TR-654

Development of a Subgrade Drainage Model for Unpaved Roads

Final Report

Submitted to:
Iowa Department of Transportation, Highway Division
Iowa Highway Research Board
800 Lincoln Way
Ames, Iowa, 50010

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15. ABSTRACT

With over 68 thousand miles of gravel roads in Iowa and the importance of these roads within the farm-to-market transportation system, proper water management becomes critical for maintaining the integrity of the roadway materials. However, the build-up of water within the aggregate subbase can lead to frost boils and ultimately potholes forming at the road surface. The aggregate subbase and subgrade soils under these gravel roads are produced with material opportunistically chosen from local sources near the site and, many times, the compositions of these sublayers are far from ideal in terms of proper water drainage with the full effects of this shortcut not being fully understood.

The primary objective of this project was to provide a physically-based model for evaluating the drainability of potential subbase and subgrade materials for gravel roads in Iowa. The Richards equation provided the appropriate framework to study the transient unsaturated flow that usually occurs through the subbase and subgrade of a gravel road. From which, we identified that the saturated hydraulic conductivity, K_s, was a key parameter driving the time to drain of subgrade soils found in Iowa, thus being a good proxy variable for accessing roadway drainability. Using K_s, derived from soil texture, we were able to identify potential problem areas in terms of roadway drainage .

It was found that there is a threshold for K_s of 15 cm/day that determines if the roadway will drain efficiently, based on the requirement that the time to drain, Td, the surface roadway layer does not exceed a 2-hr limit. Two of the three highest abundant textures (loam and silty clay loam), which cover nearly 60% of the state of Iowa, were found to have average Td values greater than the 2-hr limit.

With such a large percentage of the state at risk for the formation of boils due to the soil with relatively low saturated hydraulic conductivity values, it seems pertinent that we propose alternative design and/or maintenance practices to limit the expensive repair work in Iowa. The addition of drain tiles or French mattresses my help address drainage problems. However, before pursuing this recommendation, a comprehensive cost-benefit analysis is needed.

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1. INTRODUCTION

1.1 Problem Statement

There are over 68 thousand miles of gravel roads in Iowa (Figure 1), which constitute nearly 60% of the overall road surface in the state (http://www.iowadot.gov/research/analytics/images%28annual%29/MIPUBRDS03.pdf). The conditions of these roads directly affect the transportation in and around farming communities, and thus strongly influence the state's largest "industry" (Smith, 2015).

For gravel roads to support efficiently the heavy farm equipment (e.g., tractors, combines, sprayers), as well as the trucks that carry the harvested crops, these roads require strong foundations. Proper water management within this farm-to-market road system becomes critical then to maintain the integrity of the roadway materials.

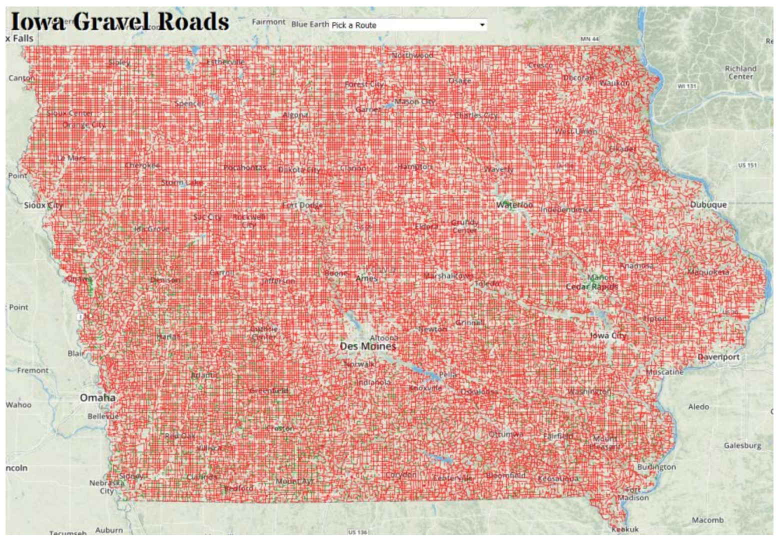

Figure 1. Map of Iowa gravel roads from IowaGravelRoads.com, which is based on the 2013 Iowa DOT dataset.

It is the build-up of water within the aggregate subbase of these gravel roads that is of most concern. The subbase sits below the gravel surface layer. The excessive water storage in the subbase results from over-abundant precipitation and poor drainage and it can considerably reduce the overall strength of the subbase. *It is suspected that the accumulated water in the subbase can lead to the formation of frost boils atop the road surface, which is a common problem for unpaved roads in Iowa*.

Boils most often occur during early spring and are by-products of residual water in the subbase that froze over the winter. As temperatures rise, this water in the subbase melts, but it cannot drain, as the soils of the deeper subgrade are still frozen. Since this melt water cannot drain, it can potentially accelerate pore water pressure build-up, thus favoring the formation of boils and ultimately of potholes in the road (Figure 2).

The most likely process behind the development of these potholes is the formation of confined water pipes or fluidization vents propagating vertically through the subbase material towards the surface (Figure 3; Papanicolaou and Maxwell, 2006). These vents are powerful enough to cut through the subbase material all the way to the surface layer. The fine soils in the aggregate mixture of the surface layer can form a *mud-slurry*, when mixed with the propagating water. As the farmers begin tilling and planting for the upcoming growing season, the weight of their heavy farm vehicles pushes this slurry to the surface, which in turn forces the aggregate material to sink. The road destabilizes and the potholes appear.

Figure 2. Boils in a gravel road.

It seems that boil formation within the gravel roads of Iowa is inevitable, especially due to the prevalent freeze-thaw cycles in the Midwest, coupled with the expected increases in precipitation for the region in the coming decades (Love, 2008; Takle, 2009). To make matters worse, this problem has been found to reoccur at the same locations, despite the best efforts by county engineers and their road crews to repair these problematic areas and re-grade the road surface. There is the need to understand further the causes behind this phenomenon, in order to limit its occurrence and ease the burden of high road maintenance costs across the state.

To address water drainage concerns in gravel roads, the Iowa Department of Transportation (IDOT) provides standards for the quality of road surface gravel (IDOT, 2011), which must contain 40-80% graded hard stone, 20-60% sand, and 8-15% fines. Despite these specifications for the road surface layer, there is little guidance for the road sublayers, namely the aggregate subbase and subgrade soils. The typical aggregate subbase that underlies the surface gravel on gravel roads in Iowa (as well as in several other states) is opportunistically chosen from the materials that can be found near the site to help minimize transportation costs from a faraway quarry. In addition, the bottom subgrade soil layer of the gravel roads consists mostly of the local soils. Many times, the compositions (% gravel/ sand/ silt/ clay) of the aggregate subbase and the subgrade soil material are far from ideal in terms of proper water drainage. Moreover, the effects of using local materials are often neglected in the drainage design and performance planning of these county roads. This oversight, ultimately, can have detrimental effects on the integrity of the surface gravel and the road itself leading to unnecessarily high and recurring maintenance costs.

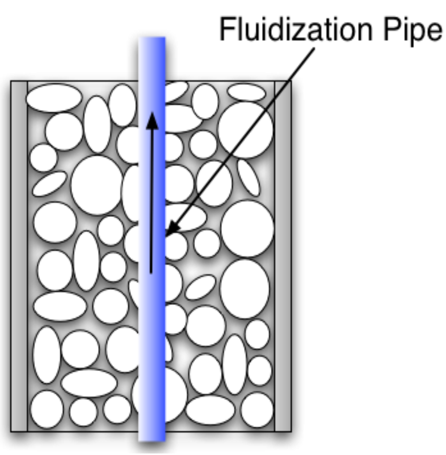

Figure 3: Schematic of fluidization process, where a vertical water pipe develops in the subbase layer.

To understand better those local site conditions that can contribute to poor subgrade drainage performance and the formation of boils in the gravel roads of Iowa, this study offers an enhanced, process-based model that captures the movement of water in a porous medium. The model guided us to those key parameters influencing roadway drainage, which allowed us to identify those areas in the state where there is a higher likelihood for the development of the frost boils. The information gained from this study will allow us to provide suggestions that can improve subbase and subgrade designs. The above products can easily be adopted by state and county engineers to not only predict potential problem areas in terms of roadway drainage, but also explore ways of abating the problem in advance.

1.2 Background

The basic design for gravel roads in Iowa was used to focus our efforts to the most problematic areas regarding drainage. Typically in Iowa, the construction of gravel roads follows the Statewide Urban Design and Specifications, or SUDAS (Wiegand and Stevens, 2007). In general, gravel roads follow the basic pattern seen in Figure 4. The gravel surface layer covers an aggregate subbase, which sits on top of the subgrade soils.

Most attention has focused on the gravel surface layer as the primary spot of failure (e.g., Skorseth and Selim, 2000). Failure of the surface gravel under heavy loads can result from marginal gravel depths or the use of substandard material. Reports like those of Skorseth and Selim (2000) detail the calculations for determining the required surface layer depths for the different regions across the US, considering the local climate and expected loads.

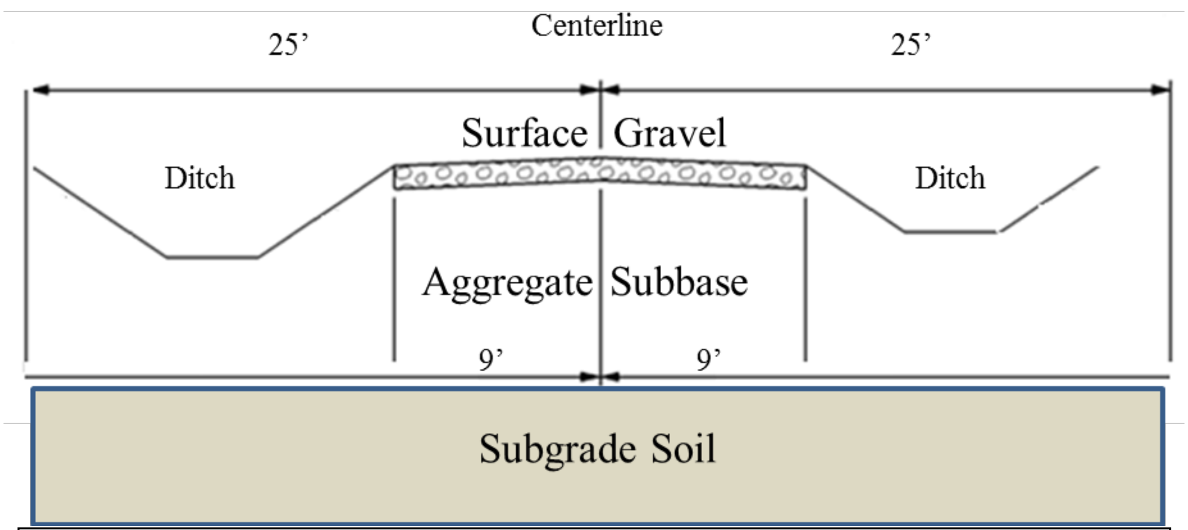

Figure 4. Example design for a gravel road following the SUDAS for Iowa. Adapted from Wiegand and Stevens (2007).

