# The hydraulic conductivity of sands with dispersed oversized particles

La conductivité hydraulique des sables avec les particules surdimensionnées dispersées

J.J. Gutiérrez
*Graduate Student, Department of Civil and Environmental Engineering, University of Pittsburgh*

L.E. Vallejo
*Professor, Department of Civil and Environmental Engineering, University of Pittsburgh*

C.I. García
*Professor, Department of Mechanical Engineering and Materials Science, University of Pittsburgh*

ABSTRACT

Engineered fills, glacial tills, mudflows, debris flows, residual soils, and colluvial deposits have a structure consisting of a soil matrix (e.g. sand) and large dispersed particles (e.g. gravel) mixed in the matrix. Mixtures of this type have received little attention in soil mechanics. The purpose of this study was to evaluate the effect of dispersed particles on the permeability of sand-gravel mixtures. Constant head permeability tests (ASTM D 2434-68) were conducted on samples having 63.5 mm in diameter and 155 mm in height. The samples were made of a matrix of Ottawa sand ($d_{ave}$ = 0.725 mm) and dispersed particles with an average diameter of 11.1 mm. The percentage by volume of gravel in the mixtures was varied between 0% and 14%. The results indicated that the permeability of the mixture decreased as the volume percentage, B, of gravel in the matrix increased. It was determined that the permeability of the mixture, $K_m$, can be obtained from the permeability of the sand matrix, $K_s$, and the percentage by volume, B, of the gravel in the mixture by using the relationship: $K_m = K_s[(1 - B)/(1 + B/2)]$. Only $K_s$ of the sand matrix and the percentage by volume, B, of the dispersed gravel need to be known in order to obtain the permeability of the mixture, $K_m$. The effect of clusters of dispersed particles in the sample was also investigated. It was found that the permeability of mixtures with clusters depends on the relative location of the clusters within the mixture.

RÉSUMÉ

Les suffisances machinées, glaciaires laboure, des coulées de boue, les débris coulent, les sols résiduels, et les dépôts colluvial ont une structure se composer d'une matrice de sol (par exemple sable) et de grandes particules dispersées (par exemple gravier) mélangées dans la matrice. Les mélanges de ce type ont suscité peu d'attention dans la mécanique de sol. Le but de cette étude était d'évaluer l'effet des particules dispersées sur la perméabilité des mélanges de sable et gravier. Les essais principaux constants de perméabilité (ASTM D 2434-68) ont été effectués sur des échantillons ayant 63.5 millimètres de diamètre et 155 millimètres de hauteur. Les échantillons ont été faits d'une matrice du sable d'Ottawa (dmoyen = 0.725 millimètre) et ont dispersé des particules avec un diamètre moyen de 11.1 millimètres. Le pourcentage par le volume de gravier dans les mélanges a été varié entre 0% et 14%. Les résultats ont indiqué que la perméabilité du mélange a diminué pendant que le pourcentage de volume, B, du gravier dans la matrice accrue. On l'a déterminé que la perméabilité du mélange, Km, peut être obtenue à partir de la perméabilité de la matrice de sable, de Ks, et du pourcentage par le volume, B, du gravier dans le mélange en employant le rapport : Km = Ks [(1 - B) (1 +B/2)]. Seulement Ks de la matrice de sable et du pourcentage par le volume, B, de la nécessité dispersée de gravier d'être connu afin d'obtenir la perméabilité du mélange, kilomètre. L'effet des faisceaux des particules dispersées dans l'échantillon a été également étudié. On l'a constaté que la perméabilité des mélanges avec des faisceaux dépend de l'endroit relatif des faisceaux dans le mélange.

