The reinforcement of soils by dispersed oversized particles

Le renforcement des sols par les particules trop grandes non réparties uniformément

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ABSTRACT: Soils containing dispersed large particles (greater than # 4 sieve) form part of many engineered fills, glacial tills, debris flows, and residual soil deposits. Very little is known about the effect that the large particles have on the shear strength of the soil-large particles mixtures. In this study, the influence of the large particles on the shear strength of the mixtures was evaluated experimentally and numerically. The experimental analysis used direct shear tests on simulated granular materials containing large dispersed particles. The numerical analysis used the Discrete Element Method (DEM). The laboratory and the DEM simulation results indicated that the shear strength of the mixtures increased with the concentration (C_a) of the simulated large particles in the mixtures. Also, this study established that the shear strength of the simulated granular materials with dispersed large particles, S_c, can be obtained if one uses the following relationship: $S_c = S_m (1 + M C_a)$. In this relationship, S_m is the shear strength of the simulated soil matrix in which the large particles are dispersed, and M is a constant that varied between 1 and 2 for the numerical and laboratory analyses.

RÉSUMÉ :Les sols contenant des particules dispersées de grande taille (supérieure à tamis # 4) constituent la majorité des remblais, argiles glacières à blocs, des coulées d'éboulis et des dépôts résiduels de sol utilisés dans la construction. Peu de travaux existent sur l'effet que les grosses particules ont sur la résistance au cisaillement des mélanges de particules de sol de grande taille. Dans cette étude, l'influence des grosses particules sur la résistance au cisaillement des mélanges a été évalué expérimentalement et numériquement. L'analyse expérimentale utilisée essais de cisaillement direct sur simulées matériaux granulaires contenant de grandes particules dispersées. L'analyse numérique utilisé la méthode des éléments discrets (DEM). Les essais en laboratoire et les résultats des simulations ont indiqué que la résistance au cisaillement des mélanges augmente avec la concentration (Ca) des particules de grandes tailles simulées. En outre, cette étude a établi que la résistance au cisaillement des matériaux granulaires simulées avec des grosses particules dispersées, S_c, peut être obtenu si l'on utilise la relation suivante: $S_c = S_m (1 + M Ca)$. Dans cette relation, S_m c'est la résistance au cisaillement de la matrice du sol simulé dans lequel les grosses particules sont dispersées, et M est constante qui varie entre 1 et 2 pour les analyses numériques et de laboratoire.

KEYWORDS:granular mixtures, shear strength, laboratory tests, DEM analysis.

1INTRODUCTION.

Materials forming part of natural slopes and engineered fills have a distinct structure, this consisting of a mixture of a soil matrix (sand) and large particles of gravel that are dispersed (fragments do not interact) in the soil matrix . The rock fragments are composed of materials larger than the No. 4 sieve (Magier and Ravina, 1982; Poesen and Lavee, 1994; Fragaszy et al. 1992; Budiman, et al., 1995 and Vallejo 1989, 2001) (Fig 1). Soil Mechanics has dealt mainly with the study of three main soil types: sands, silts, and clays. However, mixtures of soils such as those shown in Fig. 1 are more commonly found in nature and in earth construction projects than pure sands, silts and clays. Since the determination of the mechanical properties (i.e. shear strength) of mixtures such as those depicted in Fig. 1 has heretofore received scant attention, such an investigation is indeed called for. This study reports on the mechanisms involved with the shear strength of simulated granular materials with dispersed oversized particles.

2 LABORATORY TESTING PROGRAM

2.1 *Equipment and simulated granular materials*

For the purpose of understanding the mechanisms involved in the shear strength of granular materials with dispersed large particles an open face, two-dimensional direct shear apparatus was used (Fig. 2) This apparatus is called the Plane stress Direct Shear Apparatus (PSDSA) (Vallejo, 1991). The granular matrix will be simulated by a mixture of wooden sticks. Wooden sticks are strong and can be easily shaved into polygons as their cross sectionalareas. These polygons resemble the profiles of actual

