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UP-TO-DATE MEANS OF SHEAR STRENGTH TESTS COMPARISON BETWEEN SIMPLE AND DIRECT SHEAR

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Abstract

A modern laboratory for shear-strength testing has been developed in the last ten years at the Department of Hydrogeology and Engineering Geology at University of Miskolc. The own-developped computer-controlled triaxial equipment is suitable to perform tests at different stress paths. The computer controlled ring shear equipment due to its special technics of normal stresses is suitable for constant volume testing. The wall friction can also be measured. The study compares the shear equipments based on direct or simple shear theory, analyses the stress distribution, deformation fields inside the sample, formation of failure planes.

Keywords: triaxial equipment, ring shear, simple and direct shear, photoelastic test, deformation, failure planes.

1. General on Shear Strength Test

To our actual knowledge, the first true shear test was made by Collins in 1846 (SKEMPTON, 1949) for his slope stability analysis. It is not known exactly when the direct shear box was introduced, and whether Coulomb did apply at all? Its actual form is due to Krey, Terzaghi and Casagrande.

After World War 2, the new method of triaxial tests penetrated the practice of geotechnics. The first devices appeared in 1930, about simultaneously in Germany, in the Netherlands and in the USA. Several test methods emerged, but the main shortcoming of these tests — namely the equality of second and third principal stresses — subsisted.

For long, the triaxial test has been considered to surpass any other shear strength test – and some have this view even now – although, while it is seldom enounced, neither here is the stress distribution uniform inside the specimen, as seen in *Fig. 1*, showing inhomogeneities inside the specimen, after CARTER (1982).

Axial symmetry being exceptional in practical problems, researchers experimented with different shapes of specimens, in order to possibly approximate in situ conditions. Prisms with square or rectangular cross-

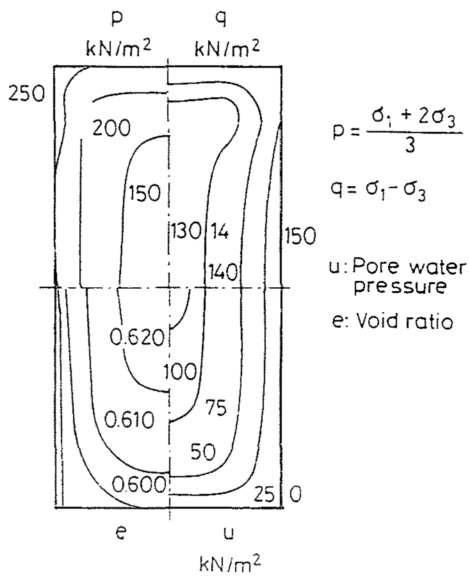

Fig. 1. Inhomogeneities inside a cylindrical soil specimen in a triaxial compression test

section, then the hollow cylinder (thick-walled tube) emerged as obvious solutions (SAADA et al., 1981).

With the advent of computers, computer-controlled testers providing arbitrary stress paths became increasingly applied. An example for the latter is seen in *Fig. 2*, sketch of computer-controlled triaxial apparatus developed jointly by our Department and the Donát Bánki Technical College of Mechanical Engineering (CZINEGE–KOVÁCS–SZABÓ, 1991).

Three main units of the equipment are the robust loading frame (ultimate force 50 kN), with a working space accommodating triaxial cells of different sizes; three-chamber pressure control device; as well as a computer controlling the system and performing measurements.

Velocity of the loading frame actuated by two ball spindles (3,4) and inching motor (7) ranges from 0.0001 ÷ 1 mm/min (*Fig. 2*). The axial load is measured by dynamometer cells F, fastened to the upper crossbar with measurement ranges of 20 kN and 100 kN. Actually, two Wykeham Farrance measuring cells (10) are available for testing specimens, Ø38 mm, and Ø100 mm, resp., permitting lateral pressure variations in the range of 0 to 2 MPa.

Vertical compression of the specimen is measured by electric displacement detector H, pore water pressure by electronic marker p_v. Cell pressure p_o is controlled by the special three-chamber device (11–15).