Keywords : hydraulic conductivity, dispersed oversized particles, clusters

## 1 INTRODUCTION

Materials forming part of engineered fills, glacial tills, solifluction sheets, mudflows, debris flows, residual soils, and colluvial and desert soil deposits have a distinct structure, this consisting of a mixture of a soil matrix (sand, clay, silt or a combination of these soils) and large particles of gravel that are dispersed (the large particles do not interact) in the soil matrix (Fragaszy et al. 1992; Vallejo 1989, 2001; Vallejo & Lobo-Guerrero 2004). Soil Mechanics has dealt mainly with the study of three main soil types: sands, silts, and clays. However, mixtures of soils such as sands with dispersed rock particles (which are commonly found in nature and in earth construction projects) have received very little attention.

The purpose of this study was to evaluate the effect that different percentages by volume (or weight) of dispersed oversized particles have on the hydraulic conductivity of sand-gravel mixtures. The relationship between volume proportion of dispersed oversized particles and hydraulic conductivity was tested on samples in which dispersed particles were uniformly distributed throughout the sample volume. In addition to this type of test, a set of tests was designed to consider clusters of dispersed particles located at different positions across the depth of the sample.

## 2 SAMPLE PREPARATION

Constant head permeability tests (ASTM D 2434-68) were conducted on samples having 63.5 mm in diameter and 155 mm in height. The samples tested were made of a matrix of Ottawa sand ($d_{ave}$ = 0.725 mm) and dispersed oversized particles with an average diameter of 11.1 mm. The percentage by volume (or weight) of gravel in the mixtures were varied between 0% and 14% (21% by weight). In order to explore the influence of dispersed particle proportion on the bulk hydraulic conductivity of the sample, dispersed particles were organized in layers equally spaced across the depth of the sample.

*Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*
*M. Hamza et al. (Eds.)*

*doi:10.3233/978-1-60750-031-5-163*

Figure 1. Layer of dispersed large particles in sand matrix

Figure 2. Layer of rotated dispersed large particles in sand matrix

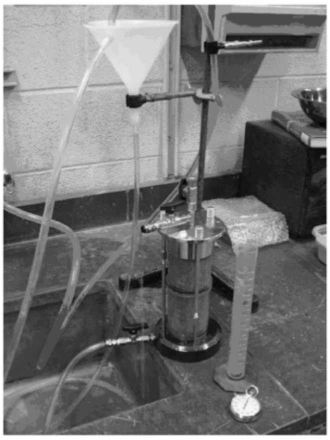

Figure 3. Test assembly

As shown in figures 1 and 2, particles in a layer were rotated 45 degrees with respect to the adjacent layer since no particular alignment was desired. The rotation of dispersed particles was thought to give the sample a sense of randomness as in a natural situation. Four different proportions of dispersed particles were tested, namely 0%, 1.4%, 9.8%, and 14% by volume (0%, 2.2%, 15%, and 21% by weight). The number of layers of dispersed particles to achieve the 14% level was 16, for a total of 64 dispersed particles; 11 layers for the 9.8% level, for a total of 44 particles, and one layer with 6 particles for the 1.4% level.

For the second type of test, aimed at studying the influence of dispersed particle clusters at varying locations accross the depth of the sample, the same configuration of layers as in figures 1 and 2 was used with a total of 4 layers or 16 particles. The location of the cluster was varied at 7 different locations across the depth of the sample (Figure 4). The proportion by volume of the cluster in the sample was equal to 3.19%.

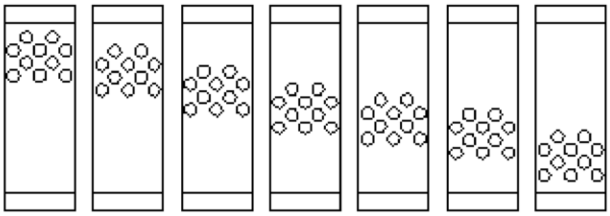

Figure 4. Varying location of dispersed particle cluster

## 3 EFFECT OF DISPERSED PARTICLE PROPORTION

Four different proportions (B) by volume were tested: 0% (sand matrix alone), 1.4%, 9.8%, and 14% as described in the previous section. In order to find the effective hydraulic conductivity of the sample itself, the following adapted formula (Chik 2004) was employed in order to isolate the effect of the hydraulic conductivity of the porous stones:

$$K_{equivalent} = \frac{h}{\frac{h_1}{K_1} + \frac{h_{sample}}{K_{effective}} + \frac{h_2}{K_2}} \tag{1}$$