Figure 1.Natural slope in Wisconsin made of a soil-rock mixture

granular materials (Fig. 3) .The wooden sticks forming the granular matrix will have 3 different average diameters. These will be equal of 6, 4, and 2.7 mm. Thus, thegranular matrix as a whole will be made of sticks having an average diameter equal to 4.2 mm. The oversized large particles will be simulated by rough wooden circular cylinders with a diameter equal to 12 mm. The irregular sticks as well as the circular cylinders have a length equal to 25 mm. The mixture of wooden sticks and cylinders were placed inside two U forms that comprise the box in the Plane Stress Direct Shear apparatus (PSDSA)(Figs. 2 and 3). The area inside the two U forms is a square area with sides measuring 7.6 cm in length. The open face of the shear apparatus formed by the two U forms allows the recording of the changes taken place in the mixture during shearing. Two proving rings measure the normal and shear forces applied to the mixtures. Dial gauges measure the normal and shear displacements. The changes in fabric experienced by the mixture as well as the interaction between the granular matrix and the large particles during shear was recorded using digital photographs of the open face of the PSDSA .

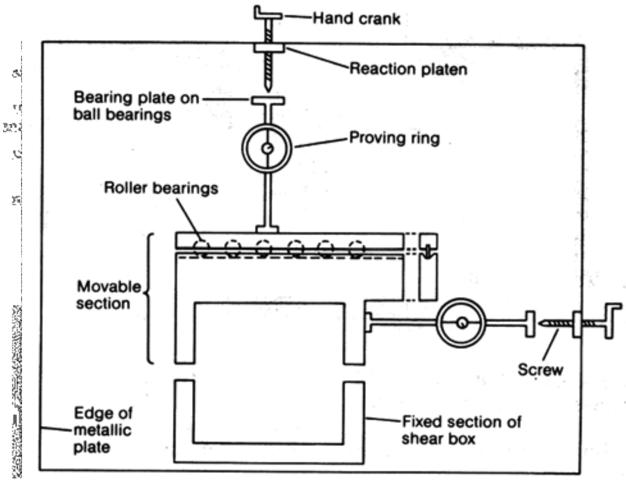
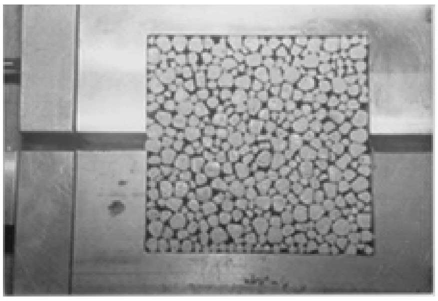


Figure 2. The Plane Stress Direct Shear Apparatus (PSDSA) (Vallejo, 1991)

(a)



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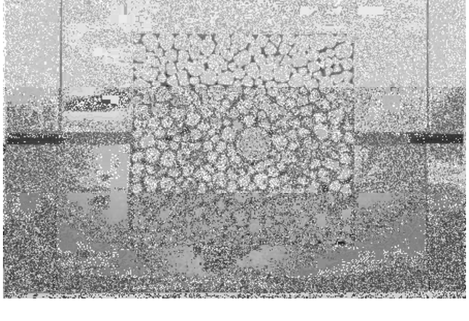

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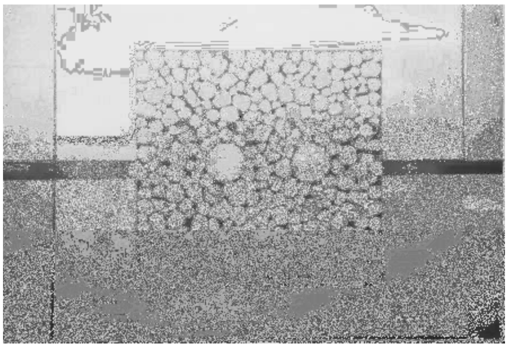

Figure 3. Simulated granular mixture in the PSDSA before shearing: (a) sample with no oversized particles, (b) sample with one oversized particle, (c) sample with two oversized particles.

