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Designing Pavement Drainage Systems: The MnDRAIN Software



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16. Abstract (Limit: 200 words) This report outlines the development of a suite of computer codes embedded in a Microsoft Excel spreadsheet collectively referred to as MnDrain. These codes provide a user-friendly environment in which the consequences of an edge drain design decision can be investigated. Edge drains consist of pipes that run along the length of a road to remove moisture from the granular base of the road system. The pipes are placed in a high permeability gravel trench below the shoulder/road surface. The rate at which moisture is removed will depend on the geometry and materials used in the base and the soil type in the sub-grade. A full copy of the MnDrain code, including all source programs and an on-line manual, can be downloaded on visiting http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html . The main attributes of the MnDrain system are: a relevant easy to use graphical interface, meaningful drainage design scenarios, flexible assignment of materials properties, an easy to maintain database for unsaturated properties, and a state of the art saturated/unsaturated numerical solution engine. The code is freeware that can be readily reconfigured for alternative and novel applications. As it stands the MnDrain code is a solid initial framework from which further developments can be made. In this project the operation of MnDrain was purposely constrained to work with simple geometries (the scenarios) to establish a system that could be used by a field engineer with only a limited knowledge of soil physics and numerical modeling. Because MnDrain offers free access to all source codes, it can be reconfigured to deal with a large array of pavement drainage issues. To take advantage of this feature, further investigation is recommended.			
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DESIGNING PAVEMENT DRAINAGE SYSTEMS: The MnDRAIN SOFTWARE

Final Report

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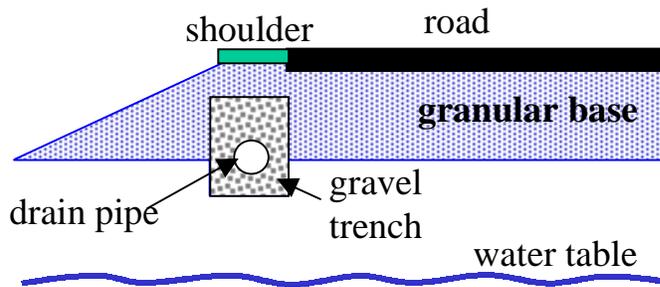
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EXECUTIVE SUMMARY

This report outlines the development of a suite of computer codes collectively referred to as MnDrain. These codes, embedded in a Microsoft Excel spreadsheet, provide a user-friendly environment in which the consequences of an edge drain design decision can be investigated. Edge drains consist of pipes that run along the length of a road. The pipes are placed in a high permeability gravel trench below the shoulder/road surface.



Schematic of Edge Drain (not to scale)

The purpose of an edge drain is to remove moisture from the granular base of the road system. The rate at which moisture is removed will depend on the geometry and materials used in the base and the soil type in the sub-grade. The FHWA measures the quality of drainage based on the time to reduce an initially saturated (100% moisture) base to a moisture level of 85%

Table 5.4. Pavement rehabilitation manual guidance for time to drain from 100 to 85 percent saturation (ERES 1987; FHWA 1994).

Quality of Drainage	Time to Drain
Excellent	Less than 2 hours
Good	2 to 5 hours
Fair	5 to 10 hours
Poor	Greater than 10 hours
Very Poor	Much greater than 10 hours

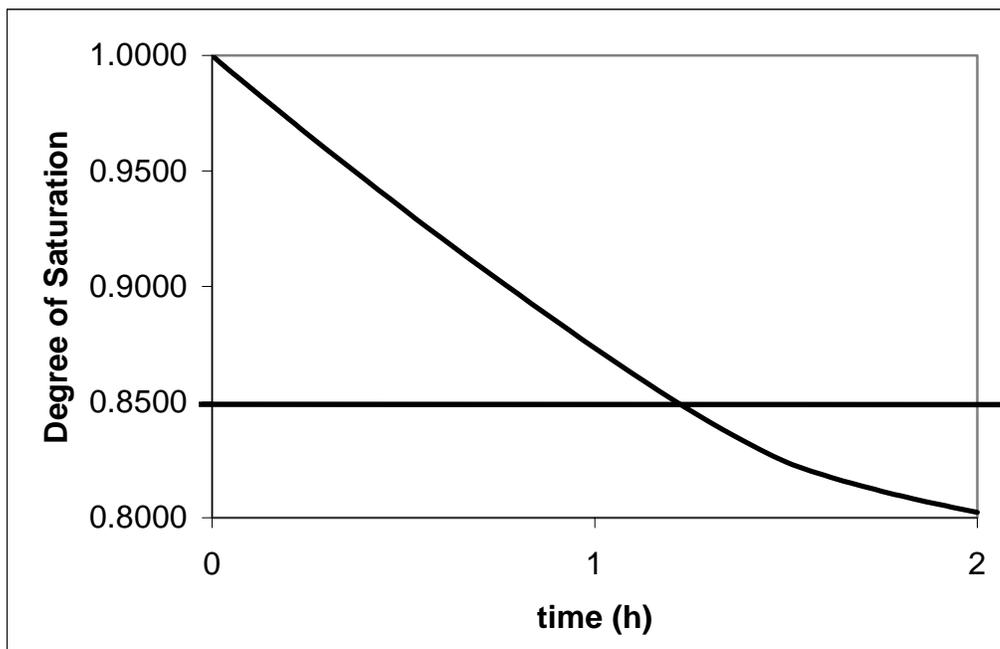
MnDrain allows for evaluation of a given drain design against the FHWA requirement. In

MnDrain the user can

Choose from three basic scenarios.

Select material types and adjust geometries for each scenario.

Calculate the moisture removal vs. time curve over a two-hour drainage time for comparison with the FHWA 85% cut off.



Part of Output from MnDrain Program

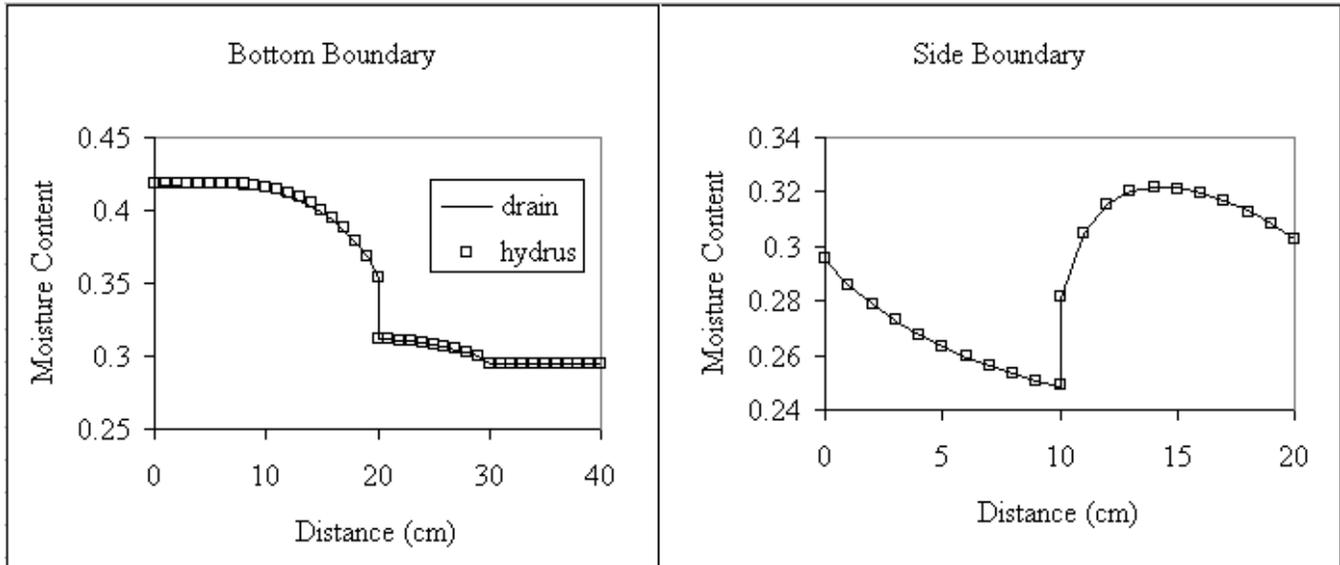
A full copy of the MnDrain code, including an on-line manual, can be downloaded on visiting

http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html

A critical and significant part of MnDrain is a Control Volume Finite Element (CVFE) solution of the Richard equation for variably saturated flow in a layered media

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K(h) \nabla h) + \frac{\partial K}{\partial z}$$

where h is the pressure head, θ (a function of h) is the moisture content and K (also a function of h) is the hydraulic conductivity. Note h is negative in the unsaturated region. The performance of this CVFE algorithm, implemented on an unstructured mesh of linear finite elements, has been fully verified by comparison with results obtained with commercial codes



Example of Comparison between MnDrain and the commercial code Hydrus2D

The work in this report shows that MnDrain is:

- Easy to use.
- Has a high degree of flexibility
- Produces accurate approximate solutions of the Richard's model of variable saturated flow in a
- Layered media.

Further, although commercial code, e.g.,

Hydrus 2D (<http://www.ussl.ars.usda.gov/models/hydrus2d.htm>) and

SEEP/W (<http://www.geo-slope.com/products/seepw.asp>)

have been successfully used to simulate edge drain performance, there are two distinct advantages offered by the MnDrain code.

1. The commercial codes are primarily intended as multi-purpose research tools and they include many sophisticated features not required in an evaluation of an edge drain performance. As a result there is a steep learning curve required to master the operation of these codes. Such codes are ideal for use in a central research facility but are less than ideal for distribution among field engineers. In contrast the MnDrain code only has one feature, the ability to solve unsaturated flow in layered media. This lack of general utility allows for a well-focused user interface that promotes rapid acquisition of the skills required to run the code. The ability to learn the code operation rapidly is enhanced by the fact that the code is embedded in a Microsoft Excel interface.
2. The code in MnDrain is freeware. This means that the source software is freely available and can be reconfigured for more general applications.

CHAPTER 1

INTRODUCTION

This report outlines the development of a suite of computer codes collectively referred to as MnDrain. These codes, embedded in a Microsoft Excel spreadsheet, provide a user-friendly environment in which the consequences of an edge drain design decision can be investigated. Edge drains consist of pipes that run along the length of a road. The pipes are placed in a high permeability gravel trench below the shoulder/road surface, Figure 1.1.

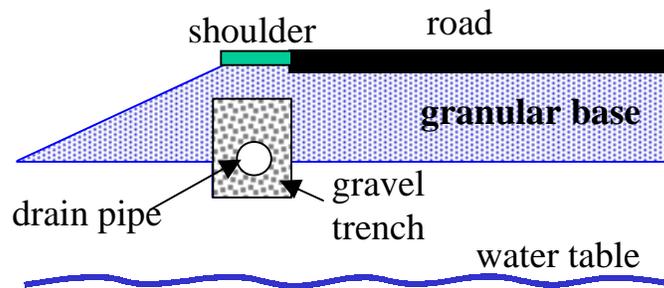


Figure 1.1 Schematic of Edge Drain (not to scale)

The objective of the edge drain is to remove moisture from the granular base of the road system. The rate at which moisture is removed will depend on the geometry and materials used in the base and soil type in the sub-grade. The FHWA measures the quality of drainage on how it takes to reduce an initially saturated (100% moisture) base to a moisture level of 85%, see Table 1.1.

Table 1.1 Pavement Rehabilitation Manual Guidance for Time to Drain from 100 to 85 Percent Saturation

Quality of Drainage	Time to Drain
Excellent	Less than 2 hours
Good	2 to 5 hours
Fair	5 to 10 hours
Poor	Greater than 10 hours
Very Poor	Much greater than 10 hours

The objective of MnDrain is to test a given drain against this requirement. A description of the full operation of MnDrain can be found in the online manual at

http://www.ce.umn.edu/~voller/voller_research/task5/mndrainmanual.pdf

In MnDrain the user

1. Can choose from three basic scenarios, each based on geometry similar to that shown in Fig 1.1.

These scenarios are:

- An initially saturated base, drain trench, and edge drain on a permeable sub-grade with an adjustable water table height.
- An initially saturated base on a permeable sub-grade with an adjustable water table height. No drain or drain trench is present.
- An initially saturated base and fouled edge drain on a permeable sub-grade with an adjustable water table height. This case accounts for the drain trench but does not allow water to enter the drainpipe.

2. Select material types and adjust geometries for each scenario

3. Calculate the moisture removal vs. time curve over a two-hour drainage time for comparison with the FHWA 85% cut off, see Figure 1.2

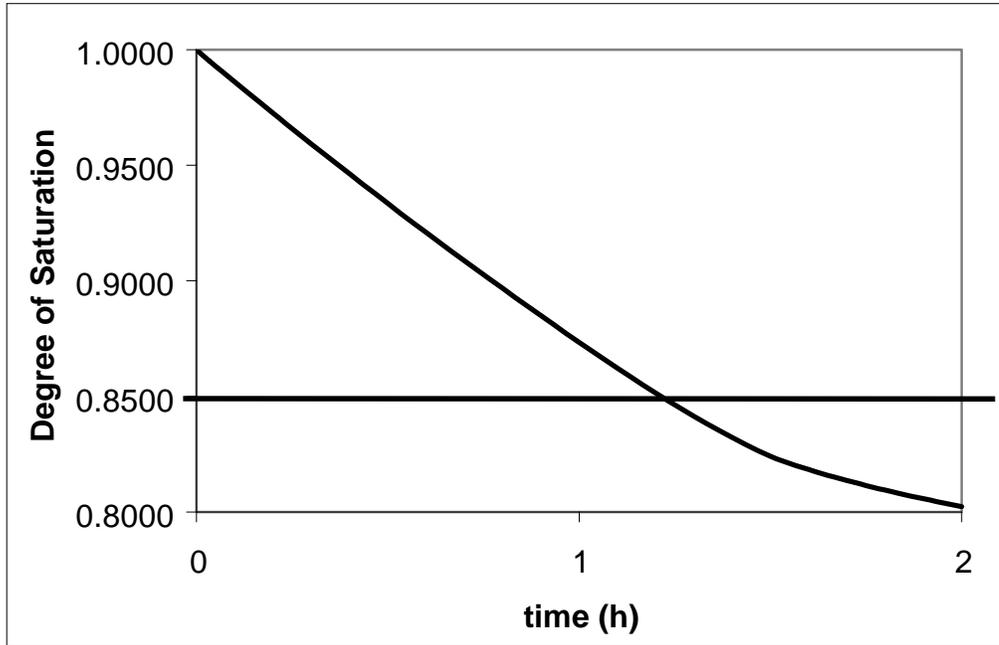


Figure 1.2 Part of Output from MnDrain Program

The calculations performed in the operation of MnDrain are based on an unstructured Control Volume Finite Element (CVFE) solution [1] of the Richard equation [2,3] for variably saturated flow in a layered media

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K(h) \nabla h) + \frac{\partial K}{\partial z} \quad (1.1)$$

where h is the pressure head, θ (a function of h) is the moisture content and K (also a function of h) is the hydraulic conductivity. Note h is negative in the unsaturated region.

The main tasks of this report are to

1. Explain, demonstrate, and verify the CVFE solution used in MnDrain.
2. Explain and demonstrate the operation of the MnDrain code.

To accomplish these tasks the report is structured as follows

Chapter 2: General background on the modeling of variably saturated flow.

Chapter 3: Brief review of available code for modeling variably saturated flow.

Chapter 4: Description of the MnDrain CVFE numerical procedure for predicting unsaturated flow phenomenon in layered systems.

Chapter 5: Verification of the MnDrain CVFE procedure.

Chapter 6: Discussion of the material data and boundary conditions used in MnDrain.

Chapter 7: Outline of the operation of MnDrain (this chapter is essentially an introduction to a hard copy of the on-line manual given in the Appendix).

Chapter 8: Conclusions and Recommendations.

Appendix: Hard copy of the MnDrain on-line manual

CHAPTER 2

MODELING VARIABLY SATURATED FLOW

Objective

The objective of this chapter is to outline some of the basic concepts used in modeling variably saturated flow. In particular various versions of the classical Richards equation and associated auxiliary relationships will be presented.

Variables

In this work the movement of moisture through variably saturated regions will be described by two main variables

The pressure head

The pressure head h (units of length) is defined as

$$h = \frac{P}{\gamma} \quad (2.1)$$

where P is pressure and γ is the specific weight of water. Note in unsaturated regions the pressure P will be equal to the minus of the suction pressure and h will take a negative value.

The moisture content

A variably saturated region can be in one of three states, see Figure 2.1.

1. The fully saturated region where all the voids are filled with moisture and the pressure head $h \geq 0$, in this region the moisture content takes the constant value $\theta = \theta_{\text{sat}}$.
2. The capillary fringe where all the voids are filled by capillary action (suction). In this state the moisture content still takes the value $\theta = \theta_{\text{sat}}$ but now $h < 0$

3. An unsaturated region where air has entered the system and some of the voids are not filled. In this region $h < 0$ and the moisture $\theta_{\text{res}} < \theta(h) < \theta_{\text{sat}}$, where θ_{res} is the residual moisture content approached as $h \rightarrow -\infty$

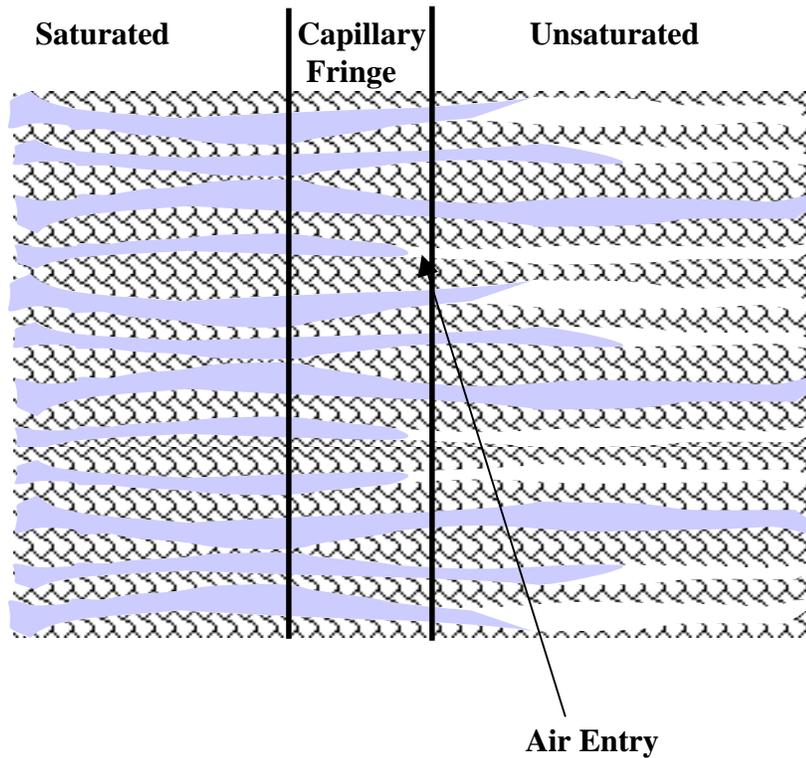


Figure 2.1 Schematic Groundwater Flow Regions

The Moisture Flux

In saturated groundwater flow movement of the moisture—volume flux, q (L^3/L^2)—is described by the Darcy equation

$$q = -K_{\text{sat}} \nabla H \quad (2.1)$$

where K_{sat} is the saturated hydraulic conductivity (L/T) and (measuring z upwards) $H = h + z$ is the total head (L). In the unsaturated states the movement of the moisture is governed by a modification of the Darcy equation suggested by Richards [2]

$$q = -K(h)\nabla H \quad (2.2)$$

where the hydraulic conductivity $K = K(h)$ is now a function of the pressure head

The Mixed Form of the Richards Equation

Consider an arbitrary fixed control volume of surface A and volume V containing both saturated and unsaturated soil, Figure 2.2 The unsaturated and saturated regions are separated by the isobar $P = 0$.

