

Research Article

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The behaviour of stress variation in sandy soil

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Abstract: This research article represents the recom-pacted dense sand sample behaviour and stress distribution in the direct shear box. In Lithuania, sand is quite common on a construction site, in general about 32%. To reduce the influence of the shear box design on the experimentally determined values of the soil strength parameters, it is necessary to know the regularities of the change of the normal load acting in the shear plane. Three different normal stresses of 50, 100, and 200 kPa were applied to the dense sand in the direct shear boxes during experimental and numerical simulation. The results showed an obvious evidence of non-uniformity of stress for standard and raised specimens. The numerical analysis exhibited that when the sample is loaded only with a vertical load, approximately 75% of that load is transferred to the sample bottom, 84% to the shear plane, and 95% to the top. At the end of the shear test, the vertical force in the shear plane reaches maximum, the normal stress is higher by 13.5% than applied on the sample top. The shear strength of sandy soils were influenced by box size and sample height too. The improved shear box apparatus allows to estimate the vertical load at shear plane.

Keywords: direct shear test, non-uniformity of stresses, normal stress, stress distribution, scale effect, numerical modelling

1 Introduction

Important information about soil properties is necessary for designers before constructing the buildings, roads, and bridges [1]. Testing data confirm that the soil is able to support the proposed structure. Incorrect testing or data processing can affect the quality and safety of construction [2]. The most popular method in laboratory to investigate the soil strength is direct shear testing. Shear failure occurs when the stresses between the particles influence their sliding and/or rolling. The bearing capacity of soil is the maximum force that carries the soil between the foundation and the ground, which should not reveal shear failure in the ground. Wrongly determined properties of existing soils can affect the behaviour of the buildings and structures; therefore, additional implements, various methods, and technologies for ground structure reinforcement and stabilization are needed, which cost extra money [3,4].

The designs of the shear apparatus are very diverse: with a sliding bottom or top ring of the shear part; different box size, height, and shape; and particular way of vertical load transmission. Shear box structure has different influence and errors on separate soil types [5,6]. When analysing the soil samples by direct shear test, boundary conditions are unclear [7]: not all of vertical load applied to the top of shear box specimen is transferred onto the soil shear plane; the regularity of change of normal stresses on a shear plane is not obvious [8]. In the direct shear test, large non-uniformity in the distribution of stress and deformation exists [9]. The deformation is concentrated around the shear plane. The principal stress changes in size and direction. The stress distribution depends on the position of the movable part of shear box, way of vertical load transmission, and horizontal displacement of the mobile part of the ring. Some factors are not evaluated during the interpretation of results, for example, friction between soil and apparatus corpus parts. The experimental results show that the friction angle of granular materials varies with the orientation of shear plane relative to the bedding plane, and the degree of anisotropy is affected by particle shape [10–12]. It is assumed that all load applied to the top of the specimen

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is transmitted to the shear plane, thus eliminating the frictional forces between the soil and the ring as the soil moves vertically. Friction between the inner surface of the ring and the soil was considered to be of great importance for the magnitude of the normal stress. If these assumptions are not right, it is important to know what size of error is determining shear strength parameters.

For all of the above reasons, soil shear rates are determined with errors. The interpretation of results requires an understanding of the degree of non-uniformity of stress and strain in a soil specimen. The numerical methods help to determine the soil parameters that cannot be determined experimentally [13–16].

In the standard direct shear apparatus where vertical movement of the top part of ring is restrained and the bottom shear ring moves horizontally, the frictional force that acts on the sample at the internal surface of the top part of ring is downward for the dense sample and upward for the loose sample, causing the real shear strength to be larger for the dense sample and smaller for the loose sample than the one calculated from the externally applied vertical load. Some authors suggest two improvements to reduce the frictional force for shear box: first, the top part of shear ring can move upright and second, the top shear ring can be pulled with a flexible rope or wire [17]. The authors tested Toyoura sand, which an initial void ratio was $e_0 = 0.7$. The measured angle of internal friction with two improvements were 41.1° and 41.8° , respectively, whereas testing with the conventional direct shear apparatus was 44.8° . Zhang and Thornton suggest to reduce the shear ring measurements ratio to less than the standard 1:2 for more reliable test results [18].

Researching the soil strength with identical physical properties by using different apparatuses, different values of internal friction angle and cohesion were determined. The explanations of that are shear box construction, process methodology of test data, and human errors. One of the reasons of this difference was distinct height of the

ring. The height of the top ring of the direct shear apparatus affects the shear strength [19]. The literature analysis of shear strength experiments for dense moraine clayey sand shows that when the height of the soil sample is 3 cm, the values of the shear strength of the soil are 10–20% lower than when the height of the sample is 2 cm [20]. The difference between the separately calculated values of internal friction angle and cohesion with a ring height of 3 and 2 cm is 7 and 35%, respectively. The dependence of the soil shear strength on the height of the ring can be influenced only by the normal load acting in the shear plane or the nature of its distribution on this plane because other conditions are the same when examining the soil. To increase the accuracy of the determination of the soil shear strength, it is necessary to investigate how the vertical load applied to the top of the specimen is transmitted to the shear plane.