Additionally, the composition of the surface gravel is important. Good surface gravel must contain a mixture of stone, sand, and fine soils. Proper blends of these material sizes will ensure that a road performs well with adequate load-bearing strength, drainability, and cohesion to keep the materials together. For example, high amounts of coarse material (i.e., gravel and sand) may increase the load-bearing strength and drainability of the roadway, but the aggregate mixture will have little cohesion to hold it all together. As a result, the roadway will remain loose and unstable on a gravel road (Skorseth and Selim, 2000).

In Iowa, that proper mixture is 40-80% hard stone with diameters uniformly graded from ¼ to 3 inches; 20-60% sand smaller than ¼ of an inch; and 8-15% fines (IDOT, 2011). One striking observation with these standards is the wide range for each size class. This wide range allows for flexibility to accommodate the natural variability in climate and local soil conditions seen in Iowa.

Despite the existence of standards for the surface layer gravel, to date there are no standards for the subbase aggregate or the subgrade soils. For convenience, the materials used for these lower layers are most often grabbed opportunistically from local sources. But, just as with the surface layer gravel, the compositions of both the subbase and subgrade materials are important for a properly functioning roadway in terms of drainage. As presented above, the fine material in the surface layer can fluidize from the upwelling of water trapped within the subbase, due to their poor drainability (a function of the material composition in both the subbase and subgrade). Due to the lack of knowledge regarding the effects of material composition on the drainability of the subbase and subgrade layers, we have focused this study on these two lower sublayers.

The metric used by the Federal Highway Administration (FHWA) to characterize how well a particular road is draining is the *Quality of Drainage* (Table 1), which we have also adopted for this study. This drainability rating ranges from "Excellent" to "Very Poor" and is correlated with the Time to Drain, T_d. The overall goal to best limit boil formation is to strive for excellent drainage, which is obtained when the Degree of Saturation, S_w, reduces from 100% to 85% within 2 hours (Figure 5). The S_w, which is defined as the ratio of the volume of water content, θ, to the volume of voids (porosity), is the central quantity for assessing subsurface drainage (Table 1).

Table 1. Levels of Quality of Drainage (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

The evolution of water content over time within the subbase and the subgrade, and hence their drainability, can be determined using the Richards equation, which combines Darcy's law for vertical unsaturated flow with the conservation of mass (Dingman, 1993). The Richards equation states the following:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K(h)\nabla \mathrm{h}) + \frac{\partial K}{\partial z} \qquad (1)$$

where θ is the water content; K is the hydraulic conductivity; h is the pressure head; and t and z are the time and vertical coordinates, respectively. The changing water content with respect to time is, in the context of subsurface drainage, the rate at which water leaves the subbase/ subgrade.

In general, this rate of movement is dependent on the hydropedologic properties of the materials that make up the subbase and subgrade. These hydropedologic properties include the saturated hydraulic conductivity and texture, as well as the water table elevation, which can be included in the Richards equation as a boundary condition. The Richards equation, therefore, provides the appropriate framework to study the transient unsaturated flow that usually occurs through the subbase and subgrade of a gravel road after a precipitation event.

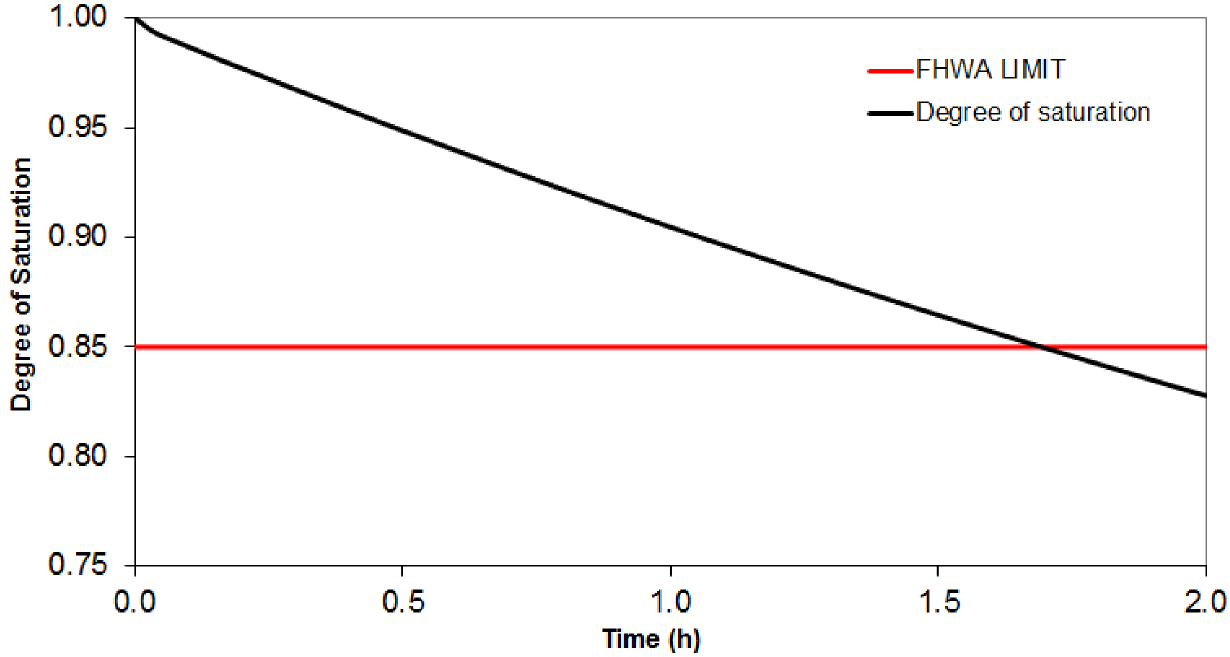

Figure 5. Example graph representing the time-evolution of the Degree of Saturation within an aggregate subbase. The FHWA LIMIT represents the degree of saturation (0.85) that is needed in the subbase within 2 hours after a rain event to have "Excellent" drainage.

1.3 Objectives

The primary objective of this project was to provide a physically based model for evaluating the drainability of potential subbase and subgrade materials for gravel roads in Iowa. The offered model works under saturated and unsaturated conditions and for a wide range of key design hydraulic and geotechnical parameters seen throughout the state. This model was used to identify those key parameters that contribute to poor subgrade drainage performance and the formation of boils in the gravel roads of Iowa.

Using this information of the key parameters from the model, we identified problematic areas in the state of Iowa by examining soil maps from the Natural Resources Conservation Service (NRCS). These maps provide the necessary information regarding the local site conditions and typically reflect the subgrade materials.

Finally using the model and the knowledge gained from examining the soils maps, we proposed alternative roadway design compositions for the subbase and subgrade layers to improve their drainability.

2. METHODOLOGY

2.1. Provide a model for evaluating drainage in the sublayers of a gravel road.

Subbase and subgrade drainage are specific examples of unsaturated flow through a porous medium. Several methods and models are available to quantify this process and they range from simple algebraic relations like a hydrologic budget to more complex differential equations (Voller, 2003). Of these, the Richards equation (Eq. 1) provides the appropriate framework to study this transient unsaturated flow through the different layers of granular materials in a gravel road (Mays, 2005).

As seen in Eq. 1 above, the key parameters to determine the time evolution of the water content, θ, in a porous media using the Richards equation are the hydraulic conductivity, K, and the pressure head, h. However, Eq. 1 must be coupled with auxiliary relationships (Brooks and Corey, 1964) to express the dependency of K and h on the water content θ. The Brooks-Corey relations follow as:

$$\begin{cases} K(\theta) = K_s \left(\frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}}\right)^{\lambda_2} & (2a) \\ h(\theta) = h_d \left(\frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}}\right)^{-\frac{1}{\lambda_1}} & (2b) \end{cases}$$

where K_s is the saturated hydraulic conductivity; θ_{res} is the residual water content; θ_{sat} is the saturated water content; h_d is the bubbling pressure (which is the minimum capillary pressure in the porous medium); λ_1 is the pore-size index; and λ_2 is a fitting parameter. In total, Eq. 2a and 2b provide a set of 6 parameters (namely, K_s, θ_{res}, θ_{sat}, h_d, λ_1, λ_2) that can describe the physical properties of the granular materials affecting the movement of water through a porous medium under unsaturated conditions.

The saturated hydraulic conductivity, K_s, is believed to uniquely link hydrologic and pedologic attributes, which include soil texture and bulk density (Papanicolaou et al., 2015). Several relationships, known as pedotransfer functions, have been developed for determining K_s using different combinations of these attributes. For Iowa, Papanicolaou et al. (2015) found that the relationships used in the ROSETTA software package (Schaap, 1999) matched best their double ring infiltrometer measurements made around the state. The baseline saturated hydraulic conductivity values for the soils in Iowa, which were supplied to the model, were determined using the ROSETTA relationships.

The saturated water content, θ_{sat}, coincides with the porosity of the material. The porosity, ϕ, was estimated using the bulk density, ρ_{bulk}, and the particle density, $\rho_{particle}$, using the following formula:

$$\phi = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \qquad (3)$$

The residual water content θ_{res}, bubbling pressure h_b and the pore-size index λ_1 were estimated using the porosity, ϕ, as well as the silt and clay contents, S and C respectively, according to the following formulae (Maidment, 1993):

$$\theta_{res} = -0.0182482 + 0.00087269S + 0.00513488C + 0.029392860\phi - 0.00015395C^2 - 0.0010827S\phi - 0.00018233C^2\phi^2 + 0.00030703C^2\phi - 0.0023584\phi^2C \quad (4)$$

$$h_b = -\exp(5.3396738 + 0.1845038C - 2.48394546\phi - 0.00213853C^2 - 0.04356349S\phi - 0.61745089C\phi + 0.00143598S^2\phi^2 - 0.00855375C^2\phi^2 - 0.00001282S^2C + 0.00895359C^2\phi - 0.00072472S^2\phi + 0.0000054C^2S + 0.5002806\phi^2C) \quad (5)$$

$$\lambda_1 = \exp(-0.7842831 + 0.0177544S - 1.062498\phi - 0.00005304S^2 - 0.00273493C^2 + 1.11134946\phi^2 - 0.03088295S\phi + 0.00026587S^2\phi^2 - 0.00610522C^2\phi^2 - 0.00000235S^2C + 0.00798746C^2\phi - 0.00674491\phi^2C) \quad (6)$$

The fitting parameter λ_2 is related to the pore-size index through the formula:

$$\lambda_2 = \frac{2+3\lambda_1}{\lambda_1} \quad (7)$$

Once all the above parameters have been provided, Eqs. 1 and 2 can be solved numerically in order to quantify the changing water content in the subbase and subgrade of a gravel road. The MNDRAIN software (Voller, 2003) provides the basic structure to solve the Richards equation numerically. MNDRAIN uses a Control Volume Finite Element (CVFE) solution for Eqs. 1 and 2 to quantify the time evolution of water content, θ, which then is used to determine the Degree of Saturation, S_w, and Time to Drain, T_d, of the subbase and subgrade for a gravel road segment (Figure 6). An important attribute of this model is the ability to simulate the changing θ in the two layers simultaneously, as they are inherently linked, meaning the drainage of the subgrade affects the draining of the subbase.