$K_{equivalent}$ is the measured hydraulic conductivity of the sample and porous stones combined. h is the total height of sample and porous stones. $h_1$ and $h_2$ are equal and stand for the thickness of a porous stone, and $K_1$ also equals $K_2$ and stands for the hydraulic conductivity of the porous stones, which was measured by Chik (Chik 2004) and equals 0.0145 cm/s.

Table 1. Test results for various proportions by volume, B

| Stone weight proportion, $C_w$ | $\rho_C$ [g/cm$^3$] | $\rho_P$ [g/cm$^3$] | B | $K_{\_effective}$ [cm/s] |
|---|---|---|---|---|
| 0% | | | 0.0% | 0.080 |
| 2.20% | 1.71 | 2.70 | 1.4% | 0.079 |
| 15.00% | 1.76 | 2.70 | 9.8% | 0.070 |
| 21.00% | 1.80 | 2.70 | 14.0% | 0.054 |

Proportions by volume were found from proportions by weight with help of the following equation (Vallejo & Lobo-Guerrero 2004):

$$B = \frac{\rho_c}{\rho_p} C_w \tag{2}$$

B is the proportion of dispersed particles by volume; $\rho_c$ is the density of the composite, $\rho_p$ stands for the density of the dispersed particles, and $C_w$ is the proportion of dispersed particles by weight.

Figure 5 graphically depicts the results presented in Table 1.

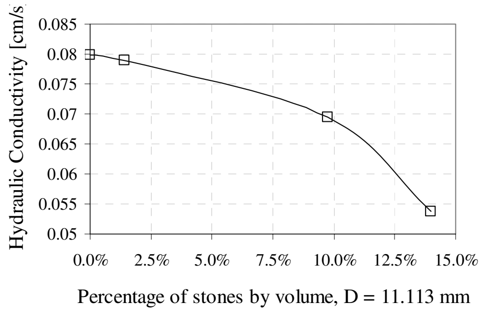


Figure 5. Hydraulic conductivity as a function of volume proportion of uniformly dispersed particles

## 4 EFFECT OF CLUSTER LOCATION WITHIN SAMPLE

Seven different positions of the cluster of dispersed particles were tested at the exact same proportion by volume (16 dispersed particles), equal to 3.19% (Figure 4). Table 2 shows the different magnitudes of hydraulic conductivity for various positions of the cluster centroid within the sample measured from the top (water flowing from top to bottom).

Table 2. Effect of cluster location within sample

| Cluster centroid position from top [cm] | K [cm/s] |
|---|---|
| 3.1 | 0.0586 |
| 4.4 | 0.0701 |
| 6.2 | 0.0855 |
| 7.8 | 0.0709 |
| 8.8 | 0.0673 |
| 10.1 | 0.0551 |
| 12.1 | 0.0565 |

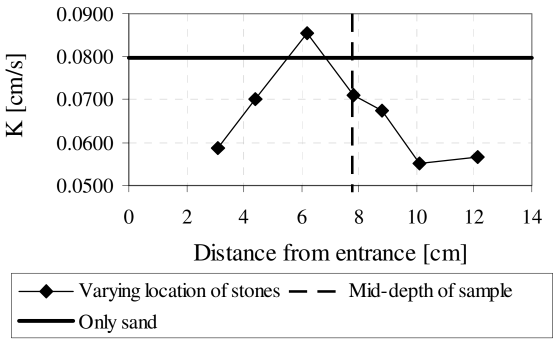


Figure 6. Hydraulic conductivity as a function of cluster location

Figure 6 depicts the behavior of hydraulic conductivity of composite systems as a function of the relative position of the dispersed particle cluster within the sample. There seems to be an optimal location of the cluster for which the hydraulic conductivity reaches a peak value. This location seems to be close to the center of the sample (Figure 6). Also, the peak value for K was found to be greater than the hydraulic conductivity of the samples made of sand alone, revealing the complexity of behavior exhibited by this type of mixture.

