

Evaluation of fine-grained soil strength using a ring shear apparatus

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ABSTRACT. It is a matter of common knowledge, that soil strength depends on the stress state when at failure. Underground construction introduces changes into a stress state of the soil mass. Soil strength characteristics are commonly determined by axisymmetric triaxial testing, direct shear, simple shear and torsional ring shear testing. Each of the methods determines soil strength characteristics under different stress conditions characterized by the Nadai-Lode factor. The paper presents the comparison results of the drained ring shear test and drained triaxial compression test on fine-grained soil. Changes of the Nadai-Lode factor as a function of the shear stress and the strain under ring shear conditions are established. It is revealed that the transformation point of the Nadai-Lode factor corresponds to the maximum dilation of the fine-grained soil. It is found that friction angle changes by 10%, and cohesion can change up to 100%, while the Nadai-Lode factor changes from -1 to 0.8.

KEYWORDS: Ring shear test, triaxial test, soil strength, Nadai-Lode factor, dilatancy angle

1 INTRODUCTION

Conventionally, soil strength and stability are assessed using Mohr-Coulomb criterion, which describes soil shear mechanism. However, it is not the only one criterion. The universal Mises-Botkin, Drucker-Prager and Lade-Duncan strength criteria consider the invariants of stress and describe soil behavior under complex loading.

If stress conditions of the tests on soil strength parameters and the further analysis of the results are the same, there is no problem which stiffness criterion to prefer. However, when the types of soil stress state are different, some restrictions referring to noninvariance of the described criteria occur. The values of strength parameters relating to enumerated criteria depend on the type of soil response (compression, tension, and shear). For instance, 2D analysis is commonly used to process triaxial compression results. In this case, the applied strength criterion must be invariant, and its parameters must be independent from the type of the soil response (Zaretskiy Yu.K., 1989).

In particular, the stress state of the soil mass can be described using Nadai-Lode factor:

$$\mu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} \quad (1)$$

The Nadai-Lode factor ranges from $\mu_\sigma = -1 \dots +1$ depending on the balance of the principal stresses (Table 1).

Bishop et al, 1973 showed and Zaretskiy, 1989 confirmed that various strength characteristics could be received depending on the stress state conditions (fig. 1a). Malyshev and Fradis, 1968 summarized the effect of the friction angle of the pure sand as a function of the density (fig. 1b). Experimental data show the difference in the friction angle in relation to the testing method (fig. 2) (Malyshev, 1963).

Table 1. The Nadai-Lode factor depending on the balance of the principal stresses.

Nadai-Lode	Principal stresses		
	$\sigma_2 = \sigma_3$	$\sigma_2 = (\sigma_1 + \sigma_3)/2$	$\sigma_2 = \sigma_1$
μ_σ	-1	0	+1

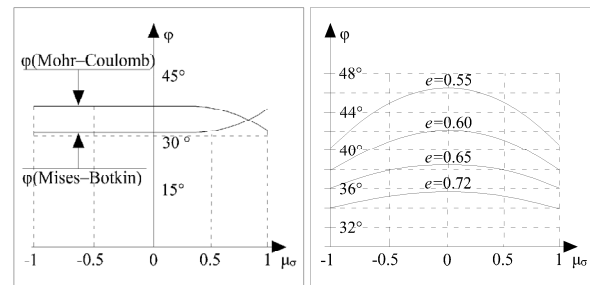


Figure 1. The effects of the Nadai-Lode factor on friction angle of sand (Zaretskiy Yu.K., 1989) (a), (Malyshev and Fradis, 1968) (b).

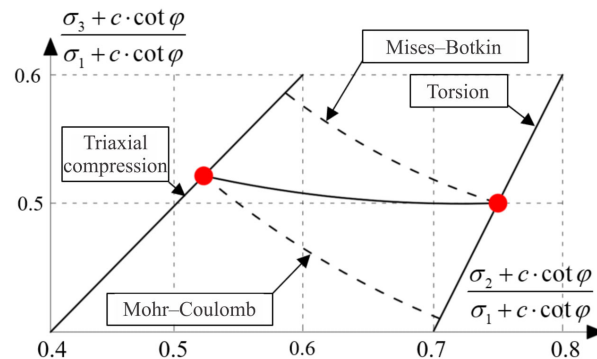


Figure 2. The results of the mean stress on failure of soils (Malyshev, 1963).