The experiments indicate that the angle of internal friction for dense angular sand decreases as box size increases, and the influence of sample size is dependent on relative density [8]. It was shown for five sand types the relative density varies from 13 to 91% that the friction angle may be up to 10° higher in a 60 mm box than in a 305 mm box for dense sands. The frictional force depends on the applied normal load, the value of the coefficient of lateral stress at rest K_0 , the roughness of the metal walls, and also the height of the specimen above the failure plane [21]. Surface roughness plays an important role in estimating the shear strength of granular materials [22]. The factors affecting the soil shear strength are summarized in Table 1.

The aim of this study is to analyse the regularity of variance of stresses in a circular form of direct shear sample throughout laboratory experiment and numerical modelling. To reach the aim of this study, standard and raised soil samples shearing behaviour were analysed. Stresses on sample top, shear plane, and bottom were analysed.

Table 1: Factors affecting the soil shear strength

Factors	Description
Friction between soil and apparatus (construction of a shear box)	Not all of added normal stress at the specimen top due to the friction between ring and a soil specimen is transmitted to a shear plane for direct shear test with movable bottom part
Height of top ring	Dependence of soil shear strength on the height of the ring can be influenced only by a normal load acting in shear plane
Scale effect	Scale effect depends on the sand type and the relative density
Regularity of a change of normal stresses on a shear plane	In a direct shear test, large non-uniformity in the distribution of stress and deformation exists. The principal stress changes in size and direction

2 Material and method

The coarse sand has been used for disturbed samples preparation. The samples have been prepared via three layers applying the compacting procedure with 8% of optimal water content. The sand specimen uniformity coefficient equals $C_u = 3.1$, the curvature coefficient equals $C_c = 0.77$, and the specific gravity of soil particles is $\rho_s = 2.66 \text{ g/cm}^3$. The properties of prepared samples are as follows: density $\rho = 1.885\text{--}1.910 \text{ g/cm}^3$ and void ratio $e = 0.504\text{--}0.532$.

This experimental study analyses the sand shear strength obtained by two different designs of direct shear apparatuses: SPF-2 (modified direct shear apparatus model) and automatic direct shear (ADS) apparatus model with mobile bottom shearing part. Using the improved direct shear apparatus SPF-2, it is possible to measure the normal stress transferred onto the shear plane and the vertical load applied onto the specimen. The vertical load is transmitted to the sample via a hinge transmission using the lever mechanism, which ensures a constant vertical loading on the top of specimen. The load transducer is embedded onto the bottom ring for determining the vertical load acting on the shear plane [20]. Improvement has been developed by constructing measuring system of vertical force at shear plane. The cut cone loading plate decreasing contact between ring and loading plate is used. The principal scheme of improved apparatus is given in Figure 1. However, for ADS apparatuses, the load transducer is embedded onto the top ring (Figure 2). For both apparatuses, the direction of movement of the bottom part is fixed, and it is parallel to the shearing plane. The gap between the shearing parts is fixed and does not change during cutting. The upper

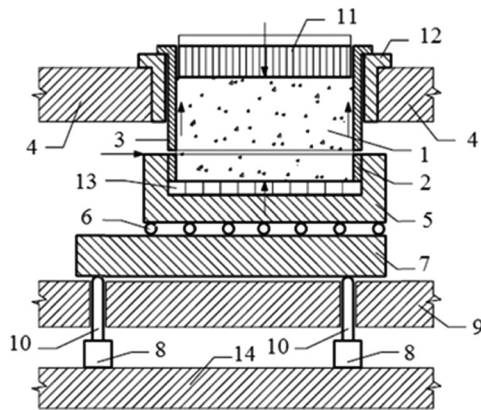


Figure 1: Principal scheme of modified shear box apparatus SPF-2: (1) soil; (2) lower ring; (3) upper ring; (4) fixed support; (5) movable part of apparatus; (6) bell track; (7) bottom part of apparatus; (8) load transducers; (9) table of apparatus; (10) supports; (11) loading plate; (12) fixator; (13) porous stone; and (14) plate of support [20].



Figure 2: Automatic direct shear apparatus model ADS.

part cannot rotate and move in a horizontal direction. The sample is loaded by a chosen vertical load via a stiff loading plate.

The experiments with two different construction apparatuses have been performed under constant normal stress measuring the vertical load at the shear plane and the top of the sample, respectively. The sample horizontal loading is applied by pushing a movable bottom ring with a constant velocity of 0.5 mm/min with SPF-2 and ADS, permanently measuring the values of the lateral force.

The soil samples have been sheared by two different apparatuses under three vertical loads magnitudes, namely 50, 100, and 200 kPa. The samples under the same load value have been sheared at least three times. The cylinder form sample height was 3.41 cm, diameter was 7.14 cm for SPF-2, and for ADS apparatus, the square form sample height was 2.9 cm, width and length were 10 cm each.