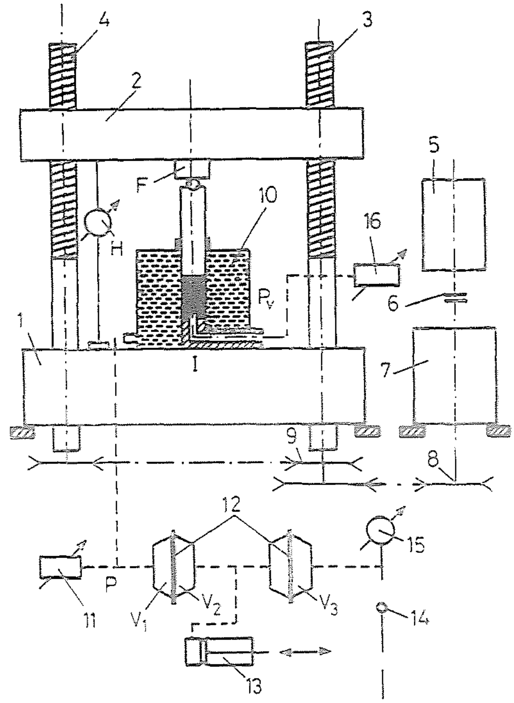

Fig. 2. Scheme of computer-controlled triaxial compression apparatus

Essential units of the electric measurement and control system are an IBM compatible computer, a measurement amplifier and a control card incorporated in the computer controlling the inching-motor drives by means of an eight-channel A/D transformer, receiving and amplifying analogous marker signals (axial force, compression, pore wear pressure, lateral cell pressure). The control program consists of routines written for the sake of versatility and comprehensibility in Quick-BASIC program language. The routines are of two kinds: measurement conversion routines to interpret marker signals, and control routines to control inching motors. In the outlined system, functioning of the control routines may be controlled by conditions written as a function of measurements and time, thereby, with some programming, any stress path may be realized by the device.

Torsional direct shear tests have been developed for eliminating inherent inhomogeneities in the direct shear box test, for extending shear displacement length and for determining residual shear strength parameters. Initially, cylindrical or disk specimens ($h \ll d$) were applied, several alternatives of which have been developed in the past half of the century. One of the most popular varieties is the Bishop equipment (BISHOP et al., 1971), that served as a model for our device developed again in cooperation with the BD Technical College. In addition to be fully automated, it is novel by recording the lateral wall friction value. Torsion velocity of the specimen may be arbitrarily selected in the range of 0.0005 to 5 degrees/min, with the maximum normal stress being 1 MPa, and max. shear stress 0.5 MPa.

Scheme of the equipment is seen in *Fig. 3.*

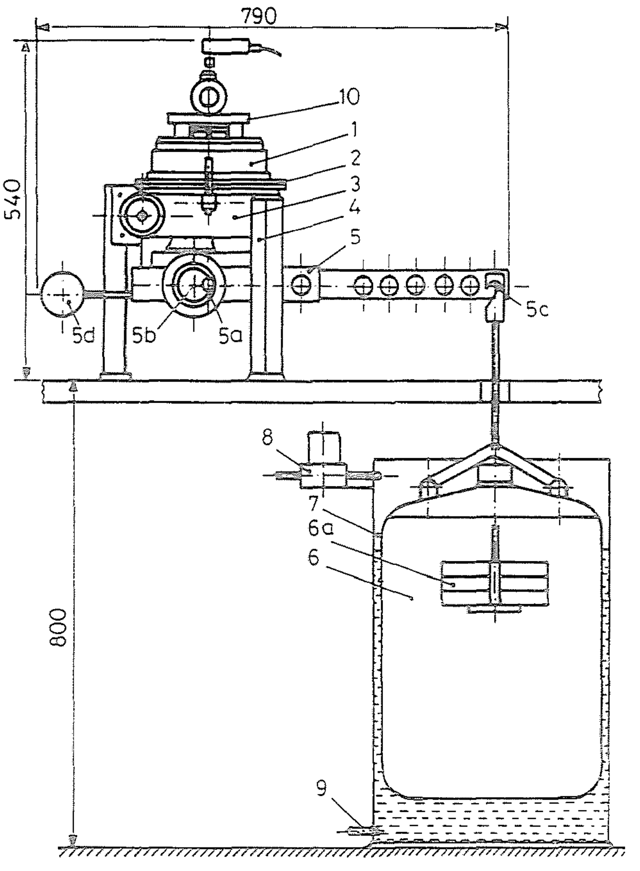

Fig. 3. Torsional shear apparatus

Lower ring of the locking ring casing (1) is fastened to the revolving table (2), while the upper ring is arrested against swerve by plate (10). The same plate transmits axial load via a vertical loading pipe and horizontal arm (5). Point 5b is steady centre of rotation of arm transmission, the landing tube is connected to the arm by pin 5a, suspension point of the variable load is at 5c. Maximum axial force is 10 kN produced by a force, 0.5 Kn in conformity with a transmission of 20 to 1. Variation with time of the loading is made by means of a simple reservoir system, based on the Archimedean law. A vessel (6) with a capacity of at least 50 l of water is floating in the reservoir (7). Water can be pumped from the vessel into the reservoir, and vice versa, by means of pump (8). If the reservoir is empty, and the vessel contains 50 l of water, the load is exactly 0.5 kN. By pumping water into the reservoir, the load is reduced due to buoyancy. Arbitrary variability of the normal force during the test permits shear at constant volume. Functioning of the electronic measuring control system is similar to that for the triaxial equipment above.

Apart from triaxial and annular shear test, recently, there has been a worldwide increasing interest in simple and direct shear, due partly to the relatively simpler testing procedure, partly to observations made in stability test (AIRY et al., 1985; FRANKE et al., 1976,) as well as to the requirement of determining shear strength parameters under dynamic loading (DE ALBA et al., 1976; AMSELL et al., 1978; FINN et al., 1971; HARA et al., 1977). It is by no chance that in 1987, Geotechnique, a leading review of soil mechanics, devoted a special volume to engineering applications of direct and simple shear tests.

In the following, only direct and simple shear tests will be considered, presenting problems emerging in the test and merits and demerits of each method.

