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# The Influence of Bulk Density on the Hydraulic Conductivity and Water Content-Matric Suction Relation of Two Soils

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# THE INFLUENCE OF BULK DENSITY ON THE HYDRAULIC CONDUCTIVITY
# AND WATER CONTENT-MATRIC SUCTION
# RELATION OF TWO SOILS

by

Rafael B. Andrade

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soils and Irrigation

UTAH STATE UNIVERSITY
Logan, Utah

1971

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Rafael Andrade A.

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# LIST OF SYMBOLS

The following symbols are used in the present work.

| | |
|---|---|
| $h$ | Matric suction. Bars |
| $K$ | Hydraulic conductivity. cm $\text{hour}^{-1}$ |
| $Q$ | Volume of water. $\text{cm}^3$ |
| $A$ | Area. $\text{cm}^2$ |
| $t$ | Time. Hours |
| $H$ | Hydraulic head. cm |
| $z$ | Gravitational head. cm |
| $D$ | Soil water diffusivity = $K\ dh/d\theta$. $\text{cm}^2\text{hour}^{-1}$ |
| $L$ | Height of soil. cm |
| $\theta_f$ | Volumetric water content at the end (the equilibrium water content). $\text{cm}^3/\text{cm}^3$ |
| $\theta$ | Fractional volumetric water content at a given time. $\text{cm}^3/\text{cm}^3$ |
| $d\theta/dt$ | Instantaneous outflow rate. $\text{cm}^3/(\text{cm}^3\text{min})$ |
| $dh/d\theta$ | Differential water capacity. $\text{cm}^3/(\text{cm}^3\text{cm})$ |
| $\theta$-$h$ | Water content-matric suction relation |
| $\theta$-$K$ | Water content-hydraulic conductivity relation |
| $\theta$-$D$ | Water content-diffusivity relation |
| $K$-$h$ | hydraulic conductivity-matric suction relation |
| $\rho d$ | Bulk density. $\text{g/cm}^3$ |

# ABSTRACT

The Influence of Bulk Density on the Hydraulic Conductivity
And Water Content-Matric Suction
Relation of Two Soils

by

Rafael B. Andrade, Master of Science

Utah State University, 1971

Major Professor: Ronald J. Hanks
Department: Soils and Meteorology

The influence of bulk density on saturated, unsaturated hydraulic conductivity, diffusivity and water content was measured on undisturbed and disturbed soil samples of Vernal sandy loam and Nibley silty clay loam. Bulk density was changed by artificially compacting the samples.

There was a very large decrease in hydraulic conductivity and diffusivity as water content decreased as has been noted by many others. For the disturbed and compacted samples of the Vernal sandy loam, the water content was higher at .33 and 1.0 bar suction than for the disturbed-uncompacted samples. The same general effect was noted for the undisturbed samples, but differences due to treatment were small. The reverse was true at .05 bars.

In the Nibley silty clay loam samples, water content was higher for the uncompacted than for the compacted samples at all suctions applied. The effect of compaction on unsaturated hydraulic conductivity and diffusivity was not consistent. At the same value of water content, both diffusivity and unsaturated hydraulic conductivity were sometimes higher in the compacted samples, others lower than in the uncompacted.

(57 pages)

# INTRODUCTION

Water transfer in the soil is of prime concern to agriculture as well as to many other interests. In the hydrologic cycle, rain water infiltrates into the soil, some to be used by plants and animals, some to be evaporated and returned to the atmosphere, some to be stored in the soil and some to slowly trickle through the profile to supply streams, rivers, and underground aquifers. All these processes are strongly dependent on the movement of water in the soil system. The term hydraulic conductivity (K), defined as the volume flux of water resulting from unit gradient in hydraulic potential, is thus a measure of the relative ease with which water moves in the soil. The hydraulic conductivity of a soil will usually be influenced by a change in any soil property, particularly by change in soil water content ($\theta$).

When water flow is steady, often the case for saturated flow, water flow can be described by means of Darcy's law. However, when the soil is not saturated and flow is not steady, as in the case of many problems having agricultural importance, Darcy's law is not sufficient. Unsaturated flow requires a knowledge of not only the hydraulic conductivity ($\theta$-K), but also the water content-matric suction ($\theta$-h) relation as well as initial and boundary conditions. The soil water diffusivity (D) combines these two terms.

In steady flow the water content does not change with time. For unsteady flow, soil water content may change with time which will result in change in hydraulic conductivity, matric suction and diffusivity. Water flow in a particular situation can be predicted from a knowledge of the $\theta$-K and $\theta$-h (thus $\theta$-D) relations of soil provided the appropriate boundary conditions are imposed as described by Hanks et al. (1969).

Measurements of $\theta$-K and the $\theta$-h relation has been reported by many investigators. There is relatively little information about the effect of changes in soil properties such as bulk density on these relations. This is the purpose of this study.

### Objectives

1. To measure the influence of changes in bulk density on the hydraulic conductivity-water content, diffusivity-water content, and matric suction-water content relation for two soils. These measurements include disturbed and undisturbed soil samples.

## REVIEW OF LITERATURE

This thesis is an attempt to determine the effect of one aspect of soil structure (defined as the arrangement of the solid particles in the soil profile) on soil water properties. Any process which alters the arrangement of the ultimate particles of the soils will alter its structure and thus probably influence soil water flow as discussed by Low (1954). This study is limited to the investigation of one aspect of soil structure change, bulk density, on soil water properties.

### Bulk density

A soil property that is of great importance is the bulk density, which is not an invariant quantity for a given soil. It varies with structure conditions of the soil, particularly those that relate to packing. For this reason, it is often used as a measure of soil structure. Bulk density changes associated with shrinking and swelling have been observed for many years. Changing moisture content is generally associated with bulk density changes. Box (1961) experimentally demonstrated that soil bulk density changes influence the moisture retention in soils.

### Water content and suction

The relationship of water content and matric suction have been widely studied. Rose (1966) pointed out that the relationship between water content and matric or suction is not unique and depends on hysteresis (the previous hystory of water adsorption or desorption).

Nevertheless, such relationships are of great significance and utility, even though they may be fairly complicated.

The application of a suction will extract water from saturated soil, more water being withdrawn as the suction is increased. Consequently, the greater the magnitude of the applied suction, the lower will be the water content of the soil at equilibrium. Thus, as the suction is increased, the remaining water is reduced and it is situated in effectively smaller pores. The pore space may be pictured as irregularly shaped voids and channels covering a wide range of sizes. It is a particular feature of such porous systems that causes the equilibrium water content at any suction to depend on whether the system is drying or wetting, a phenomenon referred to as hysteresis. Thus, for any given matric suction, the water content of a soil will be greater on drying (desorption) than on wetting (absorption). The relationship between soil water content and soil matric suction have been extensively studied in a pressure plate apparatus whose construction and use were given by Richard and Fireman (1943), Richards (1947) and Reginato and Van Bavel (1962).

It is commonly assumed that bulk density remains constant, or that bulk density changes do not influence the soil matric suction-water content relation, Taylor (1962). Lauritzen and Stewart (1942) showed that an increase in bulk density at a given suction caused a decreased water content. It was also shown that bulk density changes were greatest through the middle section of the moisture range obtained, and that bulk density decreased gradually with both increasing and decreasing water content. Hirst (1949) suggested that the observed phenomenon of hysteresis may be explained in part by changes in bulk density resulting from wetting and drying.

Box and Taylor (1962) demonstrated that the matric suction-soil water relation depend on soil bulk density. The matric suction increased with bulk density at all water contents (by volume or weight). They concluded that to clearly understand the expression used for matric suction, it is necessary to include a variable for the influence of changing bulk density.

Bulk density can be modified by either disturbance or compaction. Croney and Coleman (1954) obtained curves in compressible soils compacted to different initial dry densities, which were dried from saturation. In such soils increasing the dry density modified the pore size distribution and caused: a) a decrease in the amount of water held at low suctions, b) an increase in the air entry value, c) an increase in the amount of water held at high suctions. They concluded that compacting the soils has the effect of partially closing the hysteresis loop between the wetting and drying curves.

Recently, Hill and Sumner (1967) reported that in most soils in the plant available water range, moderate compaction resulted in an increase in water content at constant matric suction. However, severe compaction which was readily achieved in sandy loams resulted in a decrease in water content at constant matric suction. This effect was noticeable at high soil water contents. They suggested that differences in void geometry and distribution between soil types accounted for the varied effect of bulk density changes on the matric suction-water content relation.

## Hydraulic conductivity

The movement of fluids through capillary tubes was first studied by Poiseville (1846) who found that the rate of flow is proportional to the hydraulic gradient. Darcy (1856) on the basis of investigations on the flow of water through filter sands verified this observation and suggested its application to problems of water movement through water bearing material.

According to Gardner (1950) when the soil is saturated with water, the flow can be described by means of Darcy's law, however, when the soil is not saturated, as in the case of many problems having agricultural significance, Darcy's law in this simple form is not sufficient to describe the flow. Gardner, and many other, have shown that the hydraulic conductivity decreased rapidly as the water content decreased. Childs (1957) stated that the hydraulic conductivity is very sharply reduced in the first stages of reduction of moisture content. He attributed this reduction to four separated effects. Firstly, a reduction of moisture content reduces the effective porosity. Secondly, since a reduction of moisture content is brought about by an increase of suction and the largest pores are emptied of water at the lowest suctions, (i.e. before the smaller), the more effectively conducting pores are put out of action in the earlier stages of unsaturation. Thirdly, the pores which have been emptied have to be avoided by the remaining path of flow which, therefore, becomes more tortuous as water removal proceeds. Fourthly, in soils which shrink, the increase of suction which causes the removal of water from pores also reduces the size of the pores which remain full.

Philip (1957) also pointed out that as the soil water content decreased the hydraulic conductivity decreased very rapidly. This is because the larger pores are emptied first, greatly decreasing the cross section available for the liquid flow. Amenima (1960), working over a suction range of .2 to 12 bars by using the pressure plate outflow technique, found that when water content-matric suction relations were essentially unaffected by aggregate size, hydraulic conductivity was a function of volumetric water content. However, if water content-matric suction relations were affected by aggregate size, then at any given water content, conductivity values for a given aggregate size were inversely related to the suction corresponding to said water content.

### Soil water diffusivity

Where water flow in soils is characterized by changing water content, hydraulic conductivity is not sufficient to characterize flow. The θ-K relation and the θ-h relation must be known. Soil water diffusivity combines both of these properties.

The diffusivity is not constant but depends on the soil properties and is strongly dependent on the water content. Bruce and Klute (1956) found that there may be a maximum in the θ-D at a water content less than saturation. Stephen and Gardner (1963), reviewing the derivation of the diffusivity equation for unsaturated flow of liquids in porous material, pointed out that diffusivity (D) is not a unique function of water content (θ). Failure of D to be unique implies that either the suction function θ-h or the hydraulic conductivity function θ-K or both are not unique. This may occur because of hysteresis or changes in soil properties with time. Hanks and Bower (1963) showed that infiltration was governed to a large extent by the soil water properties near saturation and was little influenced by soil water properties at drier water contents. Infiltration can be greatly influenced by a change in the $\theta$-K or $\theta$-D, especially at high water contents.