MNDRAIN was modified during this study to work with a Windows 64 bit. This required recompiling the original source code while incorporating new executables. The recompilation used a g95 compiler for the Fortran source codes and with the gcc compiler for the C source codes. Both compilers were run in a Windows 64 bit machine with the program Cygwin (http://www.cygwin.com/). The enhanced model was used to quantify S_w and T_d for various aggregate subbase configurations and subgrade soils found in Iowa. A practical guide for using the enhanced MNDRAIN in Iowa is provided in the appendix.

2.2. Determine areas with a high likelihood of boil formation due to poor subgrade drainage.

To help determine those areas throughout Iowa that have a high potential for boil development, a proxy variable was determined using the model provided above. A proxy variable eliminates the need for expensive coring at all possible locations in the state. The proxy variable was determined with the help of a sensitivity analysis that was performed on the key parameters needed for solving the Richards equation (namely, K_s, θ_{res}, θ_{sat}, h_d, λ_1, λ_2). The sensitivity analysis showed that the saturated hydraulic conductivity, K_s, was the most sensitive parameter, thus making it a good candidate for a proxy variable.

To identify potential problematic areas prone to boil development, the texture maps from the NRCS were used. K_s values were determined for each of these textures with the pedotransfer functions from ROSETTA. Those areas with K_s values below a critical value that caused theTime to Drain, T_d,for the roadway surface layer to exceed 2 hours were deemed as the problematic areas and in need of further attention for the development of boils.

Double Ring Infiltormeter measurements of K_s from past studies by the PI, coupled with laboratory measurements of different soil and gravel configurations were used to confirm the values estimated from the maps.

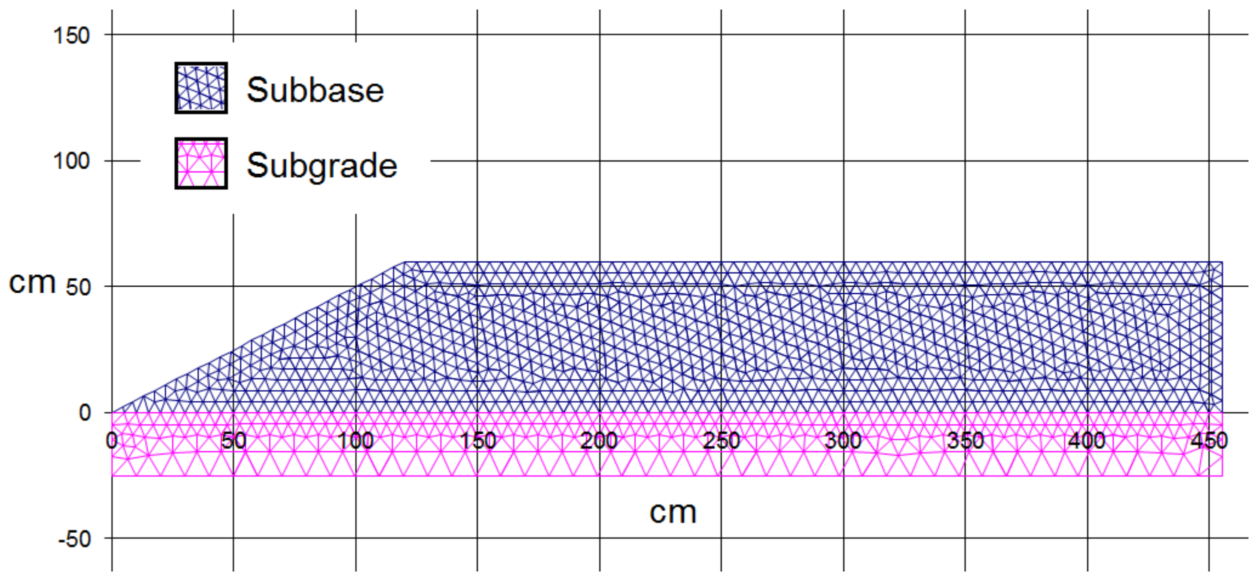

Figure 6. Example of mesh generated with MNDRAIN with the typical dimensions of an Iowa gravel road.

2.3 Determine whether there are design and/or maintenance alternatives that will improve subgrade drainage performance.

To prevent the development of boils and the need for increased levels of maintenance to gravel roads, it is first important to identify and understand the potential causes of boils. From the above, it is clear that there is a need to either limit the drainage of water into the gravel matrix of the roadway or to facilitate its removal once it is in the matrix. We conducted a literature review to identify potential alternative methods for doing both. The review focused not only on the transportation literature but also the agricultural literature, which also suffers from the effects of poorly drained sub-soils.

3. RESULTS
3.1 Provide a model for evaluating drainage in the sublayers of a gravel road.

The initial step for this study was to identify the physical ranges (Table 2) of the parameters in the Richards equation for the state of Iowa. Four different aggregate subbase compositions were developed using the IDOT (2011) specifications as a starting pad for the different combinations, along with a 100% gravel mixture. These bases were defined by the K_s values, seen in Table 2, as a function of their K_s values. The conductivity values were verified in the lab with constant head tests (Figure 7). Base values for the different soil textures found in Iowa were provided by the Iowa Soil Properties And Information Database (ISPAID), which were also verified using constant head studies employing a column.

Table 2. Range of values for typical soils

Soil	K_s [cm/s]	θ_{sat}[.]	θ_{sat}[.]	h_d [cm]	λ_1[.]
Gravel	0.1	0.030	0.450	-0.5	0.200
Granular Base A	0.0005	0.030	0.450	-1	0.200
Granular Base B	0.0002	0.030	0.450	-2	0.500
Granular Base C	0.001	0.030	0.450	-5	1.000
Gravel	10^{2}-10^{-1}	0.001-0.030	0.25-0.40	-0.50-5.00	0.200-1.000
Sand	10^{0}-10^{-4}	0.001-0.039	0.25-0.50	-1.36-38.74	0.298-1.090
Silt	10^{-3}-10^{-7}	0.000-0.058	0.35-0.50	-3.58-120.4	0.105-0.363
Clay	10^{-7}-10^{-10}	0.000-0.195	0.40-0.70	-7.43-187.2	0.037-0.293

These base values (Table 2) were supplied to simulations of the Richards equation using the above model and a representative gravel road cross-section. The goal of these simulations was a sensitivity analysis to identify the key parameters affecting the T_d in relation to prescribed 2-hr threshold for excellent drainage.

The results of this preliminary sensitivity analysis are reported in Figures 8 and 9 below. It was found that the model is primarily sensitive to changes in the hydraulic conductivity. This was attributed to the wide range of values exhibited by the different materials, which spanned from 10^{2} cm/s for gravel to 10^{-10} cm/s for clay. In contrast, the other 5 parameters from Eq. 2 all ranged within roughly the same order of magnitude (Table 2).

Figure 8 shows the changing Degree of Saturation over time for the four different subbase mixtures, represented with the blue and yellow lines. For each of these runs, the subgrade was fixed as having a loam texture.

The red line highlights the FHWA threshold of $S_w < 0.85$, which must be reached after 2 hours to have excellent drainage. The green line shows the trend direction of the K_s values for each subbase combination. As K_s decreases, which means infiltration slows down, the time required for the gravel cross-section to drain below $S_w = 0.85$ increases. In fact, for the two subbases, A & B, the time it takes to drain below 0.85 is greater than the two hour limit required for excellent drainage.

Figure 9, which is similar to Figure 8, focuses on the subgrade soils. A few of the more common textures were simulated using the same "gravel" subbase.

Similarly, as K_s decreases due to the texture becoming finer, the T_d increases. In fact, for subgrade textures finer than silty loam, it can be problematic to meet the excellent criteria in terms of drainage rates.

It was found that there is a minimum threshold in the saturated hydraulic conductivity of 1.7 x 10^{-4} cm/s or equivalently 15 cm/day required for the "excellent" surface drainage. This means that for all the soils with K_s below 15 cm/day, the reduction of S_w from 100% to 85% will exceed the 2 hours limit and therefore these soils will not have an excellent quality of drainage.

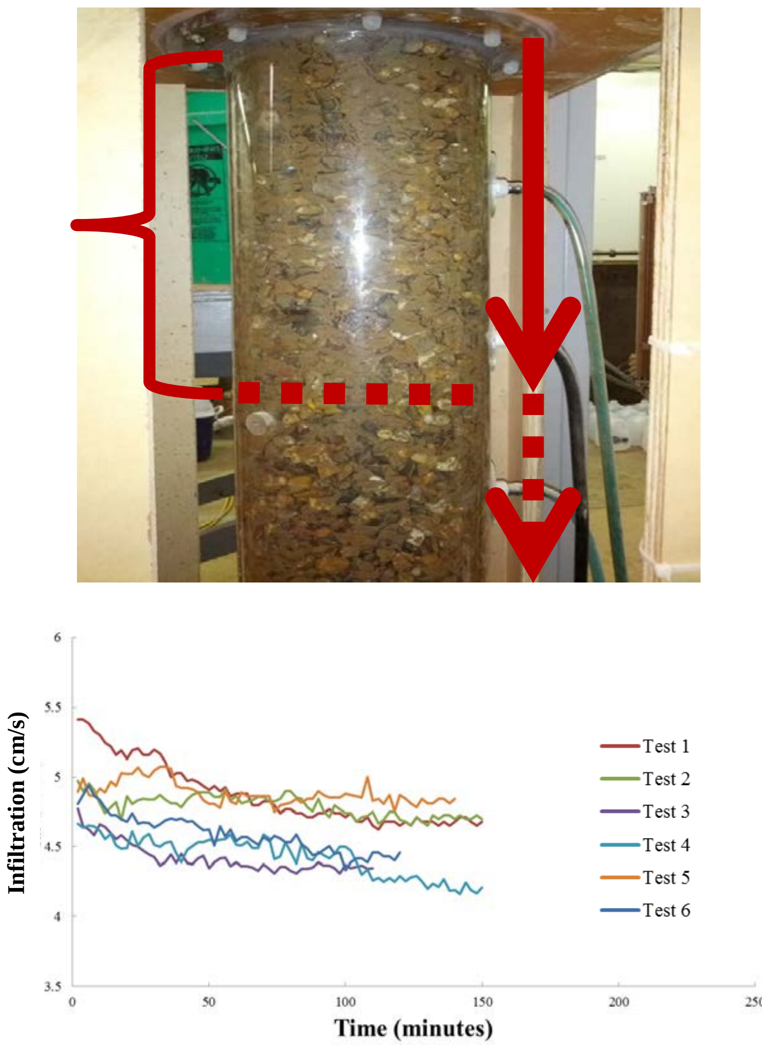

Figure 7. (a) Movement of water through a gravel-soil matrix. (b) Measurements of infiltration to determine K_s for different gravel-soil mixtures using a constant head test.