2. Comparison between Direct and Simple Shear

2. 1. Direct Shear Tests

Direct shear is that where the sample undergoes shear along, or better, by means of a forced surface. Failure may be produced by shifting or rotating two superimposed shear boxes relative to each other. The two kinds of shear fundamentally differ by the shear displacement length. For direct shear devices acting by linear shifting (*Fig. 4*) — to be considered somewhat in details — the most frequent sources of error are:

- shear area varies during test;
- displacement is other than uniform all across the cross section sheared;
- tests of moisture distribution (HVORSLEV, 1960) showed lower values at the middle then near the surface of the specimen;
- eccentricity of the shear force caused specimen bending (LAJTAI, 1969);

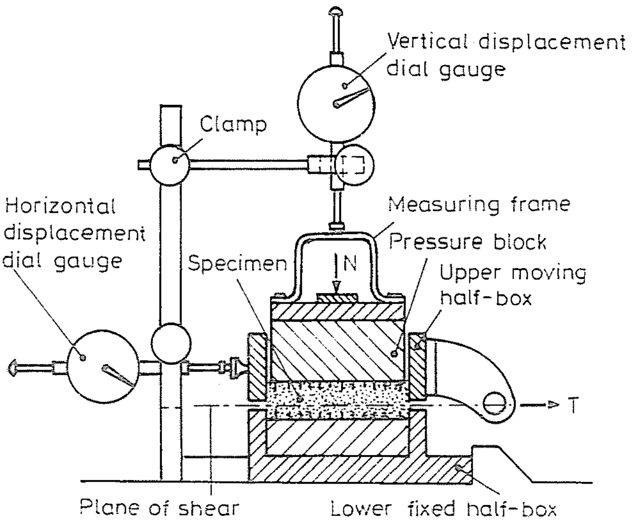

Fig. 4. Direct shear box

- with increasing shear displacement normal force often caused tilting of end faces (WERNICK, 1979) (*Fig. 5*);
- friction between box parts may significantly affect measurement results (KAST, 1986).

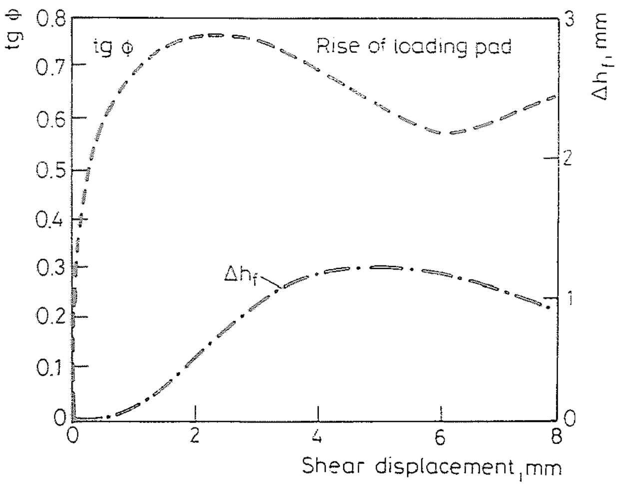

Fig. 5. Effect of loading pad tilt on angle of internal friction

As to typical sources of error in direct shear tests, one of the greatest problems, nonuniform stress distribution inside the specimen, and its consequences will be considered.

Investigations into stress distribution in shear tests may be classified as:

- theoretical analyses;
- tests on models made of an optically active material;
  a) assuming plane stress state;
  b) 3D stress state.

The order above is also that of accuracy, and that of difficulties in performing the test. Results of theoretical analyses (KISIEL, 1964; SCHNEIDER et al., 1978; KUTTER, 1971) are found in (SZABÓ – KERESZTÚRI, 1979; SZABÓ, 1988). In-plane, two-dimensional photoelastic tests are true only for a particular section but don't suit to simulate the effect of the shear box wall.

To get an exacter knowledge of the real conditions, the three-dimensional stress state was studied by the freezing method. This method primarily suits finding qualitative relations, for it has to be born in mind that there is a significant difference between physical characteristics of the model material used in photoelasticity tests and those of soils tested in geotechnical practice; on the other hand, under real conditions, assumption of an elastic behaviour is valid at most for the initial section of the test.

Shear specimens were modelled of an optically active material, actually, of epoxy resin ARALDIT D. Resin blocks cast in a mould of the shape of the shear box and then trimmed were placed in the shear box proper, loaded and heated above the softening temperature, where the material assumed a rubber-like, so-called hyperelastic state. The loaded, heated specimen was slowly recooled, thereby deformations arising in the loaded plastic specimen were preserved frozen, as were birefringence phenomena concomitant to deformation even after loading was off. Cooled specimens were sliced to be evaluated from to isochrome and isocline curves taken in transillumination. Tests have been performed on specimens with both square (100×100 mm) and circular (Ø= 94.4 mm) cross-sections.

Isochrome curves of sections at the specimen midline, and near the shear box side are seen in *Figs. 6* and *7*, respectively. Shear stress distributions are also shown inside the specimen along the forced surface S_Δ as well as at planes 7 mm below (S_o) and above (S_x) it, for specimens of square cross section. Parallel sections of specimens of circular cross section exhibit similar stress distributions (*Fig. 8*), but there is invariably a significant inhomogeneity in the shear direction.

