, IN2, KAT
      PRINT 20, KAT, IN1, IN2
                IN1   =  IN1 + 3
                IN2   =  IN2 + 3
           DO 1420 I  = IN1,IN2
                KURV(I) = KAT
                POR(I) = PN(KAT)
                WVS(I)  = WN(KAT)
 1420      CONTINUE
           GO TO 1500
 1430 PRINT 905
C     INPUT OF TABLE 5. INITIAL CONDITIONS
 1500 PRINT 500
           IF(KEEP5)9980,1510,1505
 1505      IF(NCD5) 9980,1506,1507
 1506 PRINT 905
           GO TO 1600
 1507 PRINT 906
           GO TO  1520
 1510      DO 1515 I = 1,MXP5
                WV(I) = 0.0
                WVI(I)     =    0.0
                T(I)  = 0.0
                TI(I)      =    0.0
 1515      CONTINUE
 1520 PRINT  501
                DO 1526 M =  1,NCD5
                K           =  0
```

```
      READ 24, IN1, IN2, KAT, WV1, T1, C2
      PRINT 24,IN1, IN2, KAT, WV1, T1, C2
              IN1  = IN1 + 3
              IN2 = IN2 + 3
         GO TO (1522,1523), KAT
 1522     DO 1525 I = IN1,IN2
              C1        =  IN2 - I
              WV(I) = WV(I) + WV1 + C1 * C2 * HX
              WVI(I)    =   WV(I)
              KAS(I) = 1
              I2    =  I
      CALL SUCTION
              TI(I)     =   T(I)
 1525     CONTINUE
          GO TO 1526
 1523    DO 1524 I  =  IN1,IN2
              C1        =  IN2 - I
              KAS(I) = 1
              T(I)   = C1 * C2 * HX + T1 + T(I)
              TI(I)     =   T(I)
         IF (A4) 1528,1527
 1527         WV(I)   = WVS(I)
              WVI(I)    =   WV(I)
              DTDW(I) = 1.0
              PF1       =  0.0
          GO TO 1524
 1528         I2        =  I
      CALL DSUCT
              WVI(I)    =   WV(I)
 1524    CONTINUE
 1526     CONTINUE
C     INPUT OF TABLE 6. BOUNDARY AND INTERNAL CONDITIONS
 1600 PRINT 600
          IF(KEEP6) 9980,1610,1605
 1605     IF(NCD6) 9980,1606,1607
 1606 PRINT 905
          GO TO 1700
 1607 PRINT 906
          GO TO 1612
 1610 PRINT 601
          DO 1611 I  = 1, MXP5
              KAS(I)  = 1
              DTDX(I) = 0.0
 1611     CONTINUE
 1612     DO 1645 M  =  1,NCD6
              K         =  0
      READ  25, IN1, IN2, KASE, WV1, T1, DTX1, H1, TE
      PRINT 25, IN1, IN2, KASE, WV1, T1, DTX1, H1, TE
              IN1   =  IN1 + 3
              IN2   =  IN2 + 3
          DO 1645 I  =  IN1,IN2
              I2    =  I
              KAS(I)  = KASE
          GO TO (1615,1620,1625,1630,1635) KASE
 1615         WV(I) = WV1
              WVI(I)    =   WV(I)
      CALL SUCTION
              TI(I)     =   T(I)
              KAS(I)  = 2
          GO TO 1645
 1620         T(I) = T1
              TI(I)     =   T(I)
      CALL DSUCT
              WVI(I)    =   WV(I)
          GO TO 1645
 1625         DTDX(I) = DTX1
 1660         L         =  MXP3  -  1
          GO TO 1645
 1630     CONTINUE
 1635 CALL HUMIDY (TE,H1)
              TI(I)     =   T(I)
      CALL DSUCT
              WVI(I)    =   WV(I)
              KAS(I)  = 2
 1645     CONTINUE
              K         =  1
          IF ( 3 - KAS(3) ) 1655, 1650, 1655
 1650         T(3)    = T(4) - HX * DTDX (3)
              I2        =  3
      CALL DSUCT
              WVI(3)    =   WV(3)
 1655     IF ( 3 - KAS(MXP3) ) 1670, 1660, 1670
              T(MXP3) = T(L) + HX * DTDX(MXP3)
              I2        =  MXP3
      CALL DSUCT
              WVI(MXP3) =   WV(MXP3)
 1670     CONTINUE
 1700     CONTINUE
 1800 PRINT 800
      READ 20, KEY   , NSTEP
          GO TO (1805,1840,1860) KEY
C     LIST OF TIME-STEPS WHERE B.C. CHANGE
 1805 READ 20, (KT(N), N = 1,NSTEP)
      PRINT 20, (KT(N), N  =  1,NSTEP)
              N    =  1
          DO 1830 K =  1, ITIME
          IF ( K  - KT(N))  1820,1815
 1815         KLOC(K)   =    1
              N         =    N + 1
          GO TO 1830
 1820         KLOC(K)   =    2
 1830     CONTINUE
          GO TO 1871
