Continuously loaded triaxial tests

Les tests triaxiaux chargé continuement

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ABSTRACT: As a rule conventional triaxial tests are performed in cylindrical triaxial apparatus. A specimen, which is built in the apparatus, is incrementally loaded by different stresses. The described procedure is retardatory and results can even be unreal when individual stress increments are high, followed by high gradients of pore pressure. An extent of triaxial tests performed in practice is often unpretentious, mostly due to high price and long duration of test execution. Therefore it is reasonable to supplement conventional incremental tests by continuously loaded tests in which stress or deformation conditions are changed continuously. The paper presents an example of continuously loaded triaxial tests execution on soft rocks supplemented with conventionally incrementally loaded tests. Comparison of both tests results indicates the applicability of the continuously loaded test performance. Its advantages, in comparison to conventional tests are mostly due to their quick performance, continuous stress changes, and the fact that small stress increments do not cause excessive pore pressure gradients.

RÉSUMÉ: Les test triaxiaux chargés continûement sont généralement executés dans un appareil triaxial cylindrique. Le specimen qui se trouve dans l'appareil est chargé en incréments par des charges differentes. Cette procédure est retardataire et les résultats peuvent être même iréels quant les incréments des charges sont grands et suivis par la pression des pores aux gradients hauts. Un certain nombre des tests triaxiaux est exigeant en pratique à cause du prix élevé et la durée longue de leur execution. C'est pourquoi il est raisonable d'échanger les tests conventionels par les tests chargés continûement où les conditions de déformation changent continuellement. L'exposé présente un example d'exécution des tests triaxiaux chargés continûement sur le roc mou supplementés par des tests conventionels chargés en incréments. La comparaison des résultats montre l'application d'exécution des tests chargés continûement. Leur avantage, en comparaison aux test conventionels, est leur exécution rapide, changement continué des charges et la fait que des incréments petits de charge ne produisent pas ded gradients excessifs de la pression des pores.

1 INTRODUCTION

In geotechnics, several standard procedures for soil and rock strength determination were developed in the past. With the development of the theory and test equipment, triaxial test were increasingly put into effect. Their advantages are above all:

- simulation of triaxial stress and strain in-situ conditions;
- evident and clear test conditions;
- wide spectrum of possible test executions;
- possible determination of more different characteristics (consolidation, strength, shear strength, creep).

Irrespective of described advantages, we are still restricted in triaxial tests executions. The test is carried out in cylindrical cells restoring actually axial symmetrical test conditions, which can restrict us in the research of anisotropic characteristics. Conventional tests are executed with stress increments whence it follows:

- large instantaneous changes of individual stress levels;
- high pore water pressure gradients at each stress change;
- long duration of test performance.

With the development of test and measuring equipment and with computer aid, it was possible to introduce computer guided tests, according to wish tests can be performed also with continuous load changes instead of incremental one. In the continuation, some possible approaches of continuously loaded test executions are presented.

2 TESTS EXECUTION

For the execution of continuously loaded tests, the following phases are important:

- sampling and determination of physical characteristics;
- preparing and placing of specimen;
- test equipment;
- test procedures; and
- interpretation of results according to the chosen theory.

In most of these phases, approaches are similar in incremental and in continuous tests. Essential differences are in required equipment, test procedure execution and test results interpretation. Test equipment shall be appropriately supplemented with computer and measuring equipment as well as connections, so that computer guided test execution is possible with collecting and registering data and test results interpretation. Test procedures shall be adapted, instead of stress increments their changes are continuous as regards chosen conditions. The velocity of loading is very important in test results interpretation. At higher velocity, with no consideration of corrections, obtained parameters can become incomparable.

3 TEST EQUIPMENT

To carry out continuously loaded test, the following test equipment is needed: cylindrical triaxial apparatus with a cell, a press with appurtenant electro-mechanic equipment, measuring equipment and computer hardware and software equipment.