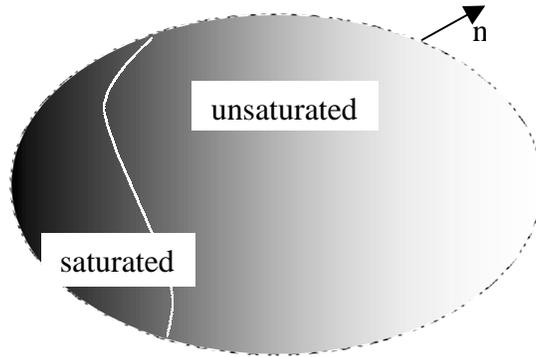


Figure 2.2 Arbitrary Control Volume in Saturated/Unsaturated Flow Domain

A volume balance of the flow over this domain can be stated as

$$\int_A K(h)\nabla h \cdot n \, dA = \frac{d}{dt} \int_V \theta(h) \, dV \quad (2.3)$$

where in the saturated region of V ($h > 0$) and on the saturated portion of the surface A , the saturated values of hydraulic conductivity and moisture content are used. On noting that the volume V is fixed in time and using the divergence theorem (2.3) can be written as

$$\int_V \frac{\partial \theta}{\partial t} - \nabla \cdot (K(h)\nabla h) \cdot n \, dV = 0 \quad (2.4)$$

Since the volume V is arbitrary the argument of the integral in Eq. (2.4) must take the value

$$\frac{\partial \theta}{\partial t} - \nabla \cdot (K(h)\nabla h) = 0 \quad (2.5)$$

at every point in V. On expanding the second term in (2.5) and rearranging we arrive at the so called “Mixed Form” Richards equation [3]

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (\mathbf{K}(h) \nabla h) + \frac{\partial K}{\partial z} \quad (2.6)$$

The main advantage of this form of Richards equation is (1) its “volume balance” heritage through the derivation outlined above, and (2) its ability to account for the transition from unsaturated to saturated flow; for these reasons Eq. (2.6) will be the general governing equation used in this work.

Alternative Forms of the Richards Equation

For completeness it is worth noting some alternative forms of Richards Equation.

The matric flux potential

On defining matric flux potential to be [1]

$$\phi = \int_{-\infty}^h K(\alpha) d\alpha \quad (2.7)$$

and using the Leibniz rule Eq. (2.6) can be written as

$$\frac{\partial \theta}{\partial t} = \nabla^2 \phi + \frac{\partial K}{\partial z} \quad (2.8)$$

In some cases, due to the linear form of the Laplacian, this form could have a computational advantage.

The pressure head form

The “specific moisture capacity” [2,3] is defined as

$$C(h) = \frac{d\theta}{dh} \quad (2.9)$$

Use of this definition in (2.6) results in the suction head form of Richards equation [2,3]

$$C(h) \frac{\partial h}{\partial t} = -\nabla \cdot (K(h) \nabla h) + \frac{\partial K}{\partial z} \quad (2.10)$$

At first sight this equation appears to be more convenient than Eq. (2.6) since, unlike the mixed form, the time and space derivatives are expressed in terms of a single unknown (h). Unlike the mixed form, however, it does not naturally extend into the capillary and saturated regions.

The moisture content form

The definition of the specific moisture capacity can also be used to rewrite the derivatives in Eq. (2.6) in terms of the moisture content alone. Use of Eq. (2.9) on the RHS of Eq. (2.7) results in the moisture content form of the Richards equation

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (D(\theta) \nabla \theta) + \frac{\partial K}{\partial z} \quad (2.11)$$

where $D(\theta) = K(\theta)/C(\theta)$ is the hydraulic diffusivity [2,3]. In a similar fashion to the suction head form this equation does not work well as the saturated limit is approached.

Auxiliary Relationships

To complete the model of variably saturated flow auxiliary relationships that relate the hydraulic conductivity and moisture content to the pressure head are needed. Forms of the unsaturated moisture and conductivity characteristics are a central component in soil physics [2] and there is an extensive literature on various developments. In a recent review and study, Ariza and Birgisson [4] have provided a comprehensive discussion of relationships suitable for pavement engineering situations. Well known examples include the following.

Brooks-Corey [5]

$$\theta = \begin{cases} (\theta_{\text{sat}} - \theta_{\text{res}})(h/h_d)^{-\lambda_1} + \theta_{\text{res}}, & h < h_d \\ \theta_{\text{sat}}, & h \geq h_d \end{cases} \quad (2.12)$$

$$K = K_{\text{sat}} \left[\frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \right]^{\lambda_2} \quad (2.13)$$

where the λ 's are material constant.

Van Genuchten [6]

$$\theta = \begin{cases} \frac{\theta_{\text{sat}} - \theta_{\text{res}}}{(1 + |\alpha h|^n)^m} + \theta_{\text{res}} & h < h_d \\ \theta_{\text{res}} & h \geq h_d \end{cases} \quad (2.14)$$

$$K = K_{\text{sat}} \left[\frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \right]^{0.5} \left[1 - \left(1 - \left[\frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \right]^{1/m} \right)^m \right]^2 \quad (2.15)$$

where α , m , and n are material parameters.

CHAPTER 3

A REVIEW OF CODES FOR VARIABLY SATURATED FLOW

Software Elements

The objective of this chapter is to review existing software that has been developed and/or is available for simulation of drainage. To initiate this review the elements in drainage software need to be identified.

Form of equation used

This could be any one of the forms of Richards equation discussed previously. It may also involve the Darcy form of Richards equation if only saturated flow is considered. Both transient and steady state cases could be considered.

Numerical discretization scheme used

In simplistic, but rigorous terms, the objective of a given numerical scheme for a governing Partial Differential Equation (PDE) is to convert the analytical description with a continuous solution into an approximate discrete system with an algebraic solution. In a broad sense there are four possible schemes to convert the governing PDE for variably saturated flow, e.g., Eq. (2.6), into a discrete form.

- Finite difference. Here the derivative terms in the governing equation are approximated in terms of Taylor series expansions [7]. A restriction is the need to have a rectangular grid of nodes (see Figure 3.1) which makes the modeling of “odd” shaped domains difficult.
- Finite Element. In this approach a weighted residual integral form of the governing equation is constructed [8]. A solution to this problem is an interpolated function, over the node points, defined at the vertices and/or edges of the elements that tessellate the domain. Numerical integration using the interpolation functions arrives at a set of algebraic equations in terms of field variables located at the node points. This method can fit complex shaped domains. A

potential drawback is an explicit satisfaction of conservation at the local scale of the region surrounding a node point.

- Finite Volume. This approach can use the same mesh and interpolations employed by the finite element method [1,9]. The algebraic equations, however, are obtained by specifically satisfying local conservation over control volumes, located around each node point, see Figure 3.1.
- Boundary Element. In this approach, by the use of a mathematical transformation, the dimension of the problem is reduced by one-order, e.g., a two-dimensional field problem will be reduced to a one-dimensional problem defined on the boundary of the domain. Standard interpolations can be used to solve the lower order problem. This approach works very well for problems with complex domains but the computations can be intense if the interior of the domain involves non-linearity.

Boundary Conditions

The boundary conditions that can be applied vary across available codes. Common boundary treatments include setting of far-field conditions and “review boundaries.” The later only allowing flow out of the domain.

User Interface.

All software needs to allow a “window” through which the user can set material and boundary parameters, run the programs, and visualize and review the results.

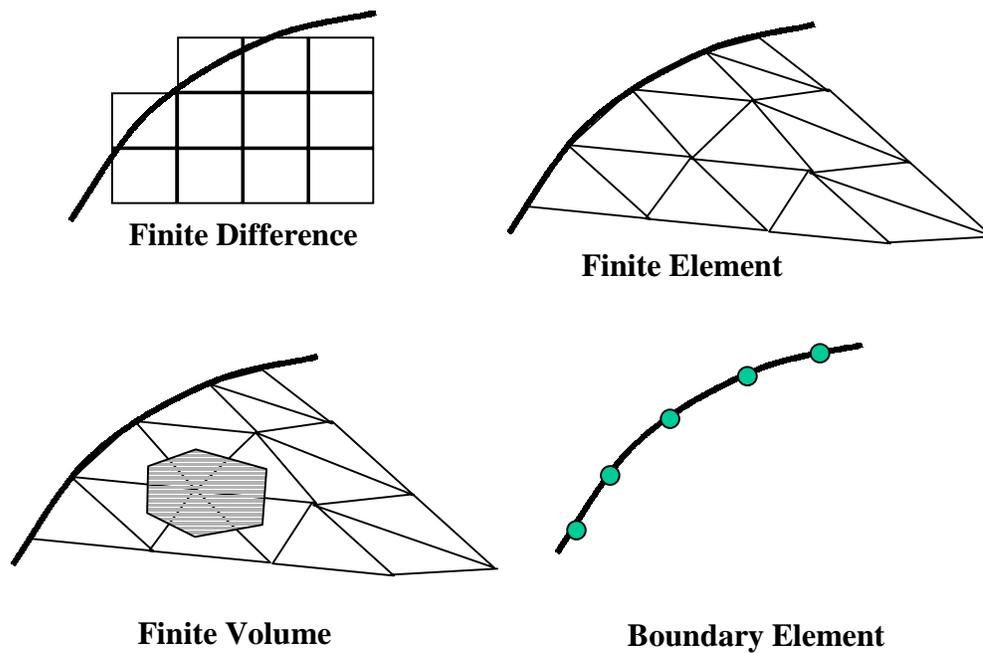


Figure 3.1. Possible Types of Spatial Discretization

Review of Software

Even a brief search through various databases, e.g., the Geo-technical and Geo-environmental software directory <http://www.ggsd.com/> reveals a vast array of methods and software for modeling the movement of moisture into and through the sub-surface. The review provided below only identifies those that would be applicable to pavement design.

DRIP: This is a windows based design program available from the FHWA [10]. It is a module-based program with the ability to combine various design modules into a comprehensive design and analysis exercise. In terms of modeling the flow of moisture in the saturated/unsaturated region, a main focus of this work, the analysis is based on initial work by Moulton [11]. In essence approximate analytical methods for the design of subsurface drainage systems based on fundamental seepage theory are used to

arrive at graphical design aids that can be readily applied by the highway designer. Although this windows based program allows the user to specify geometries etc., there is no obvious facility to specify fundamental forms of the unsaturated moisture and conductivity characteristics. The main design outputs are estimates of the drainage performance under saturated conditions and the time for the system to drain.

PURDRAIN: [12]. This software solves the two-dimensional pressure-head form of the Richards equation (2.10). Finite difference methods are used to achieve this. A simple geometric cross-section of a pavement drainage system is used. The program runs under DOS and has a menu based user interface for the detailed specification of geometry, boundary conditions, and materials types. Fundamental forms of the unsaturated moisture and conductivity characteristics are used in the program but there appears to be no user menu that allows for the exact specification of a given form. *PURDRAIN* is a research tool and its general availability is unclear.

The Integrated Climate Model [13]. This is a finite-difference model that takes into account the effect of a range of climate factors on the pavement structure. Three separate models are combined: (1) the Climatic-Materials-Structures Model (CMS) developed at the University of Illinois (2) the Infiltration and Drainage Model (ID) developed by the Texas Transportation Institute at Texas A&M University, and (3) the CRREL Frost Heave and Thaw Settlement Model developed at the United States Army Cold Regions Research and Engineering Laboratory (CRREL). The model runs under DOS with menu based user input. The emphasis is the simulation of the long-term effects of climate, rainfall, temperature, solar radiation, cloud cover, wind speed, and snow fall, on the pavement structure. The program computes the pore water pressure, temperature, frost and thaw depth, frost heave, and layer materials elastic modulus with time. The computations are made in accordance with a two-dimensional numerical model of

coupled heat and moisture flow in a medium with small volume changes. Although the Integrated Climate Model accounts for the moisture flow it is far too general in scope to be used as an effective tool for the specific investigation of drainage performance.

Hydrus2D: The HYDRUS-2D software package is distributed by the International Groundwater Modeling Center IGWMC located at the Colorado School of Mines [14]. This two-dimensional program, runs in the windows operating system, and performs a coupled analysis of subsurface moisture and solute flow. The code is supported by an interactive graphics-based interface for data preprocessing, generation of a structured mesh (an unstructured mesh option is also available), and graphic presentation of the results. A two-dimensional linear Galerkin finite element solution [8] of the pressure head form of Richards Equation is used. Integration in time is implicit and the resulting algebraic equations are solved using iterative solvers. The unsaturated soil hydraulic properties are described using van Genuchten [6], Brooks and Corey [5], and modified van Genuchten type analytical functions. The user can provide parameters that define these functions. Hydrus2D has been used to model drainage [15].

SEEP/W. This program is one of a suite of programs from Geo-Slope International [16]. It is a finite element program solely dedicated to the transient two-dimensional (plane strain and axis symmetric analysis) of saturated/unsaturated flow. A Galerkin finite element solution of the pressure head form of the Richards equation is solved. The program uses linear and quadratic triangular elements and bi-linear and quadratic quadrilateral elements. The orders of the elements determine the degree of the interpolation functions used. Fully implicit time integration is used. A consistent as opposed to a mass lumping approach is used to handle the specific moisture content. The final algebraic equations are written in terms of the total head. This equation is non-linear. A simple successive substitution technique is employed in which the conductivity and mass matrices are first calculated using the most current head

values and then the full algebraic equation, which is now linear, is solved using Gaussian Elimination. The heads obtained are then used to update the conductivity and mass matrices, and so on, until convergence. SEEP/W can handle specified flux and specified head boundary conditions. Far field boundary conditions can be set using an infinite element formulation. Unsaturated moisture content and hydraulic conductivity relationships can be defined in terms of known forms but can also be defined from scratch through the user interface. SEEP/W can and has been used for modeling pavement drainage [4].

CHAPTER 4

A CONTROL VOLUME FINITE ELEMENT SOLUTION OF THE UNSATURATED FLOW EQUATIONS IN LAYERED SOILS DURING DRAINAGE

The objective of this chapter is to outline the Control Volume Finite Element (CVFE) procedure, specifically developed for this project, for modeling drainage in layered systems. To provide a context for this discussion a schematic of a generic drainage system is shown in Figure 4.1. This simple illustrative system consists of two material types. The majority of the system is a relatively fine material with a low saturated hydraulic conductivity, around the drain, a much coarser material with a relatively high-saturated hydraulic conductivity is used. The drainage performance will depend on the exact nature of the materials used, in particular the nature of the hydraulic conductivity and moisture content characteristics in the unsaturated state [2].

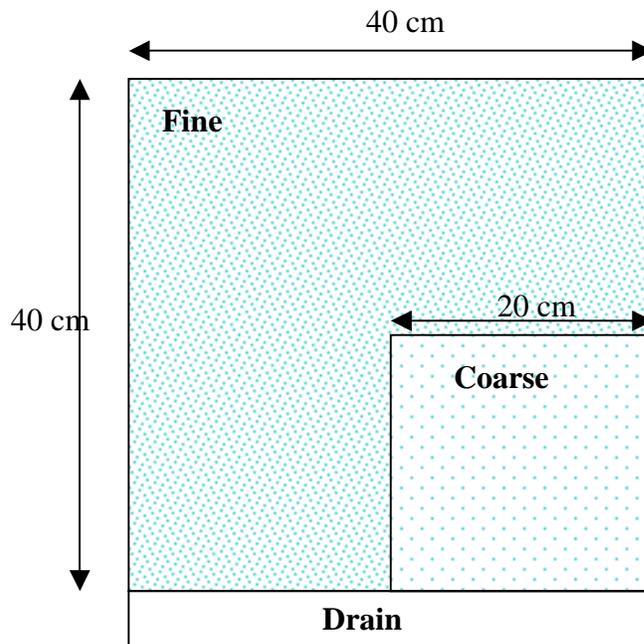


Figure 4.1 Schematic Layered Drainage System

Although numerical solution approaches are readily available for the case of unsaturated flow in a single homogeneous material, solving unsaturated flow problems with multiple layers of materials is still a research challenge [17,18]. In this chapter, the control volume finite element solution, which operates in MnDrain, for simulating the drainage in unsaturated layered systems, is outlined. This solution combines the mass conserved approach proposed by Celia et al [3] with methods and approaches borrowed and adapted from the numerical modeling of solidification literature [19,20]. The result is a robust solver that requires no special treatments for approximating the hydraulic conductivity and leads to results that retain the sharp discontinuity in the moisture content can occur at the interface between two material layers [17].

Governing Equations

With reference to Chapter 2, the governing equation for the drainage system in Fig 1 is the mixed form of the Richards equation [3]

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (\mathbf{K}(h) \nabla h) + \frac{\partial \mathbf{K}}{\partial z} \quad (4.1)$$

where h , the pressure head, is negative in unsaturated regions. Assuming only drainage, so hysteresis effects can be neglected, the moisture content can be related to the pressure head through the Brooks-Corey relationship [5]

$$\theta = \begin{cases} (\theta_{\text{sat}} - \theta_{\text{res}})(h/h_d)^{-\lambda_1} + \theta_{\text{res}}, & \text{for } h < h_d \\ (\theta_{\text{sat}} - \theta_{\text{res}}) + \theta_{\text{res}}, & \text{for } h \geq h_d \end{cases} \quad (4.2)$$

where θ_{sat} is the moisture content at saturation, θ_{res} is the residual moisture, h_d is the value of the pressure head at air entry, and the λ 's are material constants. When, for a given pressure head, the moisture content is determined the hydraulic conductivity can be calculated from the Brooks Corey expression [5]

$$K = K_{\text{sat}} \left[\frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \right]^{\lambda_2} \quad (4.3)$$

A potential problem with using Eq. (4.2) in a numerical solution of Eq. (4.1) is that, at pressure heads above the air entry, h_d , there is no direct relationship between the moisture content and the pressure head and it will not be possible to form a solution of the non-linear equations resulting from a discretization of (4.1). One way around this shortcoming is to simply introduce an artificial relationship, e.g., rewrite Eq. (4.3) as

$$\theta = \begin{cases} (\theta_{\text{sat}} - \theta_{\text{res}})(h/h_d)^{-\lambda_1} + \theta_{\text{res}}, & \text{for } h < h_d \\ C_{\text{val}}(h - h_d) + \theta_{\text{sat}}, & \text{for } h \geq h_d \end{cases} \quad (4.4)$$

If the constant C_{val} is small enough (10^{-4} is used in this work) then this extended definition of the moisture content beyond the air entry will have a minimal impact on the results. This approach is analogous to introducing a small incompressibility in compressible flow calculations [21] or imposing a high value of Young modulus in modeling rigid inclusions in an elastic medium.