C     CONTINUOUS B.C. CHANGE (READ IN NEW B.C. FOR EACH TIME STEP)
 1840     DO 1850 K  =  1,ITIME
            KLOC(K) =  1
 1850     CONTINUE
      PRINT 806
          GO TO 1871
 1860 PRINT 807
         DO 1870 K   =  1, ITIME
              KLOC(K)   =  2
```

```
1870    CONTINUE
1871 PRINT 808
     READ 20,KEYB,NOUT
        GO TO ( 1872,1882) KEYB
C    LIST OF TIME STEPS FOR OUTPUT READ IN
1872 READ 20,(KT(N),N = 1,NOUT )
     PRINT 20,(KT(N), N = 1,NOUT)
            N          =  1
        DO 1875 K  =  1, ITIME
        IF( K - KT(N))1874,1873
1873        KPUT(K)    =  1
            N          =  N + 1
        GO TO 1875
1874        KPUT(K)    =  2
1875    CONTINUE
        GO TO 2000
C    CONTINUOUS OUTPUT
1882    DO 1883 K  =  1,ITIME
            KPUT(K)    =  1
1883    CONTINUE
     PRINT 806
2000 PRINT 11
     PRINT 901
C    ZERO-OUT OF ALL TEMPORARY CONSTANTS
        DO 2005 I  = 1,MXP5
            B(I)  = 0.0
            CX(I) = 0.0
            D(I)  = 0.0
            F(I)  = 0.0
            TX(I) = 0.0
2005    CONTINUE
2008    DO 2009 I = 1, MXP5
            AL(I)    =    0.0
            BL(I)    =    0.0
            CL(I)    =    0.0
            DL(I)    =    0.0
2009    CONTINUE
C    START OF TIME STEP
        DO 9000 K  =  1, ITIME
            KOUT       =  KPUT(K)
        IF (K - 1) 9980, 1980, 1900
1900        KAT   =   KLOC(K)
        GO TO (1910,1980)  KAT
1910 READ 20, KTIME, NCD6
     PRINT 900
     PRINT 906
     PRINT 601
        DO 1945 M  =  1, NCD6
     READ  25, IN1, IN2, KASE, WV1, T1, DTDX1, H1, TE
     PRINT 25, IN1, IN2, KASE, WV1, T1, DTDX1, H1, TE
            IN1   =  IN1 + 3
            IN2   =  IN2 + 3
        DO 1945 I  =  IN1,IN2
            I2    =  I
            KAS(I) = KASE
        GO TO (1915,1920,1925,1930,1935) KASE
1915        WV(I)     = WV1
     CALL SUCTION
            KAS(I)  = 2
        GO TO 1945
1920        T(I)      = T1
     CALL DSUCT
        GO TO 1945
1925        DTDX(I) = DTX1
        GO TO 1945
1930    CONTINUE
1935 CALL HUMIDY (TE,H1)
     CALL DSUCT
            KAS(I)  = 2
1945    CONTINUE
        IF ( 3 - KAS(3) ) 1955, 1950, 1955
1950        T(3)      = T(4) - HX * DTDX(3)
            I2          =  3
     CALL DSUCT
1955    IF ( 3 - KAS(MXP3) ) 1970, 1960, 1970
1960        L           =   MXP3  -  1
            T(MXP3) = T(L) + HX * DTDX(MXP3)
            I2          =  MXP3
     CALL DSUCT
1970    CONTINUE
1980    GO TO ( 1982,1983) KOUT
1982 PRINT 809,K
     PRINT 29
1983    CONTINUE
C    ROTATION,COMPUTATION OF UNSATURATED PERMEABILITY
        DO  2010 I  = 3, MXP4
2015        TE     = ABS(T(I))
            BE     = EN(I)
            A1     = AK(I)
            C1     = BK(I)
            C2        =  1.0  +  ((TE*A1)**BE)/C1
            UNSAT     =  1.0 / C2
            P1(I) = P2(I) * UNSAT
2020    GO TO (2025,2010)KOUT
2025        I1          =  I - 3
     PRINT 28, I1, T(I), WV(I), DTDW(I), P1(I)
2010    CONTINUE
        GO TO (2120,2140) KGRCL
2120    DO 2130 I  =  3, MXP3
            CONST = HT * DTDW(I) * 0.5
            B(I)   =(P1(I) / HXE2)* CONST
            CX(I) = ( ( P1(I) + P1(I+1) ) / HXE2) * CONST
            D(I)   =(P1(I+1) / HXE2)* CONST
        GO TO ( 2121, 2122 ) KVERT
2121        F(I)=-( ( P1(I) - P1(I+1) )/ HX)* CONST
        GO TO 2130
2122        F(I)   = 0.0
2130    CONTINUE
        GO TO 2155
2140    DO 2150 I  =  3,MXP3
            A1          =  I - 3
            R           =  RO + A1*HX
```

```
            HXR    = HX * R
            CONST = HT * DTDW(I) * 0.5
            B(I)   = ( - P1(I) / HXR + P1(I) / HXE2 ) * CONST
            CX(I) = ( - P1(I) / HXR + ( P1(I) + P1(I+1))/HXE2)*CONST
            D(I)   =(P1(I+1) / HXE2)* CONST
            F(I)   = 0.0
 2150    CONTINUE
 2155    DO 2195 I  =  1,MXP5
            TX(I) = T(I)
         IF (A4)2195,2181
 2181       T(I)  = 0.0
 2195    CONTINUE