3 Experimental data analysis

The direct shear test is carried out on a number of identical specimens using different vertical stresses. Results obtained with SPF-2 testing apparatus shows that the applied normal stress on the sample top is not equal to

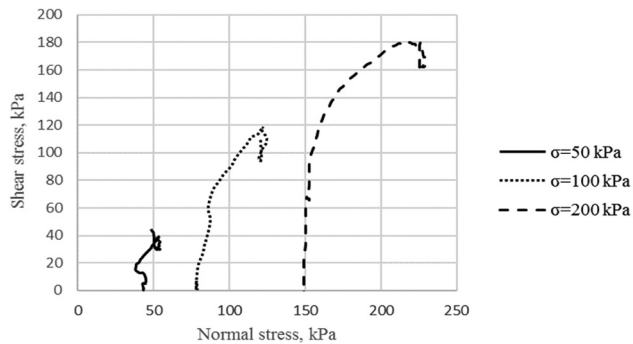


Figure 3: Laboratory test on the sand with SPF-2 measuring the normal stress on the shear plane.

the stress in the shearing plane. Difference of stress in the shearing plane and applied stress on the sample top depends on the vertical load (50, 100, and 200 kPa) during the test. The higher applied vertical load on the sample top – the lower stress formation in the shearing plane. Loading the sample top by 50 kPa of vertical load, in the shearing plane is transmitted about 10% lower stress at the beginning of experiment (see Figure 3). For case, when applied 100 kPa vertical load on the sample top, in shearing plane appears 20% lower stress. When applied 200 kPa vertical load on the sample top in the shearing plane appears 30% lower stress than applied on the sample top. Only at the test end the shear plane is loaded by the 100% of vertical load and becomes higher about 5–14% than vertical load applied on the top using the lever mechanism [19]. Figure 3 shows that testing the soil samples with the improved direct shear apparatus SPF-2 the applied vertical load of values of 50, 100, 200 kPa on the sample top is not the same as on the shear plane.

Figure 4 shows that the applied vertical load of values of 50, 100, and 200 kPa with ADS apparatus remained constant during all the test time, when the load transducer

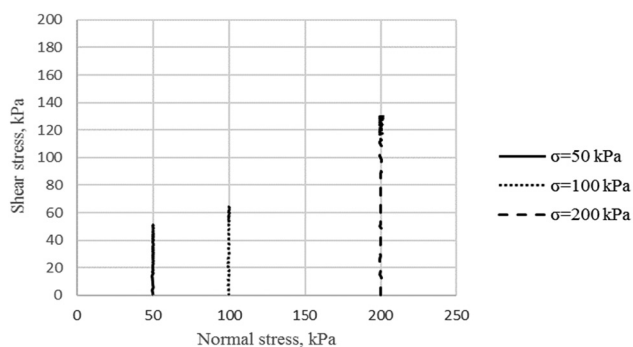


Figure 4: Laboratory test on the sand with ADS.

is mounted onto the top part. The determined stress paths of the sample differ from those measured on the SPF-2 sample (see Figure 3), where the stresses measured at the shear plane vary during the test time.

At the end of the shear test with SPF-2, when the horizontal displacement reaches 6 mm, the vertical force in the shear plane reaches its maximum value. At that moment, the shear force is close to the maximum. If we remove only the horizontal load, the vertical load in the shear plane will decrease and will be equal to average 80% of the load applied at the top of the stamp [20]. The vertical force magnitude becomes close to the magnitude of the force in the beginning of the test as the vertical load of the specimen is loaded. This decrease in vertical force indicates that the horizontal force presses the ring near the gap fixer and prevents it from moving freely in the vertical direction.

The magnitude of the normal stresses in the shear plane at the beginning of the test depends on the method of applying the vertical force and the quality of the insertion of the specimen into the shear ring. These subjective factors have a negligible effect on the shear strength of the soil. The shear strength of the soil depends on the magnitude of normal load. If the normal load value is set incorrectly, the point in the shear strength graph shifts, and the distance from the approximation line increases. The higher scattering of the shear strength values are due to the incorrectly determined normal stress value. Therefore, if the actual normal stress in the shear plane is not evaluated, a large scatter of soil strength parameters is obtained, finally, resulting in the smaller values of the angle of internal friction and the cohesion.

The effective mean values of soil shear strength parameters φ' and c' were calculated applying the least squares method. Figures 5 and 6 illustrate the peak values of the angle of internal friction of soil φ' obtained with shear apparatuses SPF-2 (constant vertical loading

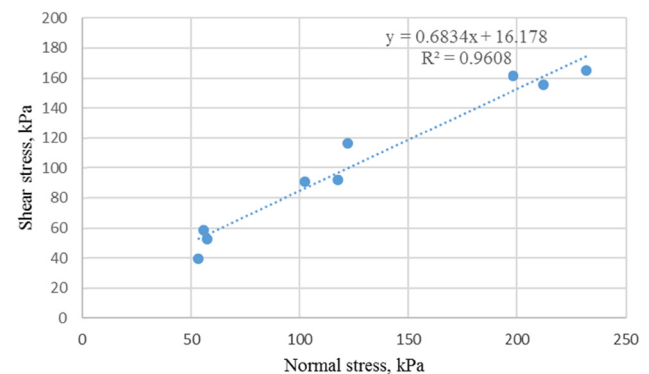


Figure 5: Soil shear strength values derived with SPF-2.