2.2 *Direct shear testing in the PSDSA*

The simulated granular mixtures depicted in Fig. 3 were subjected to shear in the PSDSA. The shear testing of the mixtures were carried out using two normal stresses. These were equal to 99.6 and 199.3 kPa. The rate of shearing of the mixtures was equal to 2mm/min. Fig. 4 shows the shear stress versus the horizontal displacement relationships for the sample containing the matrix alone and the samples with one and two 12 mm in diameter cylinders representing the large particles (Fig.3).

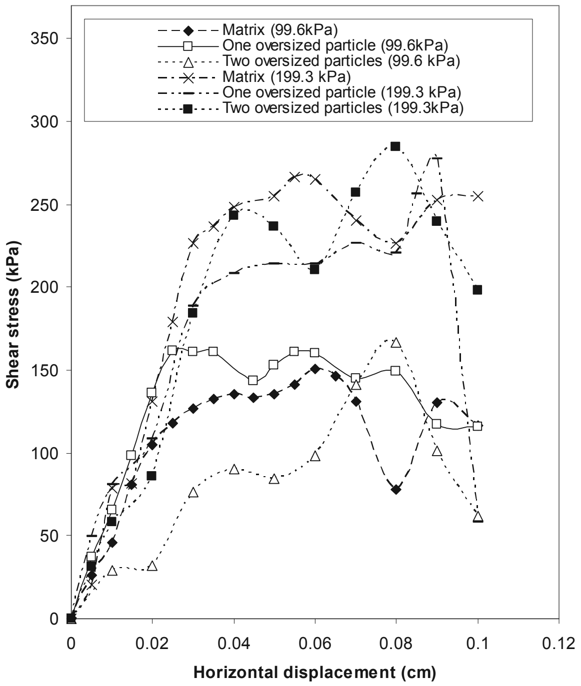

Figure 4. Shear stress versus horizontal displacement for the samples tested in the PSDSA

The peak values of the shear stress plots of Fig. 4 have been used to plot the shear strength versus the area concentration of the large cylinders in the sample. This area concentration is equal to the cross sectional area of the large cylinders in the mixture divided by the area of the whole mixture (7.62 cm x 7.62 cm) (Fig. 3). The resulting plot is shown in Fig. 5. This figure shows that the shear strength of the mixture increases as the number of large cylinders increases in the mixture. An equation that represents this increase is of the form:

$$S_c = S_m\,(1 + 2C_a) \qquad (1)$$

where S_c is the shear strength of the mixture, S_m is the shear strength of the matrix, and C_a is the area concentration of the large cylinders in the mixture. The results of Fig. 5 and Eq. (1) indicate that the overall shear strength of the simulated granular mixtures increases with an increase in the number of the large cylinders. Thus, in the case of real sand-gravel mixtures, it is expected that the shear strength of these mixtures will increase with the volume concentration of the gravel in the mixtures.

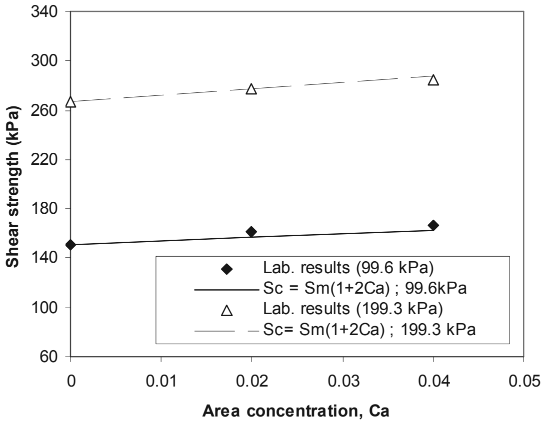

Figure 5.Shear strength of the simulated granular mixtures in function of the area concentration of the large cylinders in the mixture.

3 ANALYSIS OF THE LABORATIRY RESULTS USING THE DISCRETE ELEMENT METHOD (DEM)

3.1 Configuration of the samples

The PFC^{2D} program produced by Itasca (Itasca Consulting Group Inc., 2002) was used for the simulation of the direct shear tests on granular material with dispersed oversized particles. The first step on the configuration of the sample was the construction of the shear box. The box had two sections each with a width of 6 cm and a height of 1.5 cm. The two sections were placed on top of each other and after the circular particles were generated inside the box, the gap between the two sections was maintained at 0.5 mm. The depth of the sample was assumed to be equal to 1 m. The shear and normal stiffness of the walls forming the box were set to 1x10^9 N/m. The coefficient of friction between the circular particles and the particles and the walls was set to 0.7.

