Shear Strength Behavior and Finite Element Modelling of Soil Mixtures Under Low Confining Pressure

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Abstract. Information technology term also means that solving problems by using computers, software, middleware, storage, or sensor systems. The development of the computer technology presents to estimate soil behavior in geotechnical engineering problems. In addition, geotechnical engineers want to define soil behavior parameters easily by using software. In this study, results of direct shear tests are modelled by using Abaqus software. Mohr – Coulomb material model was used to define failure condition of soils. Necessary material properties, such as shear modulus and dilation angle were computed from the test results. Failure stresses of laboratory test and model are matched with each other. Stress and strain variation of the soil specimen was investigated and presented at the end of the study.

Keywords: Abaqus · Low confining pressure · Shear strength

1 Introduction

Soil structures are formed as mixture in nature. Mixture content may vary according to their formation process. There are many studies to investigate the behavior of mixed soils by using laboratory tests, but numerical models are limited. Hamidi et al. [1] conducted direct shear tests on gravelly sand soils to develop a mathematical relationship on prediction of friction angle. Xu et al. [2] modelled direct shear tests of soil rock mixtures using discrete element method (DEM). DEM investigation showed that, dilation is higher in case of soil rock mixture than sand soil. Chakraborty and Salgado [3] developed a formula to calculate peak angle of friction and peak angle of dilation regarding relative density and confining stress. Sadek et al. [4] conducted direct shear tests and modelled direct shear test using DEM, it is concluded that, denser and dryer soil has higher shear strength, angle of friction and cohesion. Castellanos et al. [5] investigated fully softened shear strength of soils by conducting direct shear tests. Two new correlations are determined from direct shear test results to predict continuous and nonlinear envelope by using soil index properties. Eid and Rabie [6] determined fully softened shear strength of clays. Researchers also developed correlation to predict fully

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softened shear strength of clays using plasticity index. They concluded that, non-linearity on failure envelope is more pronounced under low confining stress. Onur et al. [7] studied undrained unconsolidated (UU) behavior of saturated clay and modelled UU triaxial test numerically. Experimental results and numerical analysis results matched well in their study. Jacobson et al. [8] conducted numerical direct shear test to better understand relationship between sample dimensions and maximum particle diameter. 2D discrete element method is applied in their study. Moayed et al. [9] modelled direct shear tests for dense sand. In their study, they considered effect of cohesion but not effect of different soil type. Moradi and Abbasnejad [10] modelled direct shear tests conducted on Toyoura sand under three different densities by introducing hardening and softening behavior of sand into Abaqus.

Finite element modelling of direct shear test is also very rare in literature. Effect of different soil types is also not common. Therefore, in this study, shear strength of soil mixtures is determined by conducted direct shear test and the results are modelled. Fine content is increased from 0% to 100% step by step with 20% increments in the mixtures. Low normal stresses are used during direct shear tests and finite element study. 9.81 kPa, 19.62 kPa, 40.81 kPa and 58.86 kPa are chosen as normal stresses. Experimental results are modelled by using Abaqus 6.14 and Mohr-Coulomb material model is chosen.

2 Study Program

Sand and fine soils are used throughout the study. Sand and fine soils are also mixed in percentages. Mixtures are prepared by adding 20% fine soil into sand. Amount of fine soil is increased 20% for each different mixture. Direct shear box used in this study has 100 mm * 100 mm dimensions in cross section. Mixtures are prepared by mixing soils into each other in dry state. After that, water is added. Amount of water corresponds to optimum water content determined by standard proctor test. Optimum water content and corresponding maximum dry unit weight is given on Table 1 below.

After tamping prepared soils into shear box, shear tests are conducted under 4 different normal load. Normal loads are chosen as 9.81 kPa, 19.62 kPa, 40.81 kPa and 58.86 kPa. Shearing rate is chosen as 0.25 mm/min for samples which have higher sand content and 0.065 mm/min for samples which have higher fine soil content. Those rates of shearing values are selected so that, excess pore water pressure will not develop during shearing.

