HYDRAULIC PROPERTIES OF STONY VADOSE ZONE SOILS REVISITED

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ABSTRACT

To determine saturated and unsaturated flow parameters, a common hydraulic laboratory practice is to remove all material greater than 4.75 mm in diameter from the sample and use small diameter cores to test the fine-earth fraction. The resulting measurements are then corrected for the soil gravel content with published correction factors such as Bouwer and Rice (1984). However, such correction factors are based on testing of bi-modally graded materials containing uniform large rock fragments (boulders) and homogeneous fine earth fractions (pure sand). Large- and small-core diameter hydraulic property tests we have performed on well graded material samples with varying amounts of gravel, show poor agreement with the published correction factors.

An alluvial material sample was used to fabricate eight soils with various particle size distributions. The primary sample matrix for all testing was assumed to be the fine-earth fraction, less than 4.75 mm in diameter. Additional soil materials were then fabricated in which either part of the fine-earth fraction was removed, or gravel material ranging from 4.75 mm to 19 mm diameter was added. Test results show that saturated hydraulic conductivity (Ksat) decreased with up to 30 percent gravel content but increased dramatically at higher gravel contents. Moisture retention curve data show that the air entry value and the amount of retained water decreased at lower matric potentials with increasing gravel contents. The predicted unsaturated hydraulic conductivities also show increasing, yet parallel, differences in hydraulic conductivity as gravel contents increase. These data are in direct contrast to the findings of Bouwer and Rice (1984), who found that Ksat was inversely proportional up to 70 percent gravel contents when uniform gravel size and fine-earth fractions were used. For the materials tested in this study it was found that as the gravel content increases, larger size pores are created, and/or insufficient fine material is available to occupy the pore space, thus changing the pore size distribution and Ksat.

These results suggest that the common laboratory practice of testing the fine-earth fraction and using a gravel content correction factor can produce highly erroneous results. Consequently, the removal of the gravel and use of small diameter cores is not recommended for samples dissimilar in gradation and bulk density to the soils tested by the published method.

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MATERIALS AND METHODS

The materials tested were alluvial soil materials collected from the Nevada Test Site. The original soil sample was separated into different size fractions (Photo 1) which were then used to fabricate eight soils with various particle size distributions. The primary sample matrix for all testing was assumed to be the fine-earth fraction, that is, material passing the #4 mesh, (all particles < 4.75 mm in diameter). Soil materials were then fabricated in which either part of the fine-earth fraction was removed, or gravel material was added.

Samples were prepared by weighing the appropriate amount of each particle size fraction needed to prepare the desired particle size distribution (Figure 1). Two different fine-earth samples were fabricated by removing the 4.75 mm to 2 mm diameter fraction and the 2 mm to 0.85 mm diameter fractions, respectively. The other six distributions contained the fine-earth fraction (< 4.75 mm diameter) with 0%, 30 %, 40%, 50%, 60 % and 80% gravel fractions, respectively. The gravel fractions added were not of uniform particle size, rather they represented well graded > 4.75 mm diameter material, such as would be expected in alluvial materials.

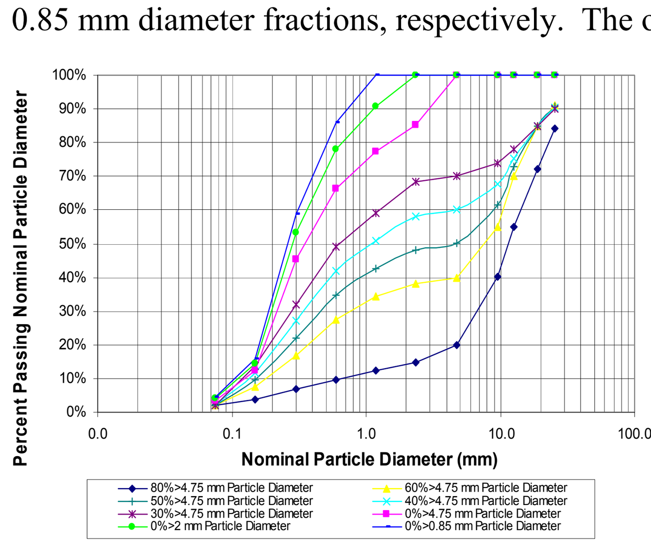

Photo 1. Different size fractions of test material

Photo 2. 15 cm diam. by 30 cm Tempe cells

The fabricated samples were homogenized and packed into rigid wall Tempe cells. The fine-earth fraction distribution (<4.75 mm, <2 mm, <0.85 mm) tests were conducted using small 6.17 cm diameter by 15 cm length cells. Soils with 30%, 40%, 50%, 60% and 80% gravel fractions were tested using 15 cm diameter by 30 cm length cells (Photo 2). Each sample was replicated three times except for the 40 %, 50% and 80 % gravel distributions. To avoid particle-wall interferences, gravel particles were limited to an upper size diameter of 2.5 cm. Fine-earth samples were packed in two-cm lifts at a target dry bulk density of 1.5 g/cm3, soils with gravel were packed at target densities of 1.6 g/cm3. The 30% gravel sample was packed to a slightly higher bulk density due to settling during the saturated hydraulic conductivity (Ksat) testing.

