INVESTIGATION OF MICROSCOPIC BEHAVIOR OF PARTICLES IN DIRECT SHEAR TEST

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ABSTRACT
In this research, the modified version of program ELLIPSE was used to study the particle assemblages microscopic behavior during of direct shear test. Several samples were generated using different methods of particle gradation modification techniques (Scalping and Parallel). Also, effects of the particle gradation (size) on shearing behavior during direct shear test are investigated. It is found that modification of sample gradation has a significant influence on mechanical properties of coarse-grained soils. By increasing the particle size in the sample, internal friction angle and shear strength of sample increases. This observation is not influenced by stress level (vertical stress). Also, microscopic behavior of samples shows that assemblies during applying the vertical stress develop more contact normal and normal force anisotropy. So, by increasing the vertical stress, the values of anisotropy coefficients increase. Results are shown that by increasing the vertical stress in direct shear test, the rate of a_n, a_t parameters variation is reduced to about zero during samples shearing simulation. On the other hand, this parameters (a_n & a_t) are constant in particle assemblages to apply direct shearing on samples.

RÉSUMÉ

1. INTRODUCTION

The presence of large particles is the source of problem in the experimental testing of coarse-grained soils. It is always necessary to remove large particles due to limitation of laboratory specimens dimensions. Therefore, there is a need to study the effect of particle size and gradation on the behavior of granular media such as coarse-grained soils.

An alternative approach is to consider the granular material as an assemblage of particles, where the numerical processes that govern the constitutive behavior can be understood more rigorously starting from the grain scale level. Many researchers have attempted to investigate the coarse-grained soils properties by experimental tests on reduced particle size samples (Marsal, 1967&1973; Marachi et al., 1972). There are two common procedures for the specimen preparation. In “parallel gradation” technique, the laboratory reduced particle size specimens are formed with size distributions parallel to that of field material. In other method, called “scalping”, all particles considered oversized are removed from the original material.

More recently work using numerical simulation with discrete element models (DEM) offers a unique opportunity to obtain complete qualitative information on all microscopic features of assemblies of particles. The process has proved to be a very useful tool to understand the factors and mechanisms that control the constitutive behavior of granular media. In an assembly of particles, each particle interacts with its neighbors through particle to particle contacts. The method was first adapted to geotechnical engineering by cundall to study the dynamic behavior of rock masses (Cundall,1978) and numerical simulations of granular materials (Cundall and Strack,1979).

This paper describes a series of numerical tests performed using the DEM on 2D assemblages of elliptical particles to study the influence of sample size and particle gradation on shear strength of coarse-grained soils. The program ELLIPSE that was originally developed by Rothenburg and Bathurst (1992) was used in this investigation. This program, which can simulate assemblies of two-dimensional elliptical-shaped particles, was adopted and modified for the purpose of direct shear test simulations.

2. MICROSCOPIC OBSERVATION

While it is obvious that forces in granular media must be carried by means of contacts between particles, it is only recently that means of quantifying the arrangement of contacts has been developed. For any angle θ , the portion of the total number of contacts in the system which are oriented at angle θ is $E(\theta)$. The distribution of contact normal orientation is described by a function such that the fraction of all assembly contact normals falls within the orientation interval $\Delta\theta$. Rothenburg (1980) showed that the distribution of such contacts takes the form:

$$E(\theta) = \frac{1}{2\pi}\left[1 + a\cos 2(\theta - \theta_0)\right] \quad [1]$$

That a is referred to as parameter of anisotropy, and so θ_o is the major principal direction of anisotropy.