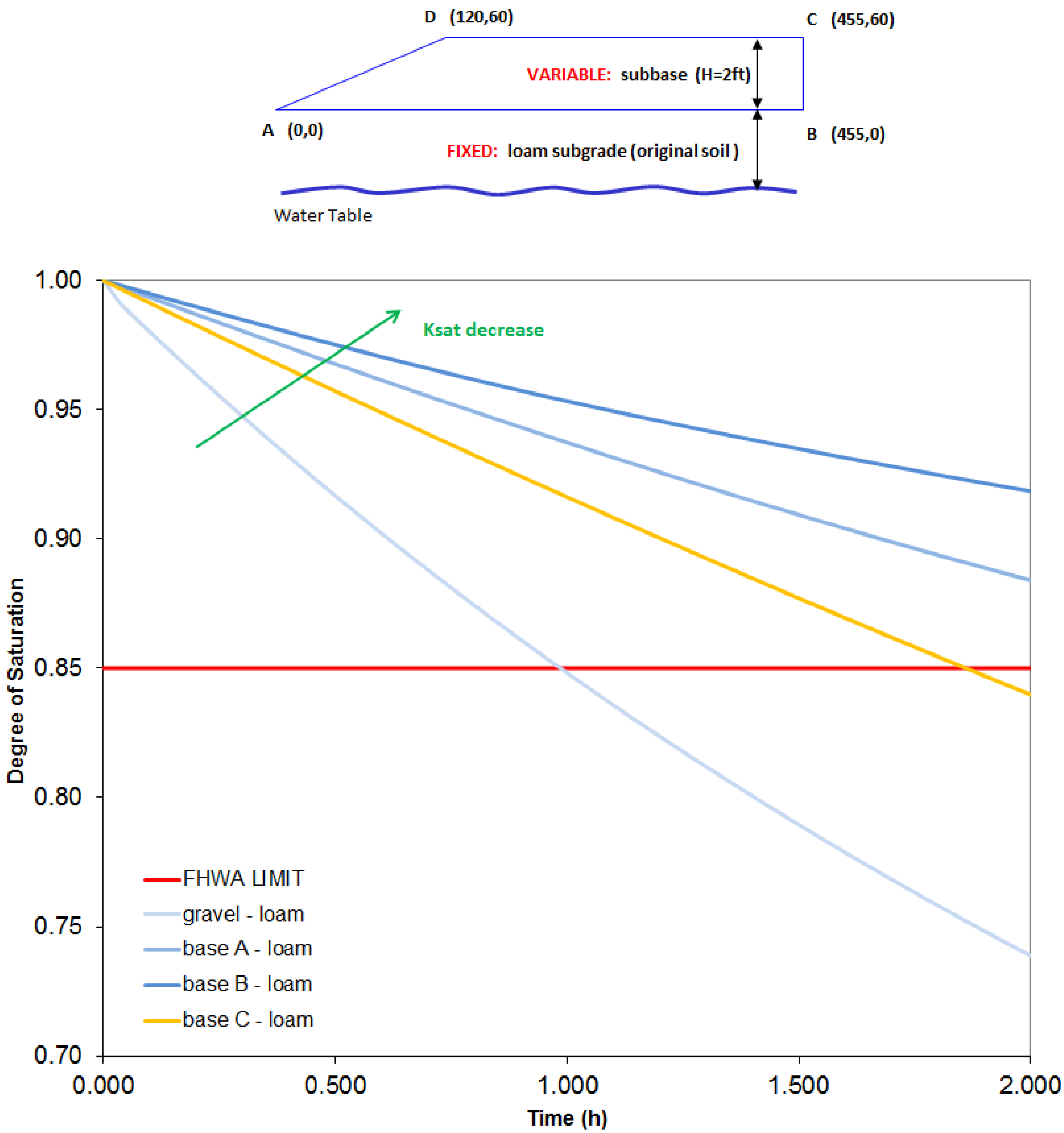

Figure 8. Results of the preliminary sensitivity analysis: effects of various aggregate subbase soils on the degree of saturation curve.

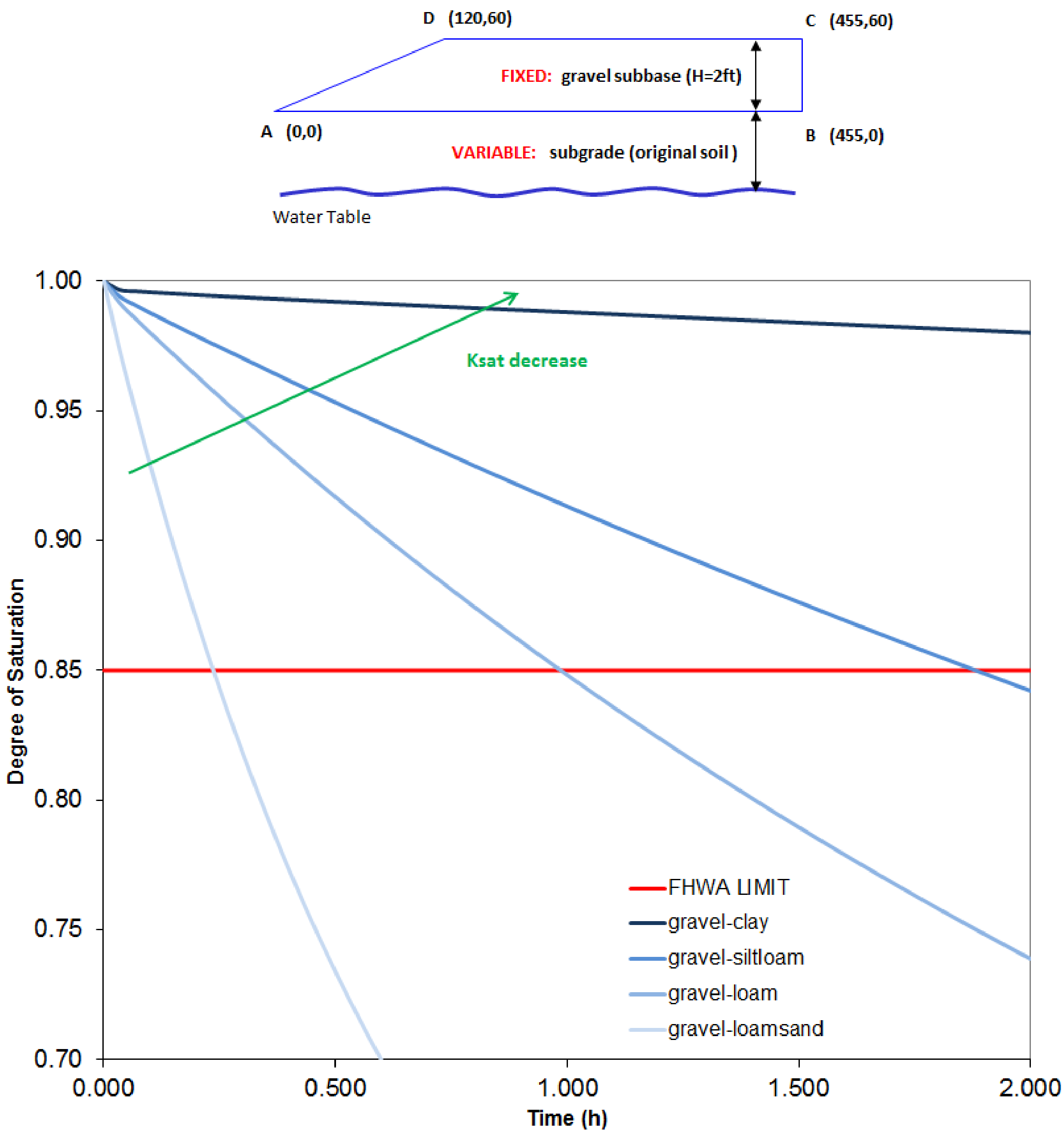

Figure 9. Results of the preliminary sensitivity analysis: effects of various subgrade soils on the degree of saturation curve.

3.2 Determine areas with a high likelihood of boil formation due to poor subgrade drainage.

To identity the areas in the state with a high potential for the formation of boils due to poor subsurface drainage, we used a proxy value of the saturated hydraulic conductivity of the local soil type. Select counties from the key landform regions throughout Iowa (e.g., Des Moines

Lobe, Iowan Surface, and Southern Iowa Drift Plain) were chosen to provide a representative pool of soil textures and saturated hydraulic conductivities to identify the variability of the soil hydraulic conductivity (Figure 10). From these counties, the data regarding soil composition were extracted from ISPAID and the respective K_s values were determined using the ROSETTA pedotransfer functions.

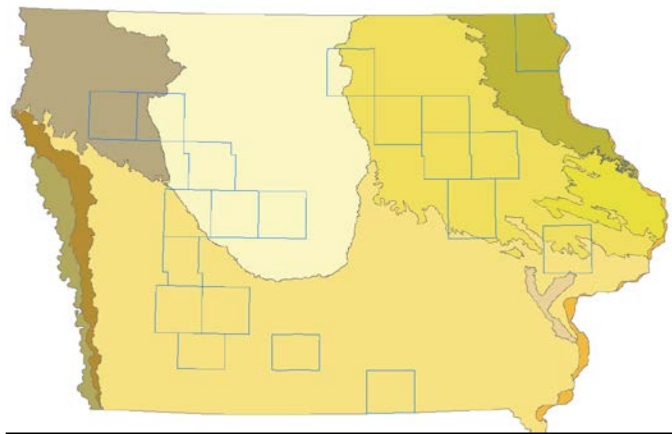

Figure 10. Map of major landforms in Iowa with highlighted counties used in the model calibration.

For each soil texture (e.g., loam, silty clay), there is a range of textures and consequently K_s values in Iowa. Therefore, histograms of K_s values for each texture were developed for the representative counties (Figure 11) to determine the most representative values for each texture.

The textures in the representative counties studied range from *gravelly sandy loam* to *clay*, which are similar for the whole state,. The most common textures in the representative countiesare *silty clay loam*, *loa*m, and *silt loam*, which cover nearly 85% of the state (Table 2). It is clear from Figure 11 that K_s varies greatly even within the same soil texture. Because of this variability in K_s, the harmonic mean was chosen to characterize the central tendency of each histogram based on the findings of Papanicolaou et al. (2015). To illustrate the variability of K_s throughout Iowa, Table 2 also reports the standard deviation of the hydraulic conductivity, given as:

$$\text{St. Dev} = \frac{1}{n}\sqrt{\sum_i \left(K_{si} - HA(K_{si})\right)^2} \quad (8)$$

where n is the total number of hydraulic conductivity observations available for each soil texture; K_{si} is the single value of hydraulic conductivity; and $HA(K_{si})$ is the harmonic average of the hydraulic conductivity.