After the construction of the box, 1000 particles representing the granular matrix and having a diameter of 0.63 mm were generated inside the box. The density of the particles was set to 2,500 kg/m^3, their normal and shear stiffness were set to 1x10^8 N/m. Their positions were randomly chosen by the program, having the limitation of no overlap between particles. A normal gravity field (9.8 cm/sec^2) was used during the simulation. In order to simulate the dispersed oversized particles, 52 particles of diameter equal to 0.63 mm were removed and replaced by an oversize particle measuring 5 mm. If an additional oversize particle was needed to be placed in the sample, the same number of smaller particles were removed and replaced by another large particle of 5 mm in diameter (Fig. 6). The tests were run under a constant normal compressive load equal to 2x10^4 N. After the normal compressive force was applied to the sample, the shearing started by moving the upper section of the shear box to the left with a constant velocity of 0.44 mm/sec. The tests ended when the horizontal displacement was equal to 5 mm. Also, using a subroutine available in the PFC^{2D} code, one can obtain the value of the shear stress in function of the horizontal deformation. In this study, the peak shear resistance that was measured in the simulationrepresents the shear strength of the mixture.

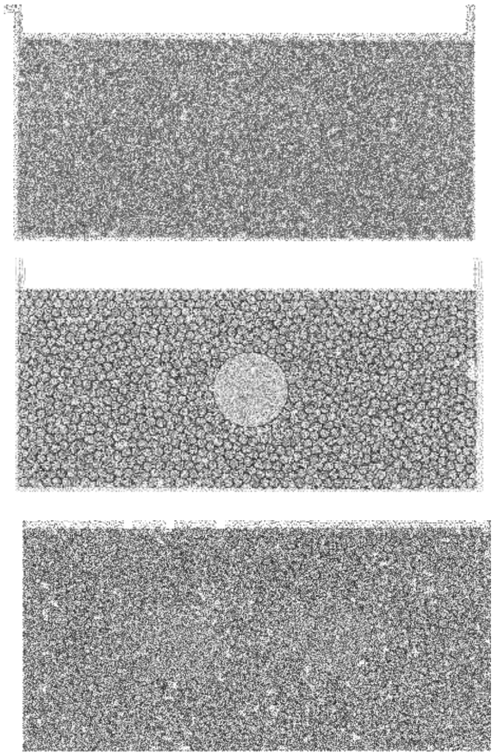

Figure 6. Simulated samples using DEM that contained zero, one, and two large dispersed particles.

3.2 Results of the simulations

The DEM simulations of the direct shear tests were carried out on mixtures having zero, one, and two oversized particles. Figs 7 shows typical DEM results for the samples with zero, one and three oversized particles. These figures shows the force chains and their intensity (the thicker the force chains, the bigger are the force chain value, their maximum values are shown on top of the figures) for the samples with 3.5 mm of horizontal displacement.

An analysis of Fig. 7 indicates that the larger force chains which were compressive in nature were directed toward the large particles and were transmitted to them by the smaller surrounding particles. When the horizontal displacement in the simulated test reached a 3.5 mm value, the force chains were inclined at about 45 and 135 degrees with respect to the horizontal axis of the cross sectional area of the large particles.

It is usually assumed that when samples of granular materials with oversized particles are subjected to either compressive or direct shear stress conditions, the smaller particles in the mixture distribute the loads uniformly around the perimeter of the bigger particles. This uniform load distribution produces low compressive stresses on the bigger particles which allows them to survive without breakage (Fragaszy et al., 1992). The results shown by Fig.7 indicate that this is not the case. Under direct shear, the smaller particles concentrate on the oversized particles, large compressive forces that are exerted on a small section of the perimeter of the large particles. These high concentrated compressive forces exerted by the smaller particles on the large particles have also been found by Cheng and Minh (2009) to be effective in granular mixtures.