The magnitudes of contact forces in an assembly with irregular geometry vary from contact to contact. Despite the apparent randomness in the variation of contact forces, regular trends emerge when they are averaged over groups of contacts with similar orientations. The average contact force acting at contacts with an orientation can be decomposed into an average normal force component $\overline{f}^c_n(\theta)$ and an average tangential force component $\overline{f}^c_t(\theta)$. By averaging the contact forces of the contacts falling within the group of similar orientation and following the same logic as for the contact normals, symmetrical second order tensors may be introduced to describe average normal contact forces and average tangential contact forces. The average normal contact force tensor can be defined as (Bathurst, 1985):

$$\overline{f}_n(\theta) = \overline{f}^o_n[1 + a_n \cos 2(\theta - \theta_f)] \quad [2]$$

where, a_n is the coefficient of normal force anisotropy, and θ_f is the major principal direction of force anisotropy; $\overline{f}^o_n$ is the average normal contact force from all assembly contacts. The average tangential contact force tensor can be defined as:

$$\overline{f}_t(\theta) = -\overline{f}^o_n[a_t \sin 2(\theta - \theta_t)] \quad [3]$$

Where, a_t is the coefficient of tangential force anisotropy, and θ_t is the direction of anisotropy.

Rothenburg and Bathurst (1989 and 1992) presented a simplified equation by assuming coaxial directions for force and fabric tensors, and expressing the stress tensor in terms of principal stresses:

$$\frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} = \frac{1}{2}\,\frac{a + a_n + a_t}{1 + (\frac{a\, a_n}{2})} \quad [4]$$

The simplified expression suggests that the capacity of a cohesionless granular assembly to carry deviatoric loads is directly attributable to its ability to develop anisotropy in contact orientations or to withstand directional variations of average contact forces. All contributions to deviatoric load capacity are additive.

Fabric description is very important to relate micromechanical parameters to macroscopic behavior. To quantify require knowledge of the number of contacts in a sample volume and also the distribution of contact orientations for the purpose of relating average forces to stress and displacements to strains. The discrete element method can be use to obtain complete quantitative information on all microscopic features of an assembly of particles.

3. NUMERICAL SIMULATION

In this research, five assemblies with different grain size distribution that each consisting of 350 two-dimensional elliptical-shaped particles were used for the simulations. According to both modification techniques (Parallel gradation & Scalping method), the particle size of four reduced-particle-size specimens prepared. The properties of selected sample for the simulations are given in Table 1.

Table 1. Properties of selected samples.

Samples	Particle Size(mm)	Modification Technique
Sample 0	5 – 38	Original Sample
Sample 1	5 – 25	Parallel
Sample 2	5 – 9.5	Parallel
Sample 3	5 – 25	Scalping
Sample 4	5 – 9.5	Scalping

Each particle was placed randomly within the prescribed six boundary particles to generate assembly of particles (Figure 1a). For each type of elliptical shaped particles the size and the eccentricity are introduced. Particle size is represented by its diameter and the eccentricity was chosen to be 0.1 for all particles.

In this research, the numerical simulations were carried out in two stages. In the first stage, the generated assemblies that were so loose, were compacted hydrostatically. In the next stage, the assemblies were sheared in the direct shear box under constant vertical load, according with direct shear test conditions. For the numerical simulations, the program ELLIPSE was adopted and modified in order to have the capability of direct shear test simulation. For this purpose, the shape of assembly boundary, which was originally circular, was changed to a rectangular shape using six elliptical particles with high eccentricity (Figure 1). Also, the program boundary control modes was modified to simulate direct shear test conditions. The required boundary forces or displacements or servo controlled boundary conditions are applied on the boundary particles to simulate the test conditions in different stages of the simulation. In this

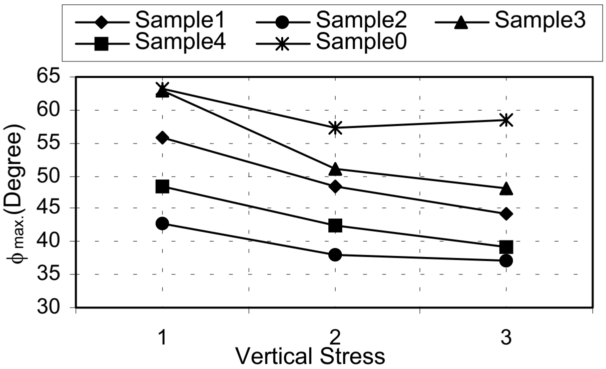


Figure 8. Peak mobilized friction angle as a function of vertical stress for different assemblies