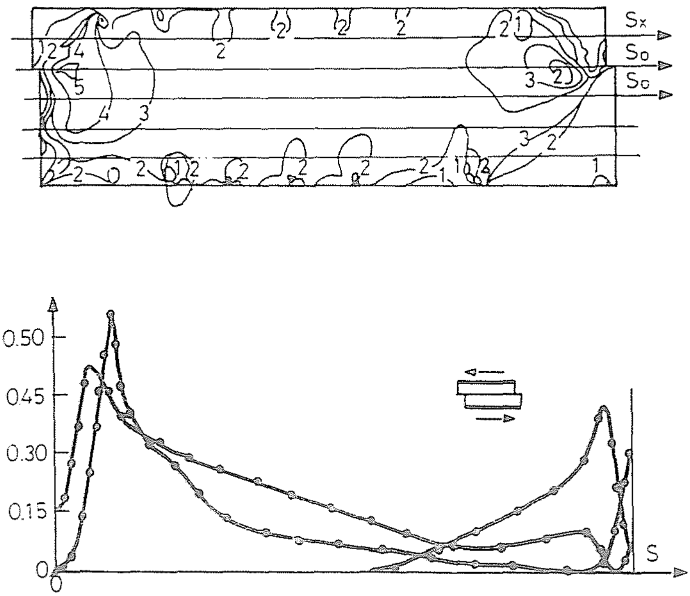

Fig. 6. Isochrome curves and shear stress distribution at mid-plane of square-shaped specimen in direct shear test

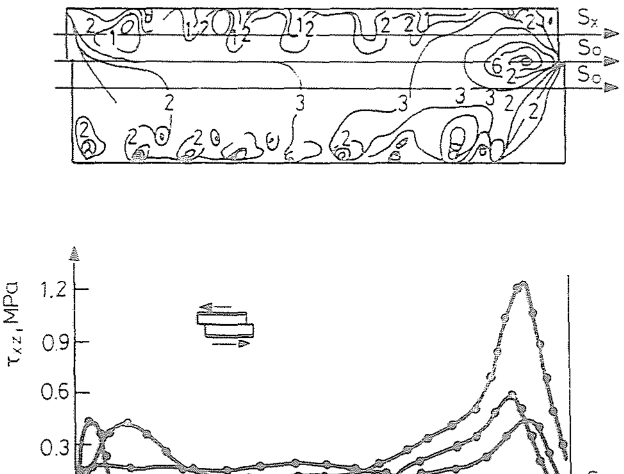

Fig. 7. Isochrome curves and shear stress distribution near side of shear box, direct shear test on square specimen

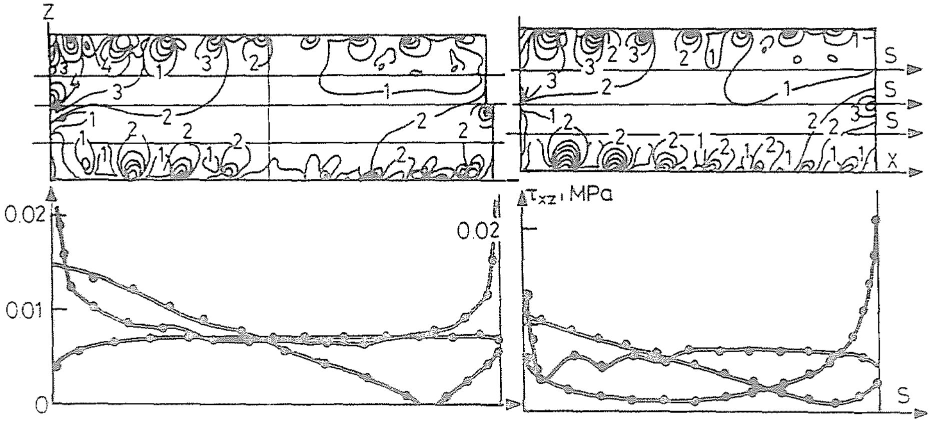

Fig. 8. Isochrome curves and shear stress distribution graphs at various sections of circular cross-sectional specimen in direct shear test

Photoelastic tests have led to the following conclusions:

- In direct shear test, stress distribution is rather inhomogeneous;
- 3D photoelastic tests illustratively pointed out the effect of stress concentration by the shear box sidewall; and the effect of the shape of the shear box. As concerns inhomogeneity, in the specimen midline there is no essential difference between specimens of circular and of square cross-sections, but stress distribution at specimen sides, is more uniform for shear boxes of circular cross-section;
- in either case, end plates of shear box have an important stress concentrating effect.