 2215    DO 2200  I  =  3, MXP3
            AL(I) = - B(I)
            BL(I) = CX(I) + A4
            CL(I) = - D(I)
            DL(I) = B(I) * T(I-1) - ( CX(I) - A4 ) * T(I)
     1              + D(I) * T(I+1) + 2.0 * F(I)
 2200    CONTINUE
C     COMPUTE CONTINUITY COEFFICIENTS
         DO 2300 I  =  3, MXP3
         IF ( 3 - KAS(3) ) 2305, 2304
 2304    IF ( I - 4) 2305,2300
 2305       KAT    = KAS(I)
         GO TO ( 2350,2320,2330,2350) KAT
C     SUCTION SET
 2320       CC(I)      =  1.0
            BB(I)      =  0.0
            AA(I) = T(I)
         IF ( I - 3) 2324,2322
 2322       BB(2)      =  1.0
            AA(2)      =  0.0
         GO TO 2300
 2324    IF (I - MXP3) 2300,2326
 2326       BB(I+1)    =  0.0
            AA(I+1) = T(I)
         GO TO 2300
C     SLOPE SET
 2330    IF ( 2 - KAS(I-1) ) 2334, 2332
 2332       CC(I)      =  1.0
            BB(I)      =  0.0
            AA(I)      = T(I-1) + DTDX(I) * HX
         GO TO 2300
 2334    IF ( I - 3) 2336,2338
 2336    IF ( I - MXP3) 2340,2338
 2338       AA(I-1) = - DTDX(I) * HX
            BB(I-1)    =  1.0
            BB(I)      =  0.0
            AA(I)    = TX(I)
            CC(I+1)    =  1.0
            BB(I+1)    =  0.0
            AA(I+1) = AA(I) * BB(I-1) + HX * DTDX(I)
         GO TO 2300
C     PIPE INCREMENT SLOPE SET
 2340       CC(I)      =  BL(I) + AL(I)*BB(I-1)
            BB(I)      =  -CL(I) / (CC(I))
            AA(I)      =  (DL(I) - AL(I)*AA(I-1))/(CC(I))
            CTEMP      =  1.0  +  CC(I-1)*(1.0 - BB(I-1))/(CC(I))
            BTEMP      =  BB(I)/CTEMP
            ATEMP      =  (AA(I) + CC(I-1)*(AA(I-1) + HX*DTDX(I)   )
     1                       /(CC(I)))/CTEMP
            AA(I-1)    =  -DTDX(I ) *HX
            BB(I-1)    =  1.0
            AA(I)      =  ATEMP
            BB(I)      =  BTEMP
            CC(I)      =  CTEMP
         GO TO 2300
 2350       CC(I)    =  BL(I) + AL(I)* BB(I-1)
            BB(I)    =  -CL(I)/ CC(I)
            AA(I)    = (DL(I) - AL(I)* AA(I-1))/ CC(I)
 2300    CONTINUE
         DO  2360  IR =  2, MXP4
            I    =  MXP4  + 2  - IR
            TX(I)    = AA(I) + BB(I) * TX(I+1)
 2360    CONTINUE
C     OUTPUT OF TIME STEP RESULTS
         GO TO (2625,2630)KOUT
 2625 PRINT 809, K
      PRINT 804
 2630    CONTINUE
        DO 2700 I  =  3,MXP3
            T(I)    =  TX(I)
            I2      =  I
 2665 CALL DSUCT
         GO TO (2670,2700) KOUT
 2670       I1         =  I - 3
      PRINT 805, I1, T(I), WV(I), PF1
 2700    CONTINUE
C     COMPUTE VERTICAL MOVEMENT AT EVERY POINT
         GO TO ( 2800,9000 ) KOUT
 2800       DVERT      =    0.0
      PRINT 811
         DO 2820 I = 3,MXP3
            I2         =    I
      CALL GULCH
         IF ( I - MXP3 ) 2815,2810
 2810       DV(I)      =    DV(I) * 0.5
 2815       DUP        =    DV(I)*HX
            DVERT      =    DVERT + DUP
            IN1        =    I - 3
      PRINT 27, IN1,DVERT,DUP
 2820    CONTINUE
 9000    CONTINUE
         GO TO 1010
 9980 PRINT 907
 9999    CONTINUE
      END
```

```
      SUBROUTINE SUCTION
      COMMON/ONE/PFM(10),PFR(10),BETA(10),DTDW(40),PF1
     1/TWO/T(40),I2
     2/THREE/WVS(40),KLH,K
     3/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(40),
     4KURV(40),WV(40),GAM,ALF,P,DP,DALF,MX,HX,PN(10)
     5/FIVE/WVI(40),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
     6SRCH,PCTUP,DV(40),ALFB,VTP
             I         =  I2
             L     = KURV(I)
         IF ( WV(I) - WVS(I) ) 1525, 1524, 1524
 1524        DTDW(I) = 1.0
             PF1        =  0.0
             T(I)     = 0.0
         GO TO 1530
 1525        AT        = 100.J * WV(I) / WVS(I)
             TAT        =  (100.0*PFR(L))/(PFM(L))
             B          =  BETA(L)
             RECB       =  1.0/(1.0 + B )
             C          =  2.302585
             D          =  PFM(L) - PFR(L)