The indicated features have to be especially considered when designing slope stability, foundations, and excavations, as well as when complex stress state comprising zones of compression, tension, and shear is forming. (fig. 3).

In practice, strength parameters are determined from direct shear, direct simple shear or triaxial compression tests, though these tests do not fully simulate the foundation stress behavior during failure. Moreover, the direct shear test has some limitations (Meschyan, 1995):

- a narrow area of the deformation behavior;
- non-uniform shear stress distribution on the shear plane and variability of the shear plane due to transferring shear forces to the sample through its lateral and horizontal surfaces;
- the stress concentration at the edges of the sample; variability of the shear area, etc.

The torsional ring shear apparatus is free from these shortcomings.

The direct simple shear apparatus has also been used to determine strength parameters. However, the apparatus provides restricted shear deformation and does not often meet the condition of paired shear stresses, since the loaded sample comprises stacked protective rings (Bernhardt-Barry et al. 2021).

Application of the sophisticated true-triaxial apparatus is reasonable but for research works (Kryzhanovskiy, 1983). The method is too difficult to be utilized in bulk engineering survey.

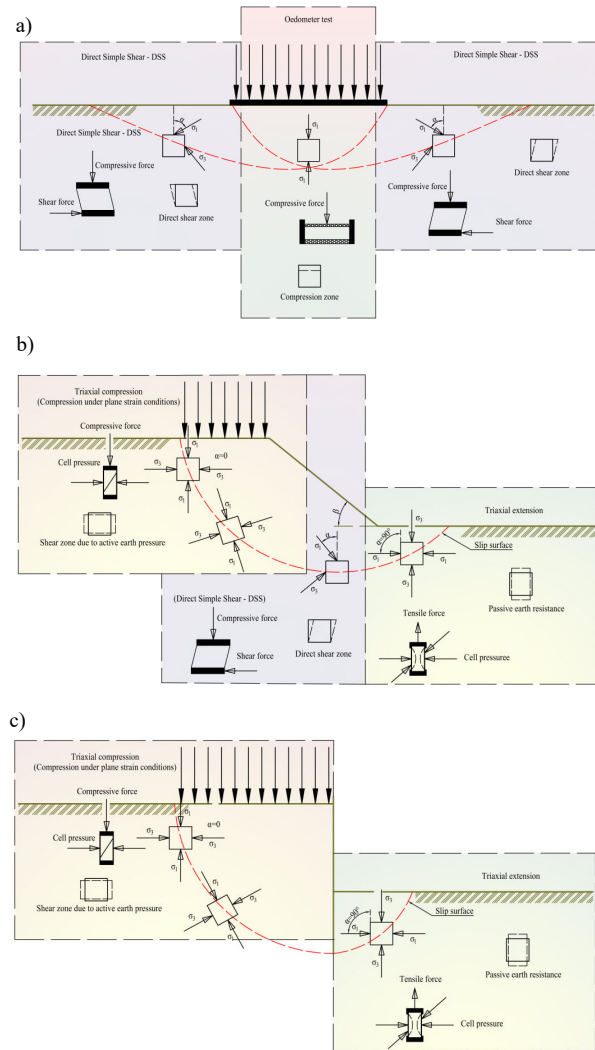


Figure 3. The behavior of the stress state at different zones of the slope slip surface (a), excavation envelope (b) and beneath the foundation (c).

Nowadays, the discrepancy between strength parameters at various stress-strain-states is offset by the application of the soil safety factor, as well as load safety factor and responsibility level. However, in the realm of modern parametric regulation approach, the application of the safety factors may not be enough to prove design solutions and should be done carefully.

The paper presents the results of drained fine-grained soil tests conducted using a torsional ring shear apparatus, and their comparison with axisymmetric triaxial test data.

2 MATERIALS AND METHODS

In this study, medium sand densified to $2.0\text{--}2.1\text{ g/cm}^3$ (fig 4) was subjected to consolidated isotropic drained triaxial compression and torsional ring shear tests.