After the experiments are completed, all the experiments are modelled on Abaqus 6.14. Dynamic analysis is conducted with two steps. In the first step normal stress is applied to sample. Afterwards, shear stress is applied to sample by defining horizontal movement. An example of Abaqus model is given in Fig. 1 below. Deformation is allowed on y axis for two steps.

Table 1. Maximum dry unit weight and optimum water content of soils.

Mixture	Maximum dry unit weight	Optimum water content
100% Sand	17.4	11.5
80% Sand + 20% Fine	20.7	8.0
60% Sand + 40% Fine	20.5	8.0
40% Sand + 60% Fine	20.6	9.1
20% Sand + 80% Fine	20	11.0
Fine soil	18.5	12.5

Deformations of side walls of the model are prevented in both x and z axis for both bottom and top part of the sample during step one. However, in the second step, deformations in z axis are allowed only for top part of the shear box. Then shear force is applied by defining shear deformation on z direction.

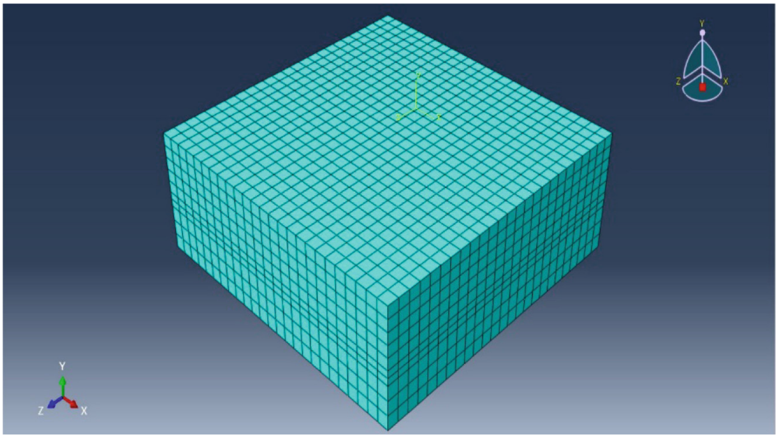


Fig. 1. Abaqus model of tested soils.

Mesh sensitivity is checked before performing finite element analysis of the models. In order to find out mesh sensitivity of model, part is seeded in each 12 mm, 10 mm, 8 mm, 6 mm, 4 mm, 2 mm and 1 mm. Mesh size refers to dimension of element before application of any type of loading. Shear tests are conducted for each mesh size. It is seen that, as size of mesh decreased computed shear stress decreased. However, when mesh size is selected as 1 mm, calculated shear stress increased enormously. This behavior is given on Fig. 2.

As it can be seen on Fig. 2, M4 and M2 almost produced the same results. Therefore, mesh size of 4 mm is selected in this study to save time.

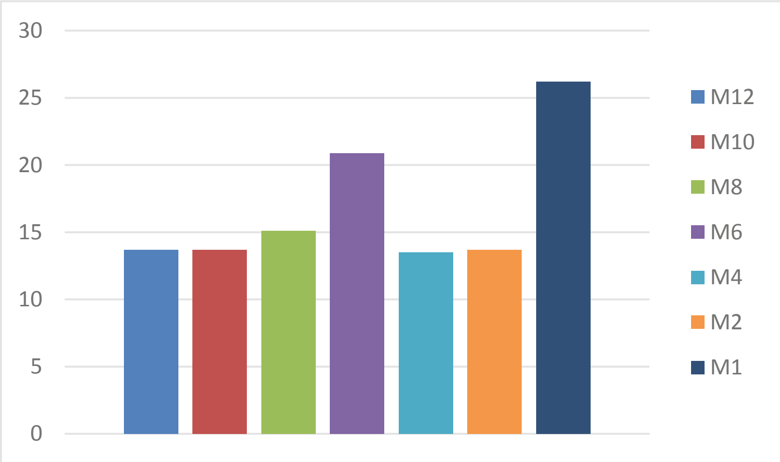


Fig. 2. Mesh sizes and calculated shear stresses.