## 5 DISCUSSION

The effect of dispersed oversized particles in a sand matrix is to reduce the effective area across which water flows. Since the measured hydraulic conductivity is based on a constant area A which is the cross sectional area of the test cylinder, the bulk discharge per unit of area or bulk velocity, v, turns out to be reduced as the proportion of dispersed particles by volume is increased. Even though the hydraulic conductivity of the matrix material (i.e. sand) remains constant, it is the bulk hydraulic conductivity of the system what is important for practical purposes. Since the dispersed particles do not make contact with each other, they create no room for large voids in the contact interface, thus acting as large independent barriers to water flow.

A linear relationship between the hydraulic conductivity of the matrix, the proportion of dispersed oversized particles by volume, and the composite hydraulic conductivity seems to exist for a wide range of volume proportions, and is given by:

$$K_m = K_s\left(\frac{1-B}{1+B/2}\right) \tag{3}$$

Equation 3 is useful in that only the volume proportion of a sample and the hydraulic conductivity of the matrix need to be known in order to estimate the hydraulic conductivity of the composite system.

The effect of cluster location within a sample adds complexity to the behavior of porous flow in composite systems. On one hand, there seems to be a unique relationship between hydraulic conductivity of such systems and the proportion of dispersed particles by volume, provided the distribution of dispersed particles within the matrix is uniform. On the other hand, clusters of dispersed particles at varying locations within the sample can have a huge effect on the bulk hydraulic conductivity, even while keeping the proportion by volume of dispersed particles constant. The two phenomena can be visualized in Figure 7. The verticality of the set of points at a proportion of dispersed particles by volume of 3.19% dramatically shows the influence of cluster location within the sample. This result seems of importance because clusters could be present in many natural soil deposits.

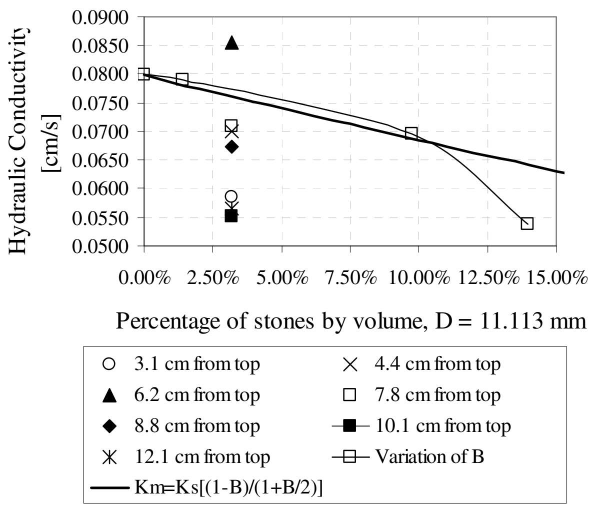


Figure 7. Graphical summary of the study results

Figure 6 suggests that an optimal hydraulic conductivity is reached when the location of the cluster is close to and above mid-depth of the sample. On the other hand, hydraulic conductivity drops dramatically when the cluster is at both entrance and exit zones of the cylinder. This phenomenon seems to be related to the length of the sample that is affected by the cluster. When the cluster is at the center of the sample, the water not only accelerates within the cluster but in regions close to the cluster which are located just above and below the cluster. When the cluster is on top or at the bottom of the sample, the regions affected by the cluster decrease in number. When the cluster is on top of the sample, there is only one region affected (below the cluster location). When the cluster is at the bottom of the sample, there is only one region affected by the presence of the cluster (above the cluster location). Thus the average velocity of the water (or the hydraulic conductivity) is higher for the sample with the cluster located at the central portion of the sample than for the samples that have the cluster at either the bottom or top of the sample. This ability of water to accelerate seems to be characterized by a certain measure of symmetry with respect to the optimal central location of the cluster. Thus, the entrance and exit zones of the sample are not good locations for the cluster in order for the samples to reach high magnitudes of hydraulic conductivity.