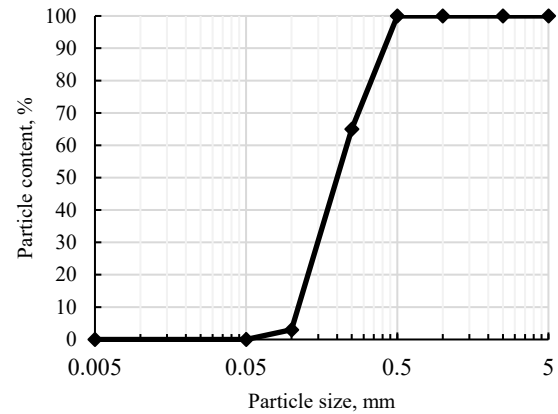


Figure 4. Cumulative curve of the grain size distribution.

Cylindrical specimens 50 mm in diameter and 100 mm in height prepared using layer-by-layer dry compaction technology were used in the triaxial test (fig. 5). The effective confining pressure was 100, 200, and 300 kPa. Vertical load was applied in a strain-controlled mode at a rate of 0.1 mm/min. The Nadai-Lode parameter was set to $\mu_\sigma = -1$ (axisymmetric triaxial compression).

In torsional ring shear test, ring-shaped specimens with an outer diameter of 100 mm, an inner diameter of 50 mm, and a height of 25 mm were used (Figures 6-7). The vertical stress of 100, 200, and 300 kPa, corresponding to $\mu_\sigma = -1$ was applied to the specimens. The lower ring was then rotated, inducing shear stresses in the specimen and gradually changing the Nadai-Lode parameter. The method allowed us to record peak and residual values of the of friction angle ϕ and cohesion c .

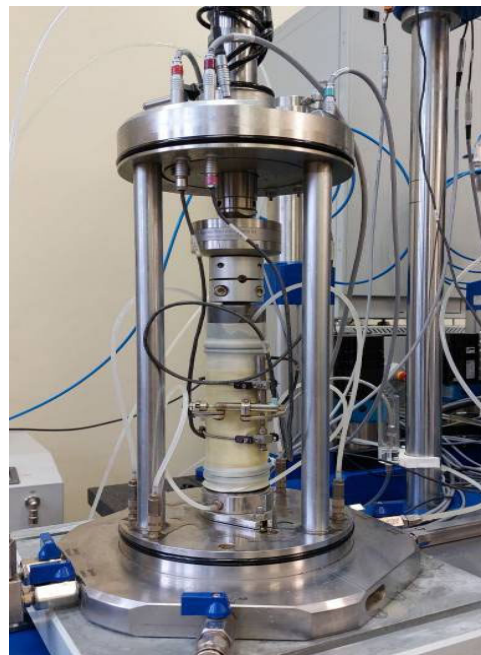


Figure 5. The sand specimen installed into triaxial compression apparatus before testing.

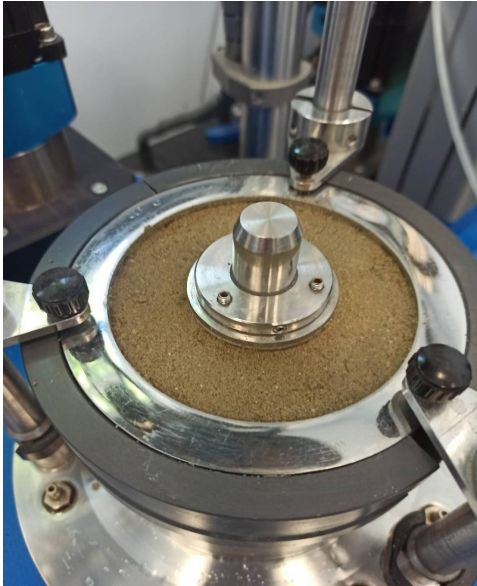


Figure 6. The sand specimen installed to torsional ring shear apparatus.



Figure 7. The torsional ring shear apparatus during testing.

3 RESULTS

Figure 8 shows typical curve of the torsional ring shear test and diagrams of the stress components and Nadai-Lode factor in relation to the twist angle.

Analyzing the results showed that due to the shear strain the shear stress increased in accordance with hyperbolic law and stabilized after the maximum values at the twist angle of 10 degrees was reached. The Nadai-Lode factor affected by shear μ_σ changed from -1 (compression) to +1 (tension). The maximum value of $\mu_\sigma = +1$ was recorded at a twist angle of approximately 2.5 degrees and corresponded to the maximum of vertical strain rate, i.e., the maximum dilatancy of the specimens. A decrease in dilatancy and a change in the μ_σ value

up to μ_σ 0.7–0.8 (at the state of residual strength) was recorded at higher values of strain.