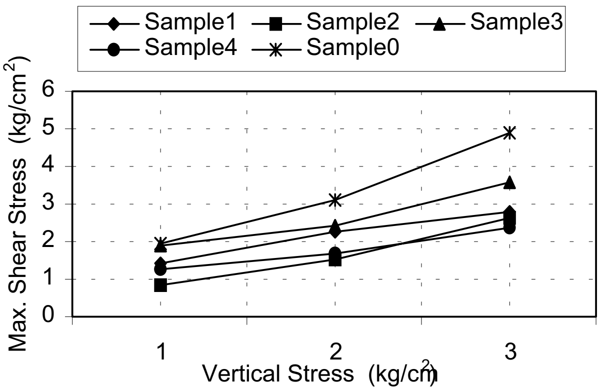


Figure 9. Maximum shear stress versus vertical stress

Also, for the samples with the same $d_{max,}$ shear strength increases if the assembly gradation is prepared using scalping method. The observed behavior is independent of stress level.

It can be concluded that coarse-grained assemblies with higher maximum particle size, posse more friction angle. Also, assemblies produced by scalping method provide more internal angle of friction. Results comparison indicate that the coarse grained samples dilate more during direct shear test. Assemblies generated by scalping method show more tendencies to dilate comparing to those produced by parallel method with the same d_{max} values.

5. SUMMERY AND CONCLUSIONS

In this research, the modified version of program ELLIPSE was used to study the particle assemblages microscopic and macroscopic behavior during direct shear test. Several samples were generated using different methods of particle gradation modification techniques (Scalping and Parallel). Each sample was initially compacted and then was sheared by the means of simulated direct shear box under three different vertical stresses (1,2&3 kg/cm^2). Also, effects of the particle gradation (size) on shearing behavior during direct shear test are investigated.

It is found that modification of sample gradation has a significant influence on mechanical properties of coarse-grained soils. By increasing the particle size in the sample, internal friction angle and shear strength of sample increases. This observation is not influenced by stress level (vertical stress). Also, it is showed that in the samples with the same range of particle size, the internal friction angle increases if the particle gradation is produced by the scalping method.

From a micro mechanical point of view, it was shown that the maximum values of $\mathbf{a_n}$ and $\mathbf{a_t}$ parameters are independent on the vertical stress levels. Also, microscopic behavior of samples shows that assemblies during applying the vertical stress develop more contact normal and normal force anisotropy. So, by increasing the vertical stress, the amount of anisotropy coefficients increases.

Presented results shown that by increasing the vertical stress in direct shear test, the rate of $\mathbf{a_n}$ & $\mathbf{a_t}$ parameters variation is reduced to about zero during shearing simulation.

6. REFERENCE

Marsal, R.J. (1967) “Large scale testing of rockfill material”, J. of the soil mechanics and foundation Division, Vol.93, No.SM2.

Marachi, N.D. & Chan, C.K. and Bolton, H.B. (1972) “Evaluation of properties of rockfill material”, J. of the soil mechanics and foundations Division, Vol.98, No.SM1.

Marsal, R.J. (1973) “Mechanical properties of rockfill”, Embankment Dam Engineering, Casagrando Volume, Hirshfield, R.C. and Polous, S.J.(eds.), John Wily & Sons Inc., Newyork, pp.109-200.

Cundall, P.A. & Marti, J. & Beresford, P. & Last, N. and Asgain, M. (1978) “Computer modelling of jointed rock masses.”, Technical Report N-76-4, Dames and Moore.

Cundall, P.A. and Strack, O.D.L. (1979) “A discrete numerical model granular assemblies”, Vol.30, pp.47-65.

Rothenburg, L. and Bathurst, R.J. (1992) “Micromechanical features of granular assemblies with planar elliptical particles”, Geotechnique 42(1) : 79-95.

Rothenburg, L. (1980), “Micromechanics of Idealized Granular Systems”, *Ph.D. Thesis*, Department of Civil Engineering, Carleton University, Ottawa, Ontario, 332 pp.