For future use it is also noted that a “specific moisture capacity” [2] can be defined as

$$C = \frac{d\theta}{dh} = \begin{cases} -\lambda \frac{(\theta_{\text{sat}} - \theta_{\text{res}})}{h_d} (h/h_d)^{-\lambda-1}, & \text{for } h < h_d \\ C_{\text{val}}, & \text{for } h \geq h_d \end{cases} \quad (4.5)$$

The Control Volume Finite Element Discretization

An initial concern in developing a numerical discretization of Eq. (4.1) is the treatment of the rapidly changing and possibly discontinuous hydraulic conductivity. In the proposed approach this problems is bypassed by using a Kirchoff transformation [22]

$$\phi = \int_0^h -K(\alpha) d\alpha \quad (4.6)$$

In this way mixed Richard's equation,(4.1) can be written as

$$\frac{\partial \theta}{\partial t} = \nabla^2 \phi + \frac{\partial K}{\partial z} \quad (4.7)$$

Note this is purely a temporary step, once the discretization is established, a local node-by-node inversion of (4.6) will be applied to establish a discretization, with a consistent conductivity treatment, in terms of the head.

Equation (4.7) is solved using a control volume finite element method [1]. In the first instance, a mesh of triangular elements covers the two-dimensional domain with node points located at vertices. The elements are laid out such that an interface between two layers of material in the drain lies along element edges.

In each element an unknown, e.g., ϕ , is approximated by

$$\phi(x, z) \approx N_1\phi_1 + N_2\phi_2 + N_3\phi_3 \quad (4.8)$$

Where the N's, the shape functions [8], are linear functions of x and y arranged such that N_P takes the value of unity at node P and vanishes on the line segment opposite node P. Within this arrangement, a "control volume" is constructed around each node in the domain; with linear triangular elements, see Figure 4.2, the mid points of the element sides are connected to the element centers. Balancing the fluxes across the faces of the control volumes arrives at an algebraic (discrete) version of Eq. (4.7)

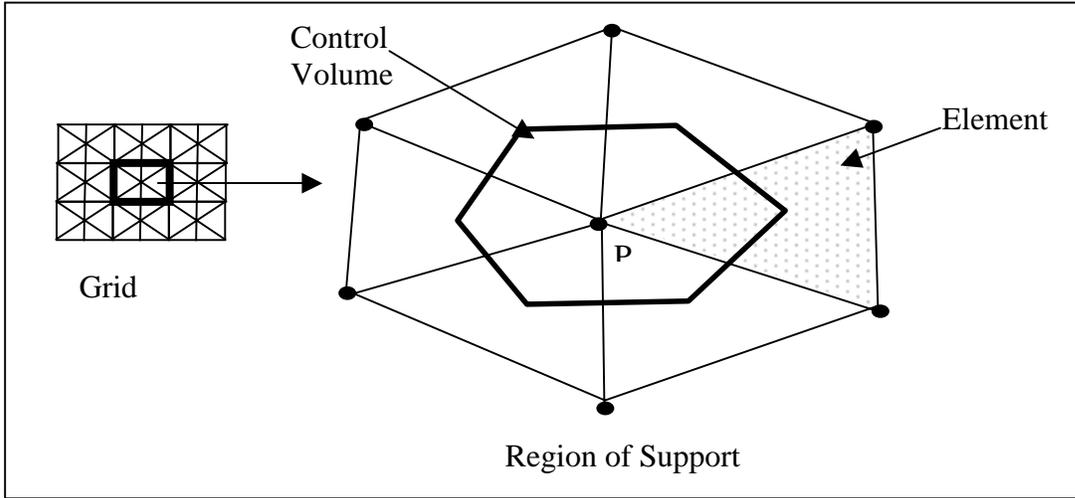


Figure 4.2 Basic Components in a Control Volume Finite Element Solution

$$A_P \bar{\theta}_P - A_P \bar{\theta}_P^{\text{old}} = \Delta t \sum_I [a_I (\phi_I - \phi_P) + S_I] \quad (4.9)$$

where I is a counter over the nodes in the grid connected to node P , the a_I are coefficients and S_I are contributions to the source term that can be associated with node I . A fully time implicit discretization has been used, Δt is the time step and the superscript “old” refers to values at the previous time step. The area of the control volume is given by

$$A_P = \sum_{\text{elements}} A^e / 3 \quad (4.10)$$

where A^e is the area of a given triangular element with a vertex at node P . The term $\bar{\theta}$ is the elemental aerial average of the moisture content in the control volume around node P ,

$$\bar{\theta}_P = \frac{\sum_{\text{elements}} \frac{\theta_P^e A^e}{3}}{A_P} \quad (4.11)$$

where θ_p^e indicates evaluation of the moisture content at node P in the element e; since the grid is set up to ensure that interface between layered material in the drain lie on element edges there will be no ambiguity in making this evaluation.

On a grid of linear elements, the coefficient a and source value S_I , obtained on considering the water flux, $\nabla\phi \cdot n + K\nabla z \cdot n$, across the four faces (S1, S2, S3, and S4) shown in Figure 4.3, are

$$a_I = a_I^{e1} + a_I^{e2} \quad (4.12)$$

where

$$a_I^{e1} = \frac{\partial N_3^{e1}}{\partial x} (\Delta z_{S1} + \Delta z_{S2}) - \frac{\partial N_3^{e1}}{\partial y} (\Delta x_{S1} + \Delta x_{S2}) \quad (4.13)$$

$$a_I^{e2} = \frac{\partial N_2^{e2}}{\partial x} (\Delta z_{S3} + \Delta z_{S4}) - \frac{\partial N_2^{e2}}{\partial y} (\Delta x_{S3} + \Delta x_{S4}) \quad (4.14)$$

and

$$S_I = -K_{AVE}^{e1} \Delta x_{S2} - K_{AVE}^{e2} \Delta x_{S3} \quad (4.15)$$

On a given face, Δx and Δz measure the change in x and z when moving in a counter-clockwise direction along the control volume boundary around node P. Note, adopting a local element numbering scheme, node P is always the 1st node in each element and moving in a counter-clockwise direction node I (in Figure 4.3) is the 3rd node in element 1 and the 2nd node in element 2. The term K_{AVE}^e is the arithmetic average of the values of the hydraulic conductivities at the nodes

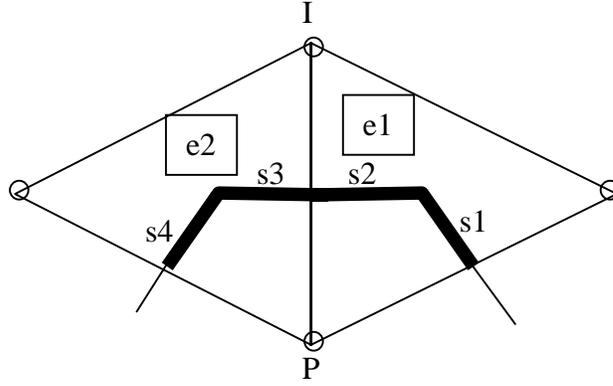


Figure 4.3 Contributions to the a_I Coefficient

Due to that fact that the $\theta = \theta(h)$, it is more convenient to write the right hand side of Eq. (4.9) in terms of the total head, h , i.e.,

$$A_P \bar{\theta}_P = A_P \bar{\theta}_P^{\text{old}} + \Delta t \sum_I K_I^e a_I^e (h_I - h_P) + S_I \quad (4.16)$$

where the sum is over the nodes connected to node P and each component in the sum includes contributions from both the elements that share the common side between nodes P and I. In Eq. (4.16), following a suggestion by Voller [23], the conductivity term is defined as

$$K_I^e = \frac{\int_{h_I}^{h_P} K^e(\alpha) d\alpha}{h_P - h_I} \quad (4.17)$$

Note that, since a given element is always within a specific layer of the drain system the function $K^e(\alpha)$ is continuous under the integration. A simple trapezoidal integration rule results in a central difference approximation for the hydraulic conductivity

$$K_I^e = \frac{K^e(z_I - h_I) + K^e(z_P - h_P)}{2} \quad (4.18)$$

Once more it is stressed that there is no ambiguity in this calculation since the grid has been arranged such that only one material type (and thereby one function for K) resides in any given element.

Solution

The solution, in a time step, of the non-linear algebraic systems in Eq. (4.16) is achieved by using the linearization introduced by Celia et al [3]. The key step is to develop an iterative solution of Eq. (4.16) by employing the linearization

$$\bar{\theta}_p^{n+1} = \bar{\theta}_p^n + \bar{C}_p (h_p^{n+1} - h_p^n) \quad (4.19)$$

where the superscript indicates the level of iteration and \bar{C}_p is calculated with the previous value of the pressure head, h^n ; note that this value is an aerial averaged value, i.e.,

$$\bar{C}_p = \frac{\sum_{\text{elements}} \frac{C_p^e A^e}{3}}{A_p} \quad (4.20)$$

With the linearization (4.16) is written as

$$c_p h_p^{n+1} = \Delta t \sum_I K_I^e a_I^e h_I^{n+1} + S_p \quad (4.21)$$

where

$$c_p = \Delta t \sum_I K_I^e a_I^e + A_p \bar{C}_p, \quad \text{and} \quad S_p = A_p (\bar{\theta}_p^{\text{old}} - \bar{\theta}_p^n) + A_p \bar{C}_p h_p^n + \Delta t \sum_I S_I \quad (4.22)$$

Main Solution Steps

1. Equation (4.21) can be solved for the current nodal values of h using any linear equation solver; in this work a simple fixed number of sweeps around a point-by-point SOR scheme is used. In this solution no flow boundaries are naturally accounted for by only taking contributions from elements inside the domain. At nodes on the surface of the drain pipe a setting $c_p = \text{BIG}$, a large value, is made, this will force the solver to return a value of $h = 0$, the atmospheric condition, at nodes along the drainpipe surface. The initial solution of (4.21) in a time step is seeded by setting an initial guess for the nodal pressure head field equal to the nodal values at the previous time step, i.e, $h^0 = h^{\text{old}}$.

2. Following the solution of (4.21), the nodal moisture contents can be updated using (4.19)

$$\bar{\theta}_P^{n+1} = \bar{\theta}_P^n + \omega \bar{C}_P (h_P^{n+1} - h_P^n) \quad (4.23)$$

where ω (~ 0.5) is an under-relaxation.

3. It is noted that the approach proposed by Celia et al [3] is similar to the methods used to solve solidification phase change problems [19,20]. Taking guidance from these solidification techniques after the resetting of the moisture content the nodal pressure head values are adjusted, through the use of (4.4), to be consistent with the updated moisture content values. At nodes that do not lie on an interface between two material layers this is readily achieved by inverting Eq. (4.4)

$$h_P = \theta^{-1}(\theta_P) \quad (4.24)$$

At nodes on the interface between two layers the nodal pressure head can be found by constructing a search algorithm which successively updates guesses for the nodal pressure head until the aerial average of the moisture contents, predicted from each of the elements connected to node P, agrees with the updated value obtained with Eq. (4.23), i.e., search on h_P until

$$\frac{\sum_{\text{elements}} \frac{\theta_P^e A^e}{3}}{A_P} = \bar{\theta}_P^{n+1} \quad (4.25)$$

where the element values θ_P^e are evaluated on using the guessed nodal pressure head in the moisture – pressure relationship, Eq. (4.4), with the appropriate material settings.

4. The coefficients and sources in Eq. (4.21) are reset by recalculating the conductivities and specific moisture capacity terms.
5. The above steps continue to convergence, which can be declared when the difference in the total moisture content in the drain between two successive iterations falls below a given tolerance.

Discussion

It is worthwhile noting the critical points that have made the numerical solution for unsaturated drainage in a layered system tractable.

1. The extended definition of the moisture – pressure head relationship beyond the air entry. This allows for a continuous relationship between θ and h throughout the solution.
2. Elements are arranged to consist of only one material type. In this way hydraulic conductivities within a given element can be calculated unambiguously.
3. The Celia et al. linearization, (4.19), to update the moisture content, this will lead to a mass conserving solution.
4. The use of the inverse moisture – pressure head relationship to ensure consistency between the nodal pressure heads and the updated moisture. Particular care is taken at nodes on the interface between layers.

As constructed, the algorithm will provide averaged values of the moisture at node points, $\bar{\theta}$. If these values are plotted then there will be a smearing across the interface between two layers. The correct sharp discontinuity can, however, be readily established on assigning, for print out and presentation of results only, two (or more if required) nodal values at a given node calculated by using the unique nodal pressure head in the moisture content relationship for each of the materials that have an element connected to the node in question.

The above CVFE algorithm, using an unstructured mesh, has been implemented in a Fortran 77 program. This program, the core of the MnDrain software, is fully verified and tested in the next chapter.

CHAPTER 5

VERIFICATION OF THE CODES IN MnDRAIN

The previous chapter detailed the operation of a Control Volume Finite Element (CVFE) algorithm for variably saturated flow in a layered medium. In MnDrain this algorithm is implemented in a Fortran 77 code, embedded in an Excel spreadsheet. The objective of this chapter is to test the operation of this code and other associated codes in the MnDrain software. This will be carried out by comparing the performance, for a set of test problems, of the MnDrain codes with HYDRUS 2D.

The MnDrain Codes

The following codes are operate in MnDrain

Easymesh

Easymesh [24], is a public domain executable that creates an unstructured grid of linear triangular elements for a given geometric configuration. In MnDrain, the input geometric data is provided by the Excel spreadsheet (see Chapter 7 for details).

Regrid

Regrid is a compiled Fortran 77 program that takes the output from EasyMesh and converts it in to a file formats that can be used by the CVFE solver.

Drain

Drain is a compiled Fortran 77 program that implements the CVFE solver on the unstructured mesh created by EasyMesh. This program is the critical and central component of MnDrain.

Verification

Previous efforts [16] have validated that commercial codes, e.g., Hydrus 2-D, can simulate field drainage conditions. Hence the objective of the verification exercise here is to show that predictions for configurations modeled with the MnDrain codes match predictions from available benchmark solutions and commercial codes. Note that the entire MnDrain software is tested in each case. This involves setting up the calculation and grid in the Excel spreadsheet in addition to running the Drain calculation program. Through the verification exercises, the following material property database in Table 5.1 and the Brooks Corey relationships, Eqs. (2.12) and (2.13), are used

Table 5.1 Verification Material Data Base

10/04/02	λ	θ_{sat}	θ_{res}	h_d	K_{sat} cm/s	λ_2
Coarse Sand	3	0.35	0.035	-15	0.0098	3.667
Fine Sand	1.5	0.35	0.07	-35	0.000098	4.333
Granular	0.2	0.45	0.03	-1	0.0005	13
Gravel	0.2	0.45	0.03	-0.5	0.1	13

Problem 1. Draining a one-dimensional layered sand column, after Marianelli and Durnford [17]

The problem set up is given in Figure 5.1

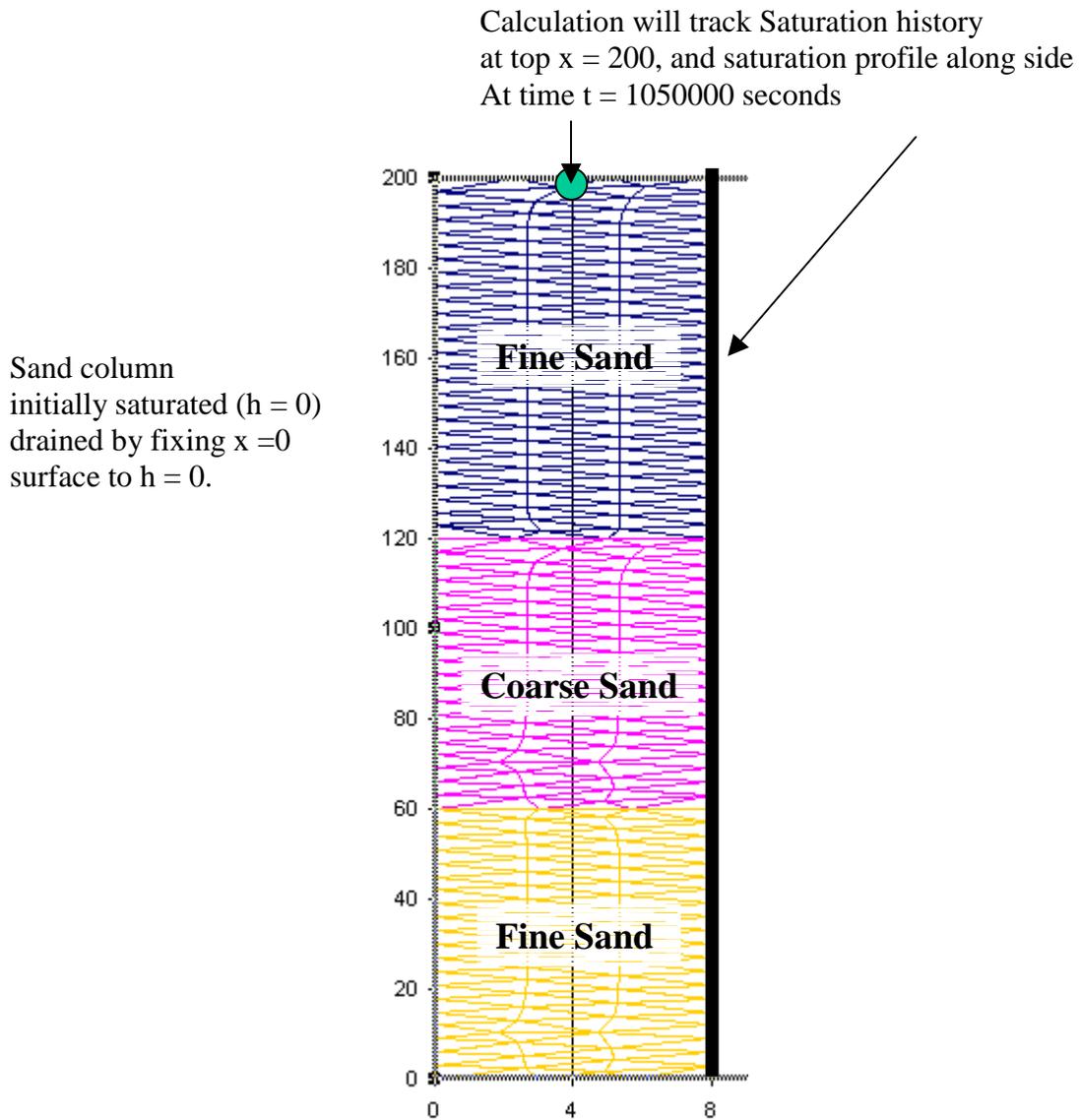


Figure 5.1 Draining a Layered Column after Marianelli and Durnford (not to scale)

This is a challenging test problem due to the fact that

1. There is a big contrast in moisture properties between the fine and coarse sands see Table 5.1.
2. The solution domain will contain a mixture of both full saturated and partially saturated regions.