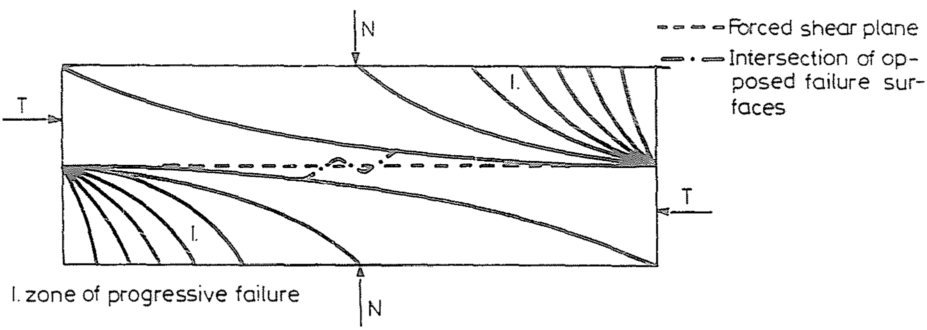

Fig. 9. Theoretical pattern of failure surfaces developing in direct shear

This latter statement is substantiated by *photo series 1* on failure surfaces developing in direct shear. Test material was powdered quartz

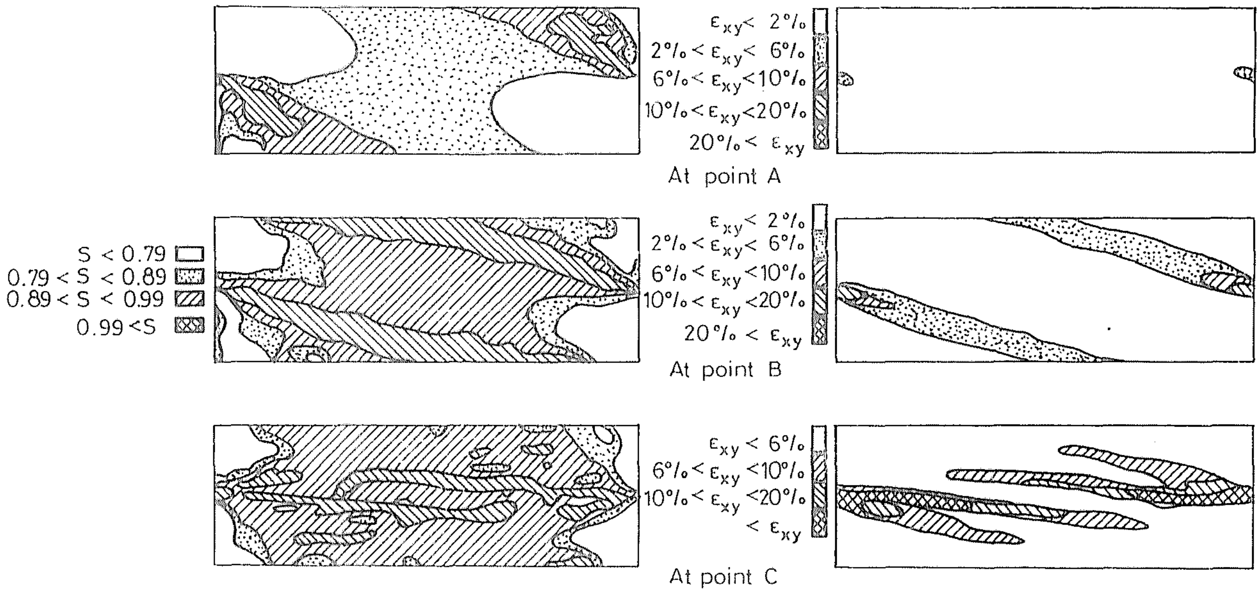

Fig. 10. Stress fields and strain fields in direct shear (After POTTS -DOUNIAS-VAUGHAN, 1987)