In the Laboratory for Soil Mechanics, Faculty of Civil Engineering, University of Maribor, we dispose with an older Wykeham Farrance triaxial apparatus that allows execution of incrementally loaded compression tests. Newer triaxial apparatus (Wille UP 25) with appurtenant measuring and computer equipment makes possible the execution of continuous test with arbitrary stress paths. The newest Wykeham Farrance triaxial apparatus makes it possible to perform tests also with cycling loading. Simultaneous usage of the listed equipment enables wide spectrum of possible tests and sufficiently short time of investigations.

4 TEST PROCEDURES

Contemporary equipment makes feasible choice of different tests and stress paths. We can choose between drained and undrained tests or between compression and extension tests. These make possible performance of wide spectrum of tests and adjustment regarding in-situ stress states. Usually the following phases are performed:

- saturation (one of the standard phases);
- consolidation (at hydrostatic stress state or adequate K_0);
- drained or undrained test, compression or extension, usually loading, unloading and reloading.

The calculation of the parameters follow from individual phases, namely: permeability k, consolidation coefficient c_v, coefficient of volume compressibility m_v, and Young modulus E, Poisson's ratio ν.

Shear parameters cohesion c and internal angle of friction φ are usually determined by three tests. The stress path of compression drained test is presented in Figure 1. In each test, the consolidation can be performed at hydrostatical stress state or at stress ration near K_0.

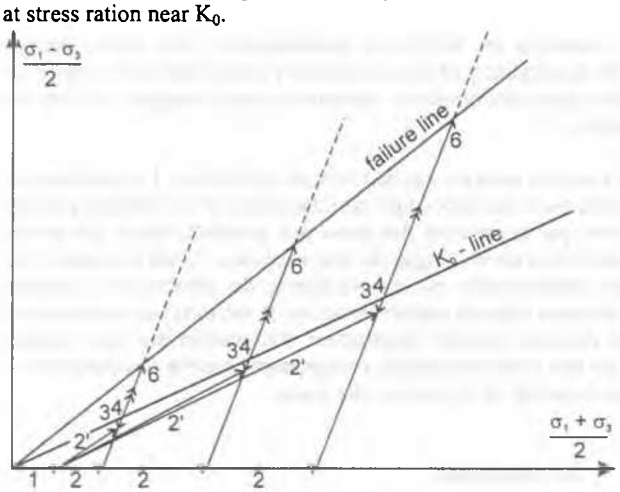

Figure 1. Stress paths for compression CD test on three specimens, 1-saturation, 2-consolidation (hydrostatic), 2'-consolidation (with K_0), 3,4,5-loading, unloading, and reloading.

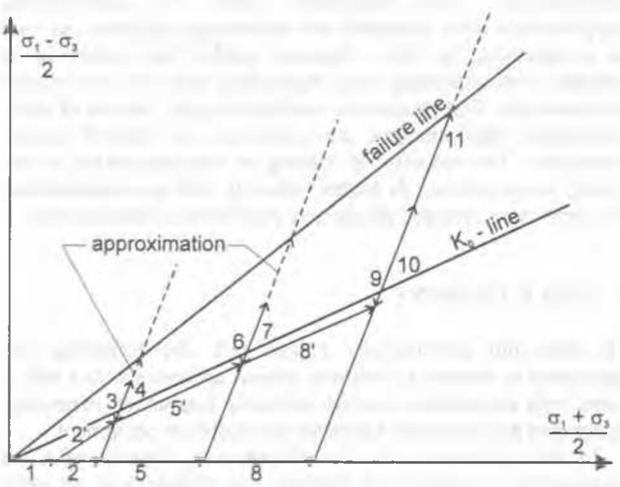

Figure 2. Stress paths for compression CU test on one specimen, 1-saturation, 2-consolidation (hydrostatic), 2'-consolidation (with K_0), 3,4,5-loading, unloading, and reloading.

When sampling gives us only one useful specimen, the test can be carried out only on this particular specimen as it is shown in Figure 2. In such cases after unloading at first constant lateral stress state σ_3 reloading does not follows but we enhance lateral stress to a higher state and repeat procedure. Not earlier than at the third lateral stress state, reloading is executed until failure occurs. The failure points at first and second lateral stress state are approximated from stress-strain functions as shown in Figure 3.