3 Results

3.1 Direct Shear Test Results

Since all the samples are compacted to their maximum dry unit weight, peak shear strength is observed for each sample. Shear stress – horizontal deformation for sand, 60% sand with 40% fine, 20% sand with 80% fine and fine soil is given on the Figs. 3 and 4 below.

Failure achieved at lower stress levels for sandy soils than fine soils. This is due to that; failure is controlled not only by friction of particles with each other but also cohesion. However, cohesion is not affected by normal stress which causes lower angle of friction.

Failure envelope is found by using peak shear stresses from experiments for all soil types. Failure envelopes for four different soil types are given on Fig. 5. Decrease in slopes of lines and increase in interception to y-axis can be seen on Fig. 5. Angle of friction of samples are computed from slope of failure envelope. Cohesion value of sample equals to interception value. Angle of friction and cohesion values are given on Table 2.

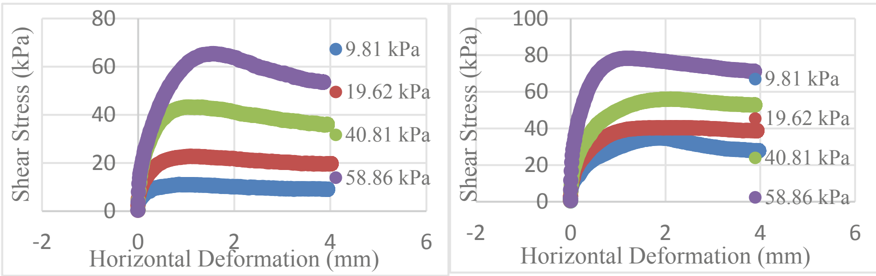


Fig. 3. Shear stress-horizontal deformation of (a) Sand (b) 60% Sand + 40% Fine.

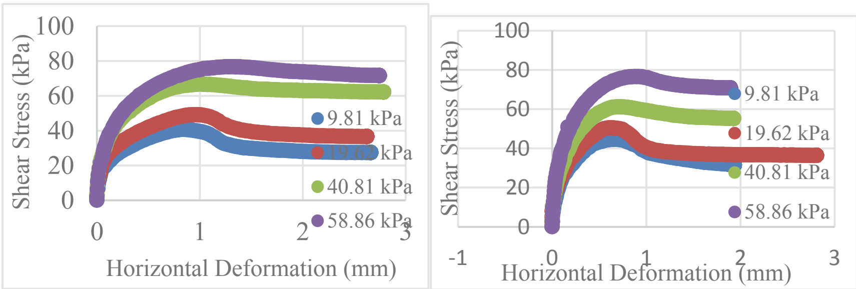


Fig. 4. Shear stress-horizontal deformation of (a) 20% Sand + 80% Fine (b) Fine.