Bathurst, R.J. (1985), “A Study of Stress and Anisotropy in Idealized Granular Assemblies”, *Ph.D. Thesis*, Department of Civil Engineering, Queen's University, Kingston, Ontario, 219 pp.

Rothenburg, L. and Bathurst, R.J. (1989), “Analytical Study of Induced Anisotropy in Idealized Granular Materials”, *Geotechnique*, **39**, 4, 601-614.

Mirghasemi, A.A. and Bagherzadeh_khalkhali, A. (2002) “Influence of particle gradation on shear strength of coarse grained soils ”, 55th Canadian Geotechnical and 3rd joint IAH-CNC and CGS Conference, Canada.

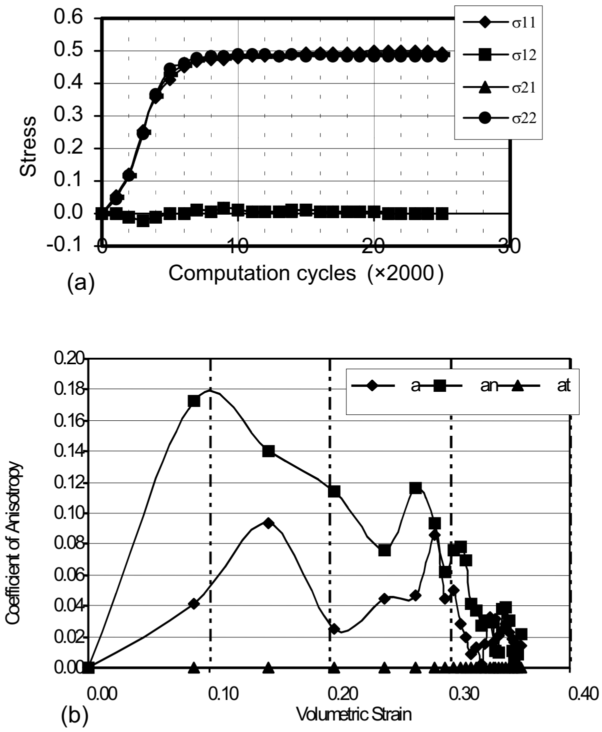


Figure 2. Results of compaction on sample 1

The following describes the main conclusions obtained from this part of simulations:

- In Figure 2-a, the stresses in particle assemblage are plotted against computation cycles. Assuming the vertical and horizontal direction for the coordinates 1 and 2, respectively, σ_{11}, σ_{12}, σ_{21} and σ_{22} define the stress tensor for the assembly. The σ_w is defined as the average of σ_{11} and σ_{22}. These figures show the accuracy of isotropic compaction in the sample, since the value of σ_{11} and σ_{22} is equal to 0.5 kg/cm^2 after about 20000 compaction cycles. Also during the simulation the shear stresses σ_{12} and σ_{21} are almost zero that indicates under hydrostatic compaction no anisotropy is developed in the assembly.

- Figure 2-b shows the independent variations of **a**, $\mathbf{a_n}$ and $\mathbf{a_t}$. The coefficient of anisotropy of contact normal force ($\mathbf{a_n}$) was found to increase during the initial stage of isotropic compaction up to the volumetric strain equal to 10 percent. The variations of **a** (the coefficient of anisotropy of contact normals) is similar to that of $\mathbf{a_n}$ parameter. This coefficient (**a**) increase to its peak value at about %15 volumetric strain and decreases continuously afterwards. The value of both coefficients reduces almost to about zero at large strains (%35 volumetric strain). This trend is due to hydrostatic pressure condition carried out on sample. The coefficient of contact shear force anisotropy ($\mathbf{a_t}$) was found to be zero during the test (isotropic compaction stage). One can clearly see that the term $\mathbf{a_n}$ is more than other anisotropy coefficients (**a** & $\mathbf{a_t}$). The strain history of the anisotropy coefficient (Figure 2-b) show the peak value of the parameter $\mathbf{a_n}$ is occurred earlier than the parameter **a**.