Hanks, Green and Larson (1964), used a numerical method to estimate field infiltration. They found that the water flow theory may be used in combination with limited field measurements to provide estimates of infiltration for simulated conditions that are of practical interest but which are difficult to measure in the field. The method shows promise as a means of accounting for water effects in comparative studies involving field measurements of infiltration under different management conditions. This method has been expanded to include many types of flow by Hanks et al. (1969).

# MATERIALS AND METHODS

## Soil samples

Undisturbed and disturbed samples were taken at a depth of 12 inches from two different kinds of soils, Nibley silty clay loam and Vernal sandy loam, whose particle size distribution is given in Table 1.

Table 1. Particle size distribution of Nibley silty clay loam and Vernal sandy loam

| | Depth inches | Horizon | % sand | % silt | % clay |
|---|---|---|---|---|---|
| Nibley silty clay loam | 7-11 | $A_{12}$ | 3.9 | 59.3 | 36.8 |
| | 11-19 | $B_{12}$ | 3.5 | 59.6 | 36.9 |
| Vernal sandy loam | 0-12 | | 56 | 30 | 14 |
| | 12-24 | | 48 | 29 | 23 |

Vernal sandy loam. This sample was collected from the Utah State University Drainage Farm (Hullinger) at Vernal, Utah. This farm is located just west of the Vernal Airport, 1.5 miles south and 0.6 miles east of the Vernal City Center. This soil has not been classified yet, thus the name is not official and is used for convenience only.

Nibley silty clay loam. This sample was collected from the Utah State University South Farm located between Logan and Hyrum. This soil has been classified but not published yet.[1] The information is available at Utah State University Soils and Meteorology Department.

## Treatments

Undisturbed samples. Relatively undisturbed samples were obtained in the field in a metal cylinder that fit into the sampling tube described in the U.S.D.A. Handbook 60 (1954). The dimensions of the cylinders used were 3.5 cm high by 5 cm inside diameter. After the samples were taken the cylinders served as the soil retainers in the conductivity determinations.

Disturbed samples. Samples were collected from the field, air dried and sieved through a 2 mm sieve. A cylinder of the same dimension used to take undisturbed samples was filled with the soil for subsequent analysis.

Compacted samples. Undisturbed samples were submitted to a mechanical pressure of 908 $gm/cm^2$, by setting a weight of 18.160 kg on the soil core contained in the cylinder of 19.6 $cm^2$ area. The compaction of disturbed samples was obtained by partially filling the cylinder with soil, compacting slightly, refilling and compacting successively until the top of the cylinder was reached.

## Unsaturated hydraulic conductivity and diffusivity

Several methods were described for the measurement of the soil water diffusivity. Gardner (1956) proposed a method for calculating diffusivity from pressure plate outflow data. Subsequently, Miller and

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[1] A. Southard, Private Communication. Department of Soils and Meteorology, Utah State University (December 1970).

and Elrick (1958) refined Gardner's method by accounting for non-negligible membrane impedance. Rijtema (1959) added a variation to Miller and Elrick's method, determining the total membrane impedance from the experimental outflow data for each pressure step applied. Jackson et al. (1963) claimed that experimentally the outflow method appears readily adaptable to routine laboratory measurements. This method would seem to be ideally suited for obtaining diffusivity on undisturbed soil cores. Data from Butijn and Wesseling (1959) and Kunze and Kirkham (1962) indicates, however, that the results obtained by this method may not be quantitatively acceptable.

Doering (1965) developed a practical modification to Gardner's method for determining the diffusivity where only one equilibration is required for a given range of water content. The assumption of constant diffusivity over a range of water content is not needed to use this method. This method was used in the present study.

The diffusivity was computed from:

$$D = -\frac{4L^2}{\pi^2(\theta - \theta_f)} \times \frac{d\theta}{dt}$$

The hydraulic conductivity was calculated from:

$$K = -\frac{D}{dh/d\theta}$$

Figure 1 shows the apparatus used.

Before pressure was applied, the sample was wet up for at least 24 hours on the ceramic plate. A very small pressure of 0.05 bar was applied to the chamber to cause the excess of water to be removed and to reach an equilibrium water content. Equilibrium was considered to have

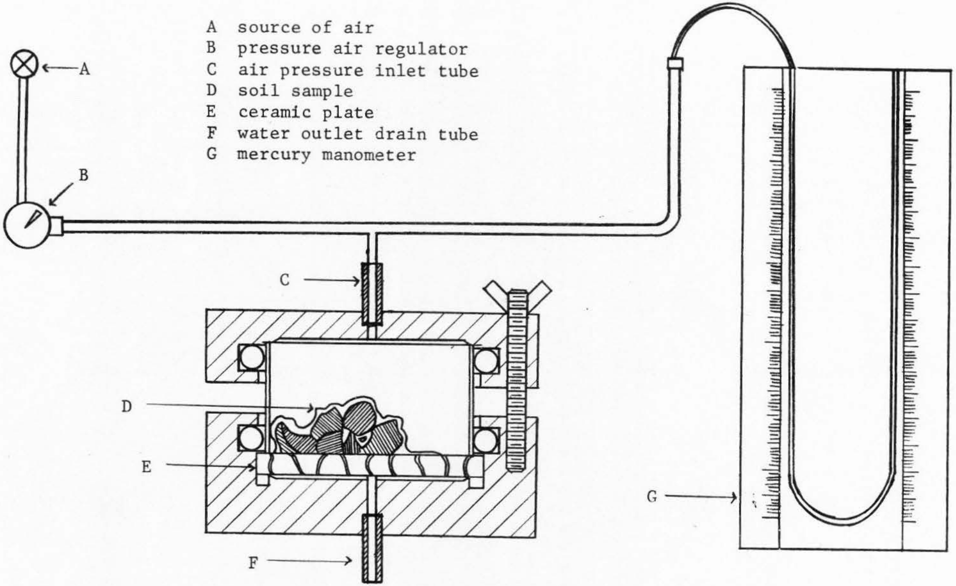


Figure 1. Diagram of equipment used to measure unsaturated hydraulic conductivity and diffusivity.

reached when the outflow from the plates had ceased for at least a period of 3 hours. All soils were subjected to a subsequent matric suction of .33 and 1.0 bar. In this way the influence of bulk density on the matric-water content relation could be studied in all the soils. A scaled buret was used to measure the outflow as a function of time. After equilibrium at 1.0 bar had been established, the samples were removed from the pressure plate apparatus. The moisture content by weight was determined by the oven dry method.

Sample calculation. The following example shows the calculations of unsaturated K and D based on the Doering's (1965) one-step method. The data from replication No. 1 of Vernal sandy loam undisturbed uncompacted sample.

Table 2. Data collected from Vernal sandy loam undisturbed uncompacted. Replication No. 1

| $\theta$ | .33 | .32 | .31 | .30 | .29 | .28 | .27 | .26 | .25 | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\theta - \theta_f$ | .11 | .10 | .09 | .08 | .07 | .06 | .05 | .04 | .03 | $\theta_f = .22$ |
| $d\theta/dt \times 10^{-2}$ from Fig 2 | -.33 | -.16 | -.083 | -.044 | -.025 | -.017 | -.013 | -.0095 | -.053 | $L = 3.5$ |
| $dh/d\theta$ from Fig 3 | -150 | -200 | -275 | -350 | -400 | -450 | -525 | -750 | -987 | |

$$D_1 = \frac{-4L^2}{\pi^2(\theta-\theta_f)} \times \frac{d\theta}{dt} = \frac{-49}{(3.14)^2(.11)} \times (-.33\times10^{-2}\ \frac{cm^3}{cm^3 min} \times \frac{60\ min}{hour}) = 8.94\ cm^2hr^{-1}$$

$$K_1 = -\frac{D_1}{dh/d\theta} = -\frac{8.94\ cm^2hour^{-1}}{-150\ cm} = .059\ cm\ hour^{-1}$$

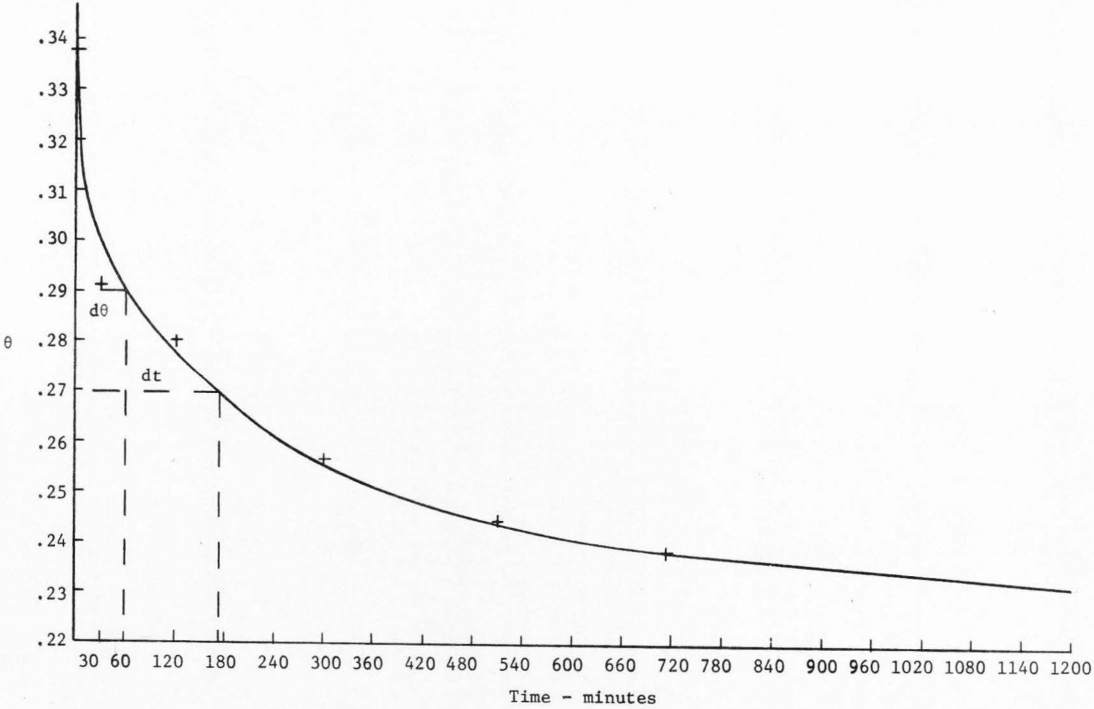


Figure 2. θ vs. t. Vernal sandy loam, undisturbed uncompacted sample.