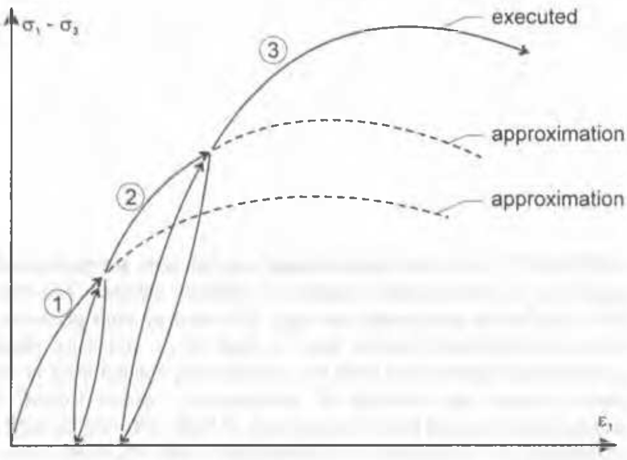

Figure 3. Distortion-strain relationship for compression CD test with approximation of failure lines.

When undrained tests are carried out the procedure is similar. After initial consolidation, drainage valves are closed, and pore water pressures and effective stresses respectively are measured. When only one specimen is available, similar procedure as in drained test is performed with approximation of failure points (see Fig. 4) or application of Watson-Kirwan technique.

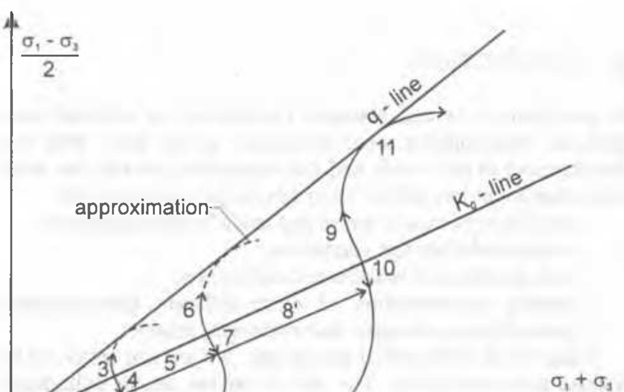

Figure 4. Stress paths for compression CU test on one specimen, 1-saturation, 2-consolidation (hydrostatic), 2'-consolidation (with K_0), 3,4,5-loading, unloading, and reloading.

4.1 *The influence of loading velocity on results*

Loading velocity is of essential importance for testing reliability or comparability respectively with incremental tests. Important is time resistance *R*, which is defined as

$$R = \frac{dt}{d\varepsilon_{zz}} = \frac{d(cause)}{d(response)} = \frac{1}{\varepsilon_{zz}} \quad (1)$$

We know from tests that after primary time of consolidation $t > t_0$ the time resistance varies linearly with time

$$R = r_s \cdot t \quad (2)$$

Let the strain time behaviour during one load step in an oedometer be given as:

$$\varepsilon = f(\sigma', t) \tag{3}$$

Mathematically the total strain differential is expressed

$$d\varepsilon = \frac{d\varepsilon}{d\sigma'} \cdot d\sigma' + \frac{d\varepsilon}{dt} \cdot dt \tag{4}$$

For t = constant and for σ' = constant we get

$$d\varepsilon = \frac{d\sigma'}{m \cdot \sigma} + \frac{dt}{r_s \cdot t} \tag{5}$$

By integrating above Eqs one gets

$$\varepsilon = \varepsilon_i + \frac{1}{m} \ln \frac{\sigma'}{\sigma'_c} + \frac{1}{r_s} \ln \frac{t}{t_0} \tag{6}$$

from which we recognize the following strain components

ε_i initial (integration constant)

$\varepsilon_p = \frac{1}{m} \ln \frac{\sigma'}{\sigma'_c}$ primary for $\sigma' \geq \sigma'_c$

$\varepsilon_c = \frac{1}{r_s} \ln \frac{t}{t_0}$ creep (secondary) for $t \geq t_p$

To run faster continuous loading is introduced. The specimen preparation, placing and initial loading are the same as in incremental tests. The specimen is loaded with continuous vertical stress increased in time. During the test performance, one of the following quantities is guided:

- change of the vertical stress σ_z (constant rate of stress);
- rate of the strain ε_z (constant rate of strain);
- ratio between water pore pressure and effective vertical stress $u_w/\sigma_{z'}$ (constant pore pressure ratio).