For each soil texture, the resulting parameter values for the Richards equation (Table 2) were included in the model simulations to quantify the T_d and hence the quality of drainage according to the FHWA criterion (Table 1). These values were used to calibrate the model for the typical soil types found in Iowa. Each value was compared to the threshold K_s value of 15 cm/d, which means that any soil with a saturated hydraulic conductivity below 15 cm/d will exceed the 2 hours limit and not have excellent quality of drainage.

In Table 3, the textures highlighted in yellow have average T_d values greater than the 2-hr limit. These include two of the three most abundant textures, namely loam and silty clay loam. The values highlighted in orange are marginal, meaning there will be some places with this texture type that may exceed the threshold limit due to the variability in the state. To put the results of Table 3 in a more visual expression, Figure 12 shows a map of K_s determined for the state of

Iowa using the pedotransfer functions described above. Essentially, any areas within the state of Iowa colored in green or yellow are at risk for the formation of boils as the soils in these areas have K_s values below the threshold limit of 15 cm/d.

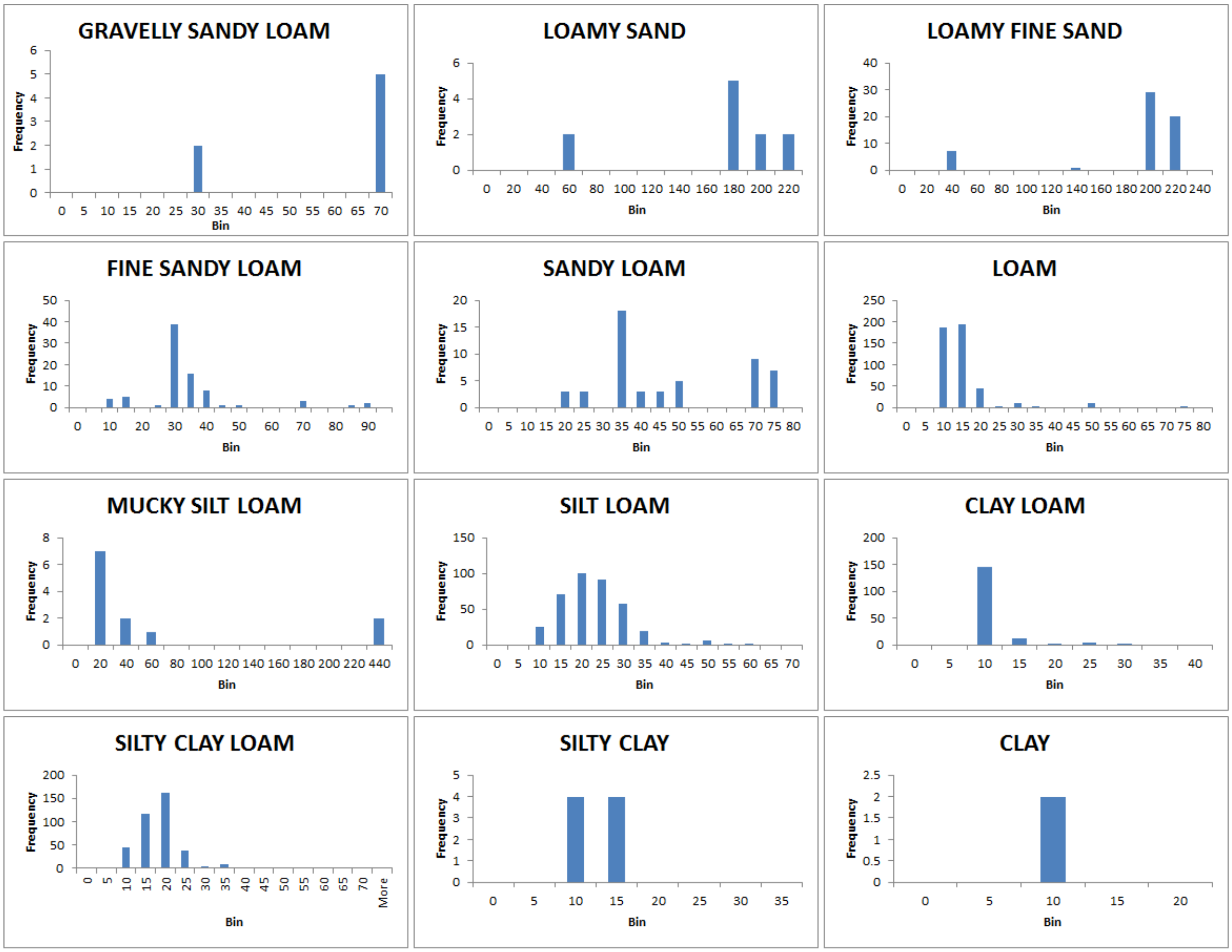

Figure 11. Histograms of the saturated hydraulic conductivity for various soil textures found in Iowa.

Table 3. Hydraulic conductivity and time to drain for various soil textures found in Iowa.

SOIL TEXTURE	Percent coverage in representative counties [%]	Percent coverage in state[%]	K_s [cm/d]		T_d [hr]			
			Harmonic mean	Standard Deviation	T_d+	T_d	T_d -	T_d with a drain
GRAVELLY SANDY LOAM	0.04%	**0.04**	**48.75**	**19.02**	0.28	0.38	1.02	N/A
LOAMY SAND	0.21%	**0.13**	**115.67**	**64.85**	0.12	0.18	0.38	N/A
LOAMY FINE SAND	1.30%	**0.86**	**103.47**	**93.36**	0.11	0.20	3.00	N/A
FINE SANDY LOAM	1.85%	**0.98**	**25.04**	**16.39**	0.46	1.14	3.30	N/A
SANDY LOAM	0.81%	**0.67**	**36.75**	**19.10**	0.34	0.52	1.44	N/A
LOAM	26.99%	**23.13**	**10.20**	**8.24**	1.40	2.58	>10	0.14
MUCKY SILT LOAM	0.25%	**0.47**	**21.80**	**170.25**	0.11	1.24	>10	N/A
SILT LOAM	16.02%	**26.63**	**17.58**	**8.16**	1.12	1.44	3.14	N/A
CLAY LOAM	9.78%	**9.23**	**7.25**	**4.08**	2.42	4.10	>10	0.16
SILTY CLAY LOAM	42.61%	**36.70**	**13.34**	**6.46**	1.32	2.16	4.24	0.14
SILTY CLAY	0.12%	**0.92**	**7.33**	**2.53**	3.6	4.08	6	0.16
CLAY	0.02%	**0.17**	**5.92**	**0.42**	4.48	5.06	5.30	0.16

T_d is time to drain; T_d + is time to drain considering the harmonic value of the hydraulic conductivity plus the standard deviation; T_d - is time to drain considering the harmonic value of the hydraulic conductivity minus the standard deviation.

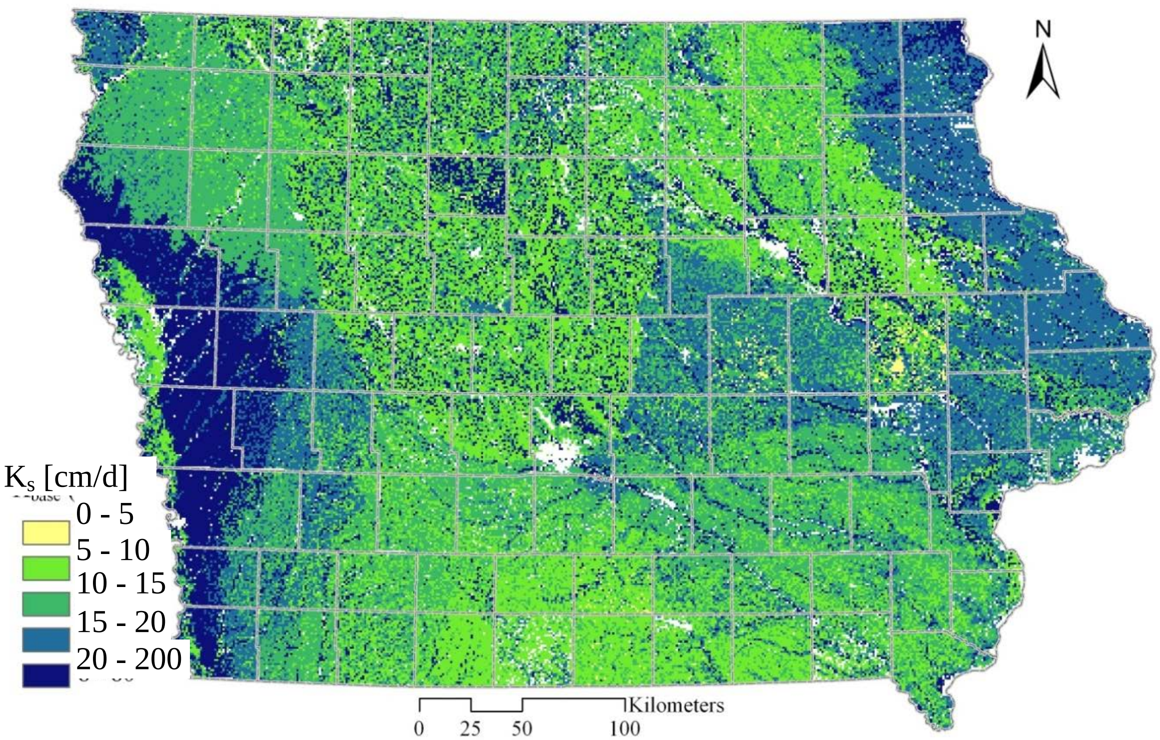

Figure 12. Map of saturated hydraulic conductivity in the state of Iowa. Essentially any areas colored in green or yellow are at risk for the formation of boils, as the soils in these areas have K_s values below the threshold limit of 15 cm/day.

3.3 Determine whether there are design and/or maintenance alternatives that will improve subgrade drainage performance.

With such a large percentage of the state at risk for the formation of boils due to the soils with relatively low saturated hydraulic conductivity values, it seems pertinent that we come up with alternative design and/or maintenance practices to limit the expensive repair work for the 68 thousand miles of gravel roads in Iowa. To help accommodate this drainage problem we can look towards the predominant agricultural sector in Iowa, who must also deal with soils having poor drainage. It may be more cost effective to consider installing either a geotextile fabric (Skorseth and Selim, 2000) between the roadway layers to help disperse the water upwelling as a vent, or a perforated drain tile (Papanicolaou et al., 2012) as a conduit for the draining water. Figure 13 shows the PIs assisting with the installation of an Alternative Tile Intake (ATI) in a farm field in southeast Iowa. An ATI is essentially a drain tile over a gravel filter. The ATIs are similar in principle to the "French Mattress", which is a clean coarse rock structure under a roadway that is wrapped in geotextile fabric through which water can drain freely (Bloser et al., 2013).