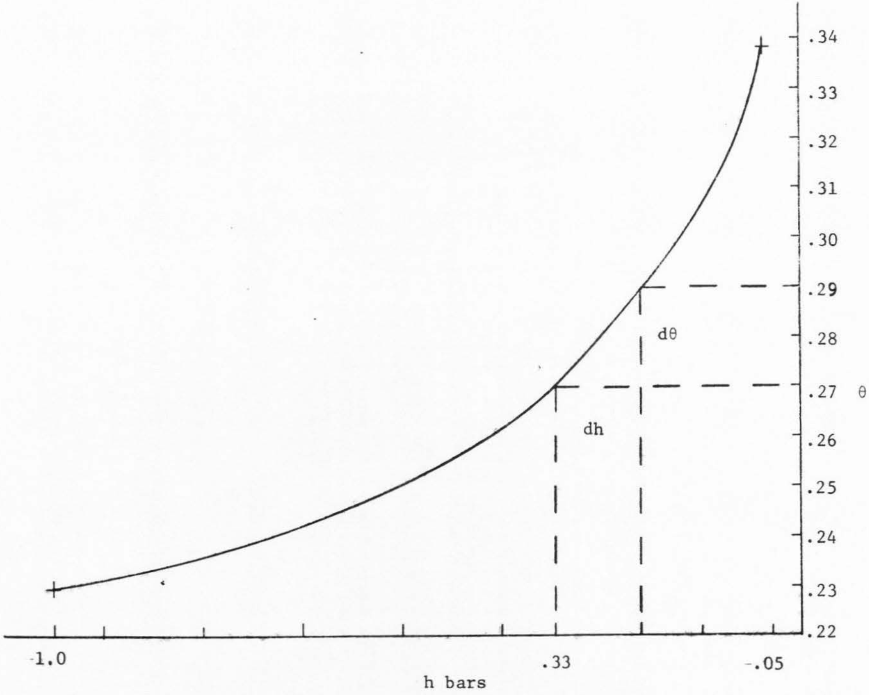


Figure 3. θ vs. h. Vernal sandy loam, undisturbed uncompacted sample.

$$D_2 = \frac{-49}{(3.14)^2(.10)} \times \left(-.16\times10^{-2}\ \frac{\text{cm}^3}{\text{cm}^3\,\text{min}} \times \frac{60\ \text{min}}{\text{hour}}\right) = 4.74\ \text{cm}^2\text{hour}^{-1}$$

$$K_2 = \frac{-4.74\ \text{cm}^2\text{hour}^{-1}}{-200\ \text{cm}} = .023\ \text{cm hour}^{-1}$$

⋮

$$D_9 = \frac{-49}{(3.14)^2(.03)} \times \left(-.053\times10^{-3}\ \frac{\text{cm}^3}{\text{cm}^3\,\text{min}} \times \frac{60\ \text{min}}{\text{hour}}\right) = .52\ \text{cm}^2\text{hour}^{-1}$$

$$K_9 = \frac{-.52\ \text{cm}^2\text{hour}^{-1}}{-987\ \text{cm}} = .53\times10^{-3}\ \text{cm hour}^{-1}$$

The values obtained for the three applications at each specific water content were plotted in a semilogarithmic paper, assuming a smooth curve; then the average of the three curves was taken. The value of $d\theta/dt$, which had a large influence in the values of D obtained, tended to decrease with time. Since it is necessary to estimate graphically the slope of the rapidly changing curve, large errors were possible, especially at low values of $d\theta/dt$ and where $\theta - \theta_f$ was small. This fact makes the method somewhat inaccurate because the computed values are highly dependent on the measurements that may have considerable inherent errors.

Saturated hydraulic conductivity

The hydraulic conductivity at saturation was determined following the method described by Klute (1965).

The soil samples were retained in a metal cylinder 5 cm diameter and 3.5 cm height, so that one dimensional flow could be obtained. The apparatus used for measurement of conductivity of saturated samples by the constant head method is shown in Figure 4 in cross section. One end of each sample was covered with a circular piece of cloth held in place by a rubber band. The sample, cloth-covered end down, was then placed in a tray filled with water to a depth just below the top of the samples and allowed to soak until completely saturated. The samples were then transferred to the rack. Flow was started by using a siphon to maintain a constant head of water over the sample. After the water level on top of the sample became stabilized, the volume of water that passed through the sample was measured each hour until a constant flow was obtained for each time interval.

Sample calculation. Based on the diagram shown in Figure 4, the saturated hydraulic conductivity is computed from Darcy's law in one replication of Vernal sandy loam undisturbed uncompacted sample.

$$K = - \frac{Q}{At\ \Delta H/\Delta z}$$

$Q_1 = 32\ cm^3$

$Q_2 = 28\ cm^3$

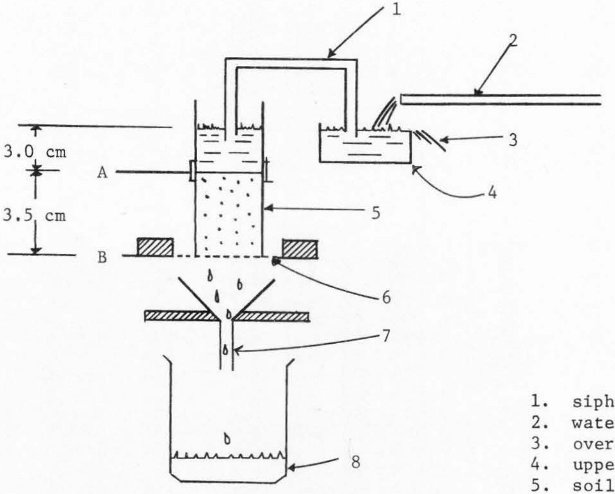
$Q_3 = 26\ cm^3$

$Q_4 = 26\ cm^3$

$Q_5 = 26\ cm^3$

$r = 2.5\ cm$

$h = 3.5\ cm$



1. siphon
2. water supply
3. overflow
4. upper trough
5. soil sample
6. wire screen support
7. funnel
8. beaker with percolate

Figure 4. Diagram of equipment used to measure saturated hydraulic conductivity.

$A = 19.6\ \text{cm}^2$

$t = 1$ hour

$\Delta H = H_A - H_B = +3.0 + 3.5 = 6.5$

$\Delta z = z_A - z_B = 0 - (-3.5) = 3.5$

$$\frac{\Delta H}{\Delta z} = 1.85$$

$$K_1 = -\frac{(-32)}{19.6 \times 1} \times \frac{1}{1.85} = .882\ \text{cm hour}^{-1}$$

$K_2 = .772$

$K_3 = .717$

$K_4 = .717$

$K_5 = .717$

## RESULTS AND CONCLUSIONS

### Water characteristic curves

The computation of θ-K from measurements of θ-D curves requires curves of θ-h. Figure 5 (Table 3 in Appendix) gives the θ-h data for all the treated samples.

Vernal sandy loam. All of the treatments show the same general trend that the water content is highest where no compaction occurred at .05 bar, whereas the reverse is true at .33 and 1.0 bar.

Undisturbed samples. The compaction treatment caused the same general effect as above but the difference due to treatment was small.

Disturbed samples. Compaction had a more marked effect on the disturbed than on the undisturbed samples. The water content was about .04 greater in the compacted samples than the uncompacted samples. However, at .05 bar suction the difference of about .05, was reversed. This is in agreement with the results reported by Croney and Coleman (1954). This indicates that the effect of compaction is to decrease the large pores and increase the small pores.

Nibley silty clay loam. There was no general trend for all treatments for this soil.

Undisturbed samples. It is not possible to make a comparison between undisturbed compacted and uncompacted samples because there was no outflow from the compacted samples. This may be attributed to the higher water content of the samples at the time of compaction. Thus, the water content was constant as matric suction varied from .05 to 1.0 bar. The samples were apparently compacted so much that all of the pores

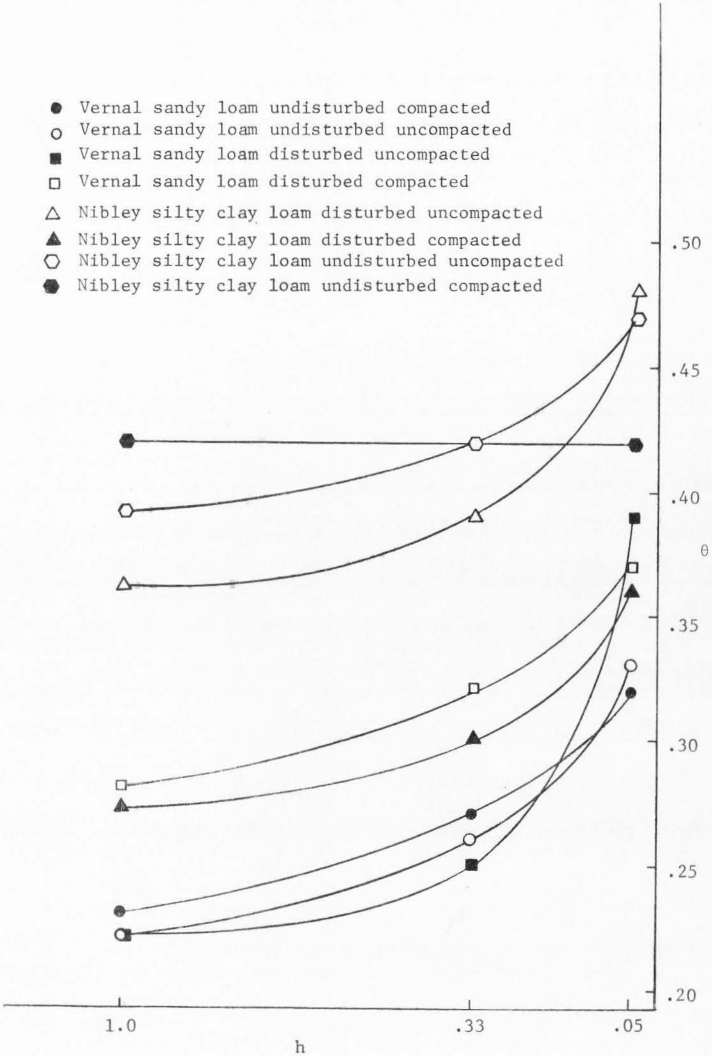


Figure 5. Water characteristic curves.

were made sufficiently small that no water was removed up to 1.0 bar suction. In Figure 5 the θ-h relation for these compacted samples is represented by a horizontal line.

Disturbed samples. The water content of the uncompacted samples was greater than the compacted samples at all suctions applied. Thus, compaction for these samples caused a decrease in large and relatively small pores. The difference in the water content was greatest at the lowest suction.

The difference in the behavior of these two soils can probably be attributed to the different particle size distribution which affected the void geometry and distribution as suggested by Hill and Sumner (1967).

## Unsaturated hydraulic conductivity and diffusivity

All the samples showed a large decrease in both conductivity and diffusivity as water content decreased. This is in agreement with other reports, Gardner (1956) and Philip (1957).

Vernal sandy loam. In most cases, but not all, K was higher at a given water content for the compacted compared to the uncompacted samples.

Undisturbed samples. Figures 6 and 8 (Tables 4 and 5 in Appendix) show the values obtained for hydraulic conductivity and diffusivity for both uncompacted and compacted samples. The uncompacted samples had a wider range of water content than the compacted samples for the same range of suction. The values of K and D at the same water content were higher for the compacted samples than for the uncompacted samples.