The solutions are similar as in incremental tests:

$$E_{oed,cor} = \alpha_E \cdot E_{oed,cal} \quad k_{cor} = \alpha_k \cdot k_{cal} \quad \text{and}$$

$$c_{v,cor} = \alpha_c \cdot c_{v,cal} \tag{7}$$

Parameters are determined using the expression of one-dimensional consolidation:

$$c_v \frac{\partial^2 u_w}{\partial_z^{\,2}} = \frac{\partial u_w}{\partial t} - \frac{\partial \sigma'_z}{\partial t} \tag{8}$$

Quantities α_E, α_k, and α_c are correlation parameters that depend on the rate of loading, ratio between water pore pressure and effective vertical stress and creep. As example for test relation $du_w/d\sigma_z$ we get

$$\alpha_E = 1 - \frac{du'_w}{d\sigma} \cdot \bar{f} \qquad \alpha_k = \frac{1}{f(\zeta)} \qquad \alpha_c = \alpha_E \cdot \alpha_k \tag{9}$$

where

$$f = \frac{d\sigma_z}{du_w}(1 + C_1 \cdot \sinh a\zeta + C_2 \cdot \cosh a\zeta) \tag{10}$$

$$a = \operatorname{arccos} h \frac{1}{1 - \frac{du_w}{d\sigma_z}} \tag{11}$$

$$f_1 = \int_0^1 f(\zeta) d\zeta \qquad \zeta = \frac{z}{h} \tag{12}$$

values f_1, f, α_E, α_k, and α_c depends on boundary conditions.

5 EXAMPLE

Described test procedures are applicable for soils as well as for rocks. Here we present an example of soft rock. For the purpose of laboratory strength tests, we received a larger number of permo-carboniferous slate samples from different locations of the Vransko-Blagovica motorway section. During erection it was namely demonstrated that the actual strength of slates, especially shear strength during the construction in slopes, is worse than it was proved by standard laboratory tests. Building contractors had a lot of problems due to instabilities of slopes.

