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COMPARATIVE STUDY ON DETERMINING THE INTERNAL FRICTION ANGLE FOR SAND

BY

ŞTEFAN CIOARĂ*, ANGHEL STANCIU and IRINA LUNGU

“Gheorghe Asachi” Technical University of Iaşi
Faculty of Civil Engineering and Building Services

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Abstract. Shear strength is the main mechanical property which governs the stability and resistance of soil massifs. Practically in most cases failure occurs by concentration of plastic deformations in the form of shear bands along which the movement of a part of the massive develops as a result of exceeding the shear strength. It can be concluded that other failure modes are not possible if one take into account the fact that soil does not have tensile strength and that at hydrostatic compression the stresses transmitted to the soil massive are too small to cause particle crushing. It is also known that the shear strength parameters for soils will vary depending on state of stress and strain. It follows therefore that for each case the specific failure mechanism must be considered and the laboratory tests capable of reproducing these conditions should be selected. These are the reasons for conducting a comparative study regarding the results obtained by three types of tests, namely direct shear, triaxial compression in axial symmetric state of stress and biaxial compression.

Key words: shear strength; plane strain; direct shear; triaxial.

1. Introduction

The purpose of laboratory tests is to study the physico-mechanical behavior of soils under stress conditions similar to those in the field and provide

*Corresponding author: *e-mail*: cioarastefan@gmail.com

the data necessary to implement this behavior in a set of constitutive equations. In this respect it is assumed that the tested soil sample is a point in a soil massive, assumption valid only if the state of stress in the sample is uniform. Also for the study of mechanical properties of soil the hypothesis of isotropy and homogeneity are admitted, but for this case, more than for other construction materials, this is not true. Hence the need to study the soils considering different states of stresses so that the above-mentioned assumptions are better met. Consequently, in the common practice several types of tests to determine the shear strength are used.

For the direct shear tests the principal stresses values can not be imposed and are practically unknown. Moreover the states of stress and strain which develop in the body of samples during the tests are irregular. Therefore the failure of soil samples occurs gradually and does not respect the principal stress directions (Saada & Townsend, 1981).

Some of the problems above mentioned are solved by triaxial compression apparatus. In this case, the principal stresses can be imposed and consequently, a wide range of stress paths can be achieved. However, they are limited to axisymmetric stress state, which does not correspond to situations in the field. Also through numerical calculations it is shown that this type of test is predisposed to induce plastic failures of samples (Peters *et al*., 1988).

From all the above mentioned facts is concluded that in common practice the tests are representative only for specific stress situations. Thus new test devices are needed in order to improve the knowledge regarding the behavior of soils under load throughout the principal stress space. Consequently, within the Faculty of Civil Engineering of Iaşi, an apparatus for testing the soils under biaxial compression was made. It was originally used to determine the mechanical characteristics of reinforced soils samples (Stanciu, 1981).

2. Original Plane Strain Apparatus

The testing apparatus (Fig. 1) consists mainly in the biaxial cell and vertical and longitudinal loading systems.

The biaxial cell (Fig. 2) consists of a metallic base plate (*1*) located at the bottom. On top of this two side plates made of 20 mm thick plexiglas (*2*) and the pressure cells (*3*) are placed. The plexiglas plate position is ensured by their indertion in special grooves laid down in the base plate and by means of profile angles (*16*). The pressure cells are jacked on the edges of the plexiglass plates using screw presses (*13*). At the top of the biaxial cell a steel plate is disposed (*8*) and fitted with three orifices with passage pieces (*9*) which are intended to allow the vertical sliding of the load piston (*10*). The unit of the cell thus formed is secured vertically through four tie rods (*15*) which by clamping press the base plate and the top plate on the edges of the plexiglass plates. In the longitudinal direction the cell position is ensured by means of pressure through the metal frame (*14*), and the screw presses (*13*).

Fig.1 – Original plane strain apparatus (Stanciu, 1981).