Disturbed samples. Figures 7 and 8 (Tables 6 and 7 in Appendix) show that the unsaturated values of K and D are greater for the

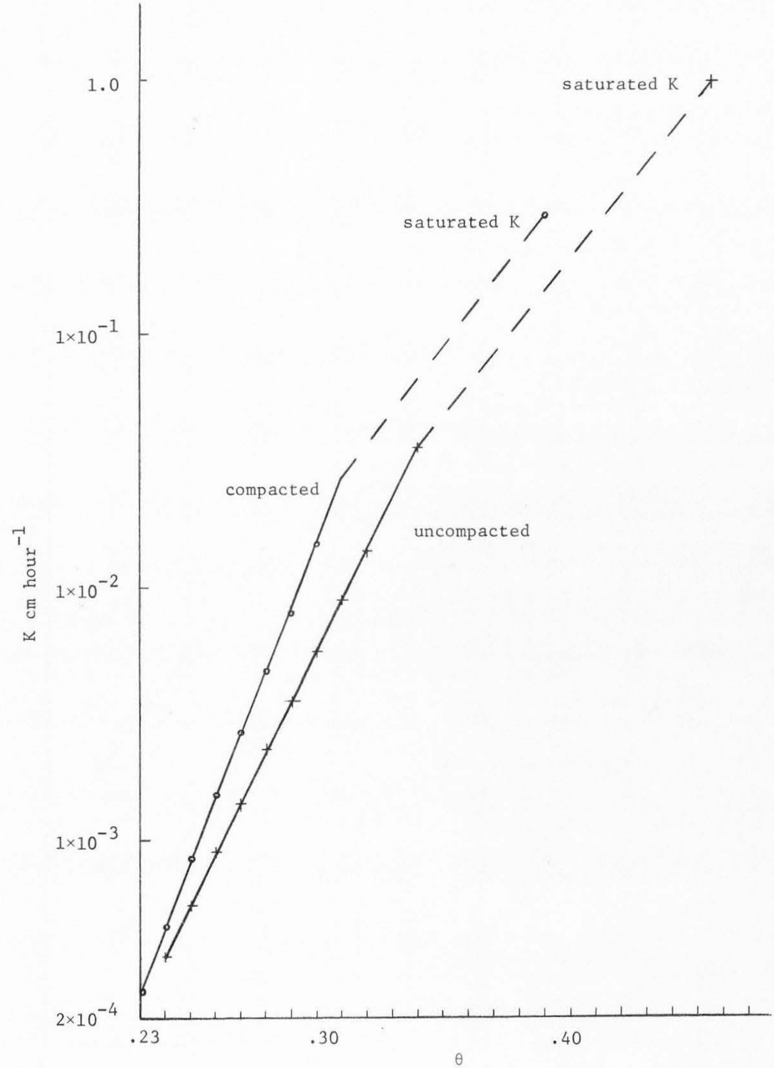


Table 6. Vernal sandy loam undisturbed samples. Average K.

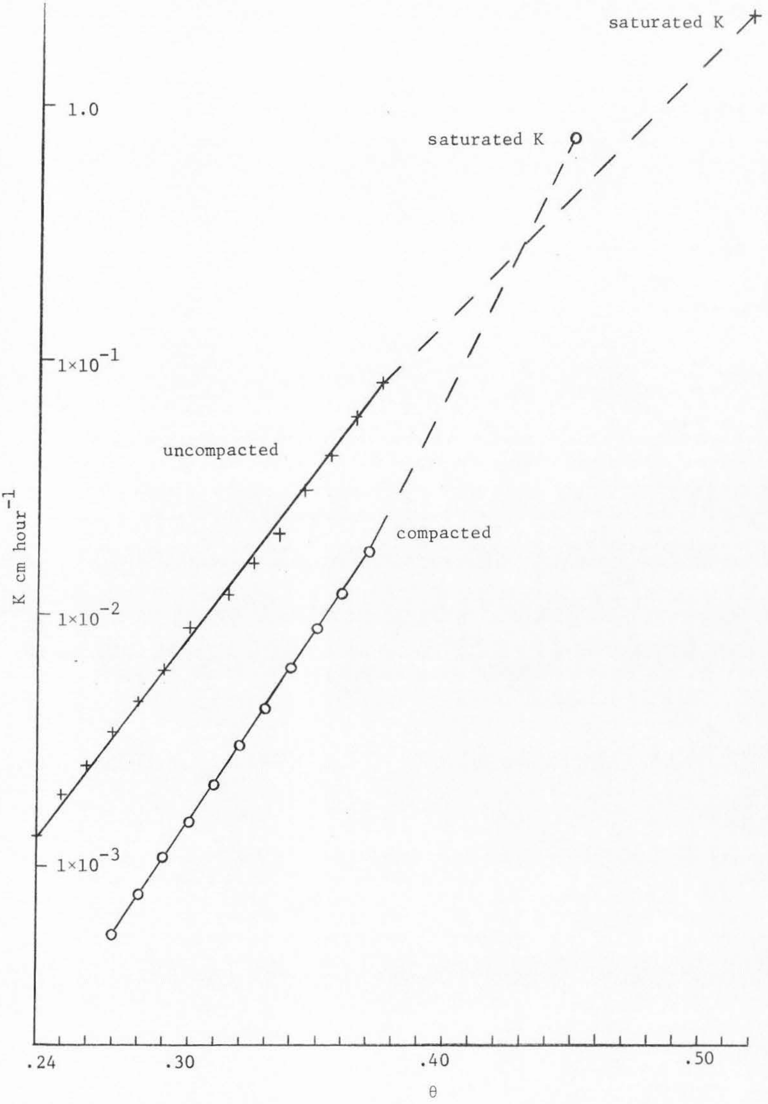


Figure 7. Vernal sandy loam disturbed samples. Average K.

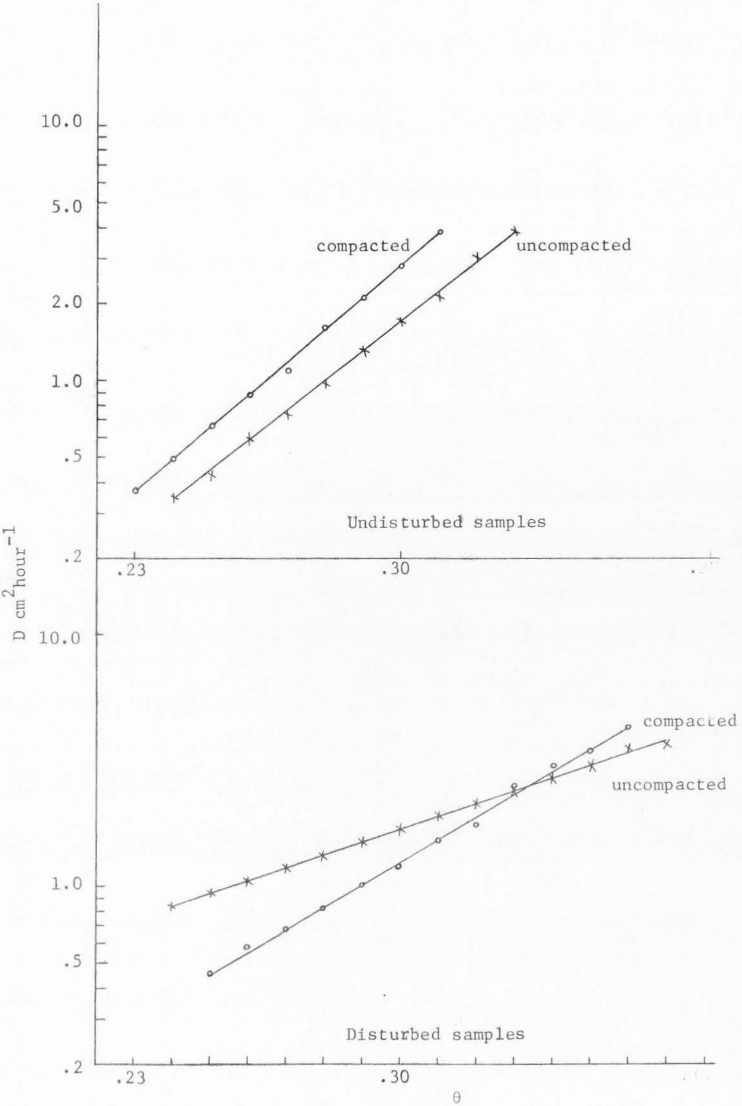


Figure 8. Vernal sandy loam. Average diffusivity.

uncompacted samples than for the compacted samples at the same water content. This difference was about 50 percent for K, and about 30 percent for D.

The values of K and D for the disturbed samples at a given water content also were greater than those for the undisturbed samples. This is possibly due to the effect of drying the large pores which confer high conductivity and are the continuous fissures which, when emptied, constitute effective barriers to flow from one aggregate to its neighbors. Also, the behavior of these samples may be attributed to a reduction in the effective porosity as the water content is reduced. This is in agreement with Childs (1957).

*Nibley silty clay loam*. Other than the expected large decrease in K and D as $\theta$ decreased, there are no general trends evident for this soil.

Undisturbed samples. Since it was not possible to accomplish this part of the experiment entirely (compacted undisturbed samples) the values obtained for the uncompacted samples only are given in Figures 9 and 10 (Table 8 in the Appendix). Since there was no outflow at a suction up to 1.0 bar, the conductivity would be the same as the saturated conductivity (essentially zero) indicated in Figure 9 as an arrow going down.