4.2. Assembly behavior during direct shear test

In this part, the results of direct shear simulations conducted on sample 1 are presented. The behavior of other samples is similar with respect to effect of confining pressure. The results are described in two following sections each corresponds to the one stage of direct shear test.

4.2.1. Applying the vertical stress

As indicated before, the direct shear test has been carried out with three different vertical stresses (Table 3) for each specimen. The behavior of sample1 during this stage of simulations has been shown in Figures 3 and 4. The main conclusion can be summarized as :

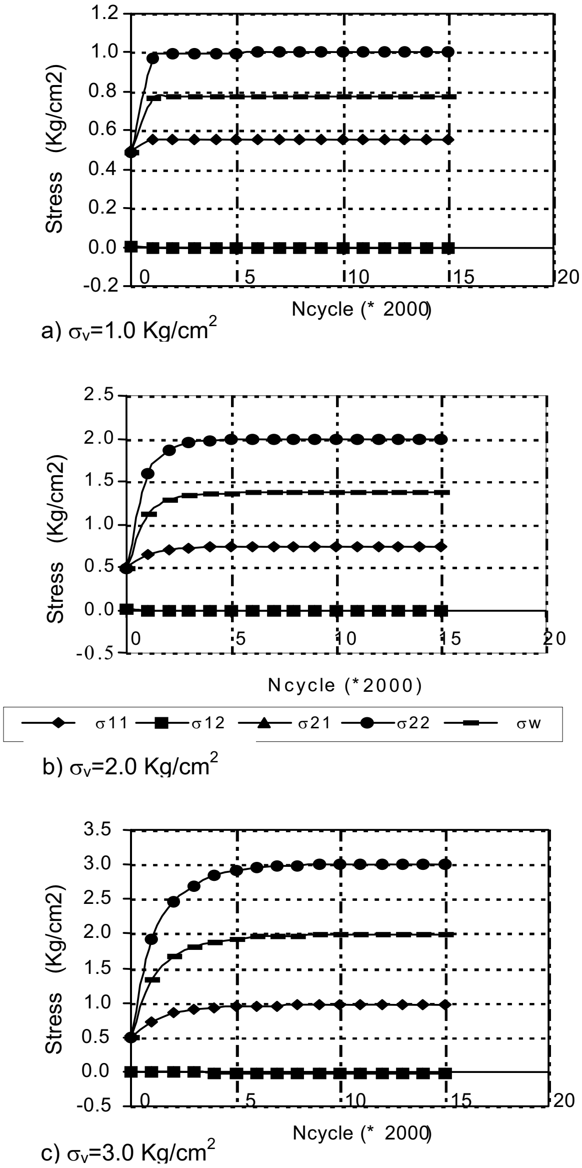
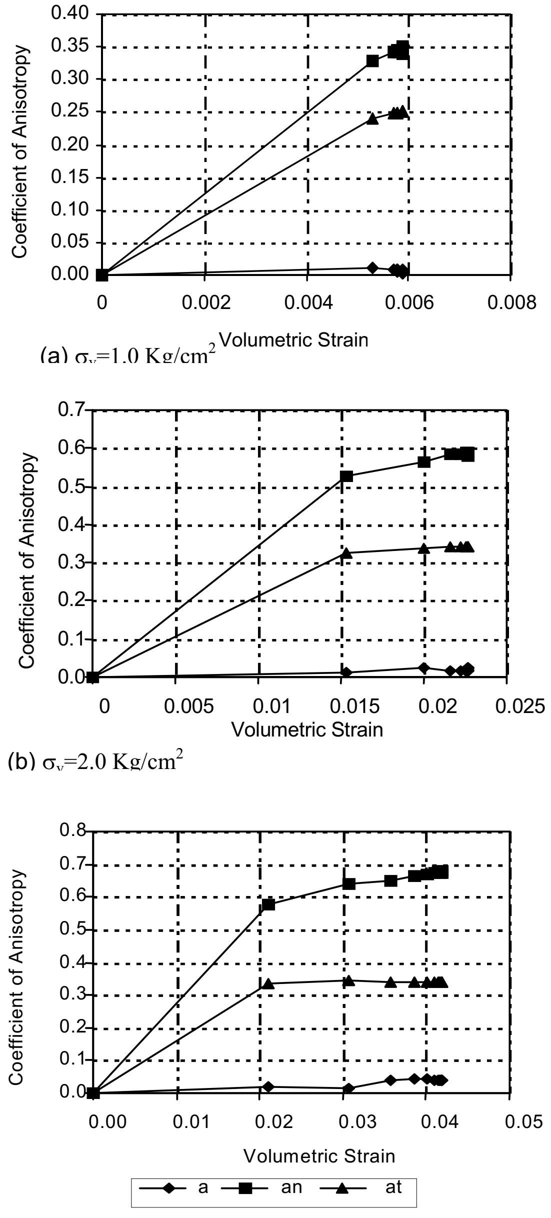