The use of drain tiles in gravel roads is not a common practice in Iowa, despite their use under paved roads (White and Vennapusa, 2011; Ceylan, 2013) and agricultural areas (Ettema et al., 2014). For the soil textures in Iowa, where T_d exceeded the limit of 2 hours to have an excellent quality of drainage, additional simulations were run using the MNDRAIN model with a drain tile installed. The re-calculated T_d values from these additional simulations with the drain installed are shown in the final column in Table 3. Clearly the drain is beneficial, as the new T_d values are well below the 2-hr limit, required to achieve "excellent" drainage conditions. A future step would be a full cost-benefit analysis to assess if retrofitting gravel roads with subsurface drainage is more effective than continually repairing the road surface.

Moreover, it was found that the opportunistic selection and use of the roadway subbase material can have detrimental consequences. It is, therefore, recommended to establish design criteria for the subbase material composition, similar to the design criteria for the surface material, in order to improve roadway drainage. The results in Figure 8 can provide an indication of the material compositions that can be used for establishing such design criteria. Along the same lines, design criteria can be introduced for the composition of the subgrade material for improved drainage characteristics of roadways and prevention of the formation of boils on their surface. The results in Figure 9 can be a useful guide for introducing such design criteria. It is recognized, however, that the transport of materials would introduce an additional expense in roadway construction. Hence, a cost-benefit analysis for such improved designs for the roadway subbase and subgrade layers relative to the perpetual repair of these roadways should be conducted first. This approach may also be implemented surgically at limited locations where boils are recurring.

Along with subsurface recommendations are different surface techniques that can divert water more quickly off the surface of the surface before it has a chance to infiltrate into the matrix. This work of White and Vennapusa (2011) offered the practical limitations of different low cost rural surface alternatives (chemical and mechanical) for stabilizing road surfaces and shedding storm runoff. Additionally, simple practices, such as crowing the road or adding rubber belts, would help diverting the water off the road way before it collects in depressions along the road (Bloser et al., 2013).

Figure 13. Installation of an ATI. (A) First, a layer of wood chips is placed in a trench over the existing drain tile. (B) Pea gravel is placed over the wood chips. (C) The gravel is slightly mounded. (D) The ATI a year-and-a-half later has still maintained its shape.

4. CONCLUSIONS

With over 68 thousand miles of gravel roads in Iowa and the importance of these roads within the farm-to-market transportation system, proper water management becomes critical for maintaining the integrity of the roadway materials. It is the build-up of water within the aggregate subbase that is of most concern, which can lead to frost boils and ultimately potholes forming at the road surface.

To address water drainage concerns in gravel roads, IDOT has standards for the quality of road surface gravel; however, the aggregate subbase and subgrade soils are produced with material opportunistically chosen from local sources near the site. Consequently, many times, the compositions of the aggregate subbase and the subgrade soil material are far from ideal in terms of proper water drainage with the full effects of this shortcut not being fully understood.

The primary objective of this project was to provide a physically-based model for evaluating the drainability of potential subbase and subgrade materials for gravel roads in Iowa. The Richards equation provided the appropriate framework to study the transient unsaturated flow that usually occurs through the subbase and subgrade of a gravel road after a rainfall. Using this approach, we identified that the saturated hydraulic conductivity, K_s, was a key parameter driving the time to drain of subgrade soils found in Iowa, thus being a good proxy variable for accessing roadway drainability. Using K_s, derived from soil texture maps from the Natural Resources Conservation Service we were able to identify potential problem areas in terms of roadway drainage .

It was found that there is a threshold in the hydraulic conductivity of 1.7 x 10^{-4} cm/s or equivalently 15 cm/day that determines if the roadway will drain efficiently, based on the requirement that the time to drain, T_d, the surface roadway layer does not exceed a 2-hr limit. Two of the three highest abundant textures (loam and silty clay loam), which cover nearly 60% of the state of Iowa, were found to have average T_d values greater than the 2-hr limit.

With such a large percentage of the state at risk for the formation of boils due to the soil with relatively low saturated hydraulic conductivity values, it seems pertinent that we propose alternative design and/or maintenance practices to limit the expensive repair work for the 68 thousand miles of gravel roads in Iowa. To help accommodate this drainage problem we suggest adopting similar solutions as those of the predominant agricultural sector in Iowa, where drain tiles with Alternative Tile Intakes (ATI's) have been used for addressing similar drainage problems. In addition, this study provided the impetus for design criteria for the composition of the subbase and subgrade materials that improve roadway drainage, which to date are lacking. However, before pursuing this recommendation, a comprehensive cost-benefit analysis is needed.

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6. APPENDICES

6.1 Notation

Variable name	Symbol	Definition
Bulk density	ρ_{bulk}	The ratio of the mass of the soil to the total volume
Saturated hydraulic conductivity	K_s	Rate of flow of water through a cross-section of unit area under a unit hydraulic gradient
Bubbling pressure	h_b	The minimum capillary pressure in the porous medium
Clay	C	Particle with dimension range of 0.5-4 micron
Degree of saturation	S_w	The ratio of the volume of water content to the volume of voids
Porosity	ϕ	The ratio of the volume of void to the total volume of soil
Particle density	$\rho_{particle}$	The ratio of the mass of the particle to its total volume
Pore-size index	λ	An index for classifying soil pore size distribution
Residual water content	θ_{res}	The minimum water content
Saturated water content	θ_{sat}	The water content at saturation (the numerical value is coincident to the porosity)
Silt	S	Particle with dimension range of 4-62 micron
Water content	θ	The ratio of the volume of water to the total volume of soil

6.2 User guide for MNDRAIN

1. MNDRAIN

The original MNDRAIN model can be downloaded from the website:
http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html
And follow the installation instructions from the website.

The main folder of MNDRAIN "mndrain" contains four subfolders (ex1, ex2, ex3, files), one main excel file and the official report.

- ex1: contains the file slave.xls to run simulations with a subdrain
- ex2: contains the file slave.xls to run simulations without a subdrain
- ex3: contains the file slave.xls to run simulations with a fouled subdrain
- files: contains all the executable files for windows 32 bit

2. Modification of MNDRAIN for Iowa

MNDRAIN was modified during this study to work with a Windows 64 bit. This required recompiling the original source code while incorporating new executables. The recompilation used a g95 compiler for the Fortran source codes and with the gcc compiler for the C source codes. Both compilers were run in a Windows 64 bit machine with the program Cygwin (http://www.cygwin.com/).

To use the recompiled MNDRAIN, the following files and folders are needed:

- ex1: contains the file slave.xls to run simulations with a subdrain in 64bit
- ex2: contains the file slave.xls to run simulations without a subdrain in 64bit
- ex3: contains the file slave.xls to run simulations with a fouled subdrain in 64bit
- files: contains all the executable files for windows 64 bit
- master.xls: is the main program file.

All these files and folders need to be copied in a folder named "mndrain" in C as shown in the figure below.

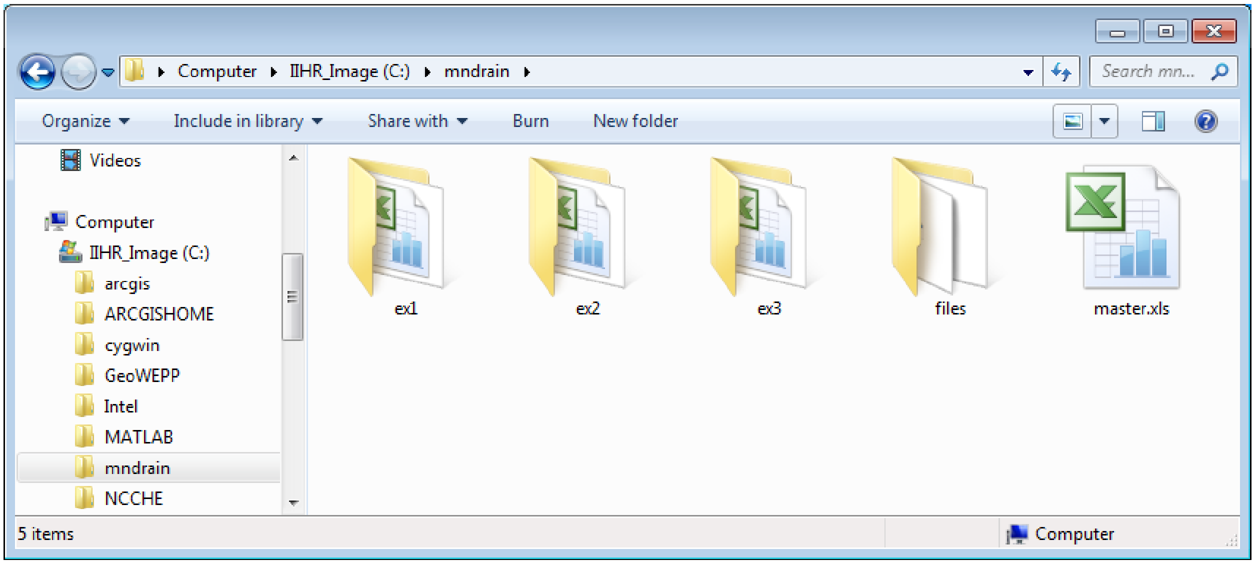


Figure A1. Folder mndrain containing the necessary files to run mndrain for Iowa.

3. Running a new simulation

The instructions reported here are adapted from the official user manual.
To run a new simulation, open the *master.xls* file. In the opened worksheet, specify the type of simulation: (1) drainage with an edgedrain in the subbase; (2) drainage without an edgedrain in the subbase; or (3) drainage with a fouled edge drain in the subbase.

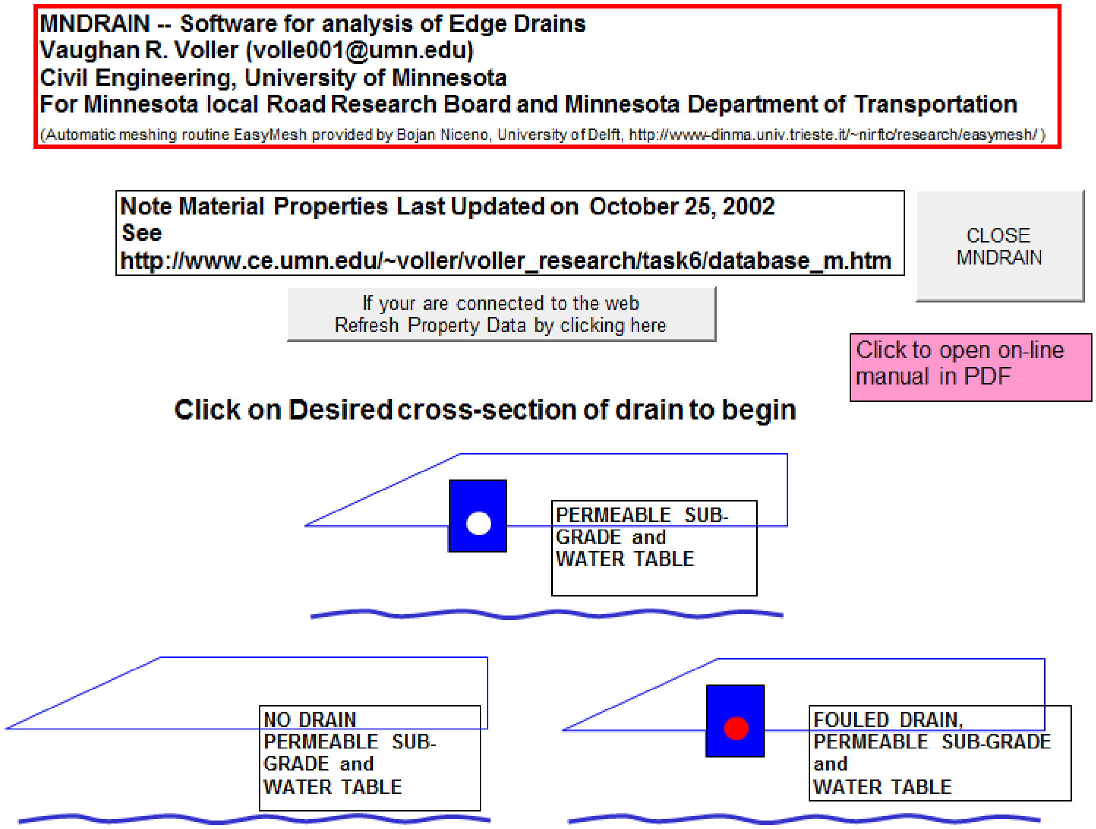


Figure A2. Main worksheet to run MNDRAIN.