Cells were saturated using upward infiltration, Ksat measurements were conducted using constant head methods. After measuring the Ksat, the moisture retention characteristic (MRC) curve was determined using six pressure steps. Hanging column methods were used up to -100 cm of tension followed by Tempe Cell pressure plate extraction up to -1000 cm of tension. The computer code RETC4 (van Genuchten, et al., 1997) was used to calculate α and N, the van Genuchten parameters needed to estimate the hydraulic conductivity function (Kunsat vs moisture content or tension), from the negative pressure potential (tension) and water content relationship (the MRC curve). If available, direct Kunsat data (40%, 50% and 80% gravel) were also used in the hydraulic conductivity relationship. The residual water content was fixed in cases where calculated values were unreasonably low. Finally, the RETC parameter M was specified to equal 1-1/N.

RESULTS

Saturated Hydraulic Conductivity

Ksat for the three finer distributions was similar and varied between 6.7x10-4 and 9.4x10-4 cm/sec. Ksat for the 30% > 4.75 mm distribution averaged 2.3 x 10-4 cm/sec which was lower than the average Ksat of 9.2 x 10-4 cm/sec for the 0% > 4.75 mm distribution. This may be attributed to the increased amount of gravel which decreased the pore space (0.4 to 0.33) and acted as barriers to flow. However, using the correction factor for percent gravel provided by Bouwer and Rice (1984), a Ksat of only 6.9 x 10-4 cm/sec is predicted, indicating that increased bulk density (Table 1) may also have contributed to the decrease in Ksat. When the gravel content of the distribution was further increased to 40%, 50%, 60% and 80 %, the Ksat values increased (Figure 2). The dramatic increase in Ksat indicates that gravel contents above 30% changed the pore size distribution and resulted in larger pores that allow significant flow. This is in contrast to the "bricks and mortar" model proposed by Bouwer and Rice (1984) to explain the observed decreased Ksat with increased rock fragment content.

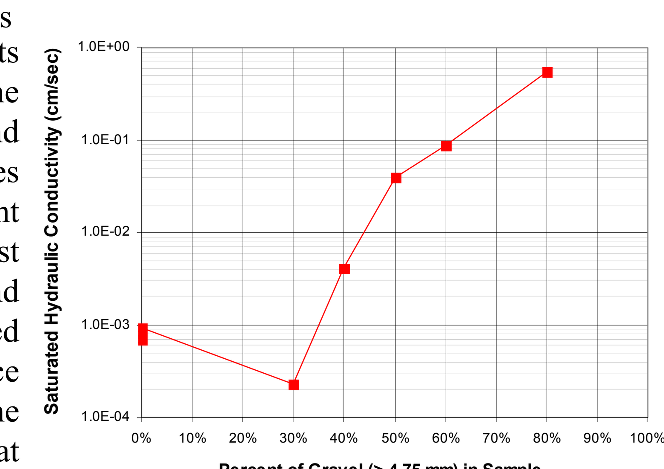

Figure 2. Average saturated hydraulic conductivity vs. percent of gravel in sample

Moisture Retention Characteristics and Predicted Unsaturated Hydraulic Conductivity

MRC data and the predicted hydraulic conductivity vs matric potential function for the <0.85 mm, <2 mm and <4.75 mm diameter materials are shown in Figure 3. The MRC and hydraulic conductivity functions for the three fine-earth fraction distributions are similar suggesting that the finest particles (< 0.85 mm) control the unsaturated flow characteristics.