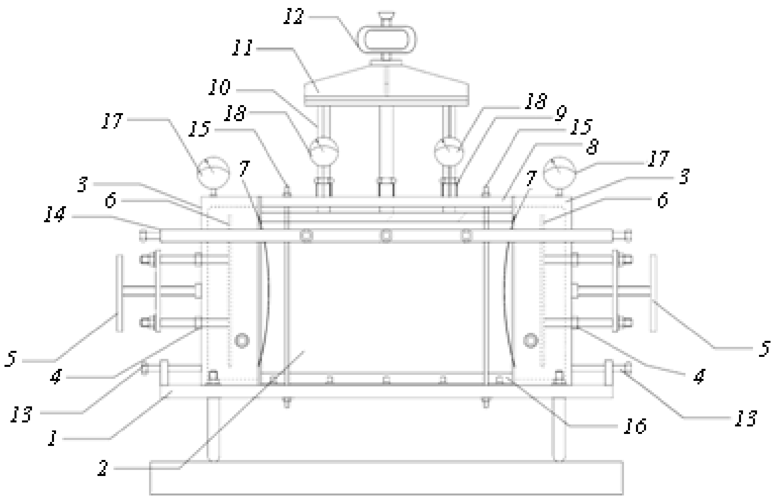


Fig. 2 – Original plane strain apparatus – biaxial cell details.

The apparatus developed within the Faculty of Civil Engineering of Iaşi, allows testing of soil samples with dimensions of 200 × 100 × 400 mm (Fig. 3).

Friction occurring at the interfaces between the soil samples and the elements of the biaxial cell (plexiglas side walls, the base plate and the cell piston) were reduced by lubricating all surfaces.

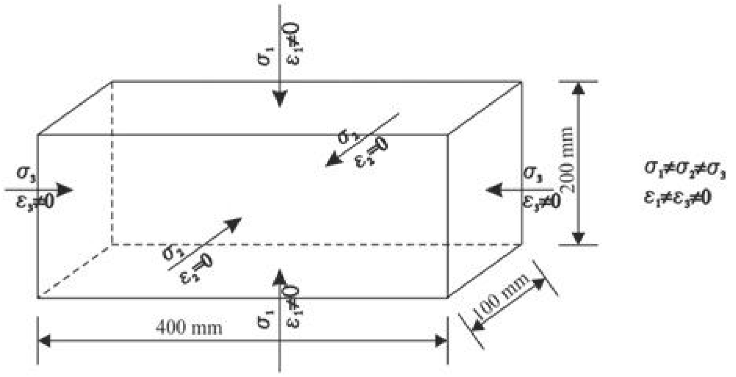


Fig. 3 – Sample sizes and stresses imposed in plane strain state (Cioară, 2012).

3. Characteristics of Sand Used for Testing

For conducting the tests below described a sand whose characteristics have been previously determined by laboratory tests was used. The grading curve of this sand is shown in Fig. 4. According to the value of the non-uniformity coefficient (U_n) the sand used for the tests is very uniform.

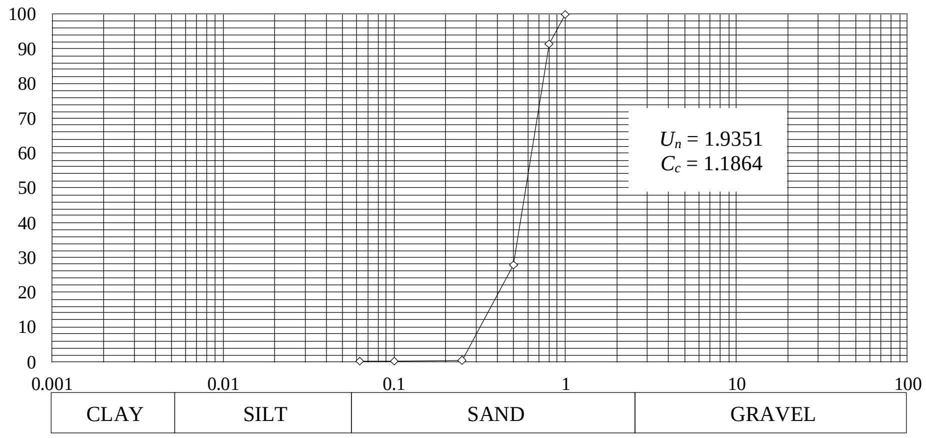


Fig. 4 – The grading curve of sand used for the laboratory tests.