Within this worksheet the parameters of the typical soils of Iowa have been included. To view the parameters, under the tab **Developer**, click **View Code** and insert the password mndrain (as specified in http://www.ce.umn.edu/~voller/voller_research/task5/mndrainrequest.html). Right click on **Sheet2 (data)** and click **View Object** (as shown Figure A3 below).

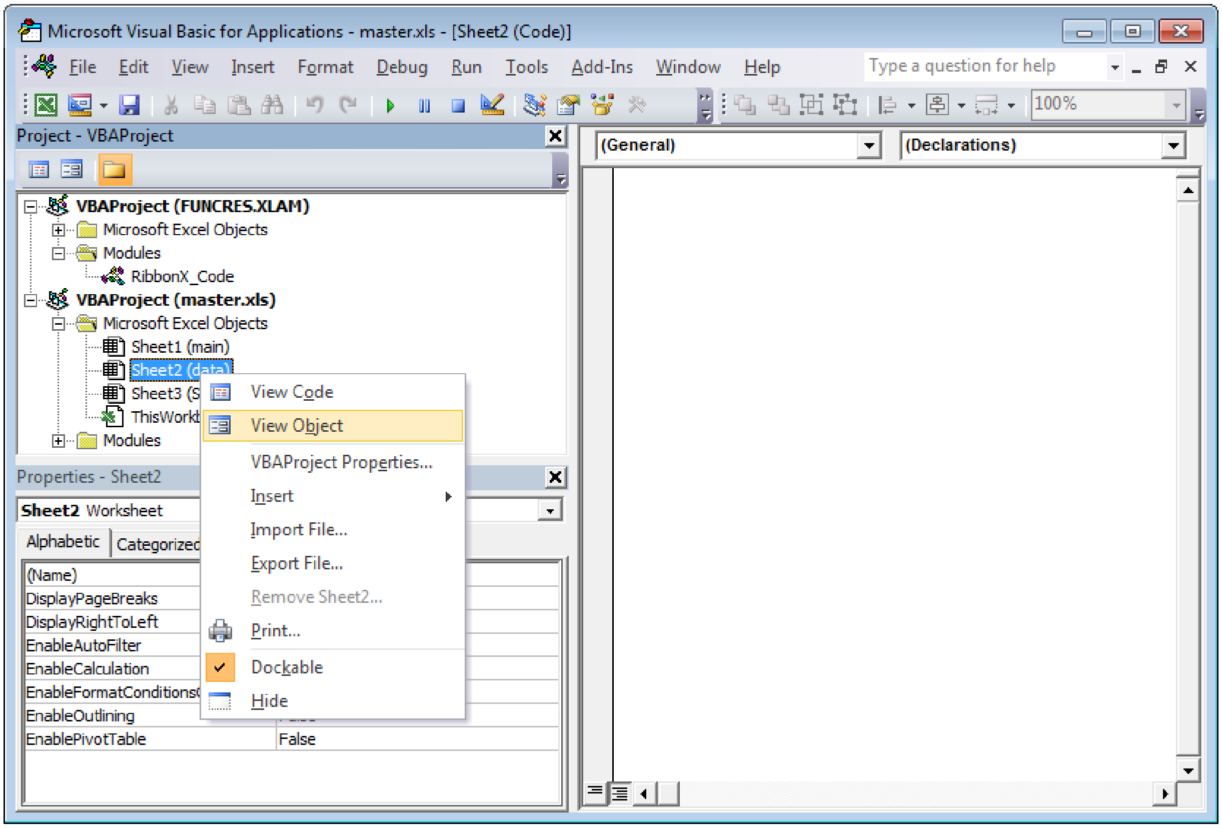


Figure A3. Viewing the parameters for Iowa.

To run a simulation with the typical geometry of a gravel road in Iowa open the NO DRAIN cross-section from the *master.xls* worksheet shown in Figure A2. The *slave.xls* worksheet from the *ex2* folder then opens (Figure A4) and from this worksheet, specify the dimensions of the gravel road cross-section, the type of material for the subbase/ subgrade, and the total simulation time (s).
The available soils and their properties for the subbase are reported in the table below.

Table A1. Soil type and properties available for Iowa in MNDRAIN.

Loamy Sand	0.553	0.437	0.035	-8.690	2.09E-03	6.617
Loamy Fine Sand	0.553	0.437	0.035	-8.690	2.28E-03	6.617
Fine Sandy Loam	0.378	0.453	0.041	-14.660	4.80E-04	8.291
Sandy Loam	0.378	0.453	0.041	-14.660	6.46E-04	8.291
Loam	0.252	0.463	0.027	-11.150	2.13E-04	10.937
Mucky Silt Loam	0.234	0.501	0.015	-20.760	2.22E-03	11.547
Silt Loam	0.234	0.501	0.015	-20.760	2.98E-04	11.547
Clay Loam	0.242	0.464	0.075	-25.890	1.31E-04	11.264
Silty Clay Loam	0.177	0.471	0.040	-32.560	2.29E-04	14.299

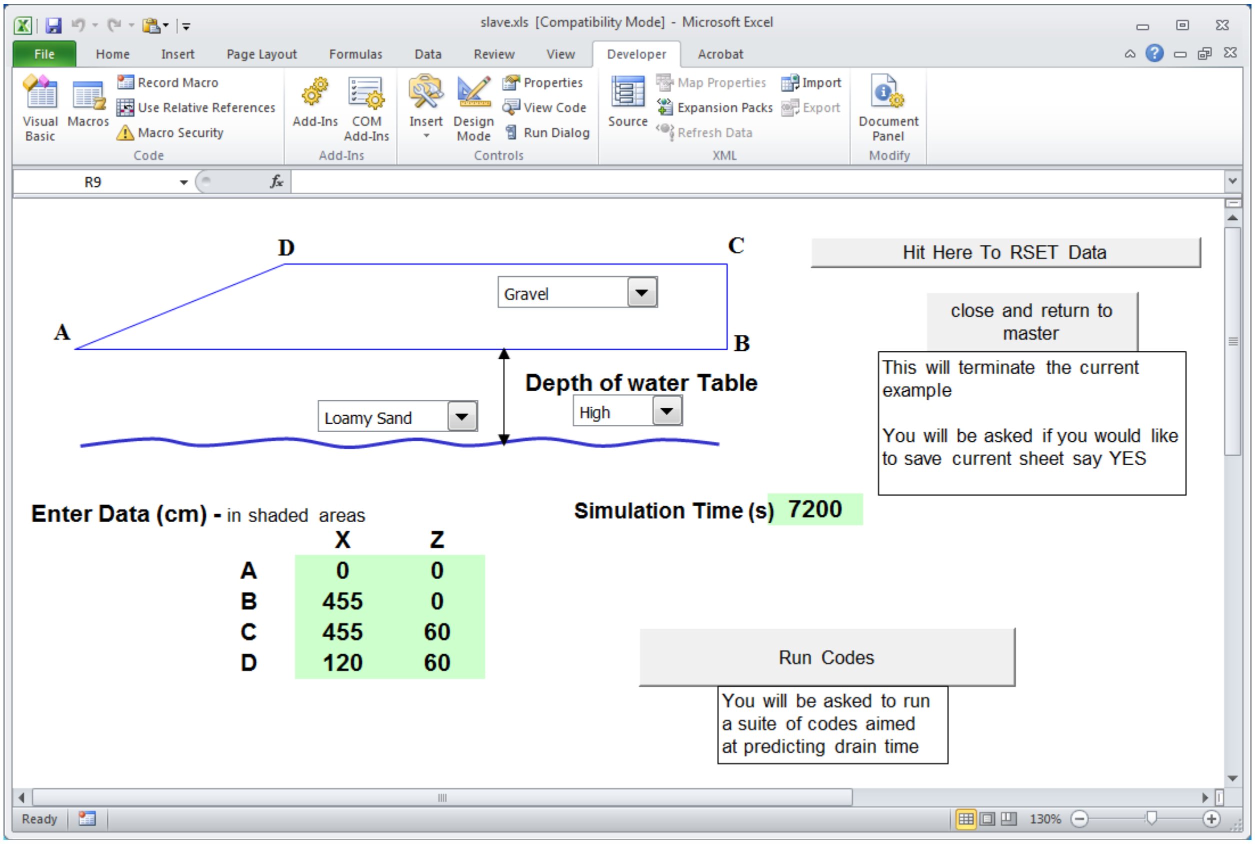


Figure A4. Setting the mesh grid.

After the geometry and the subbase material have been specified, click the “Run Codes” button, which will take the user to the worksheet shown in Figure A5 where the following five steps can be performed.

Step 1. Create Mesh and Drain Input Files

This button will run two programs that create the mesh. Click it, and click OK in the pop-up windows that appears. The mesh may not be generated if the area is too big: the limit of cells is 3700. If the code does not run, reconsider your dimensions. We recommend using the following dimensions: 60cm for the depth of the subbase which a typical value for Iowa; and 455cm for the width of the lane. An image of such a geometry is reported in the Figure A6 below.

Step 2. Click here to see Mesh and Check Geometry

You can visually check the mesh and an example is shown in Figure A6. Click “Return to User” to return to the worksheet and continue with step 3.

Step 3. Run Drainage Program

This button will run the actual drainage program. Click OK in the pop-up windows that appears and a command prompt will open where the program will run. After the program is finished, click Enter to close the command prompt.

Step 4. Look at the Drain Plot
Clicking this button takes the user to the worksheet with the plot of the degree of saturation against time and the numerical results (Figure A7). From this worksheet, the user can either click the button “Return to User” to return to the worksheet with the 5 steps (Figure A5) of click the button “return to Data Input” to return to the worksheet shown in Figure A4 where the user can redefine the geometry or chose a different soil type.