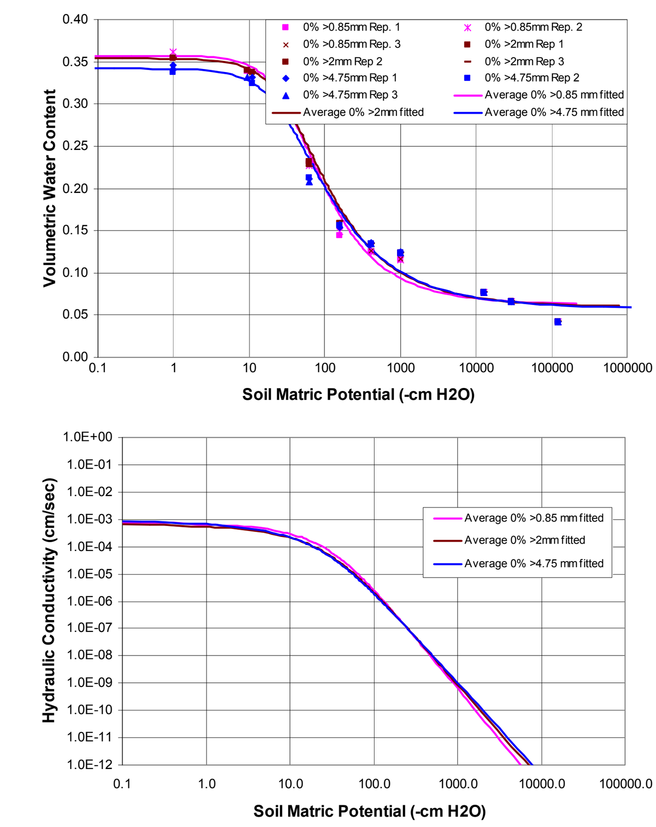

Figure 3. MRC data and predicted hydraulic conductivity matric potential functions for fine-earth samples

Figure 4 shows the MRC data and predicted hydraulic conductivity vs matric potential for the gravel content samples. The MRC data indicates that increasing gravel contents above 30% caused the air entry value and moisture retention during initial drainage to decrease. This behavior is consistent with larger pore sizes that drain under low (less negative) matric potentials. In addition, the water contents for the various gravel fraction samples appear to converge at around -1000 cm. Matric potential data collected on the fine-earth fraction at low matric potentials (i.e. < -10,000 cm) provided a poor fit with the wetter point data, consequently, the MRC data for the gravel soils was modeled without the dry point fine-earth data.

The predicted hydraulic conductivity functions for the gravel soils show a relatively parallel decrease to the 0% gravel content soil over the initial -200 cm of matric potential. With the exception of the 30% gravel content soil, the predicted unsaturated conductivities increase with increasing gravel content. The fitted MRC curves also consistently predict higher water contents for the increased gravel content soils. These predicted values suggest that assuming water contents decrease proportionally with increasing gravel content may be incorrect.

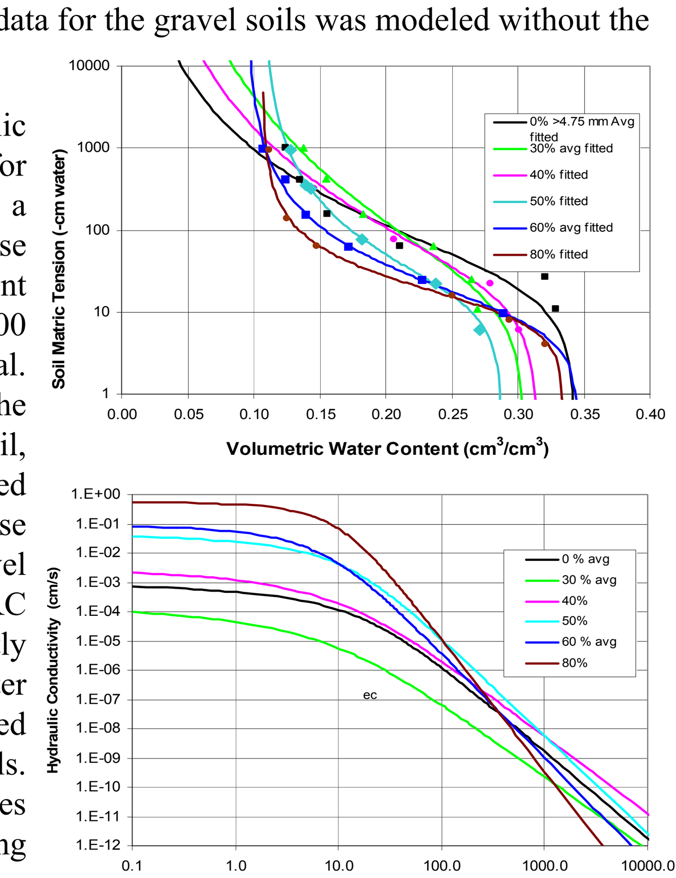

Figure 4. MRC data and predicted hydraulic conductivity - matric potential functions for gravel content samples

In other words, water may still be held on gravel surfaces or within matrix pores, even though it may not be available for flow (i.e. a dual porosity system). Certainly, the significant increase in Ksat values suggests that a dual (or more) porosity matrix most likely exists in the soils with greater than 40% gravel content. Recent work by Zhang and Chen (2005) indicates that hydraulic conductivity functions for multi-modal porosity systems can be developed via the addition of the independent hydraulic conductivity functions for each type of matrix porosity.