Disturbed samples. Figures 9 and 10 (Table 9 and 10 in Appendix) show that there are few water contents common to both compacted and uncompacted samples. Extrapolation of the data indicates that K would be greater for the compacted samples than for the uncompacted samples. This tendency holds for all the values of water content. Here the D curves differ slightly from K. Although D (compacted) was greater at

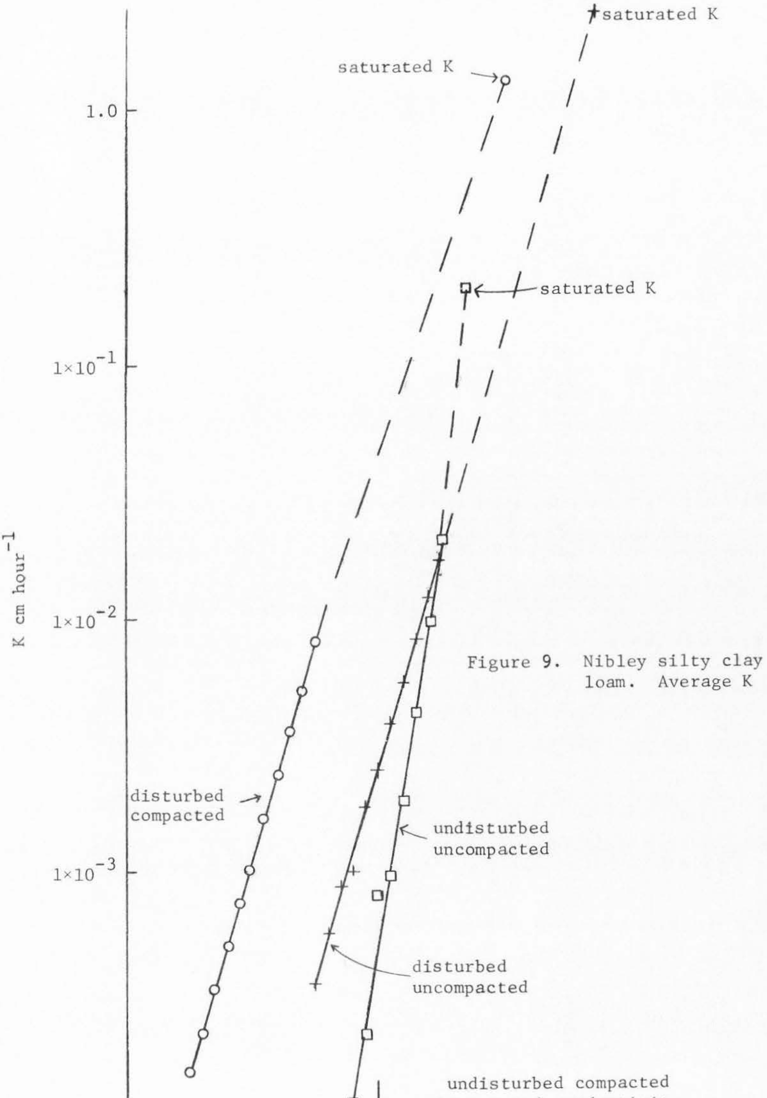


Figure 9. Nibley silty clay loam. Average K

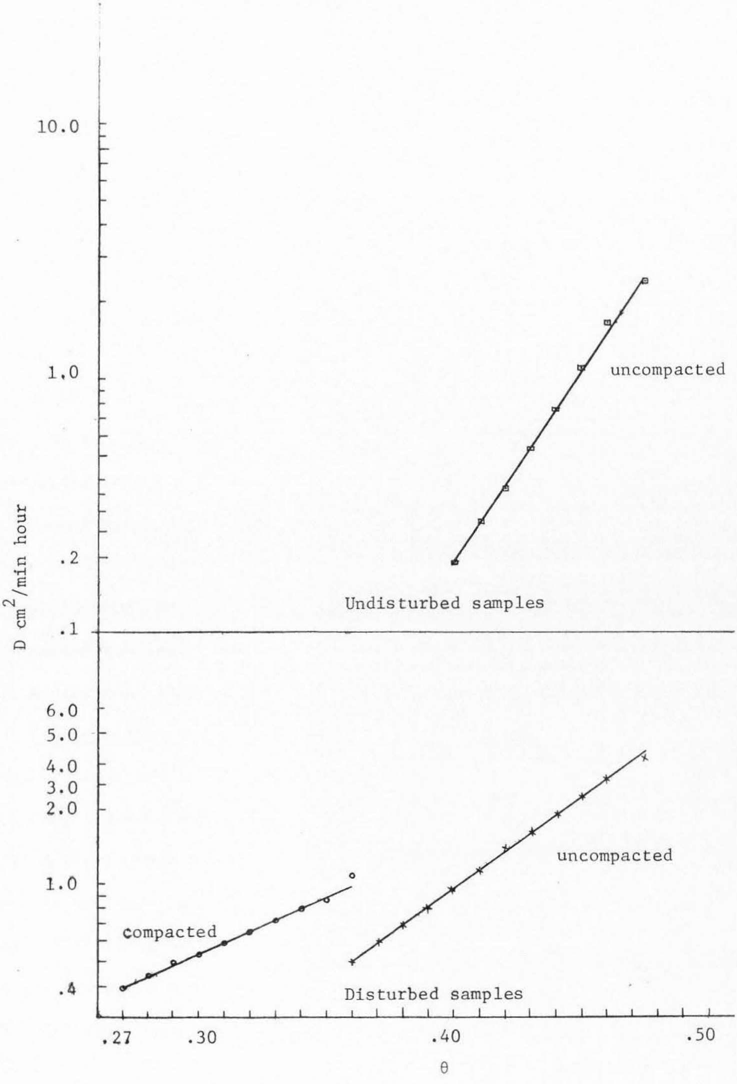


Figure 10. Nibley silty clay loam. Average diffusivity.

the lower values of water content, the curves are not parallel and would intercept if extrapolated. This tendency is similar to that of Amenina (1960) for D and K.

### Saturated hydraulic conductivity

Figure 11 (Tables 11 and 12 in Appendix) gives the average values of saturated K as influenced by time. The general trends for all the samples is to decrease the value of K with time until 5 hours after which there is little change in conductivity. The difference between the results of saturated and unsaturated K are undoubtedly due to the higher water content (and thus higher water conducting pore space) for the uncompacted than for the compacted samples.

Vernal sandy loam. The changes in bulk density have a marked effect on all the samples treated. Saturated K was about 3 times greater for the uncompacted than for the compacted. In the undisturbed uncompacted samples a reduction of about 70 percent was measured, while in the disturbed compacted the reduction was about 65 percent.

Nibley silty clay loam. The same behavior was noted for all the samples. However, it was not possible to get any outflow from the undisturbed compacted sample. In an attempt to see if there was surface sealing after compaction, the surface of the soil was removed. Still the flow was zero so the conductivity of this sample was assumed to be zero. The conductivity here also was greater for the disturbed than for the undisturbed samples in about 10 times. These results are in agreement with that stated by Childs (1957).

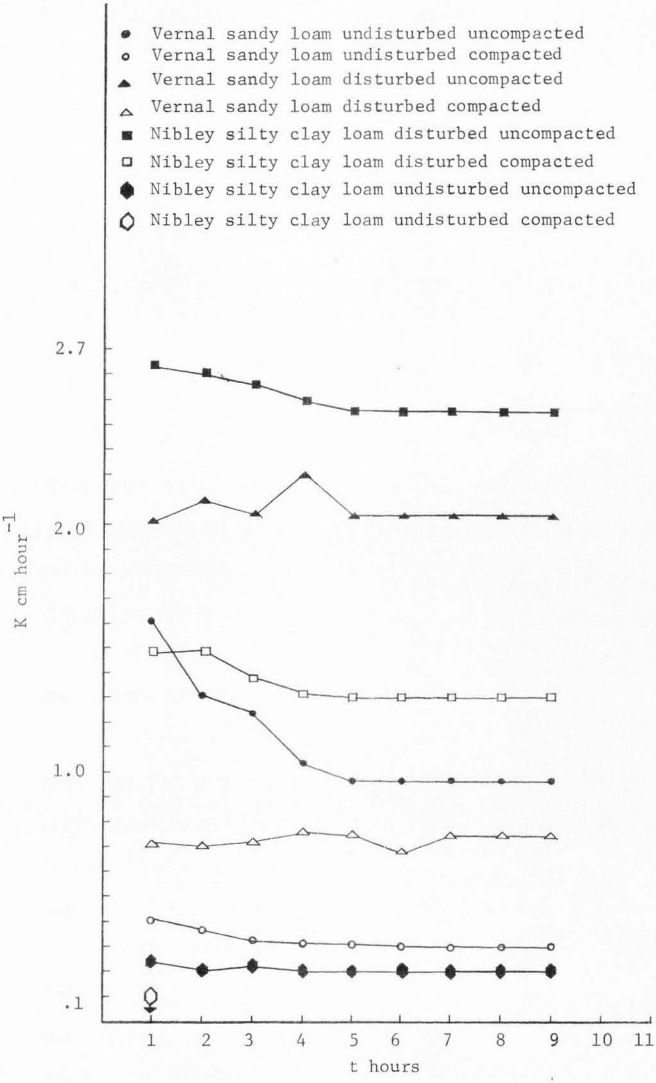


Figure 11. Average K for Vernal sandy loam and Nibley silty clay loam.

# SUMMARY AND CONCLUSIONS

1. The objective of this study was to measure the influence of changes in bulk density on the θ-K, θ-D and θ-h relations for two soils. Both disturbed and undisturbed samples were tested.

2. The water content at matric suctions of .05, .33 and 1.0 bar was measured for all samples. Three replications were measured for each treatment.

3. Compaction has a marked effect on the θ-h relation for the disturbed samples of Vernal sandy loam. The water content was about .04 greater at .33 and 1.0 bar suction for the compacted samples than for the uncompacted. The reverse was true at .05 bar suction. For the undisturbed samples compaction caused the same general effect but the difference due to treatment was small.

In the Nibley silty clay loam samples, water content was higher for the uncompacted than for the compacted samples at all suctions applied.

4. The effect of compaction on unsaturated K and D was not consistent. At the same value of water content, both diffusivity and conductivity were sometimes higher in the compacted samples, others lower than in the uncompacted samples. For all the samples a reduction in the values of K and D was measured as water content is reduced.

5. The effect of compaction on saturated K was very consistent. For all the samples treated, there was a reduction in the values of K with an increase in bulk density. For the Vernal sandy loam, a reduction of 70 percent was measured in the undisturbed compacted, while in the disturbed compacted the reduction was about 65 percent. For the

Nibley silty clay loam, in the undisturbed compacted samples K was assumed to be zero so there was a reduction of 100 percent, while for the disturbed compacted samples, the reduction was about 76 percent.

6. The method used presented the advantage that it can be conducted very easily using available equipment in a routine manner. The method has the disadvantage that it is not highly accurate. The computed values are highly dependent on the measurements that may have considerable inherent errors.