Step 5. Return to Data Input OR close and return to master
This button allows the user to either return to the data input (Figure A4) or to close the worksheet slave.xls and return to the master.xls file and chose a different cross-section.

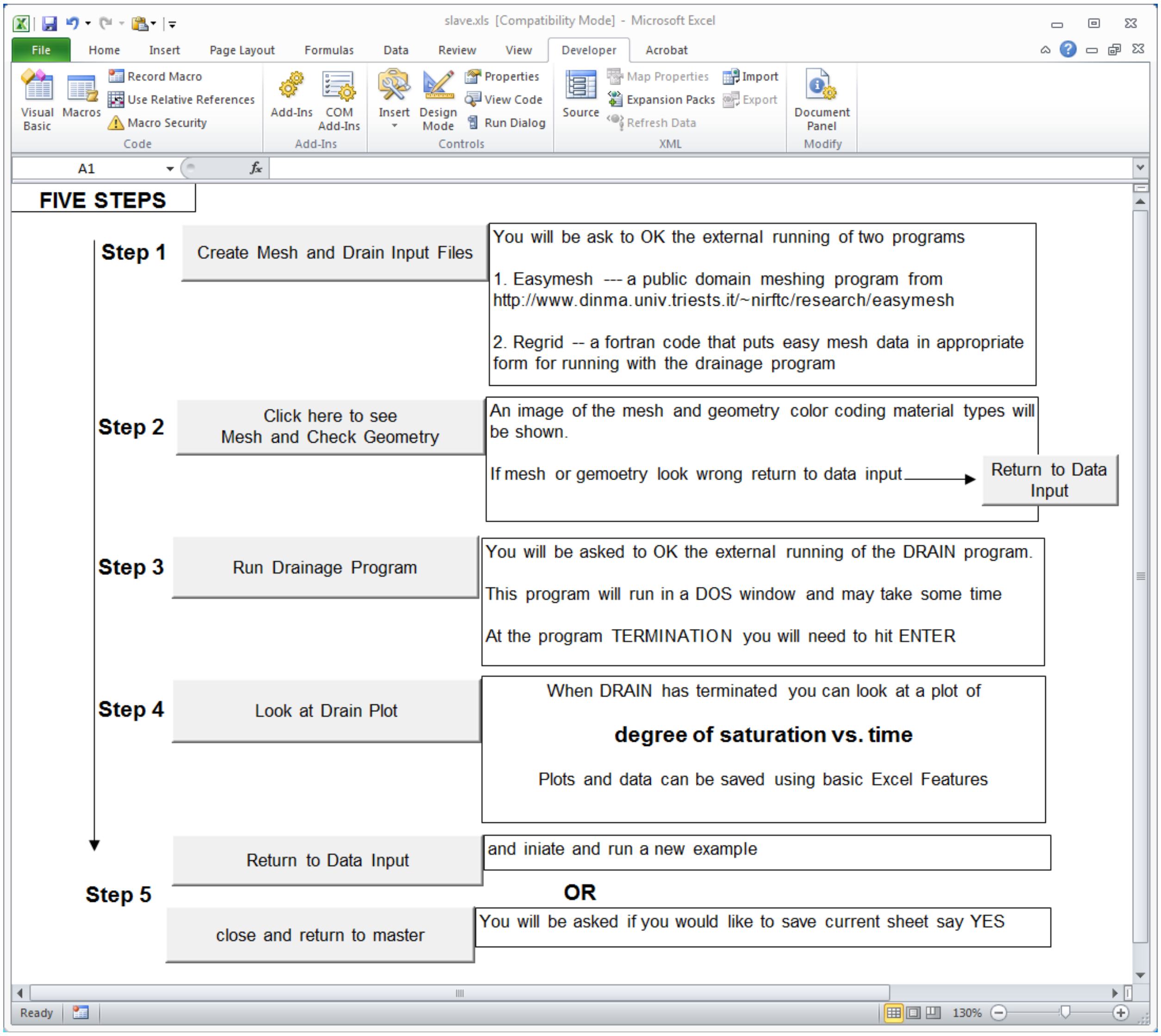


Figure A5. Worksheet to run the 5 steps for a simulation.

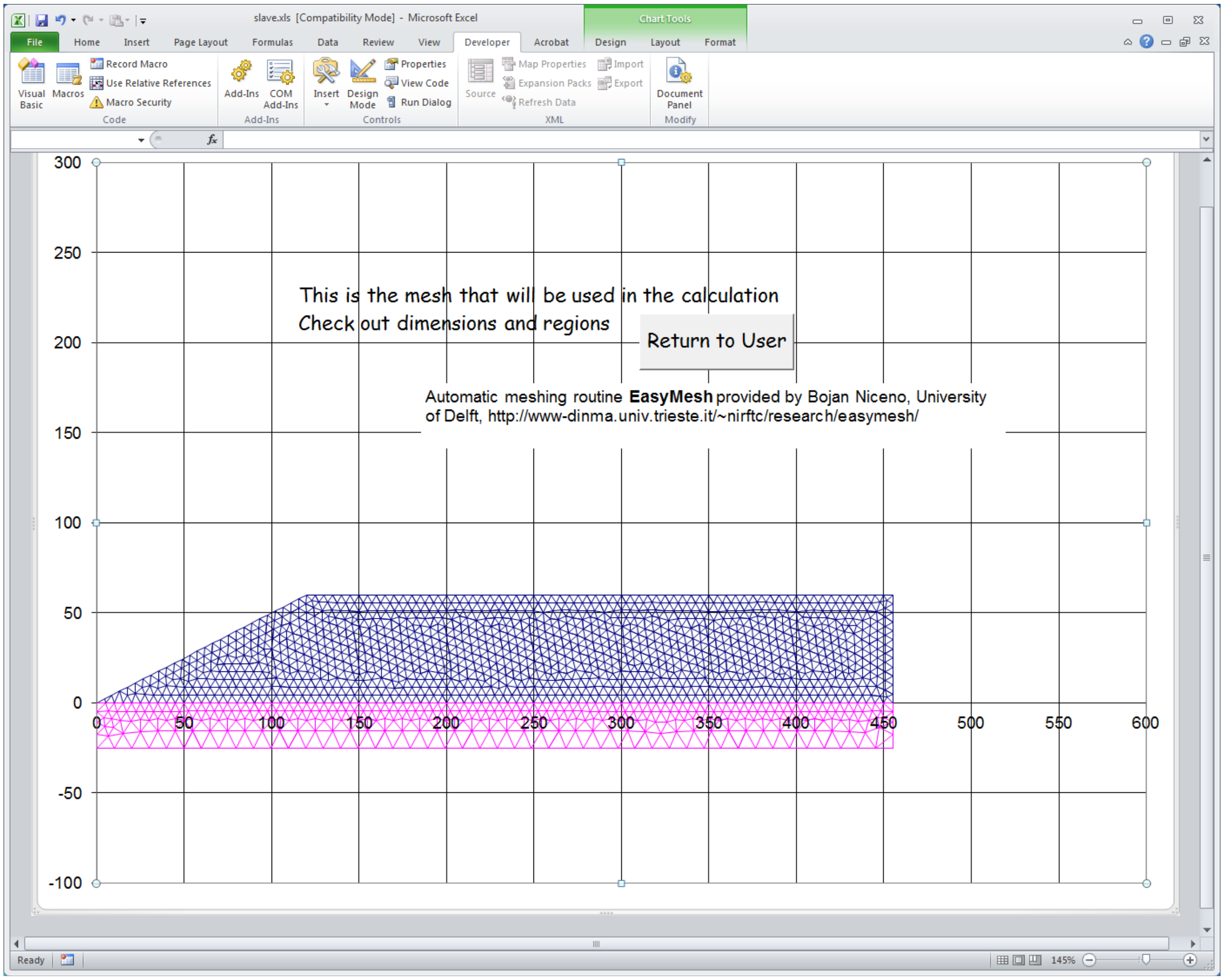
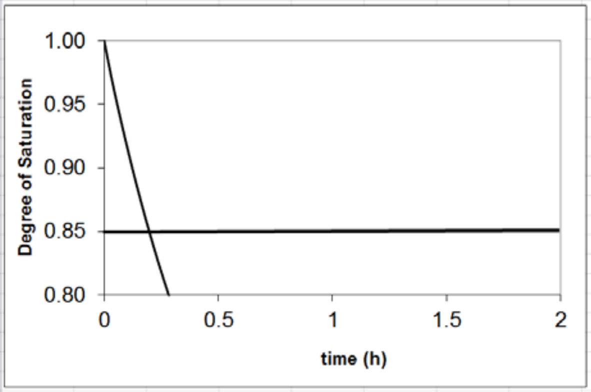


Figure A6. Example of mesh with MNDRAIN.



Return to User

Return to Data Input

	Saturation	cm^2 of moisture in granular base	cm^2 of moisture INTO drain	cm^2 of moisture INTO subbase
0	1.0000	10666.18	0.00	0.00
0.03333	0.9695	10341.26	0.00	324.92
0.06667	0.9423	10050.86	0.00	290.40
0.1	0.9167	9777.27	0.00	273.60
0.13333	0.8925	9519.10	0.00	258.17
0.16667	0.8697	9276.00	0.00	243.10
0.2	0.8482	9046.64	0.00	229.37
0.23333	0.8278	8829.92	0.00	216.72
0.26667	0.8087	8625.34	0.00	204.58
0.3	0.7905	8432.00	0.00	193.34
0.33333	0.7734	8249.26	0.00	182.74
0.36667	0.7572	8076.31	0.00	172.95
0.4	0.7419	7912.87	0.00	163.44
0.43333	0.7273	7757.50	0.00	155.37
0.46667	0.7135	7610.82	0.00	146.68
0.5	0.7005	7471.80	0.00	139.02
0.53333	0.6881	7339.81	0.00	131.99
0.56667	0.6767	7217.56	0.00	122.25
0.6	0.6660	7103.99	0.00	113.57
0.63333	0.6565	7002.76	0.00	101.22
0.66667	0.6484	6915.83	0.00	86.93
0.7	0.6416	6843.37	0.00	72.46
0.73333	0.6369	6792.93	0.00	50.44
0.76667	0.6345	6767.34	0.00	25.58
0.8	0.6327	6748.60	0.00	18.74
0.83333	0.6311	6730.97	0.00	17.63
0.86667	0.6295	6714.00	0.00	16.97
0.9	0.6279	6697.52	0.00	16.48
0.93333	0.6264	6681.48	0.00	16.04
0.96667	0.6249	6665.83	0.00	15.65
1	0.6235	6650.55	0.00	15.27
1.03333	0.6221	6635.64	0.00	14.91
1.06667	0.6208	6621.08	0.00	14.56
1.1	0.6194	6606.87	0.00	14.22

Figure A7. Example of model results: plot and numerical data.