The peak shear stress values obtained during the shearing of the mixtures shown in Figs. 6 and 7 were plotted against the area concentration of the large cylinders in the mixture. The result of the plot is shown in Fig. 8.

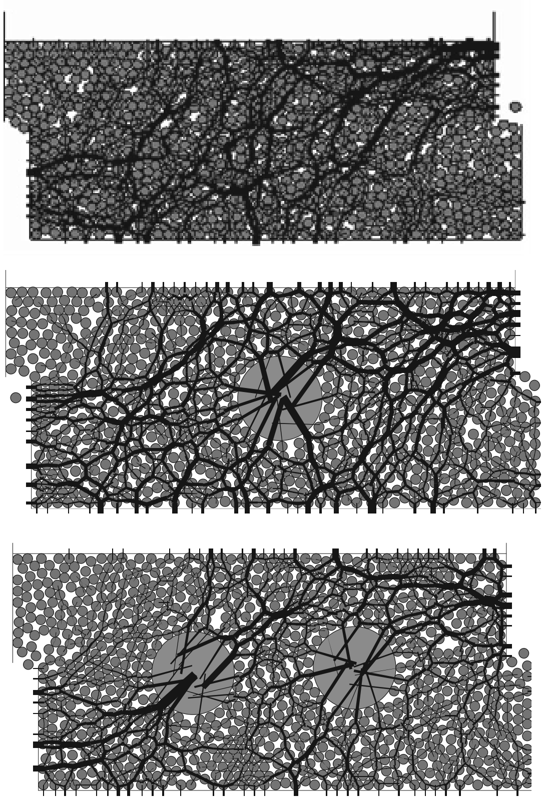

Figure 7. Force chains in the samples with zero, one and two large particles at a horizontal shear displacement equal to 3.5 mm.

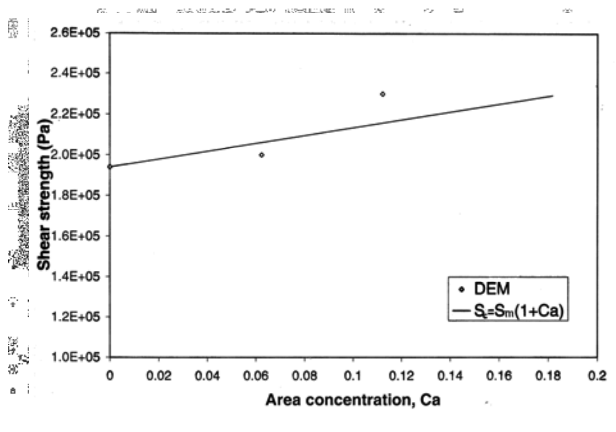

Figure 8. Shear strength versus the area concentration of the large cylinders in the simulated granular mixture.

An analysis of Fig. 8 indicates that the presence of the large cylinders in the mixture has a reinforcing effect. That is, as the number of large cylinders increase in the mixture, its shear strength also increases. The best fit line shown in Fig. 8 has an equation of the form:

$$S_c = S_m (1 + C_a) \qquad (2)$$

which is very similar to Eq. (1).

It should be noted that the DEM simulations did not represent exactly the shape of the particles forming part of the laboratory experiments. Also, the sizes of the particles used in the laboratory experiments were different than those used in the DEM simulations. However, the general results of the laboratory tests are corroborated by the DEM simulations. In addition, the DEM simulations help to explain the way internal forces are transmitted through the particles in the laboratory experiments. Thus, for the case of real sand-gravel mixtures, it is expected that the shear strength of these mixtures will increase with the volume concentration of the gravel in the mixtures. Also, it should be noted that for the case of embankments and natural slopes, the effectiveness of the oversized particles on the shear strength of the mixtures forming these structures will depend upon if the large particles are located on or near the critical failure surface (Fig.1).

4 CONCLUSIONS

In the present study the shear strength of simulated granular mixtures made of granular matrix in which large particles are embedded was carried out using laboratory and numerical analyses. Results from using both approaches indicated that the presence of the large particles has a reinforced effect in the mixtures. That is, the greater thenumber of the large particles in the mixture, the greater is the shear strength of the mixtures.

5 ACKNOWLEDGEMENTS

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