Marianelli and Durnford [17] have developed a very accurate solution for this problem based on a high order shooting method for the governing equations. This solution includes an automatic step adjustment so that accuracy is not lost in regions of rapid change in the solution fields. Marianelli and Durnford's results are presented in the form of graphs of moisture saturation profiles at selected times. These graphs have been scanned and digitized so that specific values of for comparison purposes can be recovered.

The geometry for the Marianelli and Durnford problem was coded into MnDrian. The resulting Finite Element grid is shown in Figure 5.1. Solutions from MnDrain are compared with the Marianelli and Durnford solutions in Figures 5.2. At the interface between two materials the predicted pressure head value is used to recover the two liquid fraction values required.

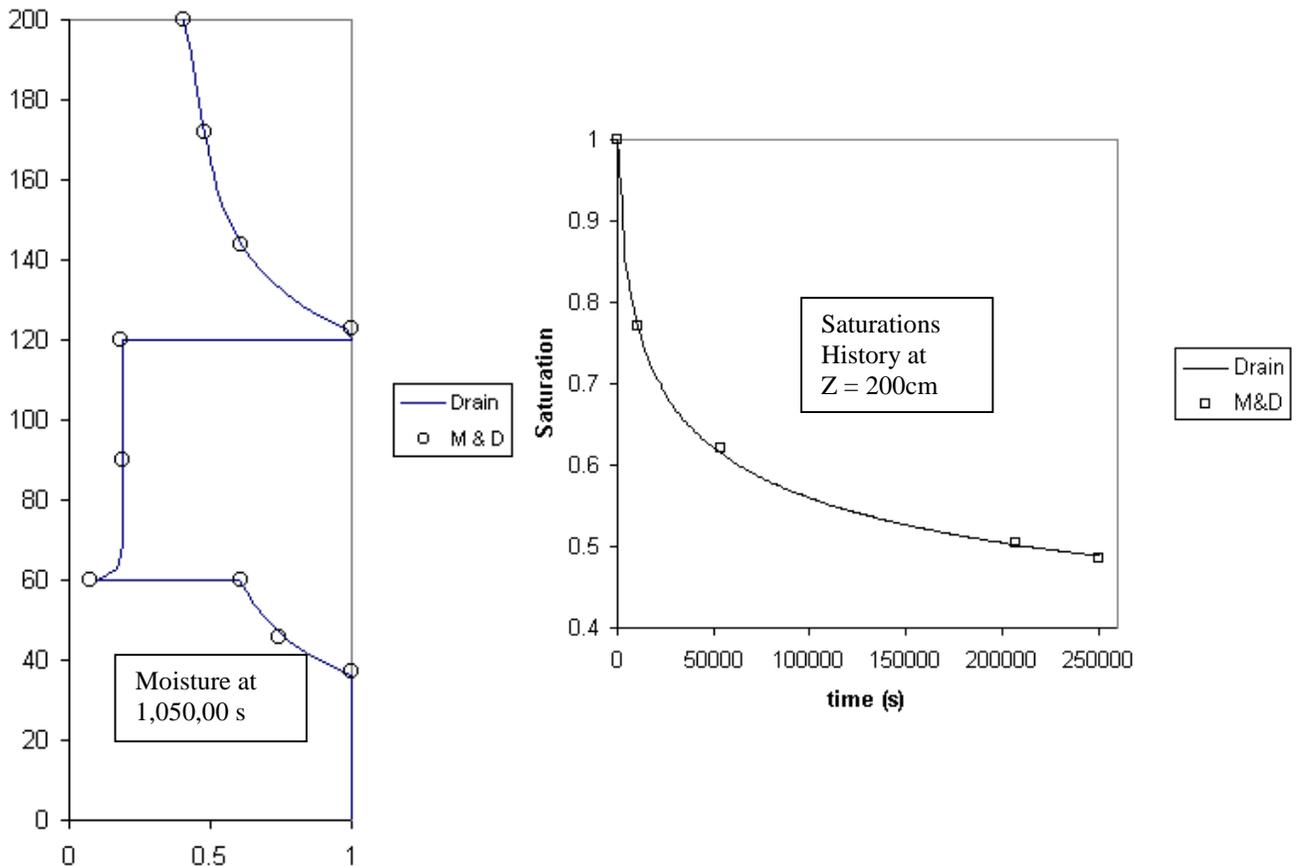
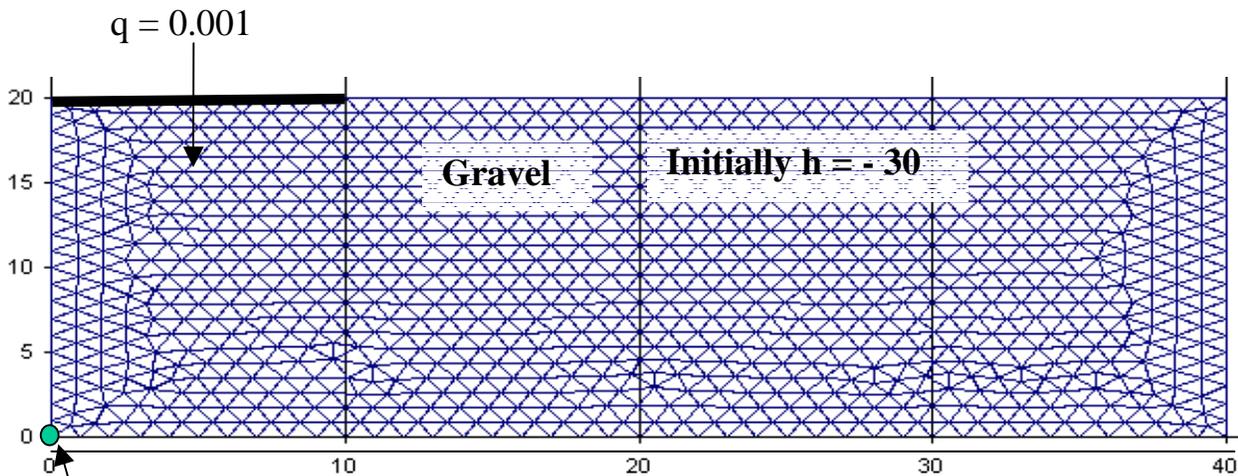


Figure 5.2 Comparison between MnDRAIN and Marianelli and Durnford [17].

Agreement between MnDrain and the accurate solution of Marianelli and Durnford is reasonable. Particularly pleasing is the ability of the CVFE drain code in MnDrain to predict the sharp discontinuity at the layer interfaces without leaking.

Problem 2. Two-dimensional Infiltration into a homogeneous domain

The second problem involves the infiltration of a constant flux into a two-dimensional homogenous domain, the domain is initially $h=-30$ and no flow crosses the boundaries, see Figure 5.3.



Predict moisture content history at origin and moisture content profile along bottom at $t = 3000$ s

Figure 5.3 Infiltration into a Two-Dimensional Homogeneous Domain

This test problem will provide a first check at how the MnDrain software can handle (1) a two-dimensional problem and (2) a problem with an infiltration boundary condition. Figure 5.4 shows comparisons of MnDrain and HYDRUS2D predictions of the moisture history at the origin and the moisture content profile along the bottom of the domain at time = 3000 seconds. The grid shown in Figure 5.3 was used with a time step of 10 seconds in the DRAIN calculations and a grid size of 1 cm was used in the HYDRUS2D calculations. Agreement is reasonable, clearly indicating that the correct treatment of infiltration is implemented in MnDrain.

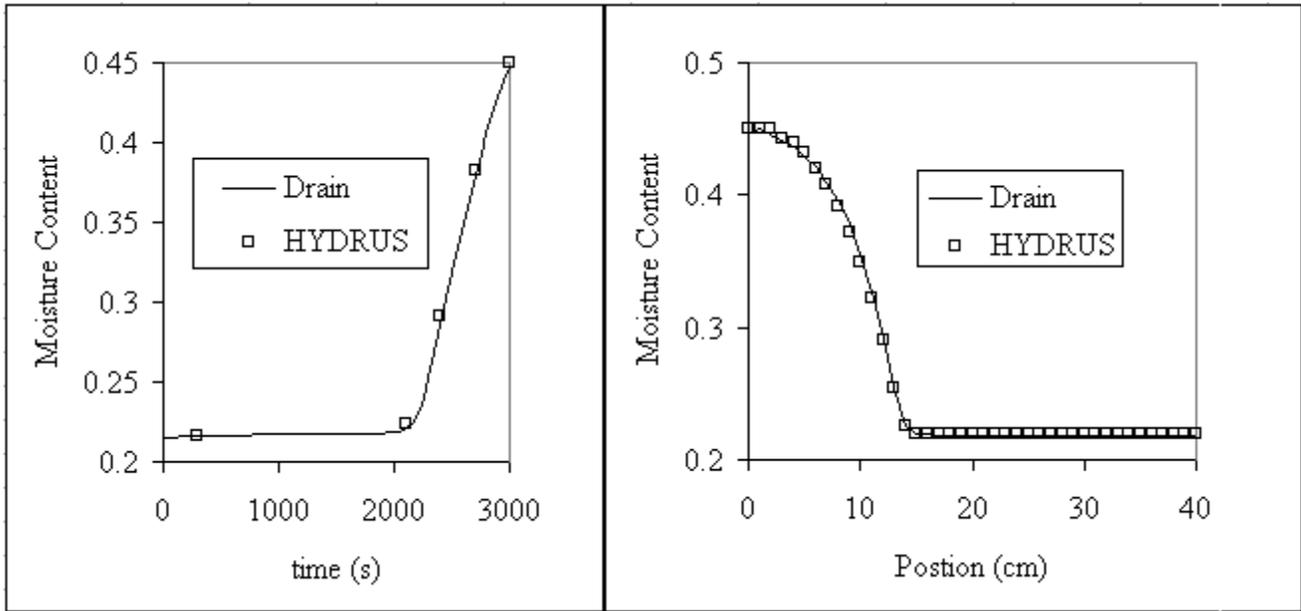


Figure 5.4 Comparisons between MnDrain and HYDRUS2D for Infiltration Problem

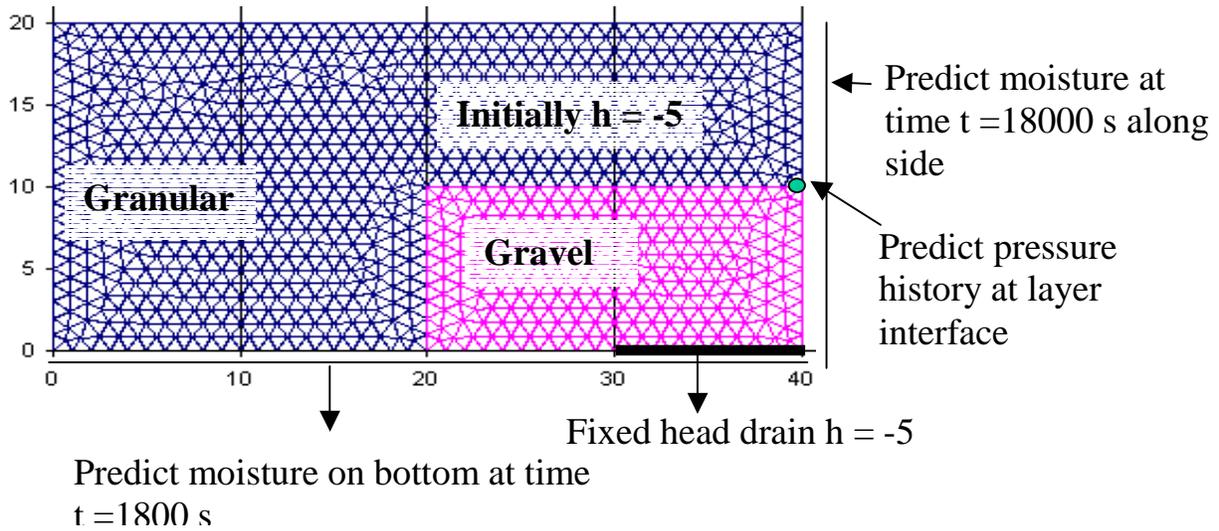


Figure 5.5 Two-Dimensional Draining from a Layered Domain

Problem 3. Two-dimensional drainage from a layered domain

The third test problem is designed to test the ability of the MnDrain software to simulate drainage in a two-dimensional layered system. The problem, see Figure 5.5, is constructed such that layer interfaces

lie parallel to both the x and z axis. Comparisons of predictions between MnDrain (grid in Figure 5.5 fixed time step of 120 s) and HYDRUS2D (a grid of 1 cm) are shown in Figures 5.6-5.7. Note that moisture at interfaces is calculated from the pressure. Once again the both the temporal and spatial comparisons between the elements of the MnDrain software and HYDRUS2D are reasonable. It is noteworthy that MnDrain is able to pick up the non-linearity across the layer interfaces.

Other test cases have been undertaken with a similar level of comparison between MnDrain and HYDRUS2D. The above results are sufficient, however, to fully test all of the required attributes of MnDrain to be able to accurately predict the drainage in a layered pavement system.

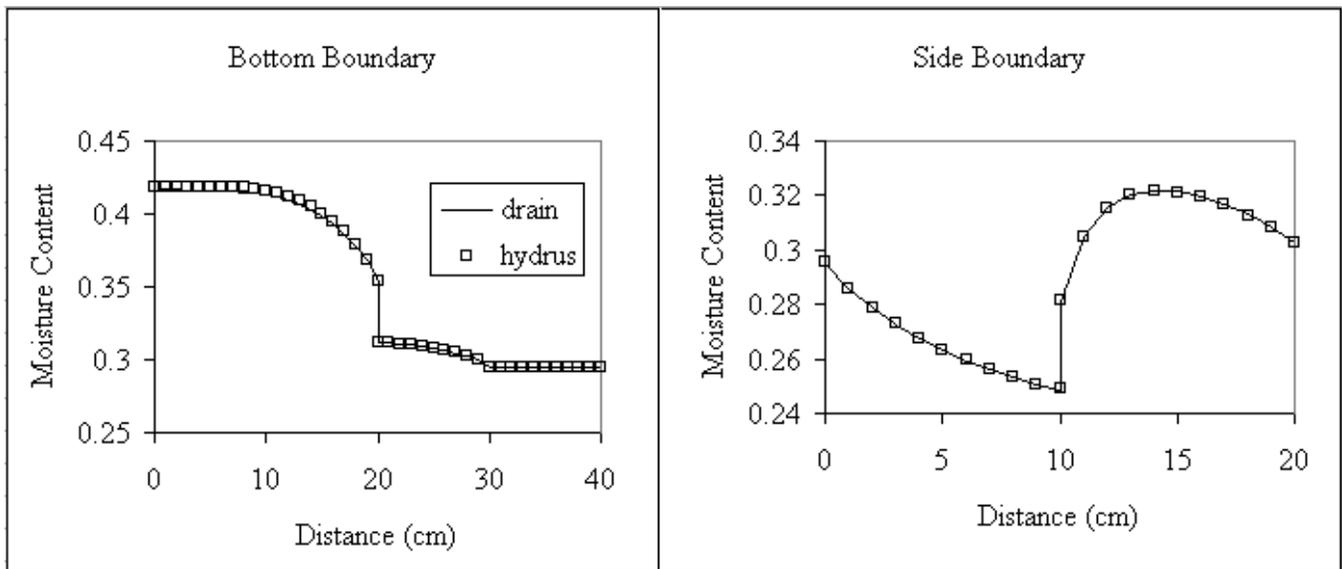


Figure 5.6 Predicted Boundary Moisture Profiles at Time $t = 18000s$

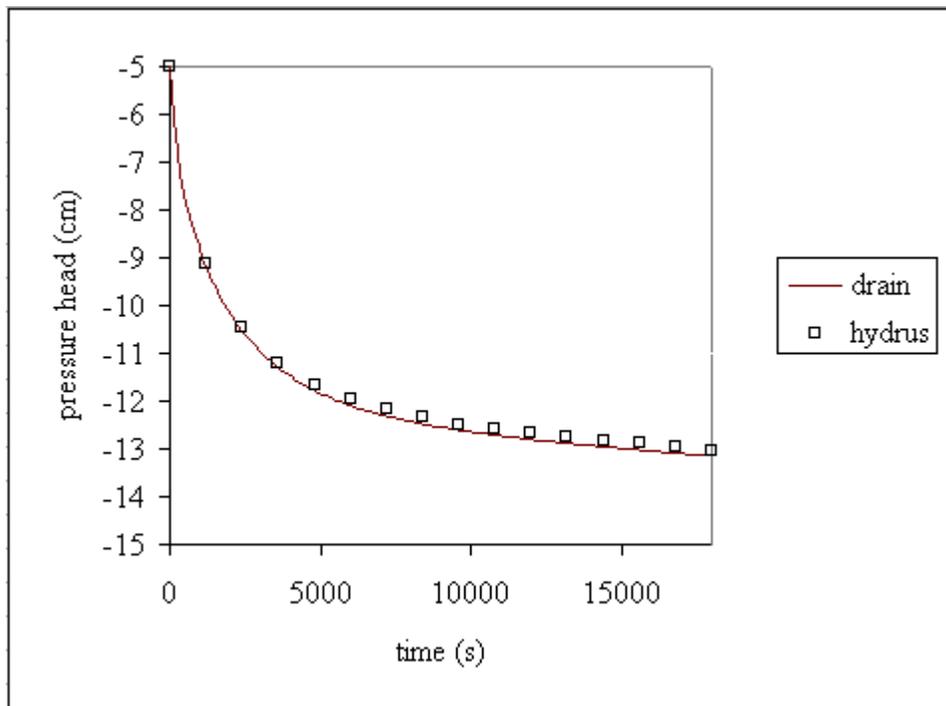


Figure 5.7 Predicted Pressure Head History at Layer Interface ($x = 40, z = 10$)

CHAPTER 6

MATERIAL DATA AND BOUNDARY CONDITIONS

The Solution Domain

Although, in MnDrain, the user has a high degree of flexibility in choosing the dimensions of the solution domain (see Chapter 7) the morphology of the domain is fixed for each of the three scenarios. The scenario with the most general geometry consists of an initially saturated base, drain trench, and edge drain on a permeable sub-grade with an adjustable water table height. A schematic is shown Figure 6.1.

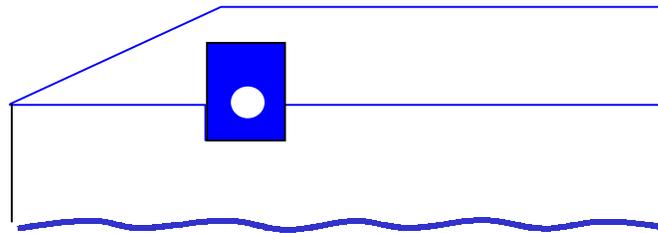


Figure 6.1 Schematic of MnDrain Solution Domain

As noted in the next chapter in MnDrain, this domain is presented to the user in an excel spreadsheet. The user specifies the dimensions and material properties in this excel spreadsheet. This is then combined with appropriate initial and boundary conditions and passed into the CVFE calculation engine in MnDrain.