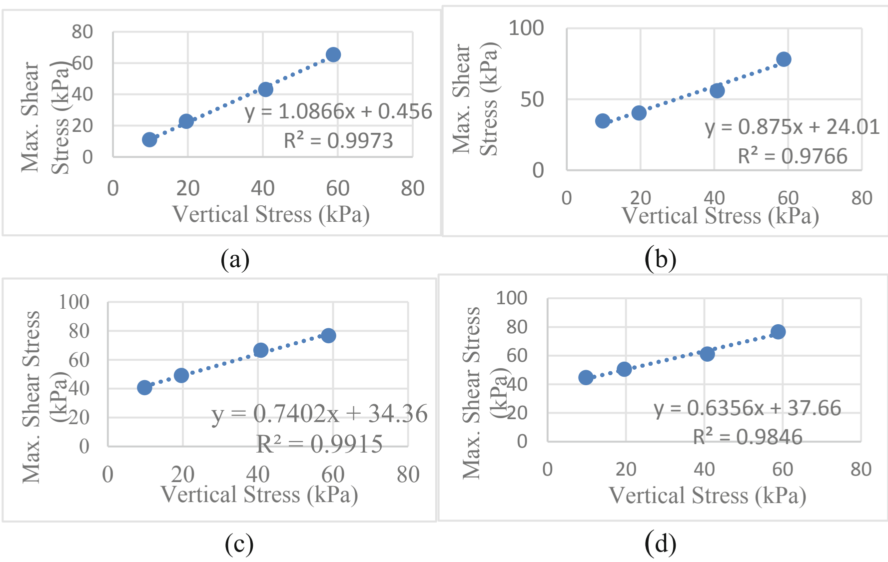


Fig. 5. Failure envelopes for (a) Sand (b) 60% Sand (c) 20% Sand and (d) Fine soil.

Table 2. Shear strength properties of soils determined experimentally.

Mixture	Angle of friction (°)	Cohesion (kPa)
100% Sand	47.4	0.5
80% Sand + 20% Fine	42.4	11.6
60% Sand + 40% Fine	41.2	24
40% Sand + 60% Fine	38.8	25.8
20% Sand + 80% Fine	36.5	34.4
Fine soil	32.4	37.7

Shear modulus is calculated from linear part of the shear stress – horizontal deformation graphics. Computed shear modulus's are given on Table 3. As the vertical stress increases, shear modulus also increases. It is also clear that, shear modulus increased as the fine content increased.

3.2 Finite Element Results

Abaqus 6.14 is used in this study to simulate direct shear tests under low vertical stresses. Results of finite element study is investigated under two parts. In the first part, maximum shear stress from simulation is compared with experimental results. After that shear stress – horizontal deformation is evaluated. Angle of friction and cohesion are found from the values from finite element study and compared with actual shear strength parameters of soil. In the second part, stress distribution inside the sample is evaluated.

Table 3. Computed shear modulus's for different soil types.

Mixture	9.81 kPa	19.62 kPa	40.81 kPa	58.86 kPa
100% Sand	4.04	7.20	13.5	14.41
80% Sand + 20% Fine	4.74	6.58	11.88	13.22
60% Sand + 40% Fine	7.76	11.04	13.77	24.08
40% Sand + 60% Fine	10.44	12.58	11.36	18.84
20% Sand + 80% Fine	13.3	15.59	22.5	22.93
Fine soil	15.73	17.77	21.05	25.39

Shear Stress – Horizontal Deformation. When results of finite element simulation is compared with experimental data, it is seen that, results are compatible with each other. Computed and experimental shear stresses are provided in Table 4.

Table 4. Peak shear stresses computed experimentally and by finite element method.

Vertical stress	9.81 kPa	19.62 kPa	40.81 kPa	58.86 kPa
Sample	Experiment/Fem	Experiment/Fem	Experiment/Fem	Experiment/Fem
100% Sand	11/10.8	22.7/24.8	43.1/44.9	65.3/64.9
80% Sand + 20% Fine	19.2/17.7	30.4/27.4	50.5/46.8	64/63.3
60% Sand + 40% Fine	34.7/34.8	40.3/41	55.8/59.5	78.1/80.2
40% Sand + 60% Fine	31.6/32.6	43.2/42.1	61.1/60.1	71.4/72.7
20% Sand + 80% Fine	40.7/39.1	49.1/45.9	66.9/74.1	76.6/73.7
Fine soil	44.6/45.3	50.4/49.7	61.1/61.2	76.6/79.5

When the shear stress - horizontal deformation behavior is investigated, finite element study complies very well with the experimental data for sand. Graphics for sand are given on Fig. 6.

However, when the fine soil content is increased, finite element results deviate from experimental results especially after the peak stress. Shear stress - horizontal deformation graph for fine soil is given on Fig. 7. More stiff behavior is computed on Abaqus than experiments as the fine content of the samples increase.

It is clear from Fig. 8 that, finite element analysis was not able to catch the strain softening behavior of the sample for fine soil. In order to determine angle of friction and the cohesion values from the finite element simulation, failure envelopes are drawn for all the cases by using results from finite element analysis. Failure envelopes and their equations are provided which further defines angle of friction and cohesion. Failure envelopes are given on Fig. 9. The computed angle of friction and cohesion values by Abaqus are given on Table 5.