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# APPENDIX

Table 3. Effect of soil compaction on bulk density and water content

| Soil | Treatment | Average bulk density | Soil suction bars | Average θ |
|---|---|---|---|---|
| Vernal sandy loam | Undisturbed uncompacted | 1.43 | .05 | .33 |
| | | | .33 | .26 |
| | | | 1.0 | .22 |
| | Undisturbed compacted | 1.63 | .05 | .32 |
| | | | .33 | .27 |
| | | | 1.0 | .23 |
| | Disturbed uncompacted | 1.29 | .05 | .39 |
| | | | .33 | .25 |
| | | | 1.0 | .22 |
| | Disturbed compacted | 1.47 | .05 | .37 |
| | | | .33 | .32 |
| | | | 1.0 | .28 |
| Nibley silty clay loam | Undisturbed uncompacted | 1.39 | .05 | .47 |
| | | | .33 | .42 |
| | | | 1.0 | .39 |
| | Undisturbed compacted (Assumed values) | 1.52 | .05 | .42 |
| | | | .33 | .42 |
| | | | 1.0 | .42 |
| | Disturbed uncompacted | 1.09 | .05 | .48 |
| | | | .33 | .39 |
| | | | 1.0 | .36 |
| | Disturbed compacted | 1.29 | .05 | .36 |
| | | | .33 | .30 |
| | | | 1.0 | .27 |

Table 4. Vernal sandy loam. Data collected for the calculation of unsaturated K and D. Soil condition: Undisturbed, uncompacted

| Replication | ρd | θ .05 bar | θ .33 bar | θ 1 bar |
|---|---|---|---|---|
| 1 | 1.40 | .33 | .27 | .22 |
| 2 | 1.45 | .33 | .26 | .22 |
| 3 | 1.44 | .34 | .26 | .24 |

| θ | h | dθ/dt | dh/dθ | D | K |
|---|---|---|---|---|---|
|  |  | Replication No. 1 |  |  |  |
| .33 | .06 | $-.33 \times 10^{-2}$ | −150.0 | 8.94 | .059 |
| .32 | .08 | $-.16 \times 10^{-2}$ | −200.0 | 4.74 | .023 |
| .31 | .11 | $-.083 \times 10^{-2}$ | −275.0 | 2.70 | .010 |
| .30 | .15 | $-.044 \times 10^{-2}$ | −350.0 | 1.62 | .0046 |
| .29 | .21 | $-.025 \times 10^{-2}$ | −400.0 | 1.02 | .0026 |
| .28 | .26 | $-.017 \times 10^{-2}$ | −450.0 | .84 | .0018 |
| .27 | .32 | $-.013 \times 10^{-2}$ | −525.0 | .72 | .0014 |
| .26 | .40 | $-.0095 \times 10^{-2}$ | −750.0 | .66 | .00094 |
| .25 | .50 | $-.0053 \times 10^{-2}$ | −987.0 | .52 | .00053 |
| .22 | 1.0 |  |  |  |  |
|  |  | Replication No. 2 |  |  |  |
| .33 | .06 | $-.16 \times 10^{-2}$ | −200.0 | 4.32 | .021 |
| .32 | .08 | $-.11 \times 10^{-2}$ | −200.0 | 3.24 | .016 |
| .31 | .11 | $-.083 \times 10^{-2}$ | −225.0 | 2.70 | .012 |
| .30 | .15 | $-.043 \times 10^{-2}$ | −275.0 | 1.56 | .0058 |
| .29 | .19 | $-.025 \times 10^{-2}$ | −325.0 | 1.02 | .0032 |
| .28 | .23 | $-.018 \times 10^{-2}$ | −400.0 | .84 | .0022 |
| .27 | .29 | $-.014 \times 10^{-2}$ | −550.0 | .78 | .0015 |
| .26 | .38 | $-.010 \times 10^{-2}$ | −812.5 | .72 | .00091 |
| .25 | .44 | $-.0042 \times 10^{-2}$ | −1,100.0 | .41 | .00037 |
| .22 | 1.0 |  |  |  |  |
|  |  | Replication No. 3 |  |  |  |
| .33 | .07 | $-.095 \times 10^{-2}$ | −125.0 | 3.12 | .025 |
| .32 | .09 | $-.055 \times 10^{-2}$ | −150.0 | 2.04 | .013 |
| .31 | .10 | $-.037 \times 10^{-2}$ | −175.0 | 1.56 | .0090 |
| .30 | .13 | $-.025 \times 10^{-2}$ | −225.0 | 1.20 | .0055 |
| .29 | .17 | $-.018 \times 10^{-2}$ | −300.0 | 1.02 | .0035 |
| .28 | .21 | $-.013 \times 10^{-2}$ | −375.0 | .96 | .0025 |
| .27 | .28 | $-.009 \times 10^{-2}$ | −600.0 | .84 | .0014 |
| .26 | .37 | $-.0039 \times 10^{-2}$ | −975.0 | .57 | .00059 |
| .24 | 1.0 |  |  |  |  |

Average K and D

| θ | .24 | .25 | .26 | .27 | .28 | .29 | .30 | .31 | .32 | .33 |
|---|---|---|---|---|---|---|---|---|---|---|
| D | .35 | .45 | .59 | .74 | .99 | 1.30 | 1.70 | 2.21 | 3.08 | 3.8 |
| $K \times 10^{-3}$ | .35 | .56 | .90 | 1.4 | 2.3 | 3.6 | 5.5 | 9.0 | 14.2 | 22.0 |

Table 5. Vernal sandy loam. Data collected for calculation of unsaturated K and D. Soil condition: Undisturbed, compacted

| Replication | $\rho d$ | $\theta$ .05 bar | $\theta$ .33 bar | $\theta$ 1 bar |
|---|---|---|---|---|
| 1 | 1.64 | .35 | .31 | .27 |
| 2 | 1.57 | .30 | .25 | .21 |
| 3 | 1.70 | .31 | .25 | .21 |

| | | Replication No. 1 | | | |
|---|---|---|---|---|---|
| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
| .34 | .10 | $-.16\times10^{-2}$ | -425.0 | 6.06 | .013 |
| .33 | .17 | $-.027\times10^{-2}$ | -600.0 | 1.14 | .0019 |
| .32 | .25 | $-.017\times10^{-2}$ | -750.0 | .90 | .0012 |
| .31 | .33 | $-.010\times10^{-2}$ | -875.0 | .66 | .00072 |
| .30 | .49 | $-.005\times10^{-2}$ | -1,100.0 | .45 | .00042 |
| .29 | .65 | $-.0022\times10^{-2}$ | -1,450.0 | .28 | .00018 |
| .27 | 1.0 | | | | |
| | | Replication No. 2 | | | |
| .29 | .07 | $-.16\times10^{-2}$ | -250.0 | 5.28 | .021 |
| .28 | .11 | $-.14\times10^{-2}$ | -350.0 | 5.28 | .015 |
| .27 | .17 | $-.055\times10^{-2}$ | -450.0 | 2.40 | .0054 |
| .26 | .25 | $-.033\times10^{-2}$ | -675.0 | 1.74 | .0025 |
| .25 | .33 | $-.019\times10^{-2}$ | -900.0 | 1.74 | .0013 |
| .24 | .47 | $-.012\times10^{-2}$ | -1,050.0 | 1.02 | .0010 |
| .23 | .63 | $-.007\times10^{-2}$ | -1,450.0 | .90 | .00063 |
| .21 | 1.0 | | | | |
| | | Replication No. 3 | | | |
| .30 | .09 | $-.11\times10^{-2}$ | -250.0 | 3.24 | .012 |
| .29 | .12 | $-.066\times10^{-2}$ | -275.0 | 2.16 | .0078 |
| .28 | .16 | $-.037\times10^{-2}$ | -325.0 | .38 | .0042 |
| .27 | .21 | $-.023\times10^{-2}$ | -400.0 | .96 | .0025 |
| .26 | .27 | $-.015\times10^{-2}$ | -600.0 | .78 | .0013 |
| .25 | .33 | $-.011\times10^{-2}$ | -875.0 | .72 | .00078 |
| .24 | .50 | $-.0064\times10^{-2}$ | -1,150.0 | .56 | .00051 |
| .23 | .68 | $-.0019\times10^{-2}$ | -1,725.0 | .24 | .00014 |
| .21 | 1.0 | | | | |

Average K and D

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $\theta$ | .23 | .24 | .25 | .26 | .27 | .28 | .29 | .30 | .31 |
| D | .37 | .49 | .65 | .87 | 1.14 | 1.59 | 2.09 | 2.84 | 3.81 |
| $K\times10^{-3}$ | .27 | .47 | .87 | 1.5 | 2.7 | 4.8 | 8.4 | 15.0 | 27.0 |

Table 6. Vernal sandy loam. Data collected for the calculation of unsaturated K and D. Soil condition: Disturbed, uncompacted

| Replication | $\rho d$ | $\theta$ .05 bar | $\theta$ .33 bar | $\theta$ 1 bar |
|---|---|---|---|---|
| 1 | 1.28 | .385 | .264 | .221 |
| 2 | 1.29 | .392 | .247 | .208 |
| 3 | 1.32 | .407 | .266 | .236 |

Replication No. 1

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .37 | .05 | $-1.6 \times 10^{-3}$ | - 50.0 | 2.33 | .046 |
| .36 | .06 | $-1.2 \times 10^{-3}$ | - 75.0 | 1.87 | .025 |
| .35 | .07 | $-.90 \times 10^{-3}$ | -110.0 | 1.51 | .013 |
| .34 | .09 | $-.76 \times 10^{-3}$ | -125.0 | 1.18 | .011 |
| .33 | .11 | $-.60 \times 10^{-3}$ | -140.0 | 1.19 | .0085 |
| .32 | .13 | $-.55 \times 10^{-3}$ | -165.0 | 1.20 | .0072 |
| .31 | .15 | $-.54 \times 10^{-3}$ | -190.0 | 1.31 | .0069 |
| .30 | .18 | $-.47 \times 10^{-3}$ | -195.0 | 1.28 | .0065 |
| .29 | .20 | $-.37 \times 10^{-3}$ | -215.0 | 1.15 | .0053 |
| .28 | .23 | $-.35 \times 10^{-3}$ | -290.0 | 1.31 | .0044 |
| .27 | .28 | $-.25 \times 10^{-3}$ | -435.0 | 1.09 | .0025 |
| .26 | .33 | $-.17 \times 10^{-3}$ | -635.0 | .93 | .0013 |
| .24 | .60 | $-.08 \times 10^{-3}$ | -1,250.0 | .87 | .00070 |
| .22 | 1.0 | | | | |

Replication No. 2

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .37 | .06 | $-3.3 \times 10^{-3}$ | - 50.0 | 4.25 | .085 |
| .36 | .06 | $-2.8 \times 10^{-3}$ | - 60.0 | 3.83 | .063 |
| .35 | .07 | $-2.5 \times 10^{-3}$ | - 65.0 | 3.64 | .056 |
| .34 | .08 | $-2.5 \times 10^{-3}$ | - 85.0 | 3.91 | .046 |
| .33 | .09 | $-2.0 \times 10^{-3}$ | -100.0 | 3.36 | .033 |
| .32 | .11 | $-1.8 \times 10^{-3}$ | -125.0 | 3.28 | .026 |
| .31 | .13 | $-1.6 \times 10^{-3}$ | -145.0 | 3.18 | .021 |
| .30 | .15 | $-1.1 \times 10^{-3}$ | -150.0 | 2.40 | .016 |
| .29 | .17 | $-.71 \times 10^{-3}$ | -160.0 | 1.72 | .010 |
| .28 | .19 | $-.66 \times 10^{-3}$ | -160.0 | 1.80 | .011 |
| .27 | .22 | $-.47 \times 10^{-3}$ | -200.0 | 1.47 | .0073 |
| .26 | .26 | $-.23 \times 10^{-3}$ | -255.0 | .83 | .0032 |
| .24 | .33 | $-.17 \times 10^{-3}$ | -300.0 | .93 | .0031 |
| .208 | 1.0 | | | | |