             XM        = PFM(L) / ( WVS(I) * ( 1.0 + BETA(L) ) )
             FACT       =    1.0 / (( 1.0 - POR(I))*GAMS(L))
         IF(TAT - AT) 1527,1526,1526
 1526        PF         =  PFR(L)*(AT/TAT)**RECB
             PF1        =  PFM(L) - PF
             T(I)      = - 10.0 ** PF1 / 2.54
             TE        = ABS ( T(I) )
             DTDW(I) =(TE * XM * C * ( PFR(L) / PF ) ** B ) * FACT
         GO TO 1528
 1527        PF1        =  D*((100.0 - AT)/(100.0 - TAT))**RECB
             T(I)      = - 10.0 ** PF1 / 2.54
             TE        = ABS ( T(I) )
             DTDW(I) =(XM * TE * C * ( D / PF1 ) ** B ) * F*CT
 1528    GO TO (1530,1529) KLH
 1529    IF(K) 1530,1523
 1523 CALL HEAVY
             T(I)      = T(I) + ALF * P
             DTDW(I) = DTDW(I) + ALF * DP + P * DALF
 1530 RETURN
      END
```

```
      SUBROUTINE DSUCT
      COMMON/ONE/PFM(10),PFR(10),BETA(10),DTOW(40),PF1
     1/TWO/T(40),I2
     2/THREE/WVS(40),KLH,K
     3/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(I0),POR(40),
     4KURV(40),WV(40),GAM,ALF,P,DP,DALF,MX,HX,PN(10)
     5/FIVE/WVI(40),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
     6SRCH,PCTUP,DV(40),ALFB,VTP
             1            =  I2
             L            = KURV(I)
         IF(T(I   ))2710,2705,2705
 2705        WV(I)    = WVS(I)
             DTDW(I) = 1.0
             PF1         =  0.0
         GO TO 2750
 2710    GO TO (2713,2711)KLH
 2711    IF(K) 2712,2713
 2712 CALL HEAVY
             TE           = - T(I) * 2.54 + ALF * P * 2.54
         GO TO 2714
 2713        TE           = - T(I) * 2.54
 2714        PF1          =  ALOG10(TE)
         IF(PF1)2715,2720,2720
 2715        PF1          =  0.0
             T(I)     = - 1.0 / 2.54
             WV(I)    = WVS(I)
             DTDW(I) = 1.0
         GO TO 2750
 2720    IF ( PF1 - PFM(L)) 2724,2724,2722
 2722        PF1          =  PFM(L)
             T(I)     = - 10.0 ** PF1 / 2.54
             WV(I)    = 0.0
             DTDW(I) = 1.0E+10
         GO TO 2750
 2724        PF           =  PFM(L) - PF1
             B            =  BETA(L)
             BP           =  1.0 + BETA(L)
             C            =  2.302585
             D            =  PFM(L) - PFR(L)
             TAT          =  (PFR(L)*100.0)/(PFM(L))
             XM        = PFM(L) / ( WVS(I) * ( 1.0 + BETA(L) ) )
         IF (PF - PFR(L))2725,2725,2730
 2725        AT           =  TAT*(PF/PFR(L))**BP
             TE        = - T(I)
             DTDW(I) = TE * C * XM * ( D / PF1 ) ** B
         GO TO 2735
 2730        AT           =  100.0 - (100.0 - TAT)*(PF1/D)**BP
             TE        = - T(I)
             DTDW(I   ) =  TE*C*XM*(D/PF1)**B
 2735        WV(I)    = AT * WVS(I) / 100.0
             FACT         =   1.0 / (( 1.0 - POR(I))*GAMS(L))
             DTDW(I) = DTDW(I) * FACT
 2750    GO TO (2760,2755) KLH
 2755    IF(K) 2760,2756
 2756 CALL HEAVY
             T(I)      = T(I) + ALF * P
             DTDW(I) = DTDW(I) + ALF * DP + P * DALF
 2760 RETURN
      END
```

```
       SUBROUTINE HEAVY                                                  611
       COMMON/TWO/T(40),I2                                               612
      3/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(40),                613
      4KURV(40),WV(40),GAM,ALF,P,DP,DALF,MX,HX,PN(10)                    614
      5/FIVE/WVI(40),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
      6SRCH,PCTUP,DV(40),ALFB,VTP
              I          =  I2                                           615
              L           = KURV(I)                                      616
C      DETERMINE OVERBURDEN PRESSURE HEAD                                617
              P1         =    ( MX + 3 - I )*GAM*HX +  SRCH
              P          =    P1 / 0.0361
              TERM       =   ( 1.0 - POR(I)) * GAMS(L)