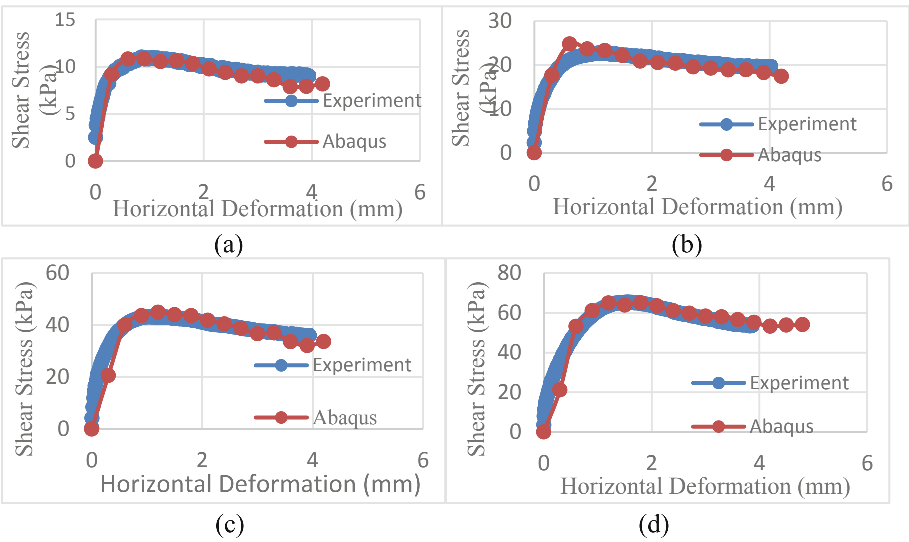


Fig. 6. Stress – horizontal deformation behavior for sand under different vertical stress (a) 9.81 kPa (b) 19.62 kPa (c) 40.81 kPa (d) 58.86 kPa.

Table 5. Computed angle of friction and cohesion values.

Mixture	Angle of friction (°)	Cohesion (kPa)
100% Sand	48.2	0
80% Sand + 20% Fine	43	8.8
60% Sand + 40% Fine	43	23.9
40% Sand + 60% Fine	39.4	25.4
20% Sand + 80% Fine	37.5	32.6
Fine soil	34.5	36.8

The evaluation of the Tables 2 and 5 shows the conformity of the experimental results and numerical models. The differences are below 10% for all samples. Except from that, cohesion is computed as 0 kPa after finite element analysis for sand, however it is found 0.5 kPa from experimental results for sand.