Material Properties

Typically the user needs to provide material properties for the granular base, the trench and the subgrade. This is achieved by in MnDrain by dropdown menus that are related to a database. The database is an excel spreadsheet in the MnDrain software; the user is locked out of this spreadsheet. In

an innovative approach the data can be updated over the web. On the user request, if a web connection is live, the latest data will be automatically downloaded into MnDrain. The current database resides at

http://www.ce.umn.edu/~voller/voller_research/task6/database_m.htm

and contains the data given in Table 6.1

Table 6.1 MnDrain Material Data

	10/25/02	lamda1	sat	res	Hd	ksat	lamda2
Gravel		0.2	0.45	0.03	-0.5	0.1	13
Granular Base A		0.2	0.45	0.03	-1	0.0005	13
Granular Base B		0.5	0.45	0.03	-2	0.0002	7
Granular Base C		1	0.45	0.03	-5	1.00E-03	5
Loamy Sand		0.474	0.401	0.035	-8.7	0.001697	7.22
Loam		0.22	0.434	0.027	-11.15	0.000367	12.1
Silt Loam		0.211	0.486	0.015	-20.75	0.000189	12.48
Clay		0.131	0.385	0.09	-37.31	1.67E-05	18.267
Impermeable		1	0.4	0.1	-5	1E-20	5
NOT IN USE							

The advantage of this approach is that updates in materials and improvements in material property values can be rapidly deployed into the field. The worry of the user using old and inappropriate data is effectively eliminated.

The data in Table 6.1, which corresponds to the Brooks-Corey model Eqs. (2.12) and (2.13), comes from two sources. The sub-grade data, in the lower half of the table, is based on descriptions and values provide with the HYDRUS2D software. The Gravel and Granular values are selected to provide the range of observed behaviors. Figure 6.2 plots the resulting saturation vs. pressure head curves for the granular materials. The shape and trends in these plots should be compared with the plots (Fig 5 in Reference 25) developed by Roberson and Siekmeier [25]. It is expected that as more appropriate values become available they will be entered into the database.

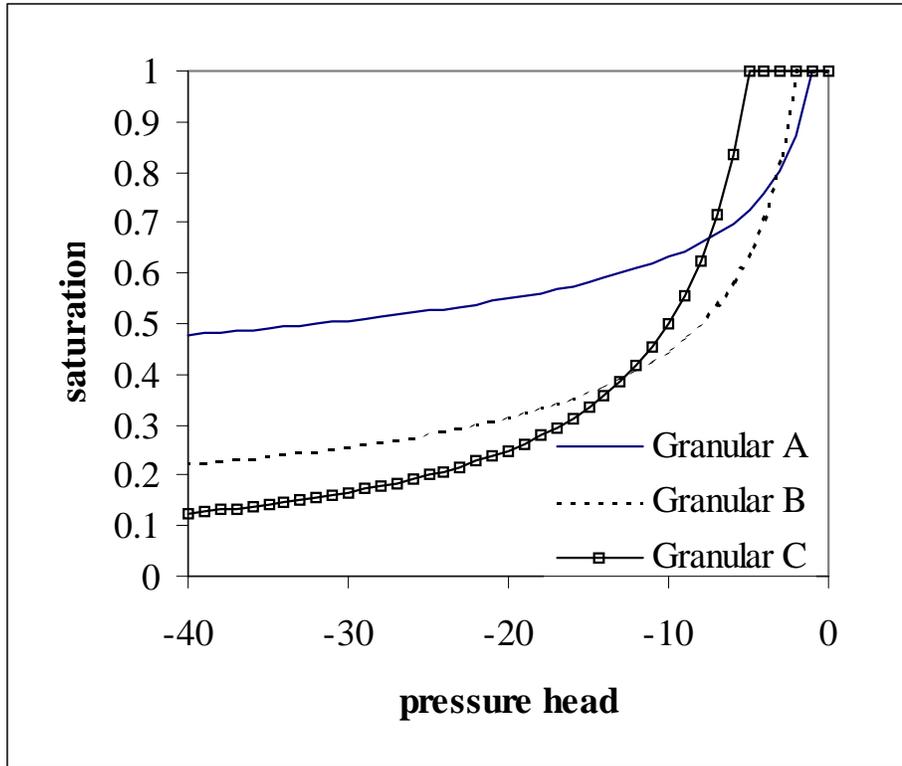


Figure 6.2: Plots of Saturation Pressure Head Relationships used in MnDrain

Boundary and Initial Conditions

The boundary and initial conditions in MnDrain are fixed. The initial condition is always one in which the solution domain is fully saturated with $h = 0$. With reference to Figure 6.1. The majority of the boundary conditions on the domain are no flow conditions. The two exceptions are

1. The water table, at the bottom of the domain, where a fixed pressure head of $h = 0$ is applied.
2. The drain pipe surface in the trench where a review boundary condition is applied. In the initial stages of the calculation nodes on the drainpipe take on a fixed pressure head of $h = 0$. If at a point in the calculation this condition leads to an influx of moisture into the trench, this fixed head condition is replaced by a no flow condition at that node.

CHAPTER 7

THE OPERATION OF MnDRAIN

The objective of this chapter is to provide information on the operation of MnDrain. A full copy of the MnDrain code, including all source programs and an on-line manual, can be downloaded on visiting

http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html

The online manual fully describes the operation of the MnDrain code and to avoid duplication this is presented as an exhibit in an appendix to satisfy the requirement for this chapter.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A full copy of the MnDrain code, including all source programs and an on-line manual, can be downloaded on visiting

http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html

The MnDrain software provides a user-friendly environment in which the consequences of an edge drain design decision can be investigated. The main attributes of the MnDrain system are:

- A relevant easy to use graphical interface.
- Meaningful drainage design scenarios.
- Flexible assignment of materials properties.
- An easy to maintain data base for unsaturated properties.
- State of the art saturated/unsaturated numerical solution engine.

This combination of facilities is not found in any other currently available code. Further although codes such as

Hydrus 2D (<http://www.ussl.ars.usda.gov/models/hydrus2d.htm>) and

SEEP/W (<http://www.geo-slope.com/products/seepw.asp>)

have been successfully used to simulate edge drain performance, there are two distinct advantages offered by the MnDrain code.

1. The commercial codes are primarily intended as multi-purpose research tools and they include many sophisticated features that are not required in an evaluation of an edge drain performance. As a result there is a steep learning curve required to master the operation of these codes. Such codes are ideal for use in a central research facility but are less than ideal for distribution among

field engineers. In contrast the MnDrain code only has one feature, the ability to solve unsaturated flow in layered media. This lack of general utility allows for a well-focused user interface that promotes rapid acquisition of the skills required to run the code. The ability to learn the code operation is enhanced by the fact that the code is embedded in a Microsoft Excel interface, a tool that is well used and familiar to a large section of the engineering community.

2. The code in MnDrain is freeware. This means that all of the source software is freely available. Hence the code can be readily reconfigured for alternative and novel applications.

Recommendations

As it stands the MnDrain code is a solid initial framework from which further developments can be made.

With minor modifications the current MnDrain can demonstrate various aspects of edge drains, e.g., the consequences of poor maintenance. It is recommended that the DOT explore how MnDrain can be used in this capacity.

In this project the operation of MnDrain was purposely constrained to work with simple geometries (the scenarios). The sole purpose of this was to establish a system that could be used by a field engineer with only a limited knowledge of soil physics and numerical modeling. MnDrain, however, does not need to be constrained in this way. The work in this project has shown that MnDrain can compete, in terms of accuracy and flexibility, with existing commercial codes. The main advantage that MnDrain offers over such codes is a free access to all the source codes. This means that MnDrain can be reconfigured to deal with a large array of pavement drainage issues. To take advantage of this feature it is recommend that The DOT investigate the development of a research version of MnDrain.

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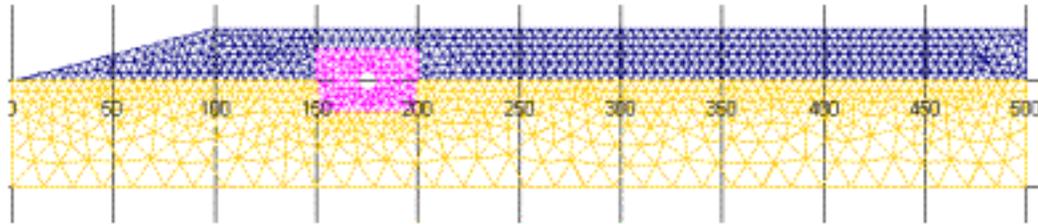
APPENDIX

THE MnDRAIN ON-LINE MANUAL

This appendix consists of a PDF facsimile of the MnDrain on-line help manual. This manual can be seen on line at

http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html

MnDrain on-line manual



Mndrain – by volle001@umn.edu, Civil Engineering, University of Minnesota.
Minnesota Local Research Board and Minnesota Department of Transportation

- [Purpose of MnDrain](#)
- [System requirements for MnDrain](#)
- [Security setting in Excel](#)
- [Downloading the MnDrain code](#)
- [Starting The MnDrian code](#)
- [The Main MnDrain Page](#)
- [Updating material properties](#)
- Running the MnDrain code
 - [Opening a Scenario Page](#)
 - [The Scenario Page](#)
 - [Close The Scenario Page](#)
 - [Reset base conditions](#)
 - [Setting up geometry](#)
 - [Choosing material properties](#)
 - The run sequence
 1. [The Run Page](#)
 2. [Preparing the input](#)
 3. [Looking at the mesh](#)
 4. [Running the drain calculation](#)
 5. [Working with the results](#)
 6. [Closing the Run Page](#)
- [Check Operation of Code](#)

Problems or Comments Contact
V.R. Voller at volle001@umn.edu

MnDrain Purpose

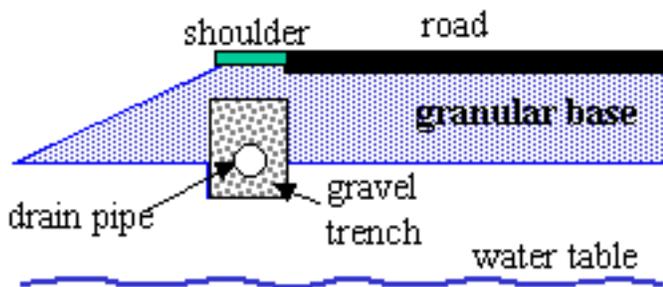
Purpose and Objective

MnDrain is a suite of codes, embedded in a Microsoft Excel windows environment, directed at the evaluation of the effectiveness of edge drains.

The objective of MnDrain is to provide a user friendly environment in which the consequences of an edge drain design decision can be investigated. MnDrain should be regarded primarily as a tool for assessment of design decisions as opposed to a tool that explicitly provides design decisions.

Background

Edge drains consist of pipes that run along the length of a road. The pipes are placed in a high permeability gravel trench below the shoulder/road surface, see schematic



Schematic of edge drain cross-section (NOT TO SCALE)

The objective of the edge drain is to remove moisture from the granular base of the road system. The rate at which moisture is removed will depend on the geometry and materials used in the base and soil type in the sub-grade. The FHWA defines the quality of drainage obtained based on how long an edge drain will take to reduce an initially saturated (100% moisture) base down to a moisture level of 85%, see Table

Table 5.4. Pavement rehabilitation manual guidance for time to drain from 100 to 85 percent saturation (ERES 1987; FHWA 1994).

Quality of Drainage	Time to Drain
Excellent	Less than 2 hours
Good	2 to 5 hours
Fair	5 to 10 hours
Poor	Greater than 10 hours
Very Poor	Much greater than 10 hours

In the MnDrain code users can

1. Choose from 3 basic scenarios
 - a. An initially saturated base, drain trench, and edge drain on a permeable sub-grade with an adjustable water table height.
 - b. An initially saturated base on a permeable sub-grade with an adjustable water table height. NO drain or drain trench is present.
 - c. An initially saturated base and fouled edge drain on a permeable sub-grade with an adjustable water table height. This case accounts for the drain trench BUT does not allow water to enter the drain pipe.
2. Select material types and adjust geometries for each scenario
3. Calculate the moisture removal vs. time curve over a two-hour drainage time.

The numerical engine that sits at the heart of MnDrain is a Control Volume Finite Element (CVFE) solution of the Richard equation

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K(h) \nabla h) + \frac{\partial K}{\partial z}$$

$h \rightarrow$ pressure head (units of length,
– ve in unsaturated region)

$\theta \rightarrow f(h)$ moisture content

$K \rightarrow g(h)$ hydraulic conductivity

for variably saturated flow in a porous media. It is noted that commercial codes are available for this type of calculation. In particular

Hydrus 2D goto <http://www.usssl.ars.usda.gov/models/hydrus2d.htm> and

SEEP/W goto <http://www.geo-slope.com/products/seepw.asp>

among others, have been successfully used to simulate edge drain performance.

There are however two distinct advantages offered by the development of the MnDrain code

1. The commercial codes are primarily intended as multi-purpose research tools and they include many sophisticated features which are not required in an evaluation of an edge drain performance. As a result there is a steep learning curve required to master the operation of these codes. Such codes are ideal for use in a central research facility but are less than ideal for distribution among field engineers. In contrast the MnDrain code only has one feature, the ability to solve unsaturated flow in layered media. This lack of general utility allows for a well-focused user

interface that promotes rapid acquisition of the skills required to run the code. The ability to learn the code operation rapidly is enhanced by the fact that the code is embedded in a Microsoft Excel interface, a tool that is well used and familiar to a large section of the engineering community.

2. The code in MnDrain is freeware. This means that all of the source software is freely available. Hence can be readily reconfigured do that further applications can be readily achieved

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System Requirements

System Requirements

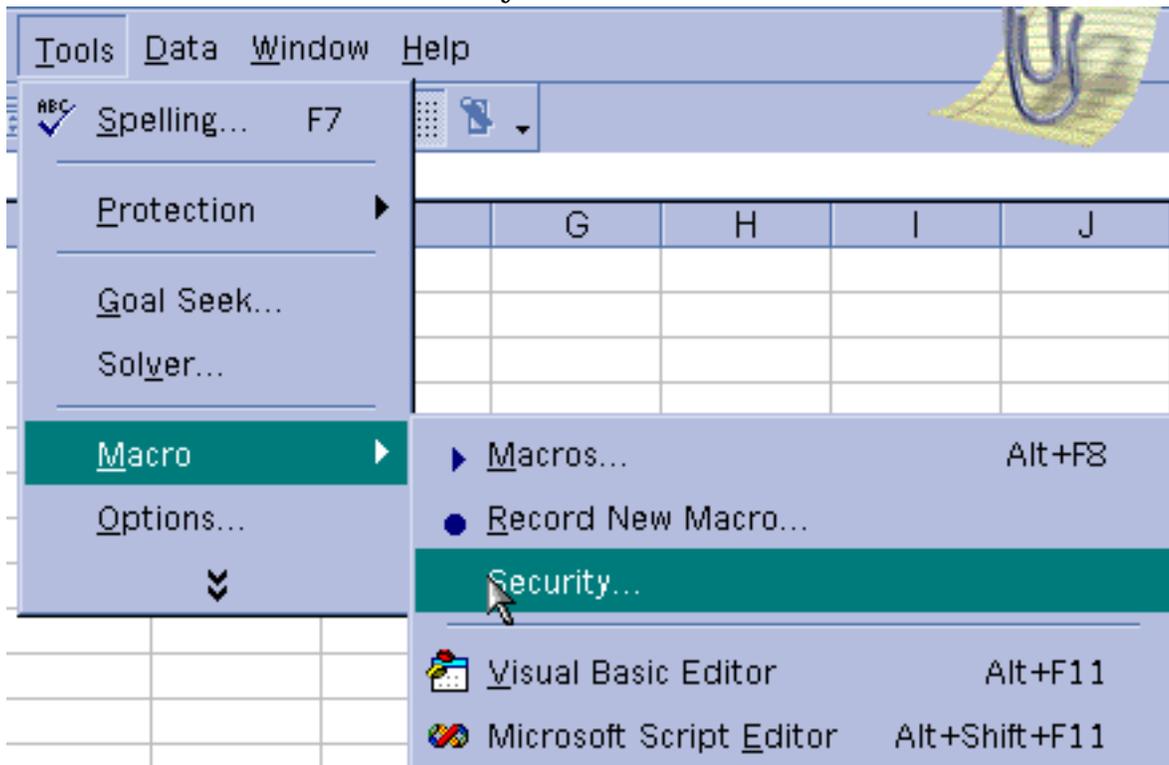
- A windows based personal computer running windows 98 or higher
- A copy of Microsoft Excel 2000 or higher must be installed
- NOTE:
A current installed copy of Netscape or Explorer is helpful BUT not required.