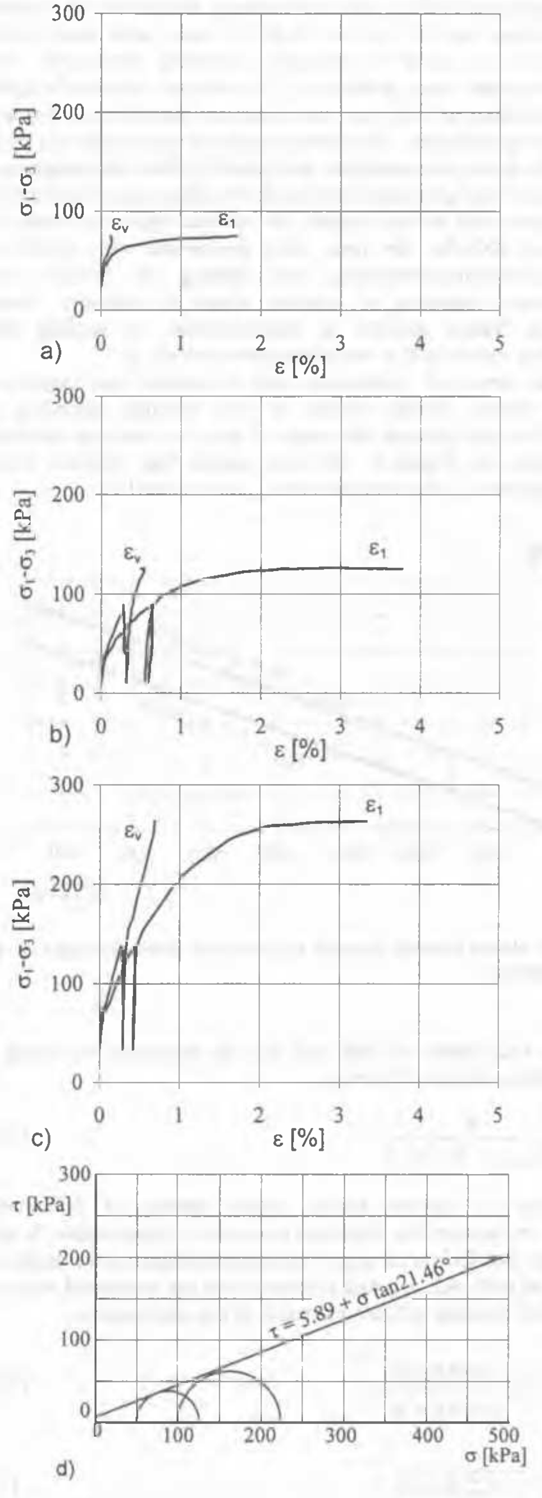

Figure 5. a) to c) Relationships diagrams of $\varepsilon_1 = \varepsilon_1(\sigma_1 - \sigma_3)$, $\varepsilon_v = \varepsilon_v(\sigma_1 - \sigma_3)$ for spherical stresses 50, 100 and 200 kPa, d) Shear strength regarding to Mohr-Coulomb yield criteria.

Investigations were performed on series of samples of equal material. Tests were performed classically with incremental and continuous loading. Owing to schist structure of soft rock, tests were carried out in triaxial cells that allow placement of specimens up to 100 mm in diameter. The average largeness of specimens was 85 mm in diameter and 170 mm in height.

All tests were performed in natural moisture content after consolidation of specimens under a stress state similar to the in-situ state. After consolidation, specimens were loaded incrementally or continuously. Incremental tests were carried out as conventional triaxial tests on three parallel specimens with different lateral stresses and vertical stress changes.

Continuous loading tests were mostly carried out at constant axial strain rate of $d\varepsilon_1 / dt = 0.001\% / \min$, with axial stress condition of $d\sigma_1/dt = 1$ kPa / min. Drained (vertically) and undrained tests were performed. The selected course of loading and unloading of each test was computer guided, recorded and saved on a computer. The interpretation of test results was done partially during test execution and partially after test completion. In Figure 5 are presented test results of compression CU tests on three specimens of one sample. At selected spherical loads 50, 100 and 200 kPa, the tests were performed with cycles of loading-unloading-reloading and loading to failure with continuous changing of vertical stress at constant lateral pressure. These enables us determination of loading and unloading modulus E, ν and shear parameters c, φ.

From series of incremental and continuous test numerous results follow. Overall results of shear strength according to Mohr-Coulomb criteria for series of tests on identical material are shown in Figure 6. We can realise that extreme shear strengths are $\tau_{min}=1+\sigma \cdot \tan 19°$ and $\tau_{max}=54+\sigma \cdot \tan 19°$.

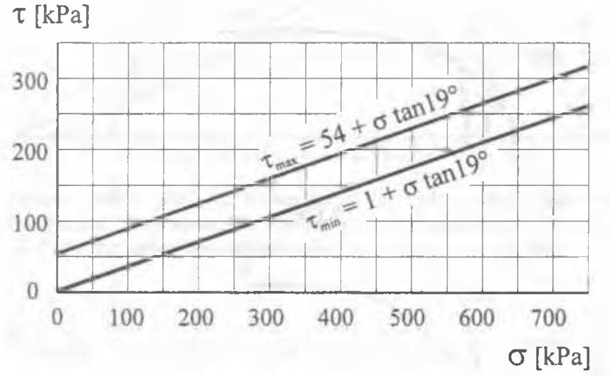

Figure 6. Mohr-Coulomb minimal and maximal shear envelopes of all performed tests