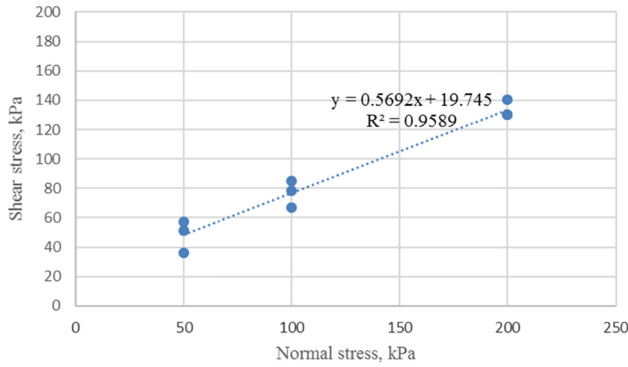


Figure 6: Soil shear strength values derived with ADS.

at top and measuring normal stress at shear plane) and ADS (constant vertical loading and measuring normal stress at sample top). One can find that the peak values are smaller $\varphi' = 29.65^\circ$ in case of using apparatus ADS, whereas bigger magnitude $\varphi' = 34.35^\circ$ corresponds to the tests performed with apparatus SPF-2 in case with implemented measuring system of vertical load at shear plane. The difference is 4.7° . The effective mean values of cohesion were obtained similarly: $c' = 16.18$ kPa with SPF-2 apparatus and $c' = 19.75$ kPa with ADS. This difference between determined shear strength parameters is because different shape and size of sample were used, and two designs of direct shear apparatuses with different measuring system of normal stress were used [23]. The experiments indicate the angle of internal friction for dense angular sand decreases as box size increases, the influence of sample size is dependent on the relative density. The literature analysis shows the same [8]. Cerato and Lutenege experimental results reveal that loose samples were influenced by box size too. The friction angles of the well-graded angular sand and the angular poorly graded gravel were most affected by sample size. The rounded and uniform sand was little influenced by box size.

Using SPF-2, the applied vertical load of values of 50, 100, and 200 kPa on the sample top, the peak values of the angle of internal friction was obtained bigger $\varphi' = 35.72^\circ$ than using the actual vertical load values acting on the shear plane.

4 Finite element analysis of soil samples

A lot of factors can affect the results of a shearing test. Using a numerical method to simulate experimental test and study of factors can be helpful. Numerical

simulations are used to evaluate soil processes and the nature of these processes. Utilizing the techniques of numerical simulation, the distribution of stress inside the experimental specimen, especially at failure plane, has been investigated. A model was made with finite element method program Plaxis 2D. The linear elastic perfectly plastic Mohr–Coulomb model was chosen analysing the stresses distribution. The accepted sample parameters: Young's modulus – 20 MPa, Poisson's ratio – 0.3, and mass density – 1.80 g/cm^3 . Two types of samples were designed for the analysis of stress distribution in soil sample: the standard sample, 7.14 cm in diameter, and 3.39 cm in height (Figure 7) and a raised specimen of the upper part, in general height of 5.39 cm. The height of the top ring was raised to analyse its effect and the impact of wall friction on stress and shear strength. Both samples were discretised into finite elements. The main drawing is made for both samples: the vertical load of 100, 150, and 200 kPa is applied on the top of the soil sample, the nodes of upper lateral wall are fixed in two directions, and lower lateral walls of sample are free in horizontal direction; the lower part of ring is pressed 0, 1, 2, 3, 4, and 5 mm on the horizontal side.

5 Results of finite element analysis

First of all, when the soil sample is loaded by the vertical load of 100, 150, and 200 kPa, no horizontal displacement acts. Analysing Figure 8 results, it can be noted that on the top, shearing plane, and bottom of sample obtains smaller normal stress than it is applied on the sample. About 75% of vertical load is transferred to the sample bottom, 84% to the shear plane, and 95% to the top. The experiments show the same tendency. When the sample is proceeded by vertical load, the produced horizontal

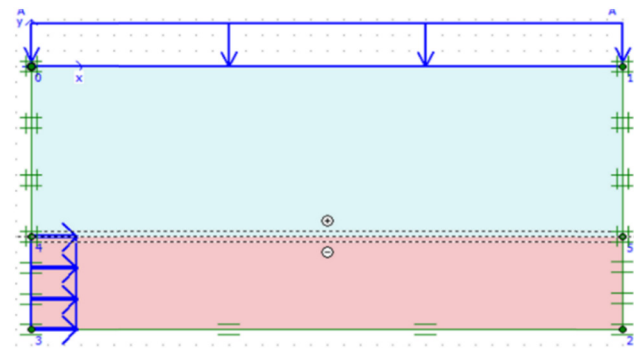


Figure 7: Finite element model of direct shear sample.