              TH         =   WV(1)*TERM / 100.0
              ENN        =    POR(I)
          IF( ENP(L) ) 1542,1541
 1541         F1         =    P1 / ( AV(L)*( 1.0 - POR(I)))
          GO TO 1543
 1542  CALL GULCH
              F1         =    ENP(L)*P1*VTP/ ( VTF(L) - VTP )
 1543         F2         =    ( 2.0*TH - ENN*( TH + 1.0 ))
          IF ( WV(I) - WVA(L) ) 1540, 1550, 1550                         619
 1540         RPO        =   R(L)                                        620
              QM1        =   Q(L) - 1.0                                  621
              QM2        =   Q(L) - 2.0                                  622
              ALF        =   ALFO(L) + (1.0 - ALFO(L))*(WV(I  )/WVA(L))  623
     1                       **QM1                                       624
              SAT        =    ( TH/ POR(I))**RPO
          IF(ENP(L) ) 1545,1544
 1544         F3         =    1.0
          GO TO 1546
 1545         F3         =    ( TH + ALF - ALFB ) / TH
 1546         RG         =    8.314E+07
              G          =    981.0
              EM         =    18.02
              PSAT       =    32.6
              TEM        =    298.0
              ENRT       =    R*TEM/G*EM
              FACT       =    T(1)*2.54 / ENRT
              F4         =    ENRT / ( PSAT * EXP(FACT))
              DP         =    F1*ENN*F3*F4 / (F2*SAT )    +    HX
              DALF      = QM1 * ( 1.0 - ALFO(L) ) * ( WV(I) / WVA(L) )   633
     1                  ** QM2                                           634
              DALF       =   (DALF*100.0)/(WVA(L) * TERM )
          GO TO 1560                                                     636
 1550  CALL GULCH
              ALF        =    ALFB
              DALF       =   0.0                                         638
              DP         =    HX   +  F1*ENN / ( F2*0.0361 )
              DTH       =(( WV(I) - WVA(L) ) / 100.0 ) * TERM
              POR(I)    = ( PN(L) + DTH ) / ( 1.0 + DTH )                641
 1560  RETURN                                                            642
       END                                                               643
```

```
       SUBROUTINE HUMIDY (TE,H1)                                         644
       COMMON/TWO/T(40),I2                                               645
              I       =  I2                                              646
              R          =   8.314E+07                                   647
              G          =   981.0                                       648
              EM         =   18.02                                       649
              AN         =   ALOG(H1)                                    650
              TM         =   (TE - 32.0)*5.0/(9.0)  +  273.0             651
              T(1)     = R * TM * AN / ( G * EM * 2.54 )                 652
       RETURN                                                            653
       END                                                               654
```

```
       SUBROUTINE  GULCH
       COMMON/TWO/T(40),I2
      1/FOUR/WVA(10),Q(10),ALFO(10),R(10),AV(10),POR(40),
      2KURV(40),WV(40),GAM,ALF,P,DP,DALF,MX,HX,PN(10)
      3/FIVE/WVI(40),VTO(10),VTF(10),WVF(10),PO(10),ENP(10),GAMS(10),
      4SRCH,PCTUP,DV(40),ALFB,VTP
              I          =    12
              L          =    KURV(I)
C      DETERMINE OVERBURDEN PRESSURE PLUS SURCHARGE
              P          =     ( MX + 3 - I )*GAM*HX  +  SRCH
          IF ( P - PO(L)) 1725,1720,1720
 1720         DV(I)      =    0.0
          GO TO 1770
C      ALL CALCULATIONS IN THIS SUBROUTINE ARE DONE USING TOTAL
C      VOLUME AND WATER CONTENTS IN THE C.G.S. SYSTEM.
C      TO CONVERT VT TO CU. IN. / LB.. MPY BY 27.7.
C      GRAVIMETRIC WATER CONTENT EQUALS SPECIFIC VOLUME OF WATER
C      IN THIS SYSTEM.