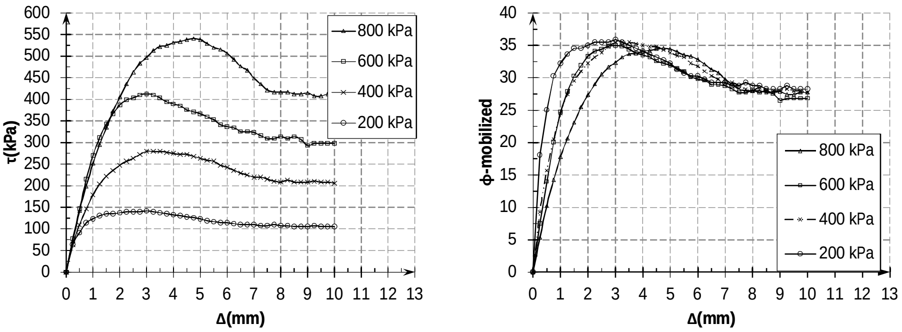
The soil samples used for all the test types, have been made by compaction of successive layers using a piston. This procedure ensures the maximum compaction state for this sand used. Also, using the same method in making of samples the same textures were obtained for the sand samples (Wanatowski & Chu, 2008).

4. Determinations by Direct Shear Tests

In order to determine the angle of internal friction through the direct shear tests, four samples were made applying normal stresses between 200 kPa and 800 kPa. Shear rate for all the test samples was 1 mm/min.

In Fig. 5 *a* the stress–strain relationship is given. It can be seen that the obtained graphs are similar for the four samples. Thus all the plotted curves show an increasing initial zone indicating that the shear strength of sand is mobilized. Then it follows the maximum point and strain softening region. At the end of the test the sand reaches the critical state and the angle of internal friction is practically constant.

Based on the obtained results (Fig. 5 *b*) it can be noticed that the peaks in terms of internal friction angle are in the range of 35° while for the critical state they are around 27°…30° (Table 1). Also, with increasing of normal stress on the shear plane, the segments that represents the mobilization of the shear strength extend while the curves maintain virtually the same shape. Consequently the horizontal displacement that correspond to themaximum values of the internal friction angle also increases.



a *b*

Fig. 5 – Relevant graphs obtained by direct shear testing: *a* – tress-displacement curves; *b* – internal friction angle mobilization curves.

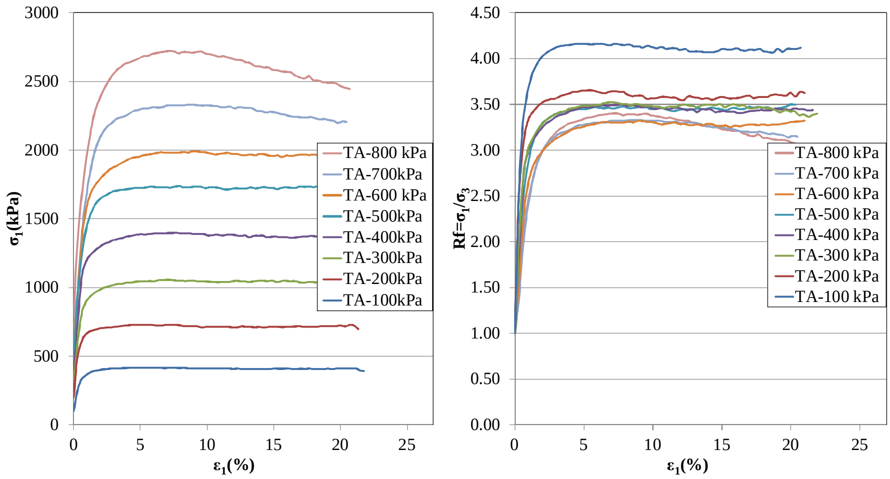
Table 1

Experimental Data Obtained by Direct Shear Tests

σ	200 kPa	400 kPa	600 kPa	800 kPa
φ_{max}	37.036	33.886	35.617	34.137
φ_{rez}	29.409	26.801	28.265	28.722