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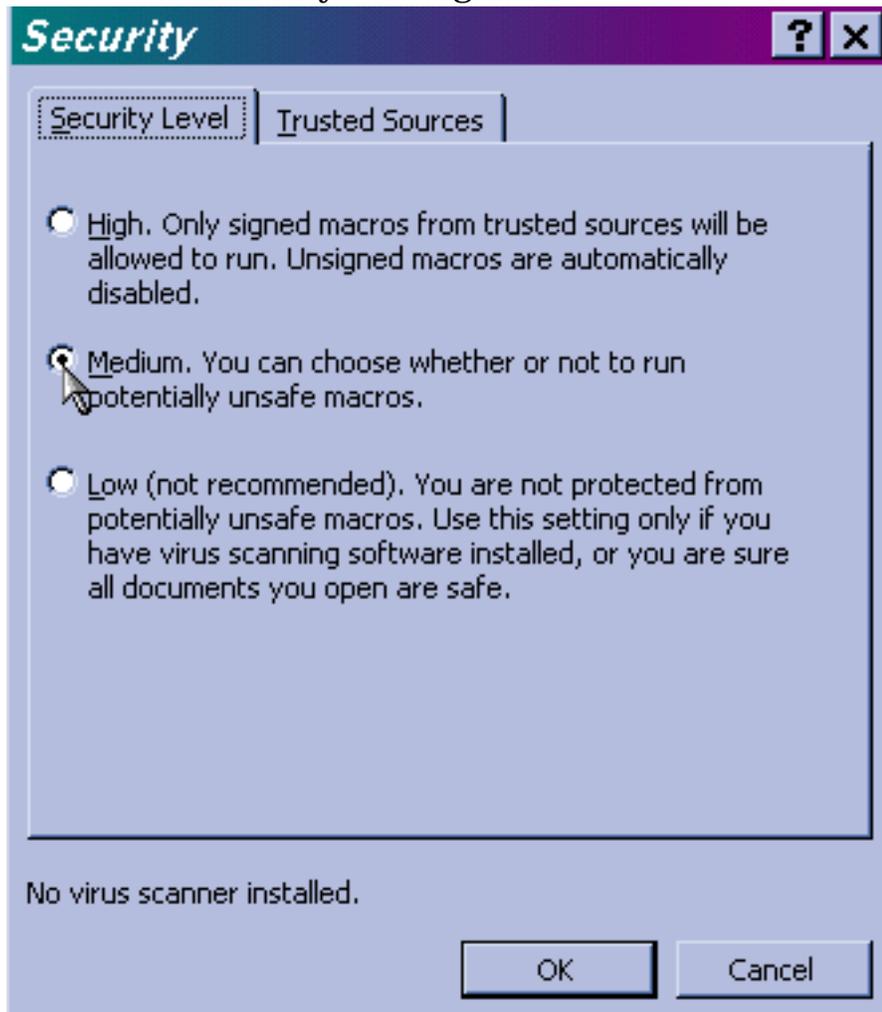
Security Setting in Excel

The Excel software on the machine where MnDrain will run needs to be set up to allow the user to enable macros. In some setups of Excel a high security setting is in place and all macros embedded in a given Excel file are automatically disabled. To run MnDrain the Excel security needs to be set to medium. This is done with the following 5 steps

1. Open Ecell on your machine
2. Choose Tools-Macro-Security



3. Make sure security setting is Medium



4. Press the OK button in the above Dialog

5. Exit from Excel

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Downloading MnDrain

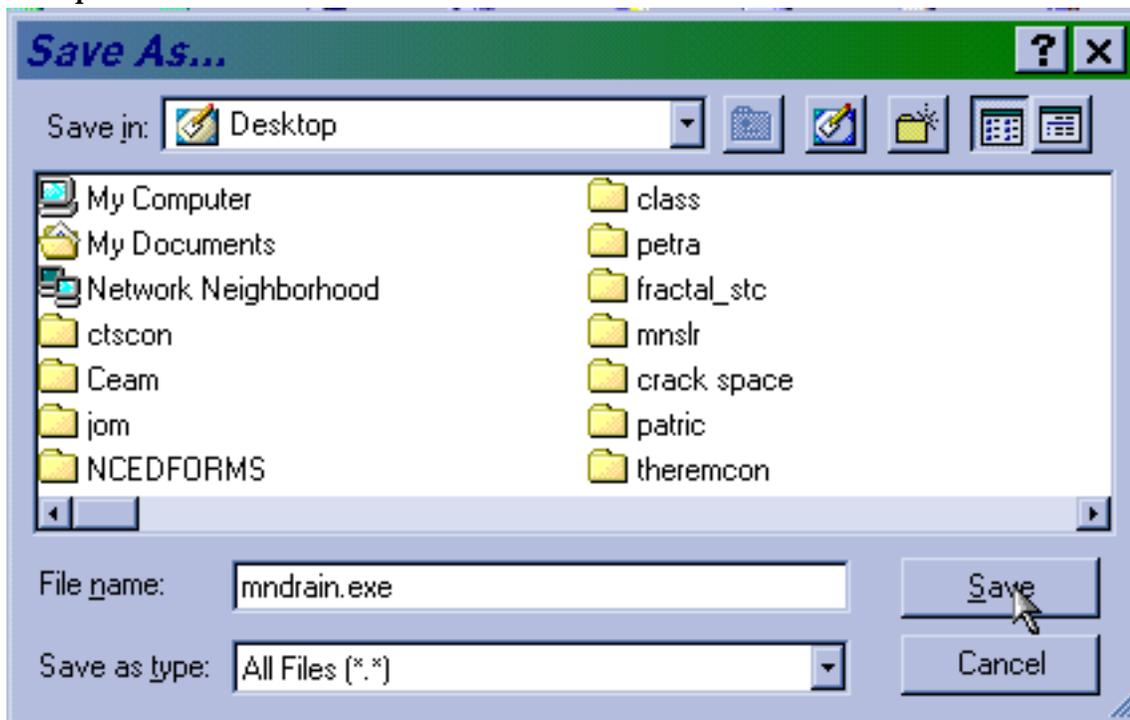
The MnDrain code is available as a self extracting executable file at http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html

To get this code

1. Go to http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html
2. In this page find the link to the MnDrain executable code--

file [mndrain.exe](#) 2.8

3. Double click on this link and save the file to the desktop of your windows based computer

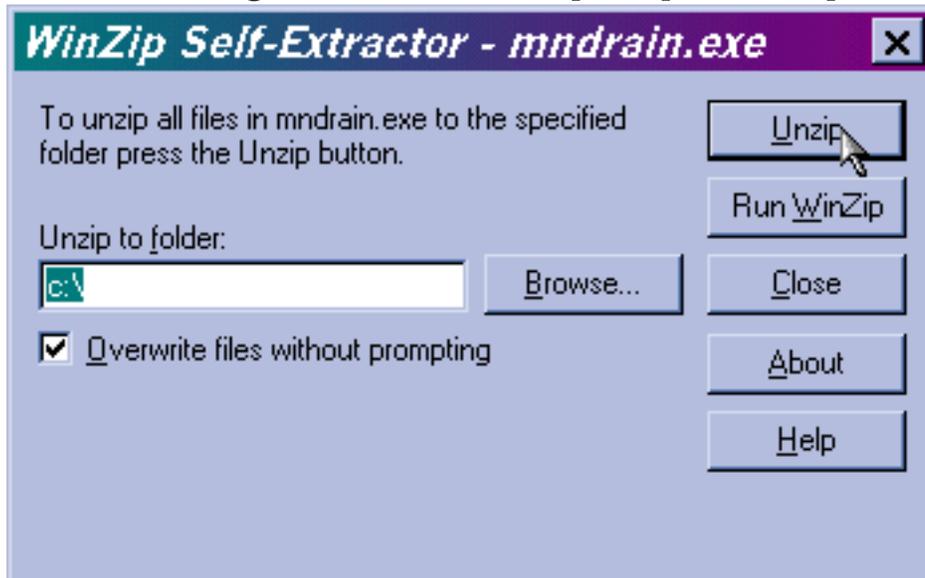


4. After the save. Find the icon



on the desktop of your windows machine

5. Double clicking on this icon will open up an un-zip dialog box



Unzip the files. DO NOT change the default drive from c:\
The unzip operation will create the windows directory

c:\mndrain

This directory and its sub-directories will contain all the implementation and documentation files for using MnDrain.

6. After completion of the unzip operation look for the icon



on your desktop.

DOUBLE CLICKING THIS ICON WILL START THE MNDRAIN CODE

NOTE

1. THERE IS NO NEED TO MODIFY ANY FILE IN THE DIRECTORY `c:\mndrain`
The running of the MnDrain code SHOULD ALWAYS be initiated by clicking the desktop icon



2. If you wish, after the files are unzipped, you can delete the program



from your desktop OR move it to another directory in your computer.

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Starting MnDrain

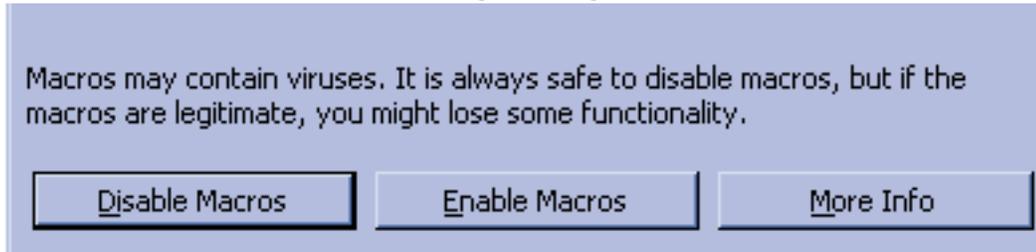
1. After completion of the [unzip operation](#) The icon



should be on your desktop.

2. DOUBLE CLICKING THIS ICON WILL START THE MnDRAIN CODE
3. This will open up a Microft Excel File--- master.xls--

4. You should see the following dialog box



You MUST HIT the Enable Macros Button to be able to run MnDrain

5. If the above Enable Macro Dialog DOES NOT APPEAR then you need to change the security setting in your copy of Excel
 - o Exit from Excel by closing the window
 - o Follow the [security setting instructions](#) in the MnDrain on-line help manual.
 - o When a medium security level has been set in Excel repeat the above open instructions.

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The Main MnDrain Page

When the MnDrain code has been successfully opened the user will be located on the Main MnDrain Page.

MNDRAIN -- Software for analysis of Edge Drains

Vaughan R. Voller (volle001@umn.edu)

Civil Engineering, University of Minnesota

For Minnesota local Road Research Board and Minnesota Department of Transportation

(Automatic meshing routine EasyMesh provided by Bojan Niceno, University of Delft, <http://www-dinma.univ.trieste.it/~nirftc/research/easymesh/>)

Note Material Properties Last Updated on October 25, 2002

See

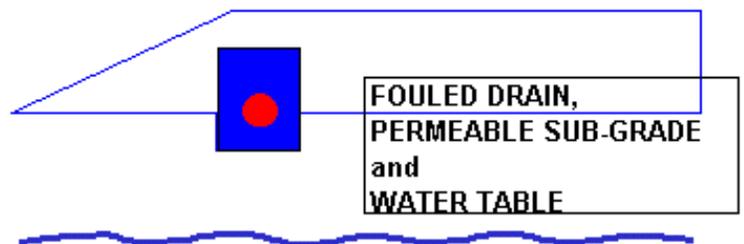
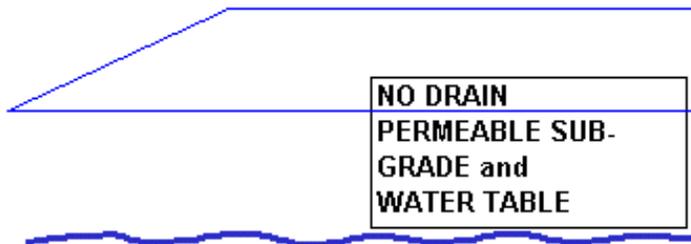
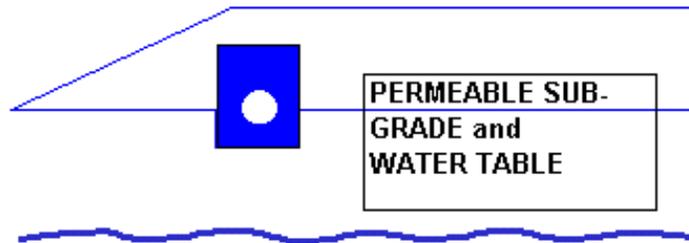
http://www.ce.umn.edu/~voller/voller_research/task6/database_m.htm

If you are connected to the web
Refresh Property Data by clicking here

CLOSE
MNDRAIN

Click to open on-line
manual in PDF

Click on Desired cross-section of drain to begin



On this page the user can

1. If a web connection is active update material data from a remote database
2. Choose a particular simulation scenario to investigate.
3. Close the application

These functions are examined in subsequent help pages.

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Updating Material Properties

Appropriate material properties are hard coded into the MnDrain software. These properties are stored in an Excel sheet that is hidden from the user. In addition a master table of material properties is stored on the secure web site http://www.ce.umn.edu/~voller/voller_research/task6/database_m.htm It is expected that as more information become available the material data in this master list will be updated. If the user is running MnDrain on a computer connected to the world wide web then clicking the button

Note Material Properties Last Updated on October 25, 2002

See

http://www.ce.umn.edu/~voller/voller_research/task6/database_m.htm

If you are connected to the web
Refresh Property Data by clicking here

found on the Main MnDrain Page, will update the data stored in the local Excel sheet.

Detailed Information on Material Properties

To carry out an unsaturated flow calculation (i) a relationship between the hydraulic conductivity and pressure or moisture content and (ii) a relationship between the pressure and the moisture content is required. In the current version of MnDrain the Brookes Corey relationships

$$K = K_{\text{sat}} \left[\frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \right]^{\lambda_2}$$

$$\theta = \begin{cases} (\theta_{\text{sat}} - \theta_{\text{res}})(h/h_d)^{-\lambda_1} + \theta_{\text{res}}, & \text{for } h < h_d \\ 0.0001(h - h_d) + \theta_{\text{sat}}, & \text{for } h \geq h_d \end{cases}$$

are used, where

θ → moisture content, θ_{sat} → saturated moisture content

θ_{res} → residual moisture content

K → hydraulic conductivity, K_{sat} saturated hydraulic conductivity

h → pressure head, h_d → pressure head at air entry (≤ 0)

The current (as of 25th October, 2002) material properties used in these equations are

25-Oct-02	λ_1	θ_{sat}	θ_{res}	h_d	K_{sat}	λ_2
Gravel	0.2	0.45	0.03	-0.5	0.1	13
Granular Base A	0.2	0.45	0.03	-1	5.00E-04	13
Granular Base B	0.5	0.45	0.03	-2	2.00E-04	7
Granular Base C	1	0.45	0.03	-5	0.001	5
Loamy Sand	0.474	0.401	0.035	-8.7	1.70E-03	7.22
Loam	0.22	0.434	0.027	-11.15	3.67E-04	12.1
Silt Loam	0.211	0.486	0.015	-20.75	0.000189	12.48
clay	0.131	0.385	0.09	-37.31	1.67E-05	18.267
Impermeable	1	0.4	0.1	-5	1.00E-20	5

NOTE

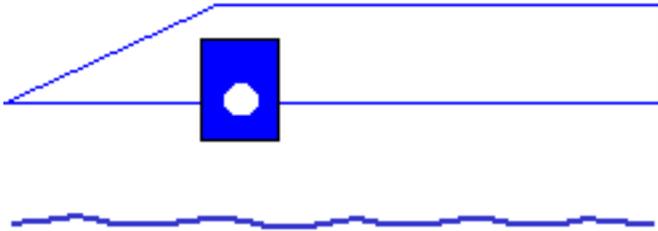
1. It would be possible to modify the MnDrain code so that other material relationships or tabular data can be used in place of Brookes Corey.
2. The definition of the moisture-pressure relationship assumes a small compressibility of the liquid in the saturated region, $h > h_d$. This step allows for an accurate and smooth transition between the saturated and unsaturated zones.
3. The current data for the Granular materials is chosen to be representative of the range that might be expected. Specific values for a given granular base still need to be defined.
4. The current data for the sub-base is taken from the Hydrus-2D data base.

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Opening a Scenario Page

On the Main MnDrain Page the user is presented with 3 basic scenarios from which to choose. These are

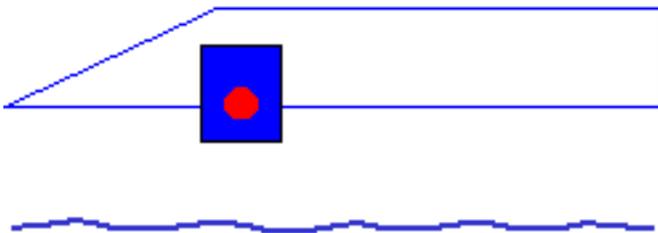
1. An initially saturated base, drain trench, and edge drain on a permeable sub-grade with an adjustable water table height.



2. An initially saturated base on a permeable sub-grade with an adjustable water table height. NO drain or drain trench is present.



3. An initially saturated base and fouled edge drain on a permeable sub-grade with an adjustable water table height. This case accounts for the drain trench BUT does not allow water to enter the drain pipe.



The user can choose the desired scenario by simply clicking on the associated schematic

Assuming the appropriate Excel security setting have been made the following dialog box will appear

Macros may contain viruses. It is always safe to disable macros, but if the macros are legitimate, you might lose some functionality.

[Disable Macros](#)

[Enable Macros](#)

[More Info](#)

Select the "Enable Macros" button. This will open up a Scenario Page where the user can choose material properties and make geometry changes to the basic scenario chosen.

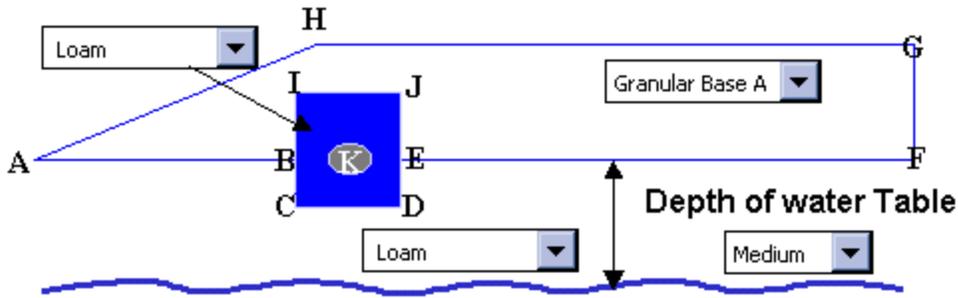
If the above Enable Macro Dialog DOES NOT APPEAR then you need to change the security setting in your copy of Excel

- Exit from Excel by closing the window
- Follow the [security setting instructions](#) in the MnDrain on-line help manual.
- When a medium security level has been set in Excel repeat the above choose scenario instructions.

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The Scenario Page

A successful open of the Scenario Page will give



Hit Here To RSET Data

close and return to master

This will terminate the current example
You will be asked if you would like to save current sheet say YES

Enter Data (cm) - in shaded areas

Simulation Time (s) 7200

	X	Z
A	0	0
B	150	0
C	150	-15
D	200	-15
E	200	0
F	500	0
G	500	25
H	100	25
I	200	15
J	150	15

K center point of drain

	X	Z
	175	0
Drain Radius	5	

Run Codes

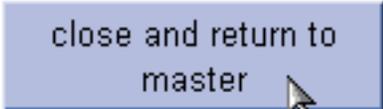
You will be asked to run a suite of codes aimed at predicting drain time

On this page the user can set material properties and geometry.
If a new run is to be undertaken the first task is to RESET the data
See next help page for details.

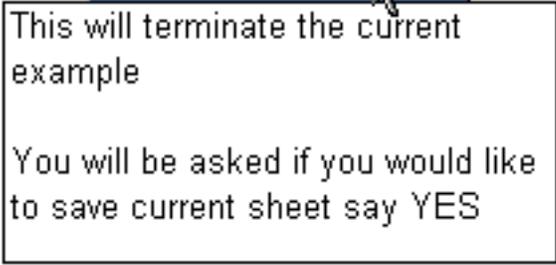
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Close Scenario

The button



close and return to
master



This will terminate the current
example

You will be asked if you would like
to save current sheet say YES

will close the current scenario and return to the Main MnDrain Page

When clicked the user may be asked if they would like to save the changes made. Unless the user feels that serious set up errors have been made it is recommended that user allows for the saving of changes.

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Reset Properties

When you arrive at the Scenario Page If you are starting a brand new run then it is a good idea to reset the the material and geometry data to the base case setting. This is done by finding and clicking the button



Hit Here To RSET Data

Failure to do this may mean that incorrect data will be used in subsequent runs.