 1725         RENP       =    1.0 / ENP(L)
              VTP        =  VTF(L) - (( P/PO(L))**RENP)*( VTF(L) -
     1                        VTO(L))
              WVP        =    WVF(L) - ( VTF(L) - VTP ) * 100.0
          IF ( WVI(I) - WVA(L) ) 1730,1750,1750
 1730         QM1        =    Q(L) - 1.0
              QMO        =    Q(L)
              VTI        =    VTO(L) + WVI(I)*( ALFO(L) + ( 1.0 -
     1                         ALFO(L))*((WVI(I)/WVA(L))**QM1)/QMO)
     2                         /100.0
          GO TO 1760
 1750         VTAP       =    VTO(L) + WVA(L)*( ALFO(L) + (1.0-ALFO(L))
     1                         /Q(L)) / 100.0
              VTI        =    VTAP + ( WVI(I) - WVA(L)) / 100.0
 1760         DELW       =    ( WV(I) - WVI(I) ) / 100.0
          IF(DELW) 1731,1731,1735
 1731         DV(I)      =    0.0
              ALFB       =    1.0
          GO TO 1770
 1735         DELT       =    ( WVP - WVI(I)) / 100.0
              S          =    DELT / ( VTP - VTI )
          IF ( Q(L) - S ) 1737,1737,1736
 1736         S          =    Q(L)
 1737         DELV       =    ( VTP - VTI )*( DELW/DELT )**S
              ALFB       =    DELV/DELW
              DV(I)      =    DELV*PCTUP/ VTI
 1770  RETURN
       END
```

APPENDIX 10

SAMPLE DATA SWELL1

```
TEST RUN OF PROGRAM SWELL1
DATA FROM WYOMING TEST  MOISTURE MEASURED FROM NUCLEAR PROBE TUBE NO. 11
TEST1      COMPUTATIONS MADE ASSUMINGSAT. WAT. CONTENT, SAT. PERMEABILITY
                                    1    1    1   24    4    1    1    1
   27         11           6.0                   691200.
    0   28                 1.0E-06    2.54       1.0E+09    3.0
    1 6.5 3.0    3.0 23.5  2.0        0.0        0.485       .08      2.0 .0695   40.0
    0.60      0.8825       42.0       40.0       1.20       0.1        1.00      2.70
    0   27    1
    3    3    1            12.85
    4    4    1            13.6
    5    5    1            14.2
    6    6    1            14.15
    7    7    1            14.0
    8    8    1            13.55
    9    9    1            13.1
   10   10    1            13.5
   11   11    1            13.9
   12   12    1            13.55
   13   13    1            13.15
   14   14    1            13.3
   15   15    1            13.5
   16   16    1            13.65
   17   17    1            13.75
   18   18    1            13.85
   19   19    1            13.9
   20   20    1            13.55
   21   21    1            13.75
   22   22    1            12.4
   23   23    1            12.6
   24   24    1            13.1
   25   25    1            14.7
   26   26    1            15.9
    0    0    1            15.2
    1    1    1            14.5
    2    2    1            13.3
   27   27    1            15.9
    1    1
    2
    1    5
    1    2    4    8    11
    2    1
   27   27    1            40.0
```

APPENDIX 11

SAMPLE OUTPUT SWELL1

PROGRAM SWELL1   R.L.LYTTON   REVISION DATE   DEC 04, 1948

TEST RUN OF PROGRAM SWELL1
DATA FROM WYOMING TEST MOISTURE MEASURED FROM NUCLEAR PROBE TUBE NO. 11

PROB
TEST1   COMPUTATIONS MADE ASSUMINGSAT. WAT. CONTENT, SAT. PERMEABILITY

TABLE 1. PROGRAM CONTROL SWITCHES.

	TABLES NUMBER				
	2	3	4A	5	6
PRIOR DATA OPTIONS (1 = HOLD)	-0	-0	-0	-0	-0
NUMBER CARDS INPUT THIS PROBLEM	1	1	1	24	4
GRID = 1, CYLINDER = 2 SWITCH	1				
LIGHT = 1, HEAVY = 2 SWITCH	1				
VERT = 1, HORIZ = 2 SWITCH	1				

TABLE 2. INCREMENT LENGTHS, ITERATION CONTROL

NUM OF INCREMENTS	=	27	
INCREMENT LENGTH	=	6.000E+00	IN
NUM OF TIME INCREMENTS	=	11	
TIME INCREMENT LENGTH	=	6.912E+05	SECS
INSIDE RADIUS	=	-0.	IN

TABLE 3. PERMEABILITY

FROM	TO	P1	AK	BK	EXPONENT
0	28	1.000E-06	2.540E+00	1.000E+09	3.000E+00

TABLE 4. SUCTION - WATER CONTENT CURVES

CURVE NUMBER		1
NUM LOCATIONS	=	1
MAXIMUM PF	=	6.50
PF AT INFLECTION	=	3.00
EXPONENT FOR PF	=	3.00
AIR ENTRY WATER CONT	=	23.50
DRYING CURVE EXPONENT	=	2.00
ALFA AT 0 WATER CONT	=	0.
INITIAL POROSITY	=	4.850E-01
REFERENCE AV	=	8.000E-02
SATURATION EXPONENT	=	2.00
SOIL UNIT WT PCI	=	6.950E-02
SATURATED WATER CONT.	=	4.000E+01

CURVE NUMBER		1
INITIAL TOTAL VOLUME	=	6.000E-01
FINAL TOTAL VOLUME	=	8.825E-01
FINAL WATER CONTENT	=	4.200E+01
SWELL PRESSURE, PSI	=	4.000E+01
EXPONENT OF P-V CURVE	=	1.20
SURCHARGE PRESS, PSI	=	1.000E-01
PCT VOL CHG VERTICAL	=	1.000E+00
SPEC.GRAV.SOLIDS	=	2.700E+00

NO.	FROM	TO
1	0	27

TABLE 5, INITIAL CONDITIONS

FROM	TO	CASE	VOL. W.	PORE PR.	SLOPE X
3	3	1	1.285E+01	-0.	-0.