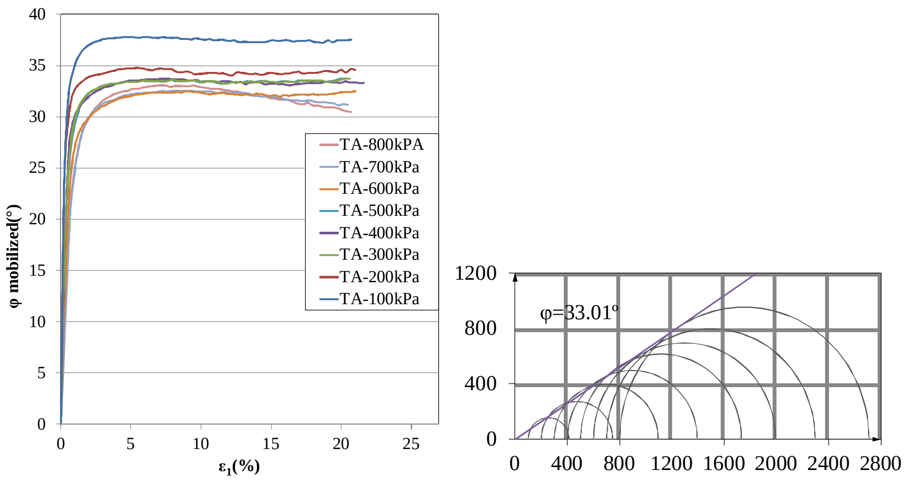
5. Determinations by Triaxial Tests

For determining the angle of internal friction using the triaxial apparatus, 8 tests have been carried out during which the values for the confinement pressure were imposed between 100 kPa and 800 kPa.



a *b*

Fig. 6 – Stress–strain curves obtained from triaxial compression test: *a* – stress–strain curves; *b* – normalized stress–strain curves.



a *b*

Fig. 7 – Value of the internal friction angle resulting from compression triaxial tests: *a* – curves of mobilization; *b* – limit circles and the intrinsic line.

During the tests two types of failures were observed. Most of the samples yielded without formation of shear bands and without an obvious peak value in terms of the vertical force. Only the samples TA700 and TA800 yielded with formation of a shear plane. Analysing the Fig. 6 *a* it can be observed that for these samples, the second zone of the graph begins to present a curved shape.

Unlike the case of direct shear testing, for the triaxial tests the strain softening phenomenon does not occur. Therefore the residual values for the internal friction angles can not be estimated. Regarding the principal stress ratios, R_f (Fig. 6 *b*), one can say that on average they are in the range of 3…5. The graphs drawn to represent the mobilizations of the internal friction angle show that the peaks are located around 33° (Fig. 7 *a*).

6. Determinations by Plane Strain Tests

For this comparative study a total of three tests in plane strain state was carried out. They were differentiated by the value of the longitudinal pressure imposed during the test. For the first sample, a pressure of 50 kPa was set, 80 kPa for the second, while for the third sample the longitudinal pressure value was 110kPa.

The tests began by imposing the values for the confinement pressure within the cells of the biaxial device. This pressure is then maintained constant throughout the testing period. After 30 min. the vertical load was applied.

In Figs. 8,...,10 the failure modes for the tested samples are shown. It can be seen that for all samples, the failures are accompanied by the formation of shear planes that develop throughout the entire mass of sand. Regarding the inclination of the shear plans, the measurements made show that the angle is constant and around 60˚. The results presented here are consistent with those obtained by Desrues (Desrues & Hammand, 1989). As a result of similar tests it was found that on the boundaries of the samples the failure plans are reflected at the same angle.

After performing the tests it can be noticed that the tested samples yielded by the same mechanism. Following the occurrence of the shear plans, compaction wedges formed through the samples. With the test advancement these wedges do not show significant changes in terms of deformations. The deformations of the sample are in large part due to slidings that occur along the shear plans. Therefore, under the constant action of the vertical load piston, the lateral wedges slide on the sides of the central wedge resulting in a tendency to expel in the longitudinal direction.

Based on the compressive forces recorded during the tests the vertical stresses were calculated. Their evolution is represented in Fig. 11 *a*. It shall be noted that the vertical stress calculation did not take into account the change of the sample section. This issue affects the accuracy of the obtained results,

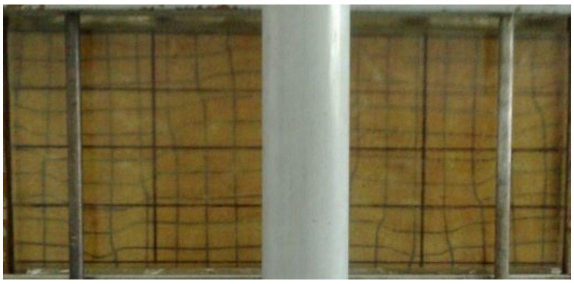


Fig. 8 – Failure of the first sample subjected to biaxial compression (σ_L = 50 kPa).