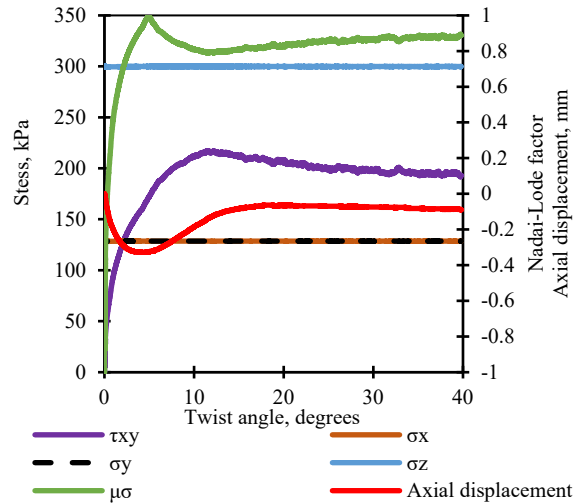


Figure 8. Stresses components and the Nadai-Lode factor versus the twist angle during the ring shear testing.

Figure 9 shows the maximum (peak) shear stress versus main stress plotted on the base of the triaxial compression and the shear ring tests results. Table 2 summarizes the results.

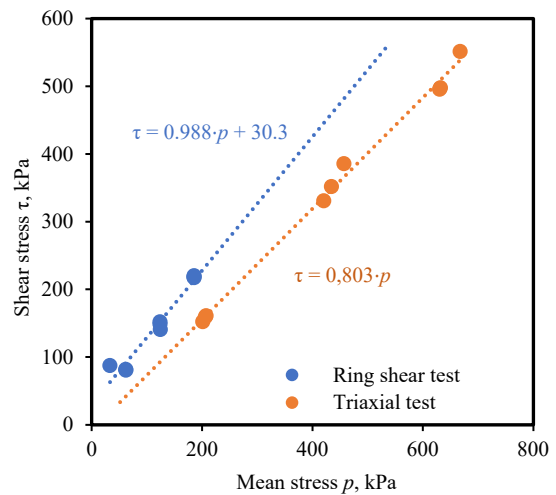


Figure 9. A comparison of the strength parameters of sands, determined via triaxial compression and shear ring methods.

It was found that the friction angle ϕ obtained by the two methods differed by approximately 13% at the peak strength and coincided at the residual state. The cohesion c values showed an even greater discrepancy: the triaxial test indicated zero cohesion both at peak and residual states, while the ring shear test yielded 14 kPa and 16 kPa, respectively.

Table 2. Summarized tests results

Test type	Strength parameter	Peak	Residual	Failure μ_σ
Triaxial test	Friction angle [°]	39	34	-1
	Cohesion [kPa]	0	0	
Ring shear test	Friction angle [°]	34	30	0.8
	Cohesion [kPa]	14	16	

Overall, the results received showed the degree of influence of the stress state on the strength parameters and were in agreement with the conclusions made by Zaretsky, 1989.

Further research will assess the influence of the considered stress state on the calculation results when determining strength properties of the soil mass.

4 CONCLUSIONS

The results confirmed the fact that strength parameters of sandy soils significantly depended on the type of stress state. This appeared in the difference in the results obtained with the triaxial compression and the ring shear tests.

The friction angle values differed by roughly 15% at peak strength and by 12% at the residual state, while cohesion showed a notable discrepancy: the triaxial test indicated zero cohesion at both peak and residual states, whereas the ring shear test yielded 14 kPa at peak and 16 kPa at residual state. This emphasizes the sensitivity of these parameters to the testing method and loading path. Furthermore, the ring shear test provided a more complete recording of residual strength values, which was crucial when assessing soil stability at significant deformations.

An analysis of the Nadai-Lode factor variation revealed a transition from -1 at the triaxial compression to $0.7-0.8$ at the ring shear test, reflecting a transition of the stress state from compression to shear and tension. This confirmed the need to consider the Nadai-Lode factor when interpreting the failure mechanism and determining strength characteristics.

The obtained data were consistent with the results of the previous studies (Zaretsky, 1989) and (Damian Stefanow & Piotr A. Dudzi, 2021) and confirmed the fact that a correct assessment of soil strength was impossible without taking into account the influence of the stress state.

Overall, the studies conducted have shown that the use of various testing methods provides a comprehensive assessment of soil behavior and enhances the reliability of engineering calculations.

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