Table 6. Continued

Replication No. 3

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .37 | .06 | $-3.3\times10^{-3}$ | − 50.0 | 5.16 | .10 |
| .36 | .06 | $-2.2\times10^{-3}$ | − 60.0 | 3.70 | .061 |
| .35 | .07 | $-2.0\times10^{-3}$ | − 80.0 | 3.60 | .045 |
| .34 | .08 | $-1.8\times10^{-3}$ | −110.0 | 3.54 | .032 |
| .33 | .10 | $-1.6\times10^{-3}$ | −115.0 | 3.49 | .030 |
| .32 | .11 | $-1.4\times10^{-3}$ | −125.0 | 3.35 | .027 |
| .31 | .13 | $-1.1\times10^{-3}$ | −150.0 | 3.00 | .020 |
| .30 | .15 | $-.90\times10^{-3}$ | −205.0 | 2.76 | .013 |
| .29 | .18 | $-.42\times10^{-3}$ | −275.0 | 1.50 | .0055 |
| .28 | .23 | $-.25\times10^{-3}$ | −375.0 | 1.08 | .0029 |
| .27 | .29 | $-.15\times10^{-3}$ | −550.0 | .82 | .0014 |
| .26 | .33 | $-.11\times10^{-3}$ | −775.0 | .80 | .0010 |
| .25 | .49 | $-.06\times10^{-3}$ | −1,025.0 | .66 | .00063 |
| .236 | 1.0 | | | | |

Average K and D

| $\theta$ | .24 | .26 | .28 | .30 | .32 | .34 | .36 |
|---|---|---|---|---|---|---|---|
| D | .86 | 1.06 | 1.33 | 1.66 | 2.10 | 2.66 | 3.40 |
| $K\times10^{-3}$ | 1.3 | 2.5 | 4.6 | 8.7 | 16.0 | 31.0 | 61.0 |

Table 7. Vernal sandy loam. Data collected for calculation of unsaturated K and D. Soil condition: Disturbed, compacted

| Replication | $\rho d$ | $\theta$ .05 bar | $\theta$ .33 bar | $\theta$ 1 bar |
|---|---|---|---|---|
| 1 | 1.48 | .33 | .293 | .245 |
| 2 | 1.46 | .36 | .325 | .28 |
| 3 | 1.41 | .432 | .353 | .337 |

Replication No. 1

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .32 | .10 | $-1.1\times10^{-3}$ | −410.0 | 3.01 | .0073 |
| .31 | .17 | $-.66\times10^{-3}$ | −525.0 | 2.06 | .0039 |
| .30 | .25 | $-.55\times10^{-3}$ | −575.0 | 2.00 | .0034 |
| .29 | .33 | $-.42\times10^{-3}$ | −310.0 | 1.83 | .0059 |
| .28 | .43 | $-.27\times10^{-3}$ | −825.0 | 1.47 | .0017 |
| .27 | .54 | $-.16\times10^{-3}$ | −880.0 | 1.16 | .0013 |
| .26 | .68 | $-.06\times10^{-3}$ | −1,200.0 | .65 | .00054 |
| .24 | 1.0 | | | | |

Replication No. 2

| | | | | | |
|---|---|---|---|---|---|
| .36 | .05 | $-1.2\times10^{-3}$ | −425.0 | 2.62 | .0061 |
| .35 | .13 | $-.95\times10^{-3}$ | −475.0 | 2.31 | .0048 |
| .34 | .20 | $-.75\times10^{-3}$ | −550.0 | 2.05 | .0037 |
| .33 | .26 | $-.65\times10^{-3}$ | −600.0 | 2.03 | .0033 |
| .32 | .33 | $-.45\times10^{-3}$ | −650.0 | 1.64 | .0025 |
| .31 | .42 | $-.25\times10^{-3}$ | −725.0 | 1.09 | .0015 |
| .30 | .51 | $-.16\times10^{-3}$ | −850.0 | .87 | .0010 |
| .29 | .61 | $-.05\times10^{-3}$ | −1,175.0 | .37 | .00031 |
| .26 | 1.0 | | | | |

Replication No. 3

| | | | | | |
|---|---|---|---|---|---|
| .41 | .07 | $-.34\times10^{-3}$ | −175.0 | .93 | .0053 |
| .40 | .10 | $-.20\times10^{-3}$ | −200.0 | .62 | .0031 |
| .39 | .13 | $-.13\times10^{-3}$ | −250.0 | .47 | .0018 |
| .38 | .17 | $-.083\times10^{-3}$ | −325.0 | .36 | .0011 |
| .37 | .21 | $-.051\times10^{-3}$ | −350.0 | .27 | .00077 |
| .36 | .27 | $-.033\times10^{-3}$ | −575.0 | .24 | .00041 |
| .35 | .33 | $-.025\times10^{-3}$ | −1,750.0 | .27 | .00015 |
| .33 | 1.0 | | | | |

Average K and D

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\theta$ | .27 | .28 | .30 | .32 | .34 | .36 | .38 |
| D | .47 | .57 | .82 | 1.21 | 1.76 | 3.03 | 4.56 |
| $K\times10^{-3}$ | .55 | .77 | 1.5 | 3.0 | 6.2 | 12.0 | 20.0 |

Table 8. Nibley silty clay loam. Data collected for calculation of unsaturated K and D. Soil condition: Undisturbed, uncompacted

| Replication | $\rho d$ | $\theta$ .05 bar | $\theta$ .33 bar | $\theta$ 1 bar |
|---|---|---|---|---|
| 1 | 1.38 | .45 | .40 | .388 |
| 2 | 1.45 | .50 | .44 | .402 |
| 3 | 1.34 | .466 | .43 | .397 |

Replication No. 1

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .44 | .06 | $-.2\times10^{-3}$ | -200.0 | .99 | .0049 |
| .43 | .09 | $-.11\times10^{-3}$ | -325.0 | .60 | .0019 |
| .42 | .15 | $-.05\times10^{-3}$ | -500.0 | .38 | .00072 |
| .41 | .23 | $-.026\times10^{-3}$ | -725.0 | .25 | .00030 |
| .40 | .33 | $-.019\times10^{-3}$ | -1,225.0 | .28 | .00018 |
| .38 | 1.0 | | | | |

Replication No. 2

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .48 | .10 | $-.41\times10^{-3}$ | -325.0 | 1.50 | .0046 |
| .47 | .15 | $-.25\times10^{-3}$ | -400.0 | 1.02 | .0026 |
| .46 | .21 | $-.16\times10^{-3}$ | -500.0 | .78 | .0015 |
| .45 | .29 | $-.11\times10^{-3}$ | -675.0 | .60 | .00096 |
| .44 | .33 | $-.084\times10^{-3}$ | -850.0 | .60 | .00072 |
| .43 | .51 | $-.060\times10^{-3}$ | -1,125.0 | .56 | .00048 |
| .42 | .68 | $-.032\times10^{-3}$ | -1,350.0 | .42 | .00030 |
| .40 | 1.0 | | | | |

Replication No. 3

| $\theta$ | h | $d\theta/dt$ | $dh/d\theta$ | D | K |
|---|---|---|---|---|---|
| .45 | .14 | $-.25\times10^{-3}$ | -550.0 | 1.70 | .0022 |
| .44 | .22 | $-.13\times10^{-3}$ | -725.0 | .72 | .0010 |
| .43 | .33 | $-.081\times10^{-3}$ | -1,000.0 | .60 | .0006 |
| .42 | .48 | $-.041\times10^{-3}$ | -950.0 | .36 | .00042 |
| .41 | .71 | $-.021\times10^{-3}$ | -1,750.0 | .30 | .00012 |
| .39 | 1.0 | | | | |

Average K and D

| $\theta$ | .40 | .41 | .42 | .43 | .44 | .45 | .46 | .47 |
|---|---|---|---|---|---|---|---|---|
| D | .19 | .27 | .38 | .53 | .77 | 1.10 | 1.68 | 2.43 |
| $K\times10^{-3}$ | .12 | .23 | .81 | .95 | 1.96 | 4.2 | 9.3 | 20.5 |

Table 9. Nibley silty clay loam. Data collected for calculation of unsaturated K and D. Soil condition: Disturbed, uncompacted

| Replication | ρd | θ .05 bar | θ .33 bar | θ 1 bar |
|---|---|---|---|---|
| 1 | 1.09 | .50 | .392 | .366 |
| 2 | 1.11 | .48 | .419 | .364 |
| 3 | 1.09 | .48 | .38 | .35 |

Replication No. 1

| θ | h | dθ/dt | dh/dθ | D | K |
|---|---|---|---|---|---|
| .48 | .06 | $-1.1 \times 10^{-3}$ | −100.0 | 2.73 | .027 |
| .47 | .07 | $-.83 \times 10^{-3}$ | −100.0 | 2.25 | .022 |
| .46 | .09 | $-.66 \times 10^{-3}$ | −125.0 | 1.96 | .015 |
| .45 | .11 | $-.39 \times 10^{-3}$ | −150.0 | 1.29 | .0086 |
| .44 | .13 | $-.25 \times 10^{-3}$ | −225.0 | .93 | .0041 |
| .43 | .15 | $-.17 \times 10^{-3}$ | −225.0 | .72 | .0032 |
| .42 | .19 | $-.12 \times 10^{-3}$ | −250.0 | .59 | .0023 |
| .41 | .22 | $-.094 \times 10^{-3}$ | −275.0 | .56 | .0020 |
| .40 | .27 | $-.072 \times 10^{-3}$ | −350.0 | .53 | .0015 |
| .39 | .33 | $-.049 \times 10^{-3}$ | −750.0 | .48 | .00064 |
| .38 | .48 | $-.028 \times 10^{-3}$ | −1,350.0 | .41 | .00030 |
| .366 | 1.0 | | | | |

Replication No. 2

| | | | | | |
|---|---|---|---|---|---|
| .48 | .05 | $-1.6 \times 10^{-3}$ | −125.0 | 3.97 | .031 |
| .47 | .07 | $-1.0 \times 10^{-3}$ | −200.0 | 2.71 | .013 |
| .46 | .11 | $-.83 \times 10^{-3}$ | −250.0 | 2.47 | .0099 |
| .45 | .14 | $-.71 \times 10^{-3}$ | −300.0 | 2.35 | .0078 |
| .44 | .19 | $-.55 \times 10^{-3}$ | −400.0 | 2.05 | .0051 |
| .43 | .25 | $-.33 \times 10^{-3}$ | −475.0 | 1.40 | .0029 |
| .42 | .31 | $-.19 \times 10^{-3}$ | −550.0 | .94 | .0017 |
| .41 | .33 | $-.16 \times 10^{-3}$ | −650.0 | .95 | .0014 |
| .40 | .48 | $-.11 \times 10^{-3}$ | −750.0 | .82 | .0010 |
| .39 | .59 | $-.079 \times 10^{-3}$ | −850.0 | .78 | .00092 |
| .38 | .71 | $-.036 \times 10^{-3}$ | −1,000.0 | .53 | .00053 |
| .36 | 1.0 | | | | |