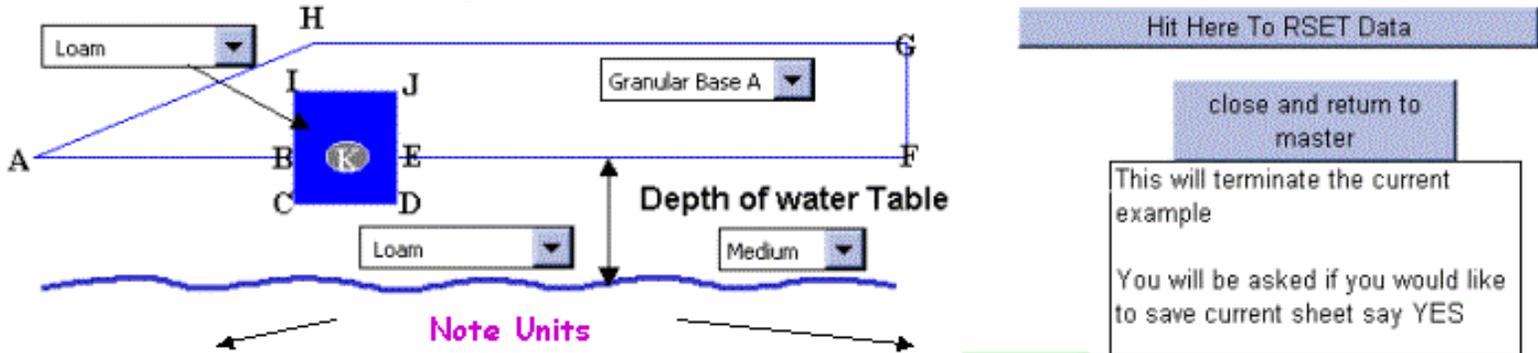
In some cases you may be returning to a previously saved run and wish to continue inputting data. In such cases the "reset button" does not need to be activated.

Note: The "reset button" Can also be used as a "start over button" in cases where the user is encountering errors in setting up a given run.

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Setting up geometry

The opening page of a given scenario includes a representative image of the geometry and a table giving the x,z positions of key points on that geometry



Enter Data (cm) - in shaded areas

Simulation Time (s) 7200

	X	Z
First point should ALWAYS be origin x = 0, z = 0	A 0	0
	B 150	0
	C 150	-15
	D 200	-15
Match the letters in the table with diagram and enter location in cm	E 200	0
	F 500	0
	G 500	25
	H 100	25
	I 200	15
Ensure morphology of geometry remains the same	J 150	15
	K center point of drain	
	X 175	Z 0
Drain Radius	5	

Make sure drain center is in trench and at least two radii removed from edge

Run Codes

You will be asked to run a suite of codes aimed at predicting drain time

The geometry is changed by overwriting the x,z coordinates in the table that correspond to the points in the image identified by uppercase letters. The user can also change the simulation time.

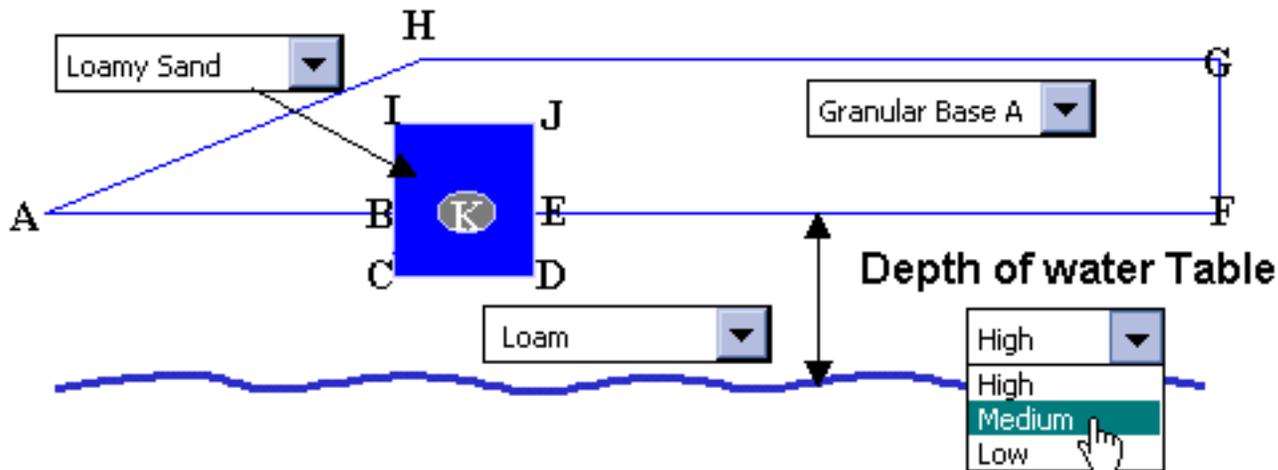
NOTE

- The first point should always be the origin (0,0). All other points are positioned relative to this location.
- Length measurements are in cm and time in seconds
- The onus is placed on the user to ensure that the revised geometry fits the morphology shown in the image (i.e., The relative location of one point to another MUST remain the same). The image on the page will NOT update as the points are modified. There is, however, a place later on in the setup where the user can get a visual check on the geometry.
- It is also left to the user to ensure that the drain location is in the trench.
- The finite element gridding will break down if the drain is "too-close" (less than two radii distances) from the edge of the trench.

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Choosing material properties

The opening page of a given scenario includes a representative image of the geometry. This image has up to three (3) material identified on it and may also include a water table position



The user can select the material type for each of the identified material regions and the position of the water table by making a selection from the scrolling menus.

Note:

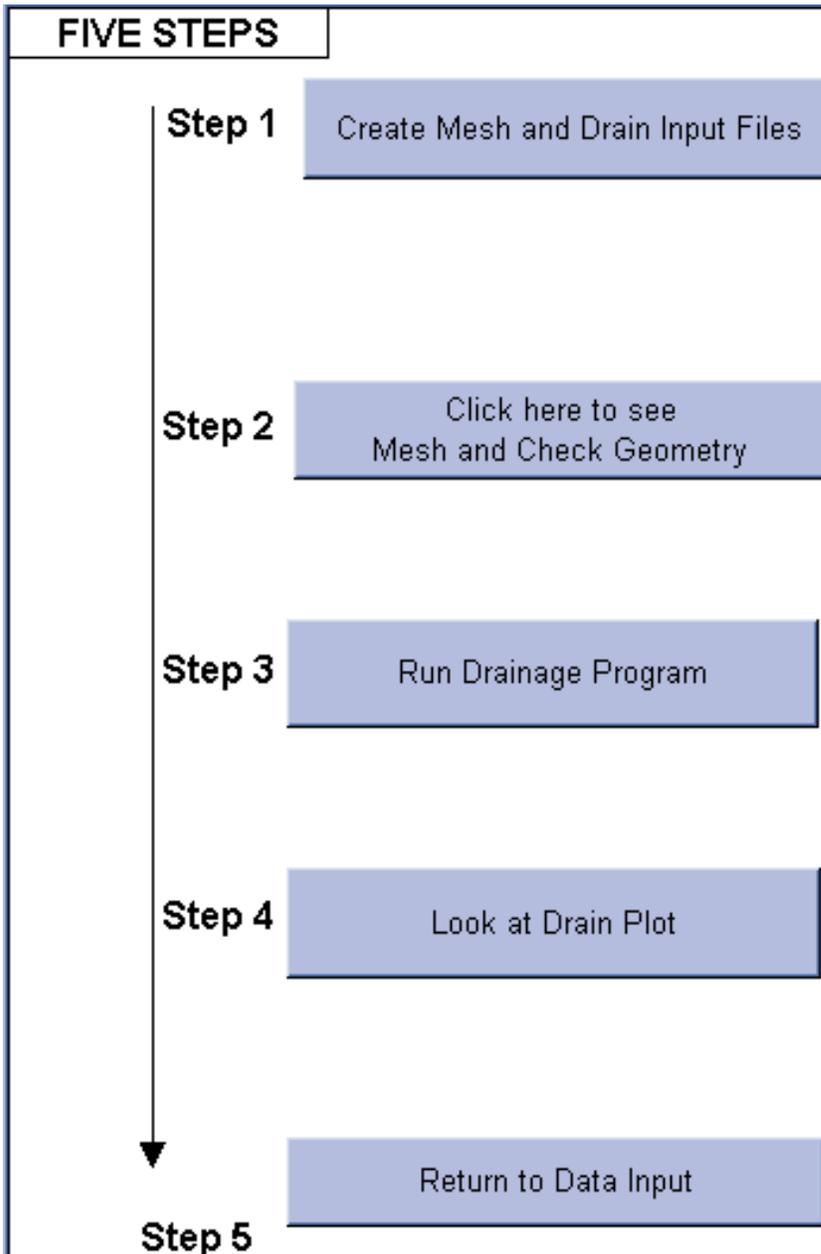
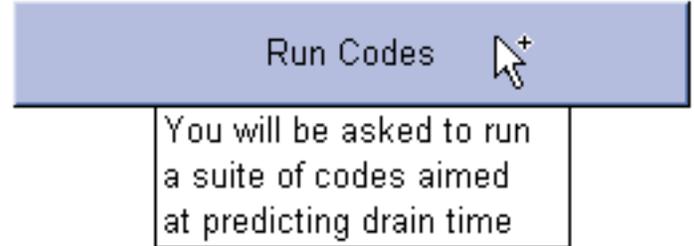
- The selection of a given material type will provide a pointer to the corresponding position in the material property data base.
- A selection of Impermeable for the sub-grade will effectively result in a no flow condition along the bottom of the granular layer.
- The selections for the water table height are "low" (1 meter below origin), "medium" (50cm below origin) and "high" (25 cm below origin).
- In the case of "high" water table setting the user should ensure that there is at least a 5 cm gap between the bottom of the trench and the water table.

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The Run Page

After the geometry and material properties have been set in the Scenario Page Clicking the button, on the right, will lead the user to the Run Page where the programs that make up MnDrain are run.

This page consists of the following set of buttons



IN EVERY case these buttons **MUST** be clicked in the order shown to run the MnDrain code.

The Function of these buttons is described in the next set of help pages

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Preparing the Input

The First button on the Run Page

Step 1 Create Mesh and Drain Input Files

Is used to

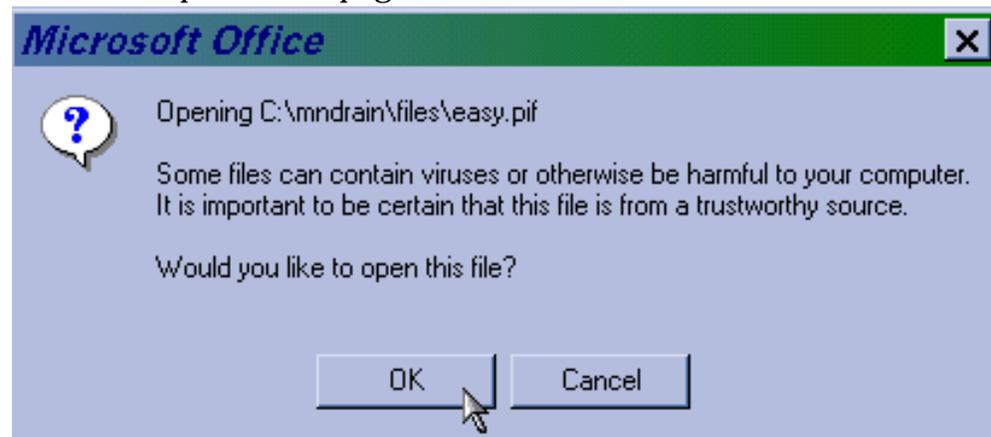
1. Create the Finite Element Grid for the programs
2. Set up the input data for the MnDrain programs

When this button is clicked Two Programs are run

The first program is an external DOS program for creating the finite element mesh based on the geometry data provided by the user. This program is a compiled version of the public domain software easymesh see the web site

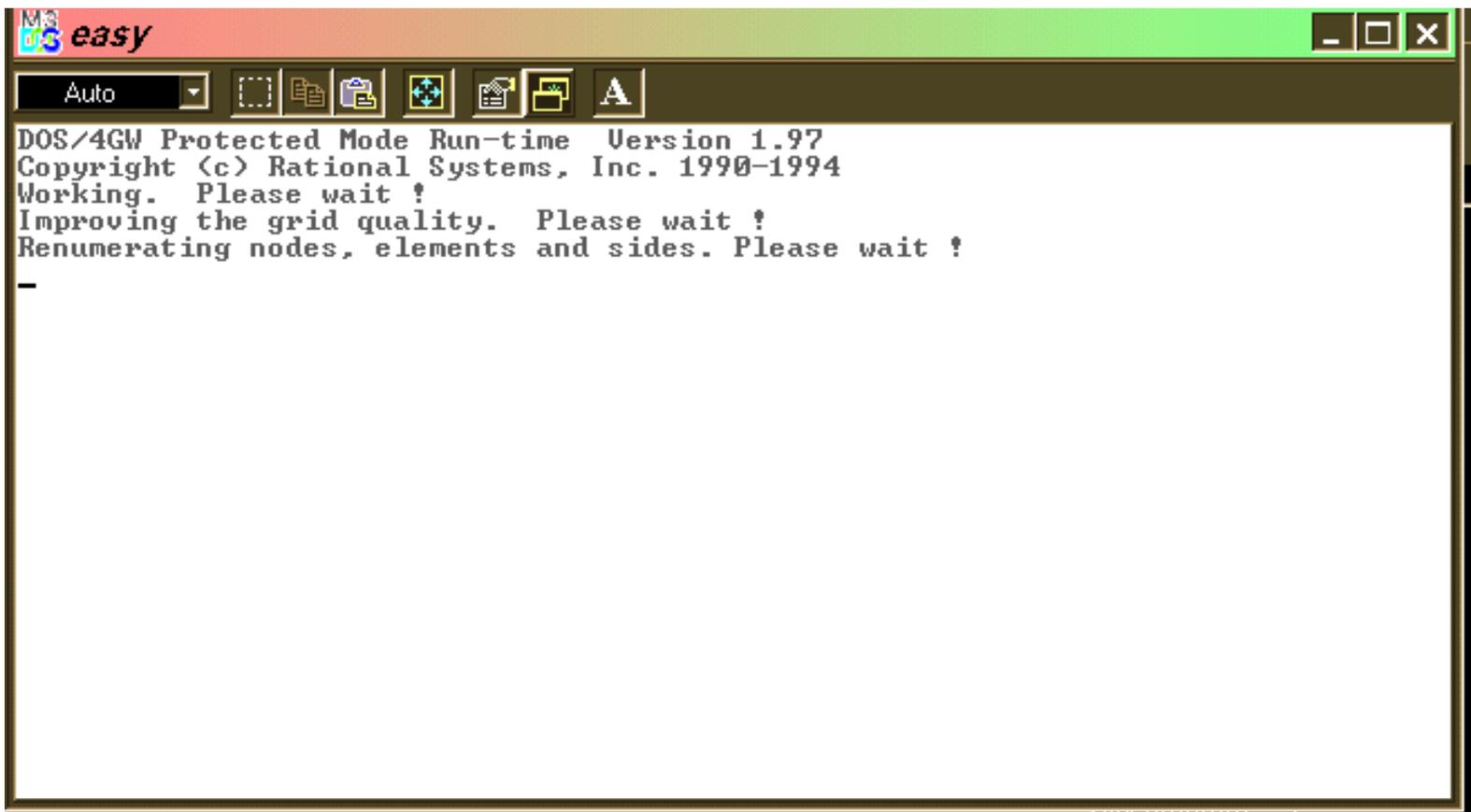
<http://www.dinma.univ.triests.it/~nirftc/research/easymesh>
for deatils.

In order to run the easymesh code the user has to authorize the running of an external application from the open Excel page



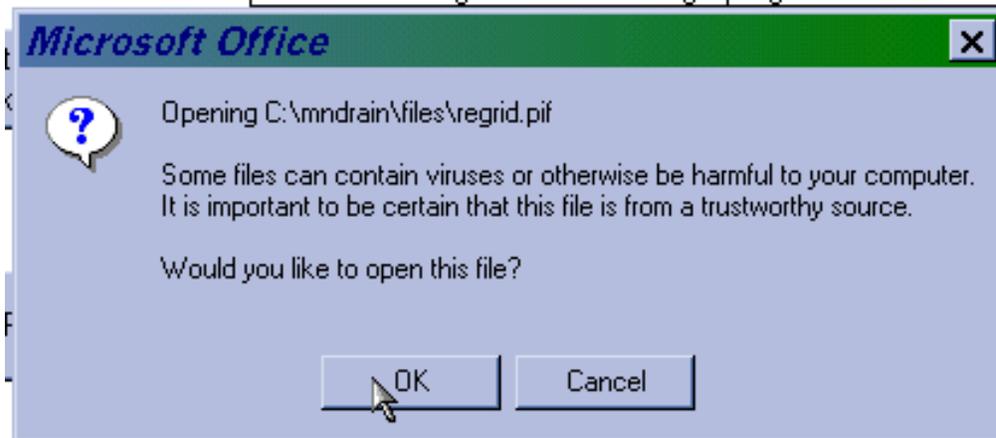
This action will open up a DOS window on the computer----

see next page---



This window will remain on the screen until the easymesh program has finished running ~ 1 minute.

When easymesh is finished the user will be asked to OK the external running of the program regrid



This program, written as part of MnDrain, reformats the output from easymesh in a form suitable for the MnDrain programs. The program also runs in a Dos Window. On completion The user can take the option of looking at the domain geometry and grid. See the next help page.

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Looking at the Mesh

The Second button on the Run Page

Click here to see
Mesh and Check Geometry

An image of the mesh and geometry color coding material types will be shown.

If mesh or gemoetry look wrong return to data input

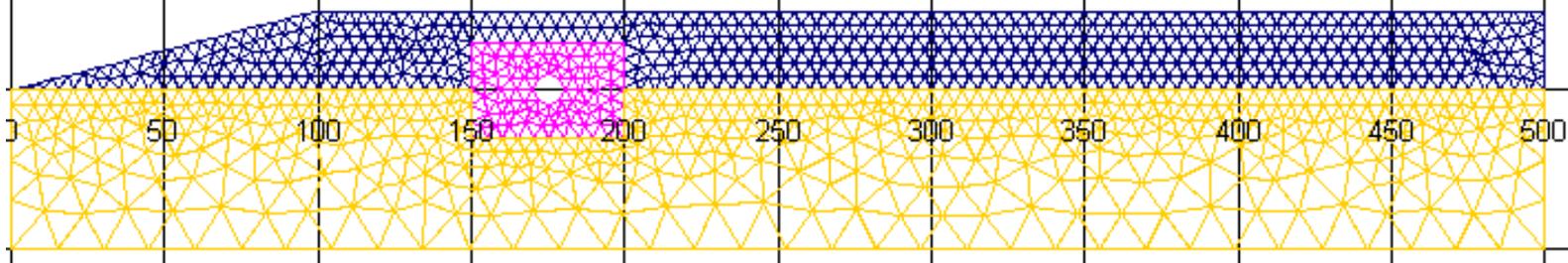
Return to Data
Input

Is used to look at the mesh. Clicking this button. AFTER the first button on the Run Page has been clicked and the associated programs run, will provide a plot of the current drain geometry and mesh, e.g.,

This is the mesh that will be used in the calculation
Check out dimensions and regions

Return to User

Automatic meshing routine **EasyMesh** provided by Bojan Niceno, University of Delft, <http://www-dinma.univ.trieste.it/~nirftc/research/easymesh/>



It is always recommended that user looks at the mesh. This is an excellent place to check that a consistent geometry has been applied.