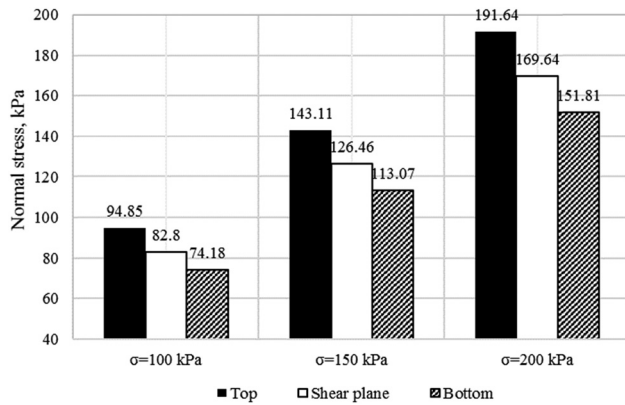


Figure 8: The mean values of normal stress of the standard sample under vertical load only.

stress presses the specimen into inside surface of the ring. As a result, the vertical displacement is limited. By failure procedure, the soil moves vertically concerning soil volume change. A part of vertical load is transmitted to the fixator of gap. Therefore, the vertical load applied to shear plane and bottom is lower than the applied on the top [19]. The difference between normal stresses measured at the different planes is 20%.

Figure 9 shows similar trend on the sample top, we see in, using raised by 2 cm top ring of sample. When compared to the standard specimen, 95% of vertical load is transferred to the top, on average ~70% of vertical load is in the shear plane, and ~64% in the bottom. The normal stress uniformity decreases as the sample height increases. The wall friction acted to reduce the stress on the shear plane and bottom comparing with the standard specimen. The direction of the frictional force depends on the type of volumetric deformation of the experimental soil. Dense or overconsolidated sample dilate during shearing; therefore, the direction of the additional force

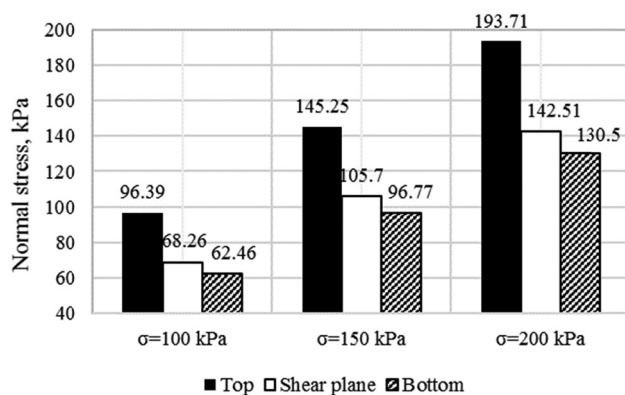


Figure 9: The mean values of normal stress when only vertical load on raised sample acts.

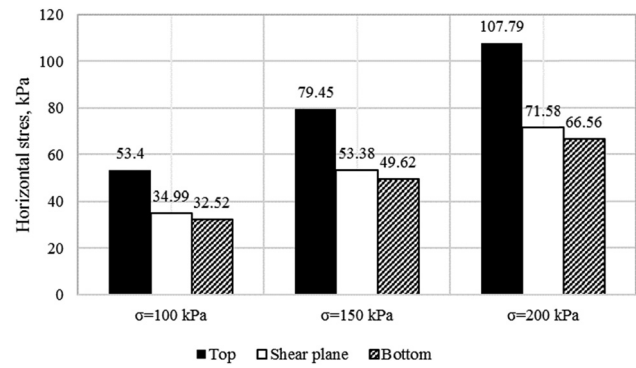


Figure 10: The mean values of horizontal stress when only vertical load acts.

on the specimen is downward. If the applied load is measured at the top plate, the normal stress acting on the shear plane is underestimated. As a result, the shear strength is overestimated. Loose or normally consolidated samples contract during shearing, the movement of the frictional force at wall sample interface is upward, opposite to the movement of vertical displacement. If the applied load is measured at the top plate, the shear strength is underestimated [21].

When the specimen is subjected to a vertical load, the lateral pressure in the soil presses it alongside the inner surface of the ring and prevents it from sliding freely in the vertical direction in regard to the ring. The horizontal stress concentrates at the junction of the ring and the stamp [24]. The highest mean values of horizontal stress act on the sample top (Figure 10). The lower and similar values proceed on shear plane and bottom. The same tendency can be noted in Figure 11. It is noticeable that horizontal stress on raised sample top is about 10% higher comparing with the standard sample and on the contrary is lower on shear plane and bottom.

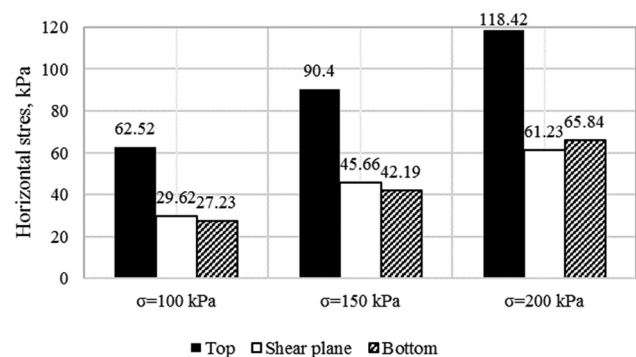


Figure 11: The mean values of horizontal stress when only vertical load on raised sample acts.