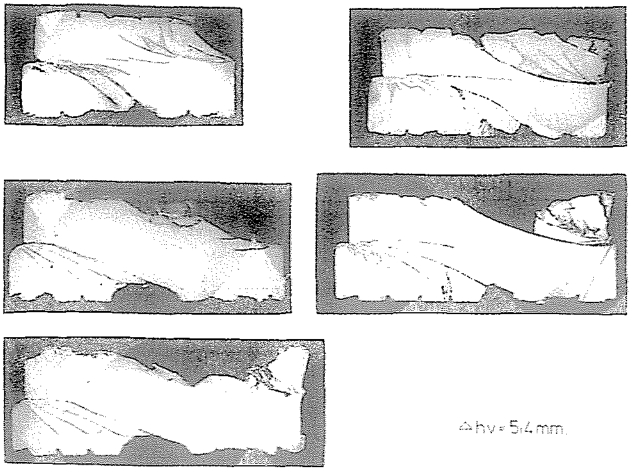

Photo 1. Failure pattern in powdered quarz specimen in direct shear test

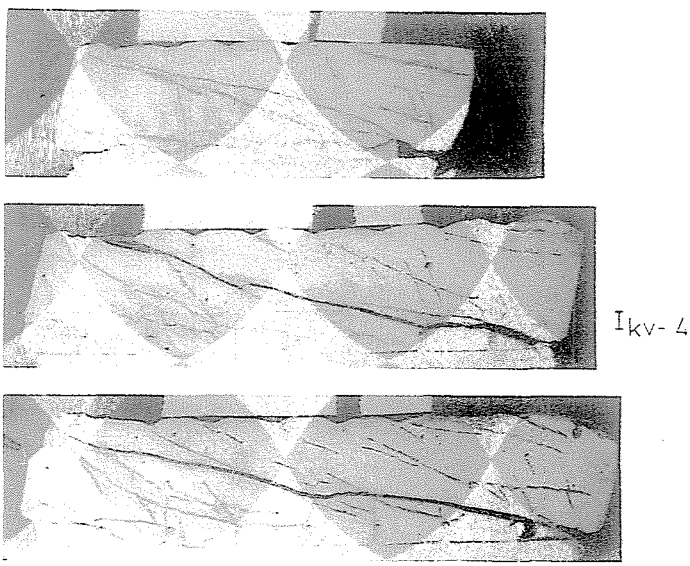

Photo 2. Failure pattern in powdered quarz specimen in direct shear test

impregnated with plastic resin after the test, then, to avoid any subsequent displacement or deformation, sliced together with the filter stone. As it is clear from the photos, the force surface is no failure surface.

Failure surfaces develop upon the stress concentrating effect by the end faces and by the shear teeth. As a function of displacement, a progressive failure zone develops, and with progressing shear the developing two zones intersect (*Fig. 9*).

Similar results as in our tests were obtained by POTTS, DOUNIAS and VOUGHAN (1987) by determining theoretically, by the finite elements method, stress distribution inside the specimen, and specific deformations in three different shear phases (*Fig. 10*).

2. 2. Simple Shear Tests

Simple shear is a special case of laminar deformation. Its principle in comparison to pure shear, is seen in *Fig. 11*. The first testing device realizing neat shear, suiting also routine tests was made by Kjellmann. By and by, several varieties emerged, but the real breakthrough was due to an apparatus developed in Cambridge by ROSCOE (ROSCOE – BURLAND, 1967). Our tests applied a modified VSG2 apparatus developed at the Freiberg Mining Academy (FISCHER, 1970). Section of the part around the specimen is seen in *Fig. 12*.

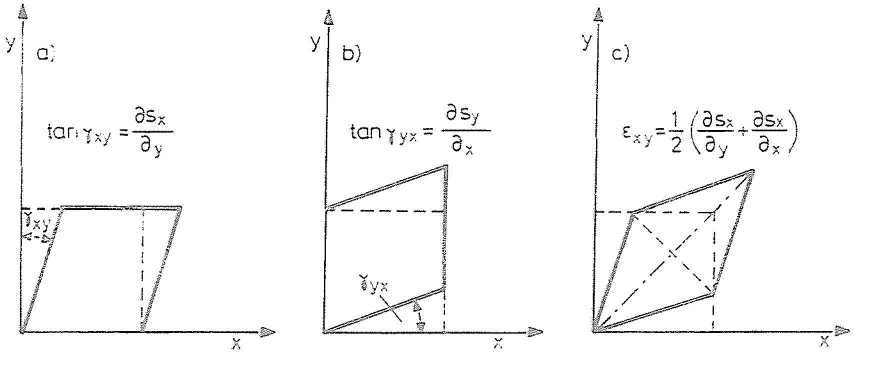

Fig. 11. Notion of simple shear and 'pure shear' (after Mozes and Vámos)

In appreciating stress distribution inside the specimen, researchers are of relatively similar standpoint in the case of direct shear tests, as against simple shear tests. The first tests to determine stress distribution were made by ROSCOE (1967), his apparatus with incorporated load cells being particularly fit to such tests. Rather important inhomogeneities were obtained by incorporated measuring cells by BUDHU, (1984), AIREY et al., (1985). According to photoelastic experiments (WRIGHT et al., 1978), the obtained inhomogeneity values are considered to be excessive, but in fact, these model tests did not conform with simple shear principle. In finite

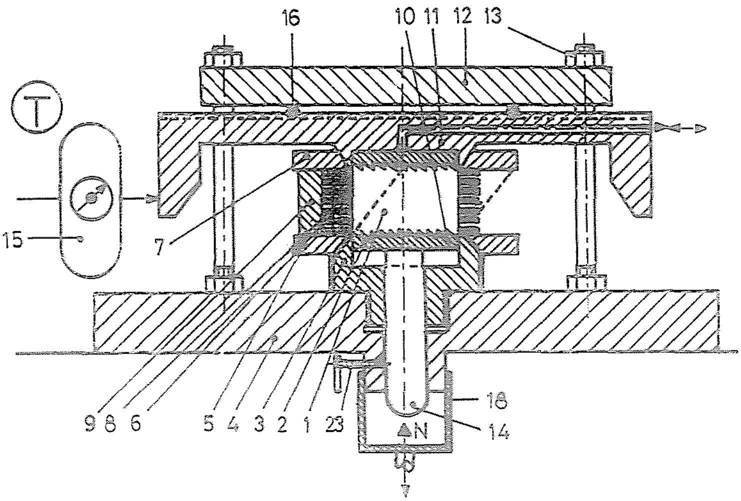

Fig. 12. Section of Fischer's 'visco-simple shear device' (VSG) (FISCHER, 1970)

element analyses (LUCKS et al., 1972) stress distribution in some 70% of the specimens, was found to be practically homogeneous.