If the geometry looks wrong the user has the option at this point to return to the Scenario Page

Note the "Return to User" Button in the mesh plot will return the user to the Run Page

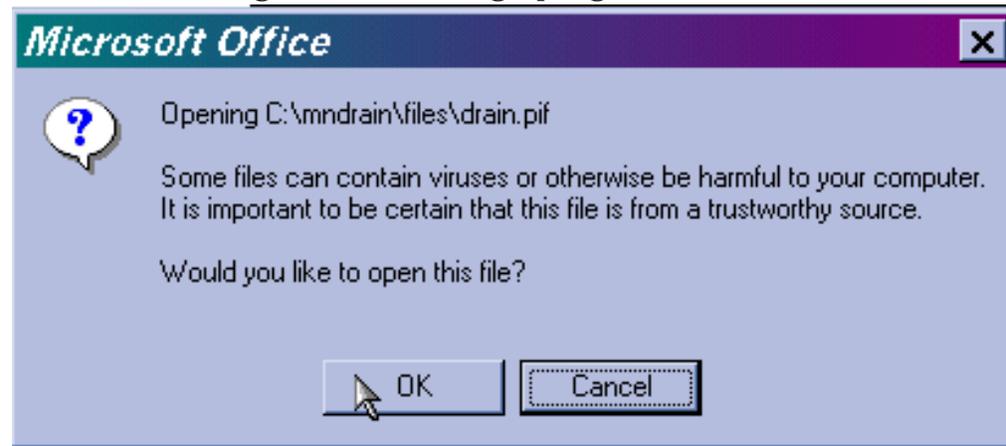
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Running the drain calculation

The Third button on the Run Page

Step 3 Run Drainage Program

Is used to run the drainage calculation. Clicking this button will request the user to authorize the external running of the drainage program



When authorised a DOS window will open in which the drain program will run

A screenshot of a DOS window titled "DRAIN". The window has a menu bar with "Auto" and several icons. The main area displays the following output:

```
PROGRAM RUNNING please wait

time(sec) -- degree of Saturation-cm^2 moist gran base    convergence~e-4
0.000000      1.000000      5369.30      0.000000
120.000      0.982174      5273.59      0.806988E-03
240.000      0.972434      5221.29      0.492515E-04
360.000      0.965166      5182.27      0.405237E-04
480.000      0.959160      5150.02      0.474613E-04_
```

The columns in this output are explained on the next page

1. Column 1: Is Time in seconds
2. Column 2: Degree of Saturation
(Volume of Moisture in Granular Base/Pore Volume in Granular Base)
3. Column 3: Total Moisture (cm²) in the granular base at the given time.
4. Column 4: Convergence. A measure of the mass error. A value of 10⁻⁴ is very good. Values of 10⁻³ are acceptable provided they do not prevail for too many time steps.

For a two hour simulation time the drain program will take about 2 minutes to run. At the end of the operation the program will signify successful completion and pause until the user hits a key

The screenshot shows a window titled 'DRAIN' with a menu bar containing 'Auto' and several icons. The main area displays a table of data with four columns: Time (s), Degree of Saturation, Total Moisture (cm²), and Convergence. The data rows range from 4680.00 to 7200.00 seconds. Below the table, the text 'Program Successfully Terminated' and 'Press Enter to Continue.' is displayed.

4680.00	0.820036	4403.02	0.442160E-04
4800.00	0.816875	4386.05	0.494760E-04
4920.00	0.813790	4369.48	0.451564E-04
5040.00	0.810786	4353.35	0.410875E-04
5160.00	0.807860	4337.64	0.654564E-04
5280.00	0.805020	4322.39	0.415807E-04
5400.00	0.802325	4307.93	0.423565E-04
5520.00	0.800004	4295.47	0.439993E-04
5640.00	0.797807	4283.67	0.381055E-04
5760.00	0.795729	4272.51	0.475000E-04
5880.00	0.793750	4261.89	0.414868E-04
6000.00	0.791859	4251.73	0.450328E-04
6120.00	0.790031	4241.92	0.470600E-04
6240.00	0.788250	4232.35	0.214773E-03
6360.00	0.786520	4223.06	0.385330E-04
6480.00	0.784839	4214.04	0.368156E-03
6600.00	0.783206	4205.27	0.435910E-04
6720.00	0.781627	4196.79	0.485388E-04
6840.00	0.780102	4188.60	0.448307E-04
6960.00	0.778629	4180.70	0.393494E-04
7080.00	0.777210	4173.07	0.444776E-04
7200.00	0.775842	4165.73	0.490766E-04

Program Successfully Terminated
Press Enter to Continue.

At this point the data has been stored and as detailed in the next help page the user can interrogate this data using standard Excel methods.

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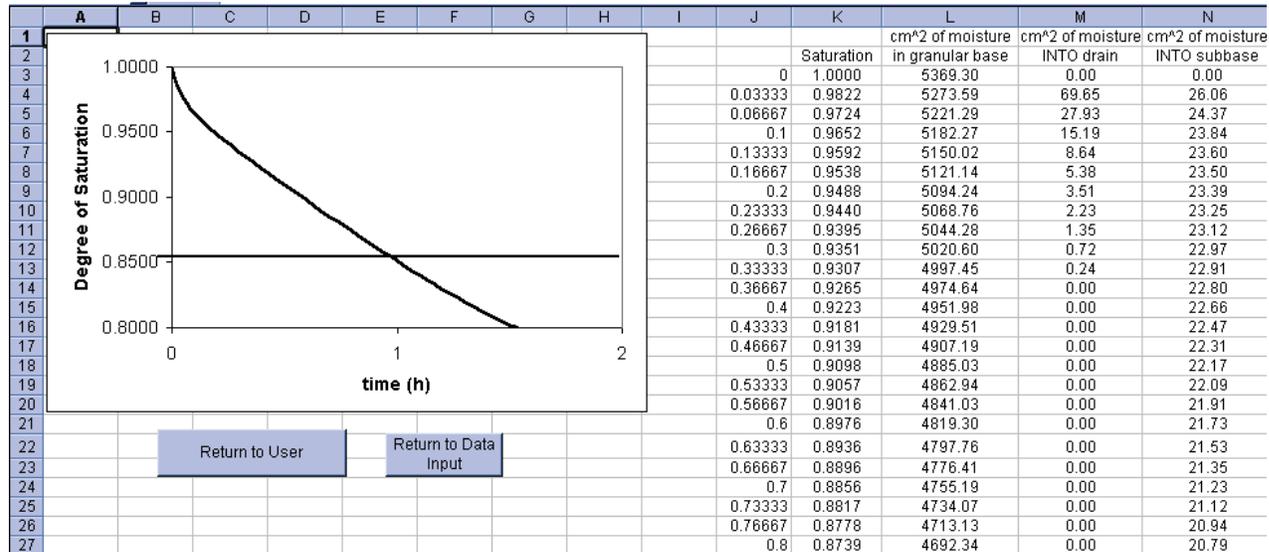
Working with the results

The Fourth button on the Run Page

Step 4

Look at Drain Plot

is used to look at the results. Clicking this button will take the user to an Excel page which contains a graph and output.



The graph of Saturation vs. time includes the 85% cut off.

The data for the graph and additional data is also tabulated on this page.

The three additional data columns are:

1. The amount (cm²) of moisture in the granular base at a given time
2. The amount (cm²) of moisture entering the drain pipe in the current time step
3. The amount (cm²) of moisture entering the subbase (subgrade) in the current time step

In a study to compare different designs it is recommended that, using basic Microsoft Excel features, this data is "cut" and "pasted" into an Excel spread sheet under the control of the user.

The user is RESPONSIBLE for saving the data generated.

Note the results page contains button to

- Take the user back to the Run Page ("Return to User")
- Take the user back to the Scenario Setup Page ("Return to Data Input")

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Closing the Run Page



Return to Data Input

close and return to master

The Fifth and Sixth buttons on the Run Page **Step 5**

are used to

- Return to the Scenario page ("Return to Data Input") where the material properties and geometry for a new run can be set up
- Or close the current Scenario and return to the Main Page ("close and return to master") where a new scenario can be chosen. Note the user will be asked if they would like to save.

To close the entire program the user needs to return to the Main Page

MNDRAIN -- Software for analysis of Edge Drains

Vaughan R. Voller (volle001@umn.edu)

Civil Engineering, University of Minnesota

For Minnesota local Road Research Board and Minnesota Department of Transportation

(Automatic meshing routine EasyMesh provided by Bojan Niceno, University of Delft, <http://www-dinma.univ.trieste.it/~nirftc/research/easymesh/>)

Note Material Properties Last Updated on October 25, 2002

See

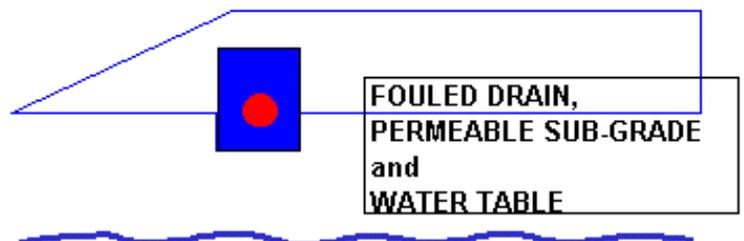
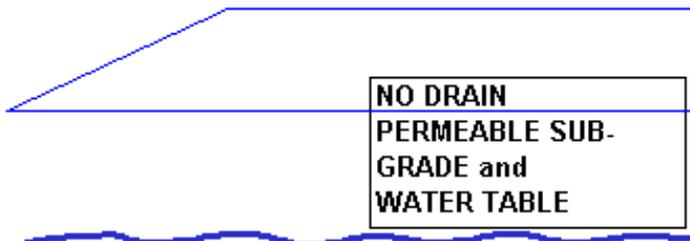
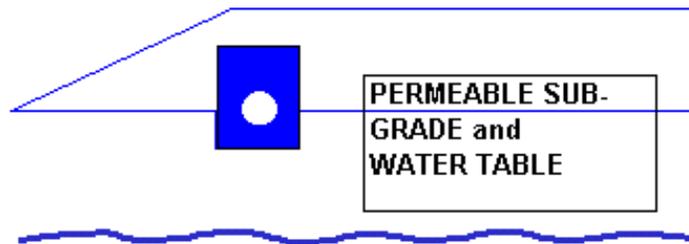
http://www.ce.umn.edu/~voller/voller_research/task6/database_m.htm

If you are connected to the web
Refresh Property Data by clicking here

CLOSE
MNDRAIN

Click to open on-line
manual in PDF

Click on Desired cross-section of drain to begin



and click the "Close Mndrain" Button

This will return the user to the desktop. It is recommended that the user OK's any save request that are made during this operation. ----- [BACK to Help Index](#)

Checking Implementation

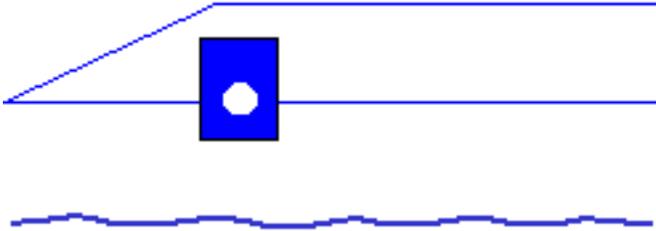
The downloading and operation of MnDrain can be checked by running each one of the three scenarios with its base settings and then comparing the drainage predicted (Saturation vs. Time) with the data given on the following pages.

REMEMBER: The Reset Button must be used before each run is set up



Hit Here To RSET Data

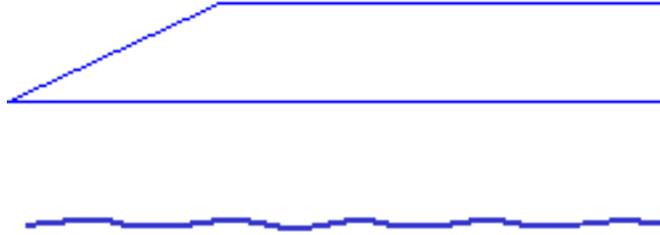
CASE 1: Initially saturated base on a permeable sub-grade with an adjustable water table height.



The results for the first hour of simulation should match

Time	Saturation
0	1
0.033333	0.982174
0.066667	0.972434
0.1	0.965166
0.133333	0.95916
0.166667	0.953781
0.2	0.948771
0.233333	0.944025
0.266667	0.939467
0.3	0.935056
0.333333	0.930745
0.366667	0.926497
0.4	0.922276
0.433333	0.918091
0.466667	0.913935
0.5	0.909807
0.533333	0.905693
0.566667	0.901612
0.6	0.897565
0.633333	0.893554
0.666667	0.889578
0.7	0.885625
0.733333	0.881692
0.766667	0.877792
0.8	0.873921
0.833333	0.870086
0.866667	0.866281
0.9	0.862502
0.933333	0.858741
0.966667	0.855003
1	0.851291

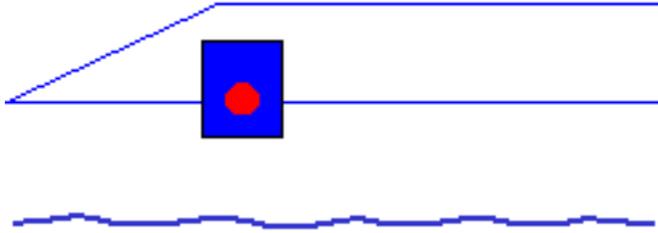
CASE 2: Initially saturated base on a permeable sub-grade with an adjustable water table height. NO drain or drain trench is present.



The results for the first hour of simulation should match

Time	Saturation
0	1
0.033333	0.995241
0.066667	0.990597
0.1	0.986026
0.133333	0.981507
0.166667	0.977008
0.2	0.972527
0.233333	0.968077
0.266667	0.963658
0.3	0.959269
0.333333	0.954891
0.366667	0.950535
0.4	0.946218
0.433333	0.941939
0.466667	0.937689
0.5	0.933461
0.533333	0.929247
0.566667	0.925064
0.6	0.920921
0.633333	0.916807
0.666667	0.912735
0.7	0.908682
0.733333	0.904646
0.766667	0.900633
0.8	0.896654
0.833333	0.892719
0.866667	0.888824
0.9	0.884954
0.933333	0.881086
0.966667	0.877253
1	0.873433

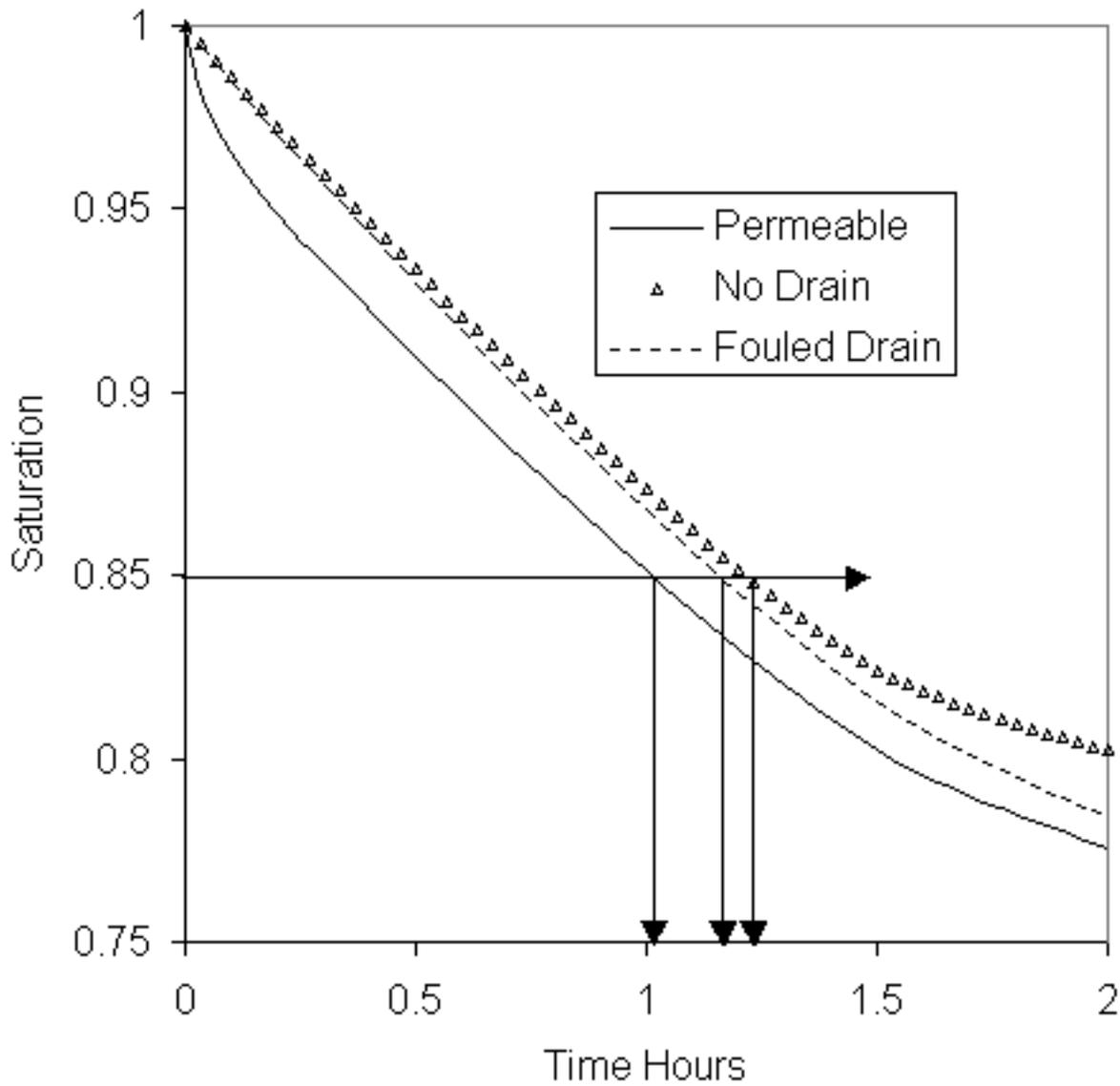
CASE 3: Initially saturated base and fouled edge drain on a permeable sub-grade with an adjustable water table height.



The results for the first hour of simulation should match

Time	Saturation
0	1
0.033333	0.994535
0.066667	0.989566
0.1	0.984733
0.133333	0.979971
0.166667	0.975254
0.2	0.97058
0.233333	0.965933
0.266667	0.961312
0.3	0.956719
0.333333	0.952146
0.366667	0.947604
0.4	0.943096
0.433333	0.938631
0.466667	0.934213
0.5	0.929836
0.533333	0.925473
0.566667	0.921144
0.6	0.916848
0.633333	0.912591
0.666667	0.908372
0.7	0.904186
0.733333	0.900029
0.766667	0.895906
0.8	0.891813
0.833333	0.887758
0.866667	0.88374
0.9	0.879751
0.933333	0.875791
0.966667	0.871869
1	0.867975

A graph of the above three runs, through two hours, is



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