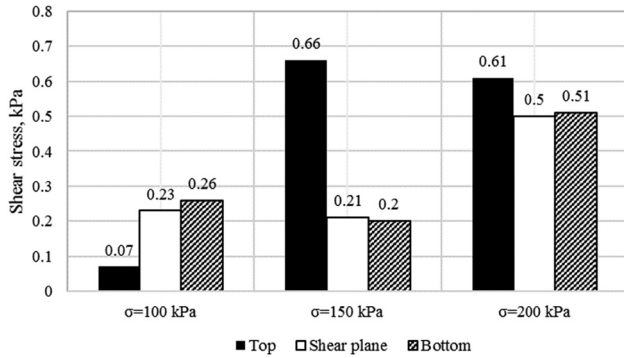


Figure 12: The mean values of shear stress when only vertical load on the standard sample acts.

When the sample is proceeded by vertical load, the shear stress does not show itself fully (Figures 12 and 13). The shear stress is the highest at the ring walls, and further away from the walls, the stress decreases [25]. The shear stress was small because these elements had not yielded during the loading.

Volume variation of soil sample causes additional normal stresses in the shear plane. Soil shear strength is dependent on normal stresses, soil volume variation during the test will affect soil shear strength. The maximum values of normal stress are achieved in shear plane when horizontal displacement acts (Figure 14). It is contrary to the case when only vertical load acts on the soil sample and the highest normal stress acts on the sample top. At first in the shear plane, the normal stress is lower, with increased displacement normal stress becomes higher and stays stable (Figure 14). At the end of the shear test, when horizontal displacement reaches the maximum value, the vertical force in the shear plane reaches its maximum. Variation of normal stress in the shear plane occurs due to the formation of the critical porosity. Low variation of the normal stress shows that the horizontal displacement of

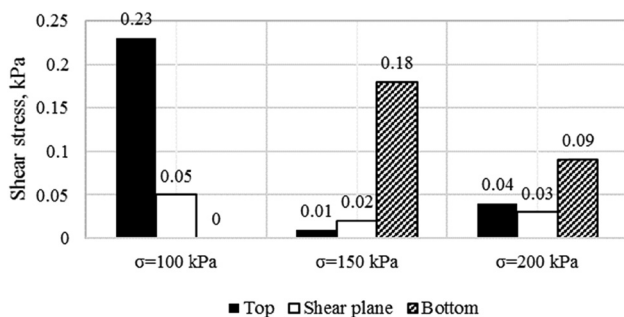


Figure 13: The mean values of shear stress when only vertical load on raised sample acts.

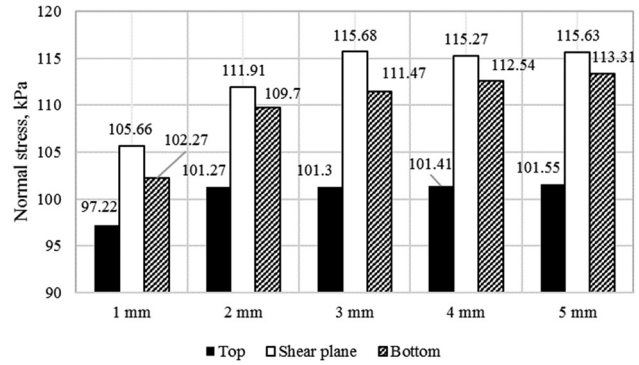


Figure 14: The mean values of normal stress when vertical load of 100 kPa acts and horizontal displacement is on the standard sample.

5 mm is enough to set the critical porosity of exactly that soil. While testing loose soil sample such horizontal displacement would not be enough. For loose soils, the critical porosity is formed at higher bottom ring displacements, whereas for denser soils the critical porosity is formed at smaller horizontal bottom ring displacements. Such horizontal stress only compacts the loose soil, and this displacement is not sufficient to form critical porosity in the shear plane.

The normal stress increased by 13.5% on the shear plane when applied on the sample top 100 kPa. On both the top and bottom of the sample, the same trend can be noticed. Difference between normal stresses measured at the beginning of test (when only normal load acts) and at the end (horizontal displacement 5 mm) on the top is 6%, on the shear plane is 28%, and on the bottom is 35%.

Analysing raised sample, it was shown similar tendency. When top ring of sample is raised by 2 cm, ~100% of vertical load is transmitted to the top like in the standard sample, normal stress increased till ~9% onto the shear plane, and a little bit less at the bottom (Figure 15). Finally, the normal stress for raised sample is lower ~4%

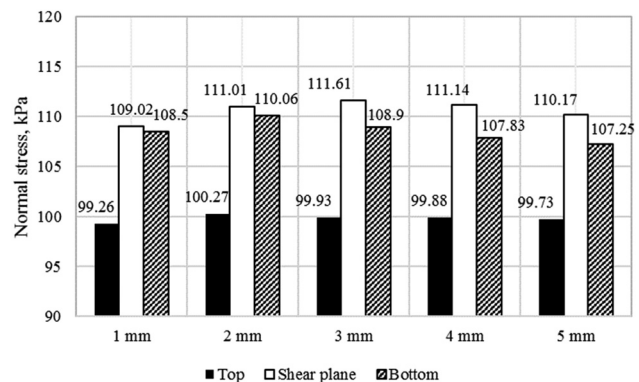


Figure 15: The mean values of normal stress when vertical load of 100 kPa acts and horizontal displacement is on raised sample.