Our experiments supported homogeneous stress distribution. The test method was the same as in direct shear tests. These model tests are advantageous in that stress distribution is determined inside the very specimen loaded in the shear apparatus. It appeared that after slicing the specimen, stress distribution in parallel sections was almost the same (SZABÓ, 1988). Evaluation of the middle section is seen in *Fig. 13.* Apparently, at specimen mid-height, shear stress is practically constant. Near shear bits, there is an important stress concentration, exceeding that in soil.

In conformity with homogeneous shear stress distribution, deformations inside the specimen are likely to show a similar pattern. Failure surfaces of the specimen in simple shear are seen in *Photo set 2.* Parallel failure surfaces are clearly recognized, but also here stress concentrating effect of shear bits is important for the development of failure surfaces.

3. Comparison between Simple and Other Shear Test Results

With the general use of simple shear tests, and with test made according to different methods, the problem arises whether results obtained by other shear test methods (triaxial, true triaxial or biaxial, hollow cylinder, direct

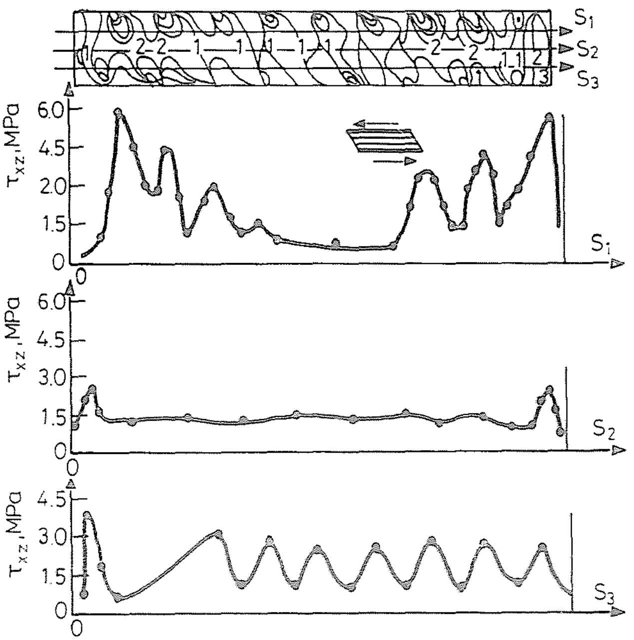

Fig. 13. Isochrome curves and shear stress distribution along reference lines S_1 to S_3 at middle-section of specimen in simple shear test

shear test, etc.) are comparable, maybe they are mutually convertible, or only some tendencies may be recognized.

The first comparative test made by BJERRUM and LANDVA (1966) is described in their classic study. An enormous landslide near Furre, induced a comprehensive set of studies on stress-strain and shear strength characteristics of highly sensitive clays. Simple laboratory shear test results were found to closely fit in-situ vane shear test results, and to show much lower shear resistances than did triaxial tests. Comparative test results for limestone debris under static load conditions made by ANSELL and BROWN (1978) are seen in *Fig. 14*. The maximum internal friction angle is seen to be due to direct shear.

It is interesting to see five degrees (10%) of difference between internal friction angle values determined from mean value (shear force/specimen area) and from load cell data in the middle third of the specimen.

Test results by different authors concerned with testing and describing anisotropic properties of clays have been compiled in *Fig. 15* (JAMIOLKOWSKI, et al., 1985). This analysis involved data of triaxial compression and tension, and of simple shear for clays of different plasticities.

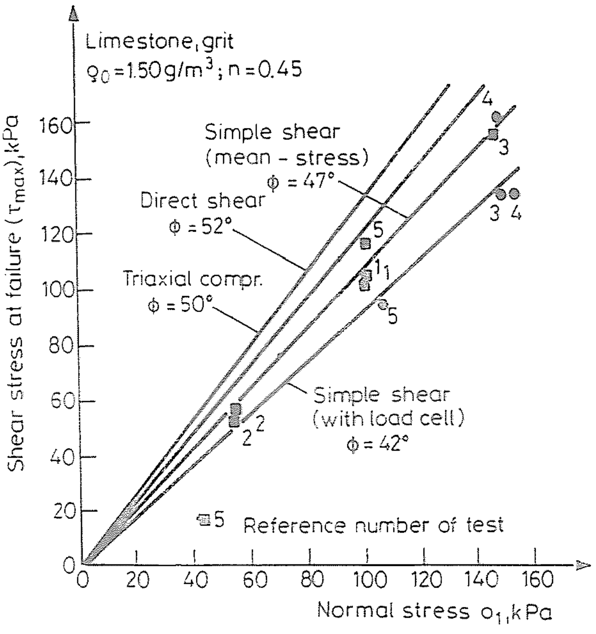

Fig. 14. Comparison of results obtained in various shear strength tests (ANSELL – BROWN, 1978)