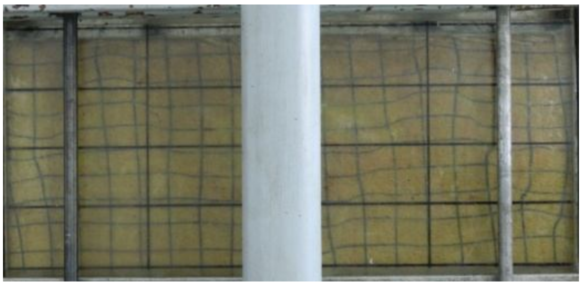


Fig. 9 – Failure of the second sample subjected to biaxial compression (σ_L = 80 kPa).

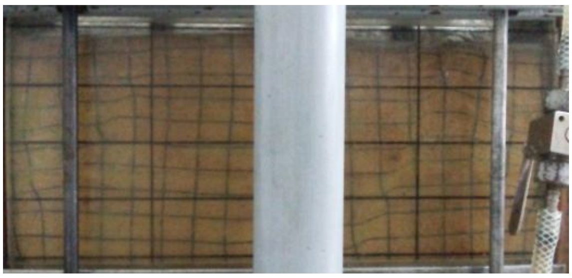
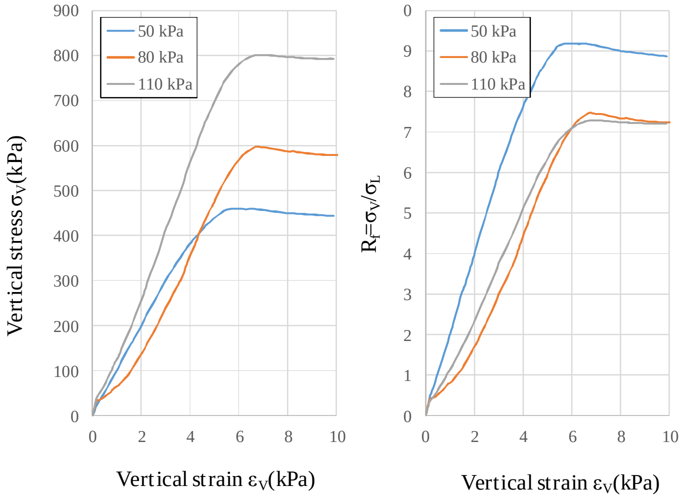


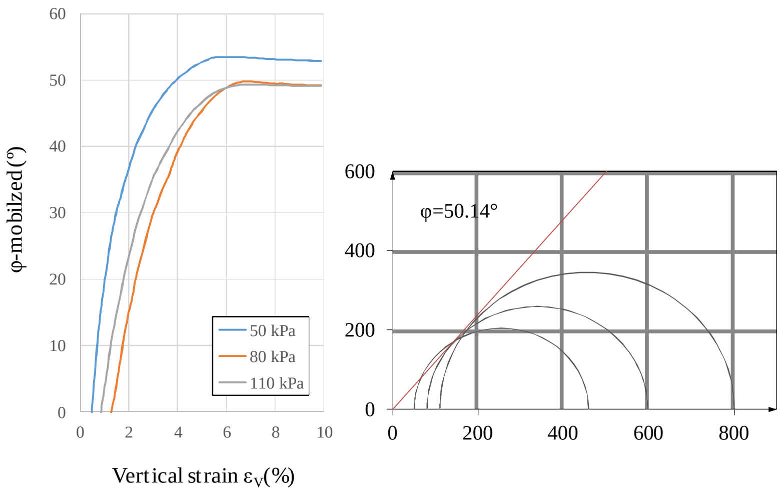
Fig. 10 – Failure of the third sample subjected to biaxial compression (σ_L = 110 kPa).

especially after the occurrence of the maximum compressive force. From this stage the section the samples change considerably due to expulsion of the lateral wedges. However, up to this point it can be considered that the sample is not significantly deformed, and therefore the correction of the cross-section for the sample is not needed.



a *b*

Fig. 11 – Stress–strain curves obtained from biaxial compression tests.



a *b*

Fig. 12 – Internal friction angle values resulting from biaxial tests:
a – curves of mobilization; *b* – limit circles and the intrinsic line.

It can be noticed from Fig. 11 that the three curves have different shapes, particularly in the case of the curve obtained for the sample 1 (σ_L =

= 50 kPa). Regarding the evolution of principal stress ratio, R_f, shown in Fig. 11 *b* note that sample 1 (σ_L = 50 kPa) has a large deviation relative to samples 2 (σ_L = 80 kPa) and 3 (σ_L = 110 kPa). A possible cause for this anomalies may be the poor lubrication of the surfaces of the cell. Analysing the data presented in Fig. 12 *a* and the Table 2 it was observed that with increasing confinement pressure (σ_L), the maximum force ($F_{\max}$) and maximum vertical tension (σ_V) are reached at higher values of the vertical strain (ε_v). As in the case of triaxial tests, it is found that sand has no strain softening zone after reaching the maximum force, even though this failure has occurred with the development of the shear planes.