Replication No. 3

| | | | | | |
|---|---|---|---|---|---|
| .47 | .05 | $-1.6 \times 10^{-3}$ | − 25.0 | 3.97 | .159 |
| .46 | .06 | $-1.3 \times 10^{-3}$ | −110.0 | 3.52 | .032 |
| .45 | .08 | $-1.1 \times 10^{-3}$ | −150.0 | 3.28 | .021 |
| .44 | .10 | $-.90 \times 10^{-3}$ | −165.0 | 2.76 | .016 |
| .43 | .12 | $-.80 \times 10^{-3}$ | −180.0 | 2.98 | .016 |
| .42 | .15 | $-.62 \times 10^{-3}$ | −250.0 | 2.64 | .010 |
| .41 | .19 | $-.30 \times 10^{-3}$ | −345.0 | 1.49 | .0043 |
| .40 | .24 | $-.19 \times 10^{-3}$ | −250.0 | 1.13 | .0048 |
| .39 | .31 | $-.18 \times 10^{-3}$ | −575.0 | 1.34 | .0023 |
| .38 | .33 | $-.095 \times 10^{-3}$ | −800.0 | .94 | .0011 |
| .37 | .52 | $-.050 \times 10^{-3}$ | −1,200.0 | 1.49 | .0012 |
| .35 | 1.0 | | | | |

Table 9. Continued

Average K and D

| $\theta$ | .37 | .38 | .40 | .42 | .43 | .44 | .45 | .46 | .47 |
|---|---|---|---|---|---|---|---|---|---|
| D | .60 | .71 | .96 | 1.34 | 1.61 | 1.90 | 2.25 | 2.65 | 3.21 |
| $K \times 10^{-3}$ | .57 | .87 | 1.8 | 3.8 | 5.5 | 8.4 | 12.0 | 18.0 | 28.0 |

Table 10. Nibley silty clay loam. Data collected for calculation of unsaturated K and D. Soil condition: Disturbed, compacted

| Replication | ρd | θ .05 bar | θ .33 bar | θ 1 bar |
|---|---|---|---|---|
| 1 | 1.30 | .38 | .32 | .297 |
| 2 | 1.30 | .35 | .30 | .261 |
| 3 | 1.29 | .37 | .30 | .28 |

Replication No. 1

| θ | h | dθ/dt | dh/dθ | D | K |
|---|---|---|---|---|---|
| .38 | .05 | $-.33\times10^{-3}$ | -140.0 | 1.09 | .0078 |
| .37 | .05 | $-.23\times10^{-3}$ | -215.0 | .762 | .0035 |
| .36 | .07 | $-.18\times10^{-3}$ | -275.0 | .670 | .0024 |
| .35 | .11 | $-.13\times10^{-3}$ | -375.0 | .646 | .0016 |
| .34 | .15 | $-.098\times10^{-3}$ | -625.0 | .584 | .00090 |
| .33 | .23 | $-.061\times10^{-3}$ | -925.0 | .454 | .00048 |
| .32 | .33 | $-.031\times10^{-3}$ | -1,750.0 | .308 | .00012 |
| .297 | 1.0 | | | | |

Replication No. 2

| θ | h | dθ/dt | dh/dθ | D | K |
|---|---|---|---|---|---|
| .35 | .05 | $-.34\times10^{-3}$ | -165.0 | 1.12 | .0067 |
| .34 | .07 | $-.26\times10^{-3}$ | -275.0 | .960 | .0034 |
| .33 | .12 | $-.19\times10^{-3}$ | -350.0 | .809 | .0022 |
| .32 | .17 | $-.16\times10^{-3}$ | -450.0 | .795 | .0017 |
| .31 | .25 | $-.11\times10^{-3}$ | -575.0 | .656 | .0011 |
| .30 | .33 | $-.089\times10^{-3}$ | -775.0 | .663 | .00084 |
| .29 | .44 | $-.051\times10^{-3}$ | -1,050.0 | .526 | .00048 |
| .28 | .60 | $-.033\times10^{-3}$ | -1,350.0 | .492 | .00036 |
| .26 | 1.0 | | | | |

Replication No. 3

| θ | h | dθ/dt | dh/dθ | D | K |
|---|---|---|---|---|---|
| .37 | .05 | $-.33\times10^{-3}$ | -100.0 | 1.09 | .010 |
| .36 | .05 | $-.29\times10^{-3}$ | -125.0 | 1.08 | .0086 |
| .35 | .06 | $-.24\times10^{-3}$ | -150.0 | 1.02 | .0067 |
| .34 | .09 | $-.19\times10^{-3}$ | -245.0 | .94 | .0038 |
| .33 | .13 | $-.13\times10^{-3}$ | -400.0 | .77 | .0019 |
| .32 | .19 | $-.10\times10^{-3}$ | -550.0 | .74 | .0013 |
| .31 | .27 | $-.08\times10^{-3}$ | -700.0 | .79 | .0010 |
| .30 | .33 | $-.07\times10^{-3}$ | -1,050.0 | .69 | .00066 |
| .29 | .55 | $-.018\times10^{-3}$ | -2,300.0 | .26 | .00011 |
| .28 | 1.0 | | | | |

Average K and D

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| θ | .27 | .28 | .30 | .32 | .34 | .36 | .37 |
| D | .41 | .45 | .54 | .66 | .80 | .99 | 1.08 |
| $K\times10^{-3}$ | .16 | .23 | .50 | 1.0 | 2.4 | 5.3 | 8.1 |

Table 11. Average saturated K for Vernal sandy loam samples

| Treatment | $Q_1$ | $K_1$ | $Q_2$ | $K_2$ | $Q_3$ | $K_3$ | Average K | Average $\rho d$ | $\theta$ sat. |
|---|---|---|---|---|---|---|---|---|---|
| Undisturbed uncompacted | 32 | .882 | 80 | 2.20 | 64 | 1.76 | 1.61 | | |
| | 28 | .772 | 70 | 1.93 | 45 | 1.24 | 1.31 | | |
| | 26 | .717 | 70 | 1.93 | 40 | 1.10 | 1.24 | | |
| | 26 | .717 | 50 | 1.37 | 38 | 1.04 | 1.04 | | |
| | 26 | .717 | 45 | 1.24 | 35 | .965 | .974 | 1.43 | .47 |
| | 26 | .717 | 45 | 1.24 | 35 | .965 | .974 | | |
| | 26 | .717 | 45 | 1.24 | 35 | .965 | .974 | | |
| Undisturbed compacted | 14 | .371 | 18 | .461 | 15 | .397 | .409 | | |
| | 12 | .307 | 17 | .435 | 14 | .358 | .366 | | |
| | 12 | .307 | 15 | .384 | 12 | .307 | .328 | | |
| | 12 | .307 | 15 | .384 | 12 | .307 | .324 | | |
| | 11 | .282 | 15 | .384 | 12 | .307 | .318 | | |
| | 11 | .282 | 14 | .379 | 11 | .282 | .303 | | |
| | 11 | .282 | 13 | .333 | 11 | .282 | .299 | 1.63 | .39 |
| | 11 | .282 | 13 | .333 | 11 | .282 | .299 | | |
| | 11 | .282 | 13 | .333 | 11 | .282 | .299 | | |
| Disturbed uncompacted | 71 | 1.95 | 68 | 1.87 | 82 | 2.26 | 2.02 | | |
| | 71 | 1.95 | 75 | 2.06 | 85 | 2.34 | 2.11 | | |
| | 70 | 1.93 | 73 | 2.01 | 80 | 2.20 | 2.04 | | |
| | 71 | 1.95 | 70 | 1.93 | 80 | 2.20 | 2.20 | | |
| | 72 | 1.98 | 70 | 1.93 | 80 | 2.20 | 2.03 | 1.29 | .52 |
| | 72 | 1.98 | 70 | 1.93 | 80 | 2.20 | 2.03 | | |
| | 72 | 1.98 | 70 | 1.93 | 80 | 2.20 | 2.03 | | |
| | 72 | 1.98 | 70 | 1.93 | 80 | 2.20 | 2.03 | | |
| Disturbed compacted | 27 | .744 | 24 | .661 | 28 | .772 | .725 | | |
| | 30 | .827 | 20 | .551 | 27 | .744 | .707 | | |
| | 30 | .827 | 24 | .661 | 27 | .744 | .739 | | |
| | 33 | .910 | 24 | .661 | 26 | .717 | .762 | | |
| | 33 | .910 | 23 | .634 | 26 | .717 | .758 | | |
| | 25 | .689 | 24 | .661 | 25 | .703 | .684 | | |
| | 31 | .854 | 25 | .689 | 26 | .717 | .753 | | |
| | 31 | .854 | 24 | .661 | 26 | .717 | .744 | 1.47 | .45 |
| | 31 | .854 | 24 | .661 | 26 | .717 | .744 | | |
| | 31 | .854 | 24 | .661 | 26 | .717 | .744 | | |

Table 12. Average saturated K for Nibley silty clay loam samples

| Treatment | $Q_1$ | $K_1$ | $Q_2$ | $K_2$ | $Q_3$ | $K_3$ | Average K | Average $\rho d$ | $\theta$ sat. |
|---|---|---|---|---|---|---|---|---|---|
| Undisturbed uncompacted | 6 | .165 | 9 | .261 | 10 | .286 | .237 | 1.39 | .49 |
| | 5 | .137 | 7 | .206 | 10 | .275 | .210 | | |
| | 5 | .137 | 11 | .303 | 9 | .264 | .237 | | |
| | 5 | .137 | 8 | .234 | 9 | .264 | .211 | | |
| | 4 | .124 | 8 | .234 | 8 | .242 | .200 | | |
| | 4 | .124 | 8 | .234 | 8 | .242 | .200 | | |
| | 4 | .124 | 8 | .234 | 8 | .242 | .200 | | |
| Disturbed uncompacted | 95 | 2.61 | 104 | 2.86 | 88 | 2.42 | 2.63 | 1.09 | .59 |
| | 97 | 2.67 | 100 | 2.75 | 87 | 2.39 | 2.60 | | |
| | 97 | 2.67 | 98 | 2.70 | 84 | 2.31 | 2.56 | | |
| | 93 | 2.56 | 97 | 2.67 | 82 | 2.26 | 2.49 | | |
| | 90 | 2.48 | 95 | 2.61 | 82 | 2.26 | 2.45 | | |
| | 90 | 2.48 | 95 | 2.61 | 82 | 2.26 | 2.45 | | |
| | 90 | 2.48 | 95 | 2.61 | 82 | 2.26 | 2.45 | | |
| | 90 | 2.48 | 95 | 2.61 | 82 | 2.26 | 2.45 | | |
| Disturbed compacted | 50 | 1.37 | 57 | 1.57 | 54 | 1.48 | 1.47 | 1.29 | .52 |
| | 52 | 1.43 | 56 | 1.54 | 54 | 1.48 | 1.48 | | |
| | 48 | 1.32 | 52 | 1.43 | 51 | 1.40 | 1.38 | | |
| | 46 | 1.26 | 50 | 1.37 | 49 | 1.35 | 1.32 | | |
| | 45 | 1.24 | 50 | 1.37 | 48 | 1.32 | 1.31 | | |
| | 45 | 1.24 | 50 | 1.37 | 48 | 1.32 | 1.31 | | |
| | 45 | 1.24 | 50 | 1.37 | 48 | 1.32 | 1.31 | | |
| | 45 | 1.24 | 50 | 1.37 | 48 | 1.32 | 1.31 | | |
| Undisturbed compacted | | | No outflow | | | | | 1.52 | .42 |

# VITA

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