Figure 3. Stresses in particle assemblage



(c) σ_v=3.0 Kg/cm^2

Figure 4. Variation of Anisotropy Coefficients (sample1)

- Figures 3-a to 3-c represent the stresses in particle assemblage versus computation cycles for three vertical stress (1, 2 and 3 Kg/cm^2). These figures show the vertical & horizontal stress increase highly during the initial computation cycles and reaches an constant value at about 4000 to 8000 cycles. As expected by increasing the vertical stresses, the induced volumetric strain and vertical settlement are also increases.
- Figures 4-a to 4-c show the variations of anisotropy coefficients in the tests with three different vertical stresses (Table 3) for sample 1. These figures indicate the variation of the anisotropy coefficients with the volumetric strain. It can be seen that at the initial stages of the simulation, the coefficients are grown up rapidly. At the end, the rate of grown up is reduced to about zero. The value of coefficients **a** and $\mathbf{a_n}$ are grown up to withstand the increasing vertical stress. Figure 4 shows the anisotropy of particle assemblages increases with applied vertical load in direct shear test. It was found the ultimate volumetric strains in sample 1 are 0.6, 2.3 and 4.2 percent for vertical stresses equal to 1, 2 and 3 kg/cm^2, respectively. The maximum value of parameter $\mathbf{a_n}$ at the ultimate volumetric strains are about 0.34, 0.58 and 0.68 for three test with different vertical stresses.

4.2.2. Shearing the sample

In the second stage of direct shear test simulation, the three upper boundary particles are moved horizontally to shear the specimen along the plan between two parts of shear box. Results of this stage of simulations conducted on sample 1 under different vertical stresses are represented in Figures 5 to 7. The most important results of the investigation can be summarized as follows :

- The variation of vertical displacement during the simulations is presented in Figure 5 as a function of shear strain for three different vertical stresses. Since the cross section of the specimen remains unchanged, the volumetric strain is proportional to the vertical settlement. It is observed that with an increase in value of vertical stress, there is an increase in the initial compression and also a decrease in dilation tendency. Furthermore, the high-applied vertical stress did not allowed the sample of test T3 to dilate.

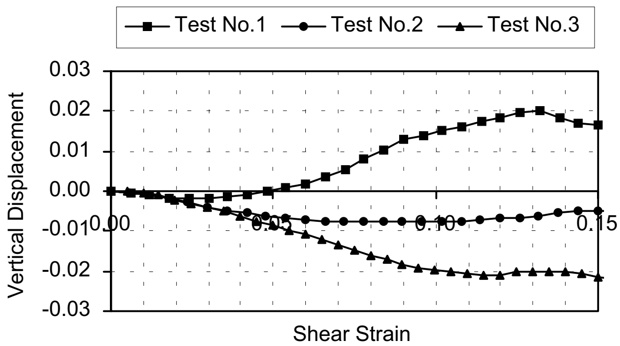


Figure 5. Variation of vertical displacement at shearing simulation

- The relation of mobilized internal friction angle with shear strain is plotted in Figure 6. This Figure shows that by increasing the vertical stress. The amount of mobilized friction angle reduces. Also, the behavior of sample during shearing simulations alters from strain softening to strain hardening as vertical stress is increased. This observation is in the agreement with the dilation behavior of samples reported in Figure 5. Assemblies with dilative behavior exhibit shear softening during biaxial stress. At large shear strains, the assemblies approached steady-state condition where no significant variation in mobilized internal friction angle is observed. At this stage of simulations, the mobilized friction angle reached a constant value for all three tests.