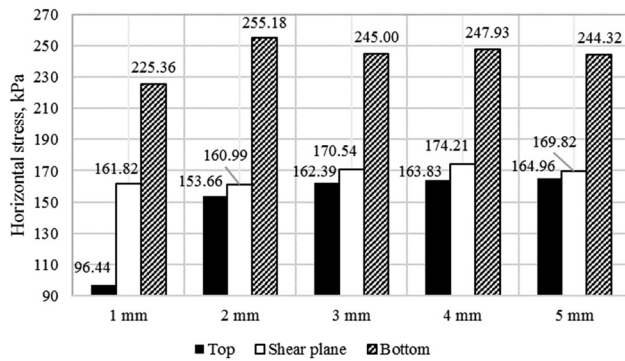


Figure 16: The mean values of horizontal stress when vertical load of 100 kPa and horizontal displacement act.

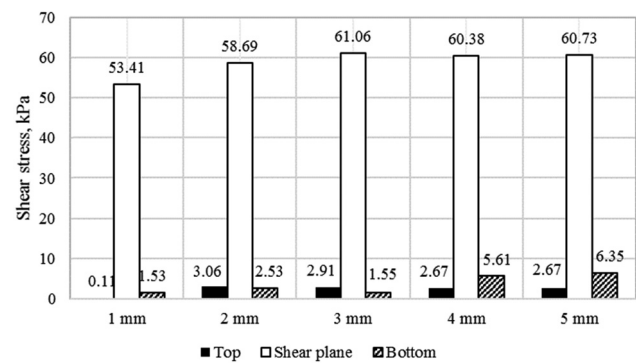


Figure 18: The mean values of shear stress when vertical load of 100 kPa and horizontal displacement act on the standard sample.

comparing with the standard sample. At first in the shear plane (and bottom), the normal stress is lower, with displacement of 2 mm, the normal stress becomes higher and later decreases minutely (Figure 15). The difference between normal stress measured at the beginning of the test (when only normal load acts) and at the end is ~45% in the shear plane and in the bottom. The shear plane allows the normal stress to increase due to dilation and more dilation that occurred near the top gave higher normal stress than those generated near the bottom [26,27].

Upon occurrence of horizontal displacement the horizontal stress distribution changes. The horizontal stress increased significantly on the bottom ring and decreased on the top for raised sample comparing with the standard sample under horizontal displacement. At the end of the shear test, when horizontal displacement reaches the maximum value, the vertical load in the shear plane reaches its maximum. At that moment, the horizontal stress is close to the maximum magnitude (Figures 16 and 17).

The shear stress is the highest in the shear plane. It is large not only in the shear plane but also in large part of the specimen. This indicates that the soil does not fail at a

fixed plane, and shear deformations occur over a large volume. The analysis does not reveal that due task conditions, but Figure 18 shows low variation of the shear stress in the shear plane. With an increase of sample height the shear stress falls ~7% (Figure 19). The contact area between a thick sample and the ring wall is proportionately greater when thin samples are used. It may follow that shear stress on the walls may affect the generation of stress within the sample. As the shearing progresses, particle rotation starts to concentrate near the shear plane and is much greater than in outside region [28]. The shear band, which has a similar thickness in both samples, in case of using the standard sample in the test occupies a greater percentage of the volume due to a smaller height. The shear stress at small horizontal displacements increases faster; at large horizontal displacements, it does not increase and in some cases decreases only marginally. The normal stress is higher at the maximum horizontal displacement too. The maximum ratio of tangential and normal stress is usually achieved at horizontal ring displacements of 2–4 mm.

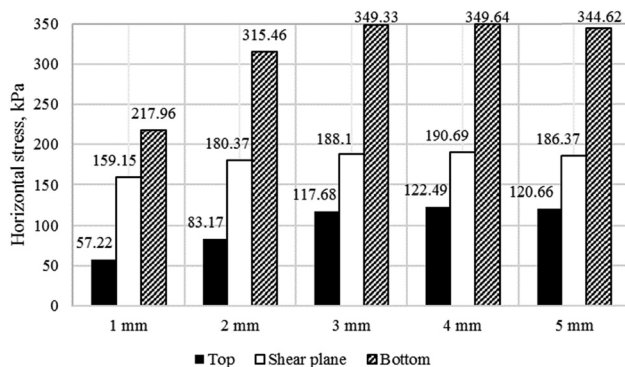


Figure 17: The mean values of horizontal stress when vertical load of 100 kPa and horizontal displacement act on raised sample.

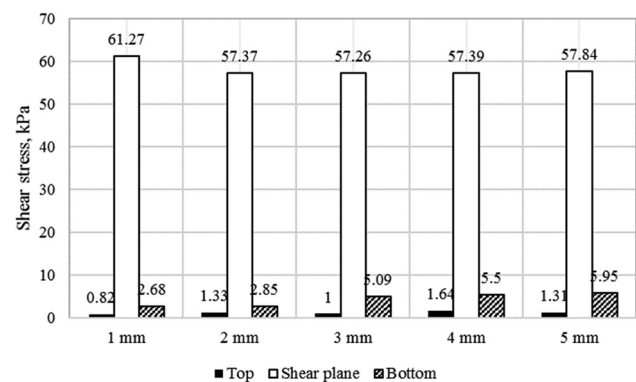


Figure 19: The mean values of shear stress when vertical load of 100 kPa and horizontal displacement act on raised sample.