4	4	1	1.360E+01	-0.	-0.
5	5	1	1.420E+01	-0.	-0.
6	6	1	1.415E+01	-0.	-0.
7	7	1	1.400E+01	-0.	-0.
8	8	1	1.355E+01	-0.	-0.
9	9	1	1.310E+01	-0.	-0.
10	10	1	1.350E+01	-0.	-0.
11	11	1	1.390E+01	-0.	-0.
12	12	1	1.355E+01	-0.	-0.
13	13	1	1.315E+01	-0.	-0.
14	14	1	1.330E+01	-0.	-0.
15	15	1	1.350E+01	-0.	-0.
16	16	1	1.365E+01	-0.	-0.
17	17	1	1.375E+01	-0.	-0.
18	18	1	1.385E+01	-0.	-0.
19	19	1	1.390E+01	-0.	-0.
20	20	1	1.355E+01	-0.	-0.
21	21	1	1.375E+01	-0.	-0.
22	22	1	1.240E+01	-0.	-0.
23	23	1	1.260E+01	-0.	-0.
24	24	1	1.310E+01	-0.	-0.
25	25	1	1.470E+01	-0.	-0.
26	26	1	1.590E+01	-0.	-0.

TABLE 6, BOUNDARY AND INTERNAL CONDITIONS

FROM	TO	CASE	WV	T	DT/DX	H	TEMP
0	0	1	1.520E+01-0.		-0.	-0	-0.0
1	1	1	1.450E+01-0.		-0.	-0	-0.0
2	2	1	1.330E+01-0.		-0.	-0	-0.0
27	27	1	1.590E+01-0.		-0.	-0	-0.0

TABLE 8A. TIME STEPS FOR B.C. CHANGE

2

TABLE 8B. TIME STEPS FOR OUTPUT

1 2 4 8 11

TABLE 10. OUTPUT OF RESULTS

TIME STEP = 1

I	T(I)	WV(I)	DTDW(I)	P1(I)
0	-7.713E+02	1.520E+01	6.739E+01	1.174E-07
1	-8.411E+02	1.450E+01	7.613E+01	9.303E-08
2	-9.830E+02	1.330E+01	9.493E+01	6.037E-08
3	-1.045E+03	1.285E+01	1.036E+02	5.075E-08
4	-9.445E+02	1.360E+01	8.970E+01	6.753E-08
5	-8.737E+02	1.420E+01	8.033E+01	8.383E-08
6	-8.793E+02	1.415E+01	8.106E+01	8.237E-08
7	-8.964E+02	1.400E+01	8.330E+01	7.810E-08
8	-9.508E+02	1.355E+01	9.055E+01	6.629E-08
9	-1.010E+03	1.310E+01	9.865E+01	5.593E-08
10	-9.571E+02	1.350E+01	9.140E+01	6.507E-08
11	-9.081E+02	1.390E+01	8.485E+01	7.535E-08
12	-9.508E+02	1.355E+01	9.055E+01	6.629E-08
13	-1.003E+03	1.315E+01	9.770E+01	5.701E-08
14	-9.830E+02	1.330E+01	9.493E+01	6.037E-08
15	-9.571E+02	1.350E+01	9.140E+01	6.507E-08
16	-9.383E+02	1.365E+01	8.887E+01	6.879E-08
17	-9.261E+02	1.375E+01	8.723E+01	7.136E-08
18	-9.140E+02	1.385E+01	8.563E+01	7.400E-08
19	-9.081E+02	1.390E+01	8.485E+01	7.535E-08
20	-9.508E+02	1.355E+01	9.055E+01	6.629E-08
21	-9.261E+02	1.375E+01	8.723E+01	7.136E-08
22	-1.113E+03	1.240E+01	1.133E+02	4.240E-08
23	-1.082E+03	1.260E+01	1.088E+02	4.597E-08
24	-1.010E+03	1.310E+01	9.865E+01	5.593E-08
25	-8.203E+02	1.470E+01	7.349E+01	9.957E-08
26	-7.094E+02	1.590E+01	5.993E+01	1.460E-07
27	-7.094E+02	1.590E+01	5.993E+01	1.460E-07
28	0.	0.	-1.833-270	1.000E-06

TIME STEP = 1

I	T(I)	WV(I)	PF(I)
0	-7.713E+02	1.520E+01	3.292E+00
1	-8.411E+02	1.450E+01	3.330E+00
2	-9.830E+02	1.330E+01	3.397E+00
3	-1.027E+03	1.298E+01	3.417E+00
4	-9.453E+02	1.359E+01	3.380E+00
5	-8.826E+02	1.412E+01	3.351E+00
6	-8.812E+02	1.413E+01	3.350E+00
7	-8.998E+02	1.397E+01	3.359E+00
8	-9.501E+02	1.356E+01	3.383E+00
9	-9.983E+02	1.319E+01	3.404E+00

10	-9.566E+02	1.350E+01	3.386E+00
11	-9.177E+02	1.382E+01	3.368E+00
12	-9.513E+02	1.355E+01	3.383E+00
13	-9.959E+02	1.320E+01	3.403E+00
14	-9.819E+02	1.331E+01	3.397E+00
15	-9.577E+02	1.350E+01	3.386E+00
16	-9.389E+02	1.364E+01	3.377E+00
17	-9.261E+02	1.375E+01	3.371E+00
18	-9.149E+02	1.384E+01	3.366E+00
19	-9.127E+02	1.386E+01	3.365E+00
20	-9.446E+02	1.360E+01	3.380E+00
21	-9.402E+02	1.363E+01	3.378E+00
22	-1.095E+03	1.252E+01	3.444E+00
23	-1.075E+03	1.265E+01	3.436E+00
24	-9.849E+02	1.329E+01	3.398E+00
25	-8.231E+02	1.467E+01	3.320E+00
26	-7.256E+02	1.571E+01	3.266E+00
27	-7.094E+02	1.590E+01	3.256E+00

STATION	TOTAL MVMT	INCR MVMT
0	0.	0.