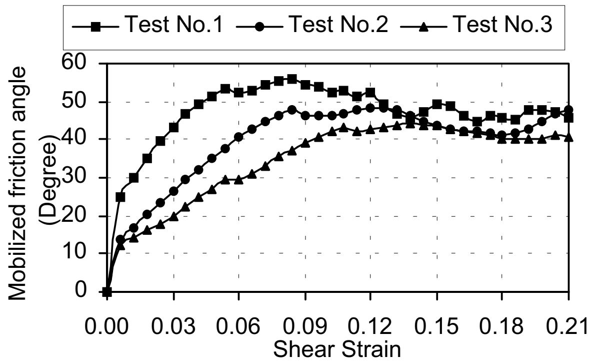


Figure 6. The value of friction angle mobilized during direct shear

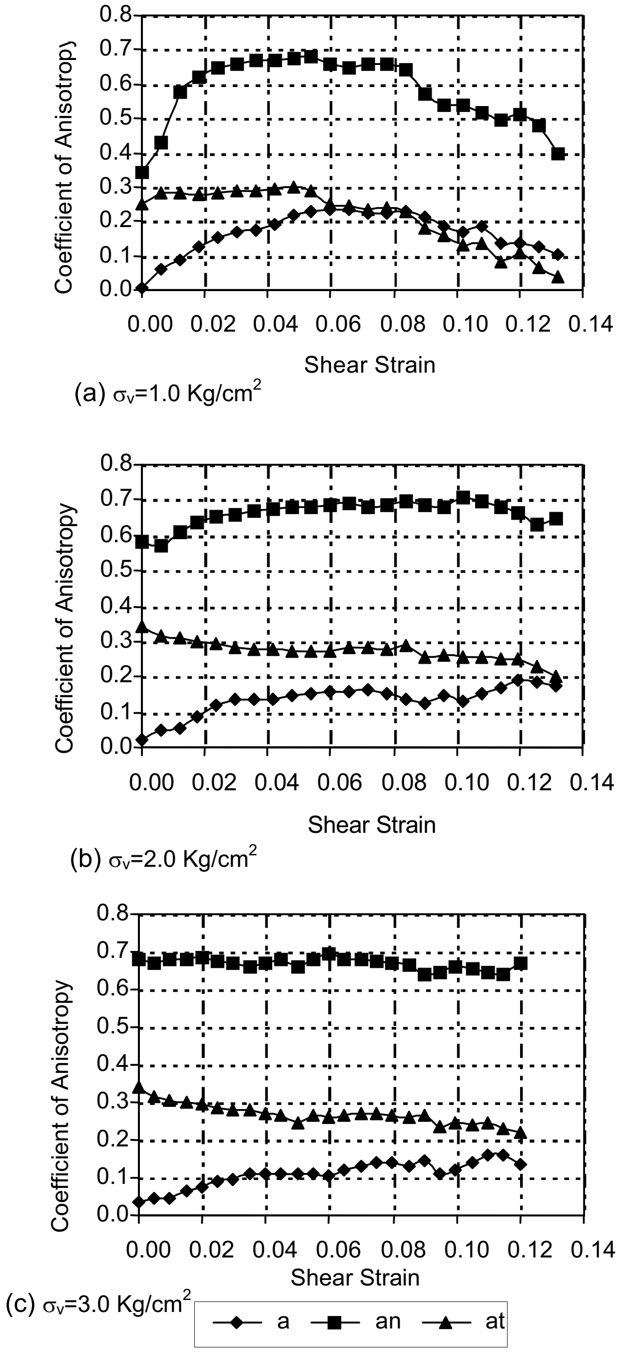


Figure 7. Anisotropy coefficient versus shear strain during direct shear simulation

- Figures 7-a to 7-c show the variations of **a**, $\mathbf{a_n}$ and $\mathbf{a_t}$ during shearing simulation in sample 1. Results of test T1 are shown in Figure 7-a. The variations of anisotropy coefficient (**a**, $\mathbf{a_n}$) in this figure indicate that the parameters increase initially and reach to peak values at %6 shear strain and after that in the post peak, value of all parameters decreased. The value of $\mathbf{a_t}$ parameter did not changed significantly and reached to its minimum value at the initial stages of the shearing part (Figure 7-a). Same trend was found for the other simulation of tests.