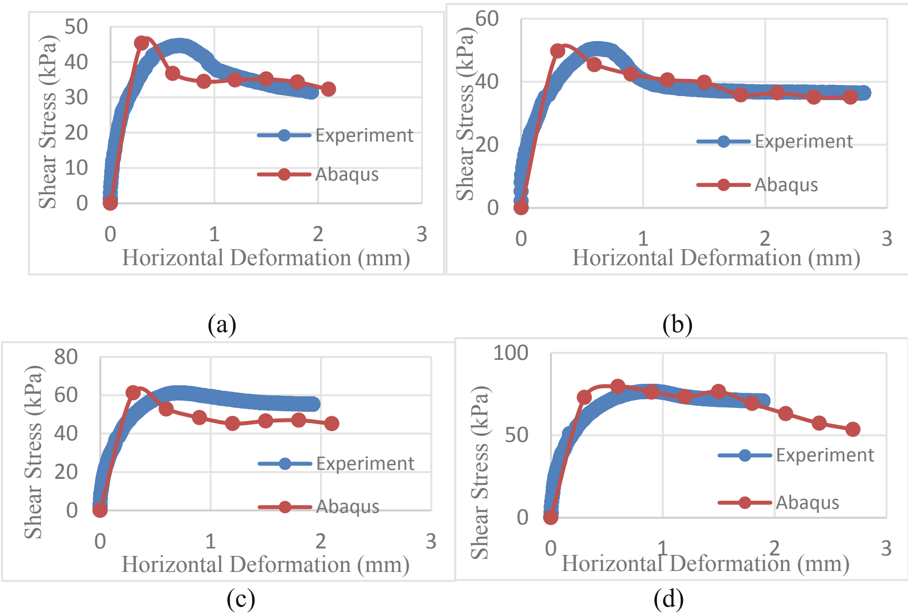


Fig. 7. Stress – horizontal deformation behavior for sand under different vertical stress (a) 9.81 kPa (b) 19.62 kPa (c) 40.81 kPa (d) 58.86 kPa.

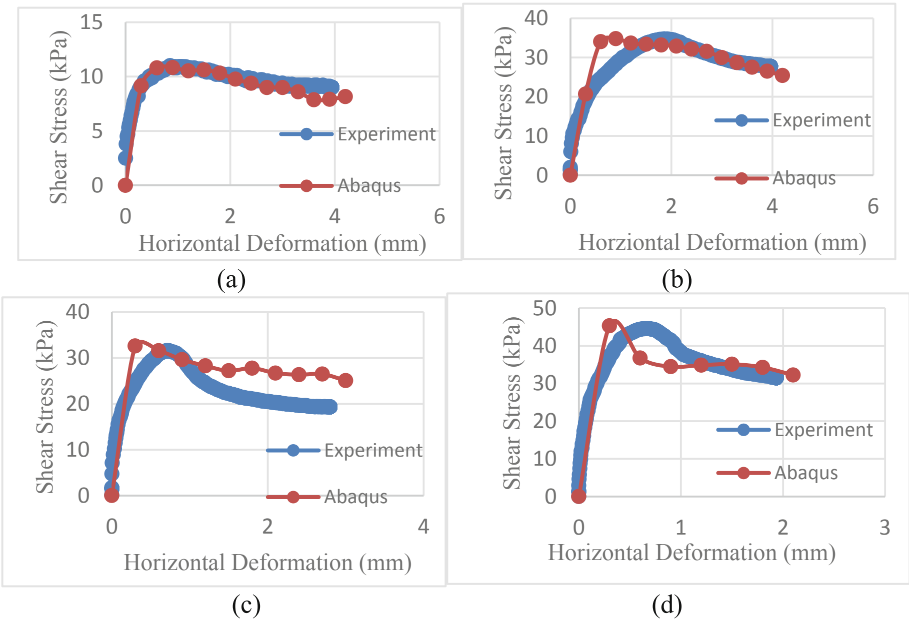


Fig. 8. Stress – horizontal deformation behavior for different soil composition (a) Sand (b) 60% Sand + 40% Fine soil (c) 40% Sand + 60% Fine (d) Fine soil.