1	0.	0.
2	0.	0.
3	5.738E-05	5.738E-05
4	5.738E-05	0.
5	5.738E-05	0.
6	5.738E-05	0.
7	5.738E-05	0.
8	5.749E-05	1.106E-07
9	8.278E-05	2.529E-05
10	8.284E-05	5.825E-08
11	8.284E-05	0.
12	8.284E-05	0.
13	9.216E-05	9.323E-06
14	9.241E-05	2.490E-07
15	9.241E-05	0.
16	9.241E-05	0.
17	9.241E-05	0.
18	9.241E-05	0.
19	9.241E-05	0.
20	9.994E-05	7.531E-06
21	9.994E-05	0.
22	1.401E-04	4.014E-05
23	1.466E-04	6.537E-06
24	2.474E-04	1.008E-04
25	2.474E-04	0.
26	2.474E-04	0.
27	2.474E-04	0.

TABLE 9. SUBSEQUENT BOUNDARY CONDITIONS

USING DATA FROM PREVIOUS PROBLEM PLUS

FROM	TO	CASE	WV	T	DI/DX	H	TEMP
27	27	1	4.000E+01	-0.	-0.	-0	-0.0

TIME STEP = 2

I	T(I)	WV(I)	PF(I)
0	-7.713E+02	1.520E+01	3.292E+00
1	-8.411E+02	1.450E+01	3.330E+00
2	-9.830E+02	1.330E+01	3.397E+00
3	-1.020E+03	1.302E+01	3.414E+00
4	-9.455E+02	1.359E+01	3.381E+00
5	-8.865E+02	1.409E+01	3.353E+00
6	-8.826E+02	1.412E+01	3.351E+00
7	-9.014E+02	1.396E+01	3.360E+00
8	-9.496E+02	1.356E+01	3.382E+00
9	-9.936E+02	1.322E+01	3.402E+00
10	-9.564E+02	1.351E+01	3.385E+00
11	-9.218E+02	1.379E+01	3.369E+00
12	-9.517E+02	1.354E+01	3.383E+00
13	-9.930E+02	1.322E+01	3.402E+00
14	-9.812E+02	1.331E+01	3.397E+00
15	-9.579E+02	1.349E+01	3.386E+00
16	-9.392E+02	1.364E+01	3.378E+00
17	-9.262E+02	1.375E+01	3.372E+00
18	-9.155E+02	1.384E+01	3.366E+00
19	-9.146E+02	1.385E+01	3.366E+00
20	-9.428E+02	1.361E+01	3.379E+00
21	-9.460E+02	1.359E+01	3.381E+00
22	-1.088E+03	1.256E+01	3.441E+00
23	-1.070E+03	1.268E+01	3.434E+00
24	-9.752E+02	1.336E+01	3.394E+00
25	-8.061E+02	1.484E+01	3.311E+00
26	-3.562E+02	2.259E+01	2.957E+00
27	0.	4.000E+01	0.

STATION	TOTAL MVMT	INCR MVMT
0	0.	0.
1	0.	0.
2	0.	0.
3	1.104E-04	1.104E-04
4	1.104E-04	0.
5	1.104E-04	0.
6	1.104E-04	0.
7	1.104E-04	0.
8	1.107E-04	3.108E-07
9	1.607E-04	5.000E-05
10	1.608E-04	9.506E-08
11	1.608E-04	0.
12	1.608E-04	0.
13	1.793E-04	1.852E-05
14	1.799E-04	6.377E-07
15	1.799E-04	0.
16	1.799E-04	0.
17	1.799E-04	0.
18	1.799E-04	0.
19	1.799E-04	0.
20	1.925E-04	1.253E-05
21	1.925E-04	0.
22	2.697E-04	7.723E-05
23	2.869E-04	1.717E-05
24	4.827E-04	1.958E-04
25	5.426E-04	5.989E-05
26	1.418E-01	1.412E-01
27	1.042E+00	9.005E-01

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