Tabel 2
Experimental Data Obtained by Biaxial Compression Tests

σ_L, [kPa]	$F_{\max}$, [daN]	ε_v, [%]	σ_V, [kPa]	$R_f = \sigma_1/\sigma_3$	$\varphi_{\text{mobilized}}$, [˚]
50	1,836.693	6.45	459.1733	9.183466	53.475
80	2,392.284	6.75	598.079	7.475988	49.821
110	3,206.348	6.9	801.587	7.287155	49.346

The mobilization curves were obtained by the same reasoning used in the case of triaxial tests with axially symmetric stress state using the following formula:

$$\varphi = \arcsin\left(\frac{\sigma_V - \sigma_L}{\sigma_V + \sigma_L}\right),$$

where : σ_V is the vertical stress and σ_L – longitudinal sress.

By applying this formula is implicitly admited that the vertical and longitudinal stresses are principal stresses and their directions are not affected by friction. Furthermore, it is accepted that σ_V is the principal maximum stress and σ_L is principal minimum stress. This assumption is not valid in the beginning of the test, during which the principal maximum stress occurs in the longitudinal direction of the sample. After the test operation is started by displacement of the vertical loading piston, the principal stresses rotate, until the principal maximum stress is set by the vertical direction and the principal minimum stress acts in the longitudinal direction. Therefore the formula is valid only after the establishing of the principal maximum stress on vertical direction.

7. Conclusion

Based on the determinations by the three types of tests one can notice that the obtained results do not match in terms of the internal friction angle or mobilization curves.

While the direct shear and triaxial compression tests, produce results of the internal friction angle wich are very close, for the tests carried out in the biaxial compression apparatus the obtained values are wider appart from each other. This difference can be attributed to the influence of intermediate stress σ_2. One must not neglect the contribution of the friction occurring between soil sample and the components of the biaxial cell.

Regarding the failure mode of the specimens subjected to compression tests, one notices that for triaxial compression tests, the yeldings are mainly plastic, without the occurrence of a shear plane. At the same time all samples yielded by showing several shear planes for the tests performed in the biaxial compression apparatus.

Although the yieldings are different, none of the compression test shows evidence of the strain softening phenomenon. The cause of this situation can be better understood if one analyses the failure mechanism for dense sand. During the first stage of shearing the interparticle sliding is practically nonexistent due to the clenching between the sand particles. Once this phase is surpassed through dilatancy, slip occurs between particles. As the movements continue, the particles tend to align with one side or the other of the formed shear plane. This is the time when the residual friction angle is recorded. The lack of strain softening phenomenon in compression tests can be attributed to insufficient displacements generated on the shear plans. From this point of view, the direct shear tests have the advantage of ensuring the formation of a shear plane. Also the obtained information characterizes directly the shear plane and not the stress state within sample.

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STUDIU COMPARATIV ASUPRA DETERMINĂRII UNGHIULUI DE FRECARE PENTRU NISIP

(Rezumat)

Rezistența la forfecare este principala proprietate mecanică care guvernează stabilitatea şi rezistența masivelor de pământ. Astfel, în majoritatea cazurilor, cedarea survine prin concentrarea deformațiilor sub forma unor planuri în lungul cărora se produce deplasarea unei părți a masivului ca urmare a depăşirii rezistenței la forfecare. ținând cont de faptul că pământul nu posedă practic rezistență la întindere, iar la compresiune hidrostatică eforturile care se transmit masivelor de pământ sunt prea mici pentru a provoca strivirea particulelor materiale, se poate concluziona că alte moduri de cedare nu sunt posibile. Totodată este cunoscut faptul că parametrii rezistenței la forfecare pentru pământuri variază în funcție de starea de tensiuni şi deformații. Rezultă deci că în fiecare caz în parte trebuie considerat mecanismul specific de cedare şi alese încercările de laborator capabile să reproducă aceste condiții. Acestea sunt motivele pentru care s-a realizat un studiu comparativ asupra rezultatelor obținute prin trei tipuri de încercări, şi anume, forfecare directă, compresiune triaxială cu stare axial simetrică de tensiuni şi compresiune biaxială.