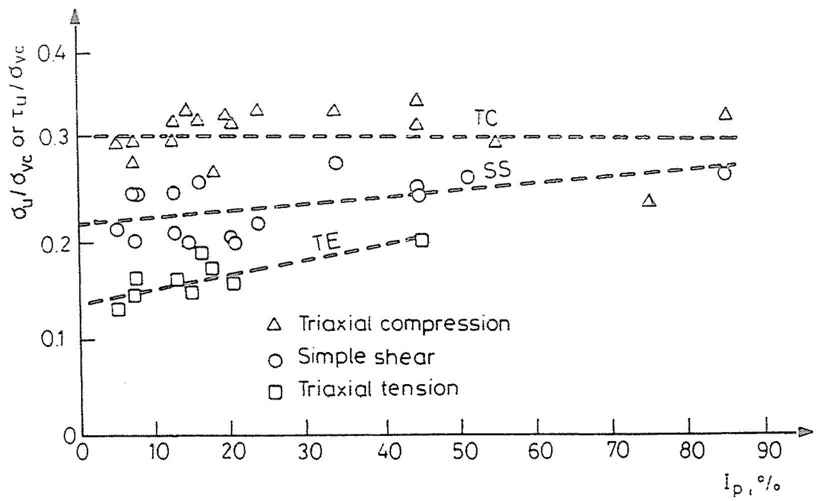

Fig. 15. Undrained shear strength values obtained by different methods vs. plasticity index (after JAMIOLKOWSKI et al., 1985)

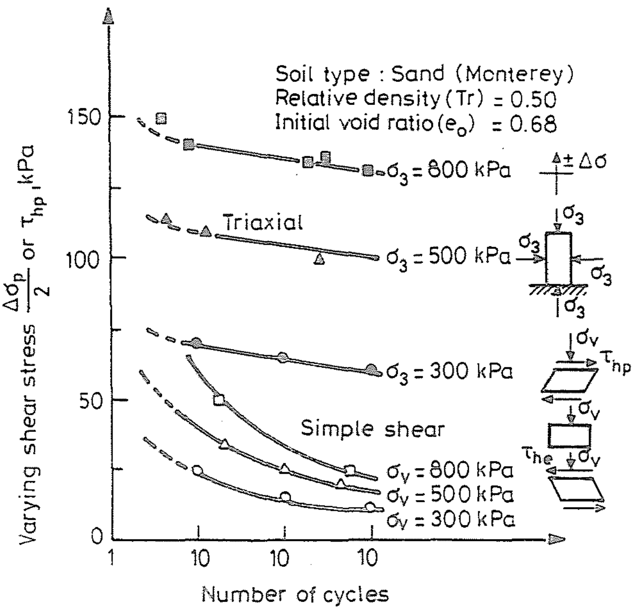

Fig. 16. Comparative analysis of triaxial compression and simple shear tests (PEACOCK – SEED, 1968)

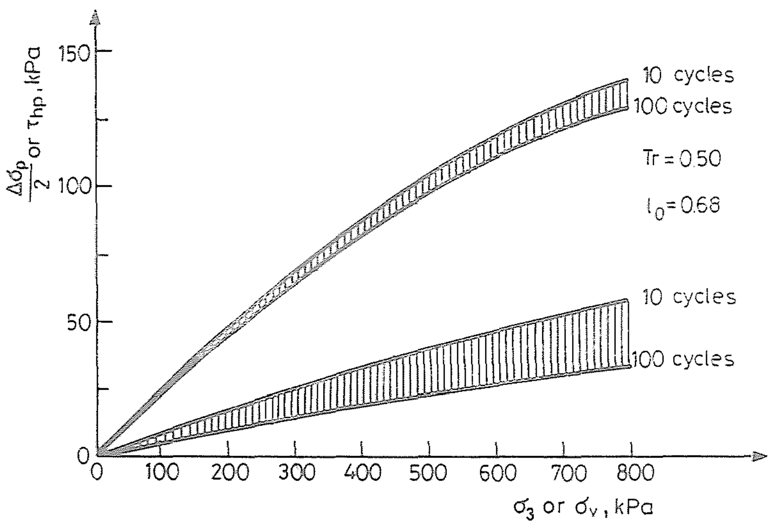

Fig. 17. Comparative analysis of triaxial compression and simple shear tests (PEACOCK – SEED, 1968)

One of the most important applications of simple shear tests is that for dynamic loading tests. This explains why a comparison between different test methods is treated from this aspect in several papers. In Hungary, dynamic tests are practically not used, but irrespective of that they suit to compare results just as do static test if, in comparison, also the effect of cycle number variation (increase) is indicated. Nevertheless, especially for major construction projects, seismic stability calculations based on dynamic shear strength parameters would be advisable, as against the current practice and regulations whereby reduced petrophysical values obtained in static tests are used for design.

Results of test series on a sand sample have been plotted in *Fig. 16*, expected to find a relation between number of cycles to failure, alternating shear stresses (simple shear) and axial (triaxial) stresses, for various normal stresses and lateral pressures (PEACOCK – SEED, 1968). Experiments have been compiled in *Fig. 17*. Obviously, simple shear tests show also here much lower shear resistances, a fact not to be ignored in certain stability test problems (e.g. seismic stability, roadway structures).

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