The axial strain of soft rock can be expressed by using a hyperbolic analytical function:

$$\varepsilon_1 = \frac{q}{2E_{50}(1 - Rq/q_f)} \tag{13}$$

where E_{50} denotes secant elastic module of soft rock, $q = \sigma_1 - \sigma_3$ denotes the distortion invariant of stress tensor, R and q_f denote coefficient of shear loading and distortion invariant at failure of soft rock. E_{50} and E of soft rock are expressed with an analytical function of lateral stresses of the specimen σ_3.

$$E_{50} = E_{50}^r \left(\frac{c \cot\varphi + \sigma_3}{c \cot\varphi + p^r} \right)^m \tag{14}$$

$$E = E^r \left(\frac{c \cot\varphi + \sigma_3}{c \cot\varphi + p^r} \right)^m \tag{15}$$

where c, φ and p^r denote the cohesive part of the shear strength, shear angle, and reference value of the lateral stress. E_r is elastic module at chosen reference lateral stress, exponent m depends on the soft rock type. Yield surfaces are expressed as a function of the major component of the plastic strain:

$$F(\sigma, k^p = \varepsilon_1^p) = \frac{q}{2E_{50}(1 - Rq/q_f)} - \frac{q}{E} - \varepsilon_1^p \tag{16}$$

The plastic potential surface in terms of principal stresses is expressed as

$$Q(\sigma) = q - (c_m \cot\varphi_m + \sigma_1 + \sigma_3)\frac{(\sin\varphi_m - \sin\varphi_c)}{(1 - \sin\varphi_m \sin\varphi_c)} \tag{17}$$

where c_m and φ_m denote mobilized shear angle, and mobilized cohesion respectively, φ_c denotes critical shear angle of the soft rock which indicates critical level of soil rock shear strength mobilization, when surface failure is formed and consequently progressive dissipation of the soft rock internal stresses begins in the region of potential failure. By additional loading of the soft rock it gradually yields along failure surface and the volume of the specimen gradually increases. We suggested use of new constitutive parameters of the considered slates in geotechnical analyses (see Table 1).

Table 1: Some suggested characteristics of considered slates.

parameters	values	values
shear angle and cohesion	$\varphi = 21°$	c = 18.6 kPa
critical shear characteristics	$\varphi_c = 18°$	$c_c = 16.0$ kPa
secant elastic module	$E_{50} = 20$ MPa	at $p^r = 100.0$ kPa
elastic module	E = 75 MPa	at $p^r = 100.0$ kPa
constants	R = 0.9	m = 0.7

6 CONCLUSION

The introduction of continuously loaded triaxial tests represents important completion of standard triaxial tests. The advantages are above all: performance with arbitrary choice of compression or extension stress path, which can essentially reduce performance time of the test. Stress changes go continuous, so pore pressure gradients, that represent a problem due to small sample size, are reduced. In general, compression and extension tests can be performed which can be undrained or drained with different vertical and/or lateral drainage conditions. With suitable equipment and when it is significant they can be supplemented with cyclic loading. Loading is carried out with constant strain rate or constant stress rate or pore pressure-stress ratio. In the existing practice so far, constant strain rate tests were shown as most suitable.

The practical example of soft rock investigation, which is presented in the paper, shows that proper choice of loading velocity (sufficiently slow) yields much lower strength parameters than otherwise. The same is valid for shear parameters c and φ. In the presented example, standard shear tests yield much higher values than they were later yielded with described test procedure.

The loading velocity is the biggest problem of continuously loaded tests. With unsuitable (too high) velocity, the results can essentially differ, when the same test results interpretation as in incremental loaded test is used. This is extra valid for materials with log duration consolidation and for materials that are creep sensitive. Then it is suitable to consider correction (correlation) factors when evaluating parameters. The values of those factors approach value 1 when test are carried out slowly.

As long as experiences are not sufficient it is suitable to perform both incrementally and continuously loaded tests, results of which shall not differ significantly.