Another interesting feature of this type of flow is that when the cluster is located at the optimum cluster position (center of sample), the hydraulic conductivity of the sample achieves a magnitude that is higher than that of the sample made of sand matrix alone. The reason for this seems to be that when the water travels within the cluster, it has to travel at high velocities because of the reduced space in the sand matrix within the cluster. This does not take place on the sample made only of a sand matrix where the flow is slow and laminar. Thus, for the optimal location of the cluster, the sample with the cluster has a higher hydraulic conductivity value than the sample made of sand alone.

Another important point with respect to the water flow in the samples with clusters relates to Darcy's law. Darcy's law applies to a laminar type of water flow in porous media. If water travels at high velocities in porous media, Darcy's law does not apply because the water flow is turbulent instead of laminar (Mitchell & Younger 1967). Thus, the results of the samples with clusters seem to violate Darcy's law because of the high velocity values of the water flow through the spaces in between the large particles forming part of the clusters.

## 6 CONCLUSIONS

Hydraulic conductivity tests on cylindrical samples made of a mixture of sand and dispersed large particles (gravel) indicated the following:

(1) The hydraulic conductivity of the mixtures was affected by the presence of the oversized particles. The hydraulic conductivity of the mixtures was found to decrease as the percentage by volume of the oversize particles increase in value. This was the case when the large particles were uniformly dispersed throughout the tested cylindrical samples.

(2) If the oversized particles were arranged in clusters in the cylindrical samples, their hydraulic conductivity varied depending on where the clusters were located. If the clusters were in the middle section of the samples, the hydraulic conductivity values of the samples were the highest when compared with those measured in the samples with the clusters in position other than the middle or those measured in samples with no oversized particles at all. When the clusters of oversized particles were located at the top or the bottom of the cylindrical samples, their hydraulic condutivity was smaller than that measured in the sample with no oversized particles.

(3) Darcy's law does not seem to apply in the samples with clusters. The water flow in the spaces between the particles forming part of the clusters moves at high velocities making the flow turbulent instead of laminar. Darcy's law assume the water flow to be of the laminar type. It does not apply when the water flow is turbulent.

## REFERENCES

ASTM. 2006. Standard test method for permeability of granular soils (constant hed, D 2434-68). ASTM Book of Standards, Vol. 0.4.08, West Conshohocken, Pennsylvania.

Chik, Z. 2004. The effect of fragmentation on the engineering properties of granular materials; laboratory and fractal analyses, Ph.D. dissertation, University of Pittsburgh.

Fragaszy, R.J., Su, W., Siddiqi, F.H., and Ho, C.L. 1992. Modeling the strength of sandy gravel. ASCE Journal of Geotechnical Engineering Vol. 118, No. 6: 920-935.

Mitchell, J.K., and Younger, J.S. 1967. Abnormalities in hydraulic flow through fine-grained soils. American Society for Testing and Materials, STP 417: 106-139.

Vallejo, L.E. 1989. An extension of the particulate model of stability analysis for mudflows. Soils and Foundations, Vol. 29, No. 3: 1-13.

Vallejo L.E. 2001. Interpretation of the limits in shear strength in binary granular mixtures. Canadian Geotechnical Journal, Vol. 38, No. 4: 1097-1104.

Vallejo, L.E. and Lobo-Guerrero, S. 2004. The elastic moduli of clays with dispersed oversized particles. Engineering Geology, Vol. 78: 163-171.