Conversely, there could be consistent laboratory error at matric potentials less then -1000 cm. Further experimentation is ongoing to determine gravel content relationships and whether laboratory error is present.

Table 1. Summary of Hydraulic Properties from Saturated Hydraulic Conductivity and Moisture Retention Testing

Sample Number	Dry Bulk Density (g/cm^3)	Saturated Hydraulic Conductivity (cm/s)[1]	Variance in Saturated Hydraulic Conductivity Replicates (cm/s)[1]	Void Space Characteristics (cm^3/cm^3)		Unsaturated Hydraulic Parameters[2,3]			
				Porosity[2]	Saturated Water Content[2]	alpha (1/cm)	n (dimension-less)	Residual Water Content (cm^3/cm^3)	Coefficient of Determination (R^2)
80% > 4.75 mm	1.67	5.50E-01	NA	0.313	0.334	0.087	1.42	0.0010	0.9676
60% > 4.75 mm Average	1.57	9.10E-02	6.7E-04	0.355	0.346	0.125	1.32	0.0070	0.9884
50% >4.75 mm	1.68	4.0E-02	NA	0.318	0.287	0.046	1.31	0.0140	0.9842
40% > 4.75 mm	1.67	4.1E-03	NA	0.321	0.314	0.036	1.35	0.0230	0.9947
30% > 4.75 mm Average	1.65	3.09E-04	6.8E-08	0.333	0.304	0.032	1.32	0.0230	0.9914
0% > 4.75 mm Average	1.50	9.20E-04	1.2E-09	0.399	0.343	0.039	1.34	0.0000	0.9411
0% > 2 mm Average	1.51	7.00E-04	7.0E-10	0.397	0.354	NA	NA	NA	NA
0% > 0.85 mm Average	1.50	7.87E-04	5.3E-10	0.399	0.357	NA	NA	NA	NA

[1] "Average" values are geometric mean of three sample replicates
[2] Unsaturated parameters calculated with RETC v6.0 code (van Genucten, et. al., 1991), van Genucten M=1-1/N
[3] The arithmetic mean of matric potential and water contents were used to calculate the unsaturated parameters

CONCLUSIONS

This study did not replicate the results reported by Bouwer and Rice (1984). Additionally, these results suggest that the common laboratory practice of only testing the fine-earth fraction and then using correction factors could provide very erroneous results (orders of magnitude). The hydraulic properties of the fine-earth material samples were controlled by the smaller diameter materials (<0.85mm). Ksat decreased with up to 30% gravel content (>4.75 mm), but increased dramatically at higher gravel contents. This is in direct contrast to the findings of Bouwer and Rice, 1984, who found that Ksat was inversely proportional up to 70% gravel contents when uniform gravel size and fine-earth fractions were used.

In this study, as the gravel content increases, larger size pores are created, and/or insufficient fine material is available to occupy the pore space. The larger clast supported pores significantly affect the pore size distribution and result in increased Ksat. Resultant pore sizes will depend upon the amount and the distribution of the gravel material.

Moisture retention characteristics were also affected by increasing gravel contents. MRC data showed that the air entry value and the amount of retained water at low matric potentials decreased with increasing gravel contents. In addition the predicted unsaturated hydraulic conductivity also increases with increasing gravel contents at the low matric potentials. However, the retained water in all of the different gravel soils appear to possibly converge at tensions less than -1000 cm, suggesting that a dual porosity type system may exist at gravel contents greater than 30%. This also suggests that assuming the water contents decrease proportionally with increasing gravel content at low matric potentials may be incorrect.

These data raise a number of questions that deserve further investigation. The following is recommended:

- Additional replicate laboratory tests be performed on the 40%, 50% and 80% gravel content soil to ensure data quality;
- Large core tests be performed on 10% and 20% gravel soil mixtures to determine the correlation between gravel content and hydraulic properties between 0% and 30% gravel.
- Large core tests be performed on 30%, 40%, 60% and 80% mixtures at high bulk densities to assess the affect of increasing bulk density on hydraulic properties.
- Additional testing of the fine-earth fraction and modeling at low (dry) matric potentials

REFERENCES

Bouwer, H. and R. C. Rice. 1984. Hydraulic properties of stony vadose zones. *Ground Water* 22(6):696-705.