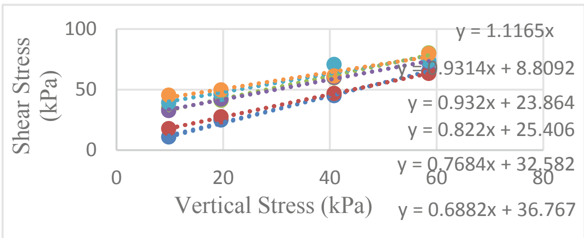
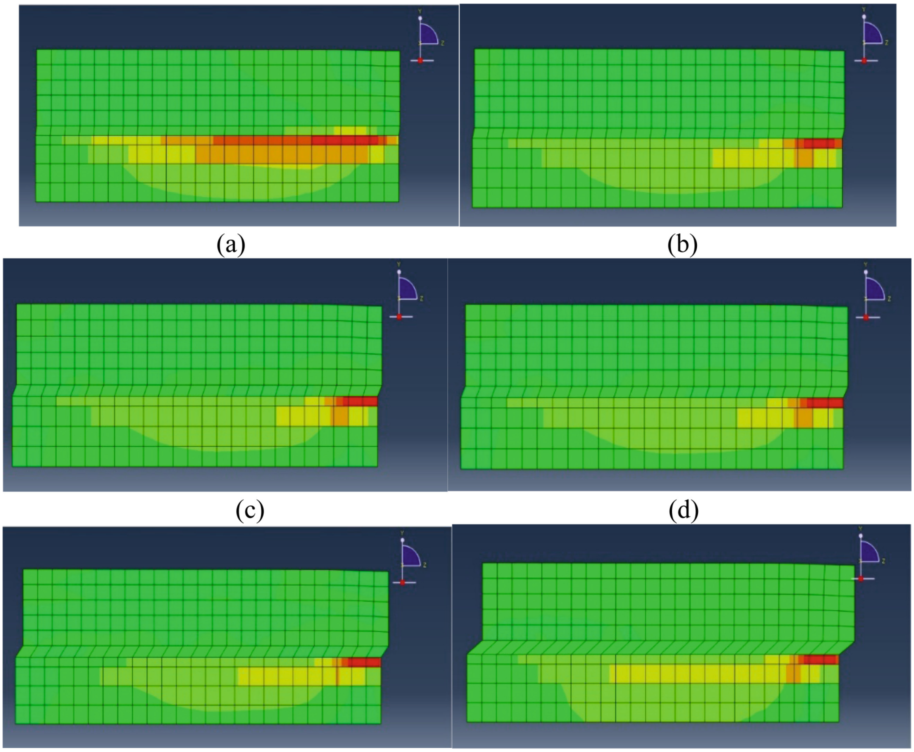


Fig. 9. Failure envelopes derived from Abaqus.

Shear Stress Distribution Inside Sample. Shear stress variation inside the sample at different deformation levels is investigated in this section. Six different deformation levels are considered. Those deformation levels are chosen to be before peak stress, at the peak stress and after peak stress. Those deformation levels are determined as 0.3 mm, 0.6 mm, 1.2 mm, 1.5 mm, 2.1 mm and 4.2 mm. Shear stress distributions are given on Fig. 10.

At the early stage of loading which corresponds to 0.3 mm, the highest stress zone is directly at failure plane and more evenly distributed when compared to other cases. This case corresponds to Fig. 10(a). When the deformation becomes 0.6 mm, the highest stress moves through the edge of sample. Area of the sample which is affected by the highest shear stress decreases. This case is shown at Fig. 10(b). The stress level



(a) (b) (c) (d) (e) (f)

Fig. 10. Shear stress distribution inside the sample for different horizontal deformation (a) for 0.3 mm (b) for 0.6 mm (c) for 1.2 mm (d) for 1.5 mm (e) for 2.1 mm and (f) 4.2 mm.

which corresponds to orange and yellow color code also decreases. Similar stress distribution is observed when 1.2 mm and 1.5 mm deformation applied to sample. Those cases are shown at Fig. 10(c) and (d). When the applied deformation becomes 2.1 mm, effected area of shear stress defined by yellow color code increases. This behavior is shown at Fig. 10(e). At the end of the simulation, although highest stress is computed at very small area, moderate stress level effected area kept growing.

In all the cases, failure wedge can be seen which covers very large area of the sample. Failure wedge covers all range of color codes which begin from light green to red.

4 Conclusion

Results of direct shear tests are modelled by using finite element method. Different soil types are tested and modelled under low vertical stresses. Total number of 24 experiments are carried out in the laboratory and all the tests are used for the modelling. Results of this study can be summarized as follows;

- The peak stresses measured at the laboratory and calculated by finite element analysis are quite compatible with each other. The maximum deviation is found as 9.87% and the minimum deviation is found to be 0.29%.
- Shear stress-horizontal displacement graphics agreed well for sand samples. As fine content increased, agreement between experimental graphics and finite element graphics are broken.
- Computed angle of frictions from finite element analysis is agreed well with the experimentally found angle of friction. Computed cohesion is also complying with experimentally found cohesion when fine content is high in the sample.
- The highest shear stress distribution inside sample depends on the amount of the deformation exerted over the sample. Failure wedge is formed starting from failure plane and propagated through bottom part of the sample.

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