The shear stress values for raised sample are a little bit lower $\sim 7\%$ comparing with the standard sample (see Figures 18 and 19). Results in terms of stress–strain, qualitatively, are similar to the experimentally observed behaviour of sandy soil tested in direct shear box. When modelling at the normal loads of 150 and 200 kPa, the trends remain similar.

6 Discussion

According to standard, square and circular shear boxes shall be used for the evaluation of shear strength. The different values of the internal friction angle and cohesion were determined by testing the strength of the soil with the identical physical properties in the different shear box apparatus. The construction of the shear box, the methodology of the research data process, and human errors influenced these different soil strength values. One of the reasons for this difference was the different height of the shear box. The height of the top part of the direct shear apparatus affects the shear strength. When the height of the dense sand sample was raised during author's numerical experiment, the vertical load and shear stress transmitted to the shear plane are lower ~ 4 and $\sim 7\%$, respectively, comparing with the standard sample. This difference is not the same for different soils. For dense soils, the higher the height of the top part of the shear box, the lower its shear strength. It is confirmed by the literature analysis. Shear box apparatus with a sliding top ring have many disadvantages. The most important thing is that the top movable part of the ring with the soil, which has to move only in the horizontal direction, moves in the vertical direction; moreover, it moves unevenly. For shear apparatus with a bottom sliding part, the direction of movement of the lower part of the ring is fixed and does not change during shearing. However, a part of the added normal stress at the top of the soil specimen due to the friction between the ring and the soil specimen is transmitted to the gap between the rings. In this case, the force perpendicular to the shear plane is less than that applied to the top of the specimen under the stamp. The experiments with the improved SPF-2 apparatus and numerical simulations performed by the authors show that the load on the shear plane is reduced by about 10–30% applying 50, 100, and 200 kPa of vertical load at the test beginning. The experiments and numerical modelling performed by the authors showed an obvious evidence of non-uniformity of stress under various normal stresses for specimens. The magnitude of the normal stress

in the sand test was found to vary by 35% within the normal stress range. The soil shear strength analysis shows dilatation. The volume variation occurs due to the tangential stresses that affect soil strength parameters. However, the change in volume during the shear test is constrained. For apparatuses of different designs, this volume variation limitation is different. The change in volume results in additional normal stresses in the shear plane. As the shear strength of the soil depends on normal stresses, the change in soil volume during the test will affect the shear strength of the soil. The experiments carried out by the authors indicate the angle of internal friction for dense angular sand decreases as box size increases. The difference is 4.7° . The mean values of cohesion obtained were similar. The influence of sample size is dependent on relative density. Cerato and Lutenege [8] experimental results reveal that loose samples were influenced by box size too. Under some circumstances, the internal friction angle of the constant volume of loose soils was more affected than that of dense sand. The friction angles of the well-graded angular sand and the angular poorly graded gravel were most affected by sample size. The rounded and uniform sand particles were a little influenced by box size. The angle of internal friction is recommended to determine with the largest size specimen possible.

7 Conclusion

After a detailed analysis of stress state, stress regularity in the sample was determined, and the main findings and conclusions can be stated:

(1) The laboratory results showed different stress path using different designs of the shear box apparatus. The applied vertical load of values of 50, 100, and 200 kPa with ADS apparatus remained constant during all the test time when the load transducer is mounted onto the top part. The determined stress paths of the sample differ from those measured on the SPF-2 sample where the stresses measured at the shear plane vary during the test time.

(2) The experimental results showed that after loading the SPF-2 direct shear sample by 50, 100, and 200 kPa of vertical load at the beginning of the test the shear plane is loaded by less load, respectively, ~ 10 , 20, and 30%. Only at the test end, the shear plane is loaded by the 100% of applied vertical load and becomes higher about 5–14% than vertical load applied on the top using the lever mechanism.

(3) The numerical modelling showed an obvious evidence of non-uniformity of stress under various normal

stresses for specimens. When the standard sample is loaded only with a vertical load, approximately 75% of that load is transferred to the sample bottom, 84% to the shear plane, and 95% to the top. This is confirmed by the literature and the authors' experimental result analysis.

(4) The similar tendency can be observed when the top ring of sample is raised by 2 cm. The wall friction reduced the stress on the shear plane and bottom comparing with the standard specimen. The type of volumetric deformation of the experimental soil determines the direction of the frictional force.

(5) The raised height of dense sand sample reduced the normal and shear stress on the shear plane about ~4 and ~7%, respectively, comparing with the standard sample. This is confirmed by the literature.

(6) The scale effect is one of the reasons of determined different shear strength parameters by two designs of direct shear apparatuses. The angle of internal friction for dense sand decreased 4.7° as box size increased.

(7) Angles of internal friction calculated from a small direct shear samples should be used with careful design of the foundation. This change in the friction angle would change the design of the foundation.

(8) The improved shear box apparatus allows to estimate the vertical load at shear plane. The computational data can be used to develop engineering methods for processing soil investigation results.

The presented results and conclusions are suitable for the dense sandy soil. Testing the dense and consolidated soils are recommended in future researches.

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