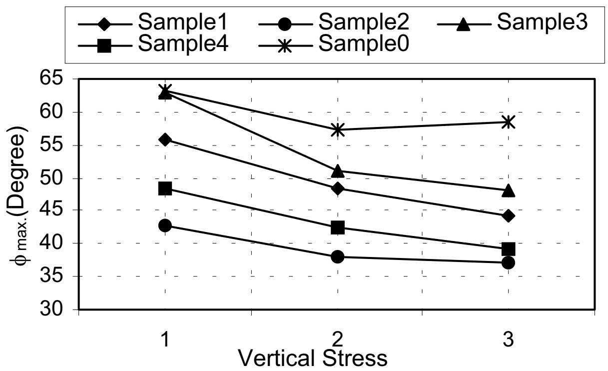
Figures 7-a to c show that by increasing the vertical stress, the rate of variation of **a** and $\mathbf{a_n}$ is reduced to about zero. It means by applying higher vertical stresses, the initial induced anisotropy increases and leads to less changes in further stages of simulations. One can clearly see that the maximum values of $\mathbf{a_n}$ and $\mathbf{a_t}$ parameters are independent on the vertical stress levels. Results for sample1 show that the maximum values of $\mathbf{a_n}$ & $\mathbf{a_t}$ parameters are about 0.7 and 0.3, respectively. This observation is in agreement with the result reported in Figure 6.

4.3. Effect of particle gradation on strength

In the previous sections the effect of vertical stress on micro mechanical behavior of selected specimen during different stages of direct shear simulations was investigated. To determine the influence of particle gradation and sample size on direct shear test, the results of numerical simulations of all samples are compared. The results are shown in Figure 8 and 9.

Figure 8 represents the maximum mobilized friction angle obtained for all samples as a function of vertical stress. In coarse grained samples (sample 1 & 3), the peak mobilized friction angle is greater than that of samples 2 and 4. On the other hand, by increasing d_{max} (maximum size of particles) internal friction angle of assembly increases for all stress levels. The difference between friction angles of assemblies produced by different methods is about 5-10 percent. It can be observed that in high stress levels the difference is the minimum.

Figure 9 shows the variations of maximum shear strength versus vertical stress. It can be noticed that by increasing the maximum particle size, the shear strength ascends.



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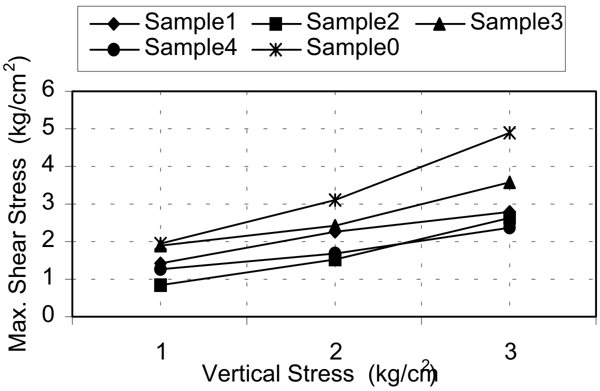

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Cundall, P.A. & Marti, J. & Beresford, P. & Last, N. and Asgain, M. (1978) “Computer modelling of jointed rock masses.”, Technical Report N-76-4, Dames and Moore.

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Mirghasemi, A.A. and Bagherzadeh_khalkhali, A. (2002) “Influence of particle gradation on shear strength of coarse grained soils ”, 55th Canadian Geotechnical and 3rd joint IAH-CNC and CGS Conference, Canada.