Plane strain tests on strain softening soils

Essais de déformation plane sur sols radoucissants

Annamaria Cividini – *Department of Structural Engineering, Technical University of Milan, Italy*

ABSTRACT: Some aspects are discussed of the plane strain testing of geomaterials. The plane strain apparatus is particularly suited for investigating the shear band formation in prismatic samples and for evaluating the soil behaviour under different principal stresses, even though only two of them can be independently imposed. After recalling the basic features of the apparatus, some preliminary results are presented concerning the behaviour of medium dense sand and of overconsolidated kaolin. The experimental results permit, in particular, to evaluate the accuracy with which the plane strain condition is attained during the test.

RESUME: On discute quelques aspects des essais de deformation plane sur geomateriaux. L'appareil de deformation plane donne la possibilite' d'etudier la formation de bandes de cisaillement dans des echantillons prismatiques et de evaluer le comportement du sol sujet a' trois valeurs differentes des composantes de tension principale, bien que deux seulement soient independantes. Apres avoir revu les caracteristiques de base de l'appareil, on presente des resultats preliminaires sur le comportement d'une sable de densite moyenne et d'un kaolin surconsolide'. Les resultats experimentaux permettent de verifier le developpement de la condition de deformation plane pendant l'essais.

1 INTRODUCTION

An increasing interest exists nowadays for the laboratory evaluation of the complete response of "stiff" soils, such as dense sands or overconsolidated clays, during loading tests. In fact, on the basis of the experimental results the parameters of constitutive laws can be evaluated in view of their use in the numerical analysis of geotechnical problems. A particular characteristic of stiff soils is the so called "strain localization" which is often observed in approaching the maximum load level. It leads to the formation of sliding surfaces, or shear bands, and to the loss of continuity of the sample. In addition, after the bands are formed, the overall mechanical resistance, and stiffness, tend to decrease with increasing shear deformation (strain softening).

Two approaches for the numerical analysis of strain softening problems have been considered in previous studies (Sterpi, 1997) and implemented in the finite element program SoSIA2, for Soil-Structure Interaction Analysis (Cividini & Gioda, 1992). In both cases the loss of strength and stiffness is accounted for, but different assumptions are adopted for the initiation of the phenomenon. The numerical results show that these approaches reproduce qualitatively the overall behaviour observed during laboratory tests, such as direct shear tests, and that they are potentially applicable to the stability analysis of slopes and unsupported excavations (Sterpi et al. 1995; Cividini et al. 1996). On this basis it was decided to carry out an experimental investigation aimed in particular at improving the accuracy of the parameters of the adopted strain softening law.

Among the various tests which could be adopted to this purpose (Budhu, 1988; Lee, 1970), the conventional triaxial tests on cylindrical specimens presents some drawbacks. In fact, two principal stresses coincide throughout the test, while in most geotechnical problems the values of the three principal stresses are different from each other.

Taking into account that many field problems can be reasonably studied in plane strain conditions, it was decided to base the mentioned experimental investigation on a series of plane strain compression tests (Hambley, 1972).

Even though the plane strain apparatus is less complex than the true triaxial one, it allows a development of localization planes quite similar to that observed during true triaxial tests (Desrues et al., 1985). It also permits a direct observation of the transition from homogeneous to localized mode, e.g. by means of stereophotogrammetry (Finno et al., 1996), which is in general prevented by the outer mechanical components of the true triaxial device.

The plane strain apparatus used in this study presents some advantages with respect to other devices discussed in the literature (e.g. Marachi et al., 1981; Vaid & Campanella, 1974). In particular, it minimizes the constraints imposed by the apparatus to the formation of shear bands and it permits to measure the horizontal "out-of-plane" stress and, hence, to evaluate its influence on the behavior of the tested material (Cornforth, 1964; Tatsuoka et al, 1986).

In the following the basic features of the apparatus and the testing procedure are first summarized. Then the results of tests on Ticino sand and on remoulded kaolin are presented. In order to get some insight into the influence of the testing procedure on the observed soil behaviour, the plane strain results are compared with those obtained from conventional triaxial tests on the same materials.

Finally, some comments are presented on the accuracy with which the plane strain condition is mantained during the tests.

2. CHARACTERISTICS OF THE EXPERIMENTAL EQUIPMENT

The main features of the experimental equipment are described in this section, considering in particular the plane strain device, the loading systems, and the data acquisition system.

2.1 Plane strain device

The plane strain testing device was originally developed by Drescher et al. (1990) and is presently produced by Geotest Instrument Corp., IL (USA). It is designed for testing prismatic soil specimens having width and length of 40 mm and 80 mm, and height up to 140 mm. The specimen, protected by a rubber membrame, is placed on an enlarged circular platen. Its lateral confinement is obtained through two vertical rigid walls, 80 mm apart, connected by four tie rods. The axial load is applied by an enlarged upper platen connected to the loading piston. On the top and bottom platens two porous stones are mounted and are connected to the drainage lines.

The platens and the vertical walls are glass lined and lubricated to minimize the frictional resistance.

One important feature of the apparatus is that the base platen rests on a linear bearing sled, sliding over a trackway normal to the plane strain direction. Consequently, as shear band develops, the lateral displacement of the lower part of the specimen are allowed. The specimen deformation during the test can be observed through one of the vertical walls which is made of plexiglas.

Before testing, the plane strain device is placed within a plexiglass cell filled with silicon oil.

The instrumentation set is located inside the confining pressure cells and includes seven transducers (RDP Electronics D2/200 LVDTs having a range of 15 mm) and seven load cells (one Cooper Instruments LGP 310 tension/compression load cell and six Cooper Instruments LPM510 subminiature load cells). Two LVDTs are mounted apart of the loading ram for measuring changes in the heigth of the specimen and allow to control its tilting. Two pairs of LVDTs are mounted horizontally, above and below the specimen midheigth, for measuring its changes in width. The volume changes of dry or unsaturated samples can be evaluated on the basis of the measured lateral and vertical strains. The seventh LVDT is used for monitoring the sled movement.

One 22.2 kN load cell measures the axial load above the specimen while three 2.2 kN subminiature load cells are mounted in the lower loading platen for monitoring the axial load at the specimen base. Consequently it is possible to evaluate the friction resistance on the lateral, rigid walls. The use of more than one load cells would allow a check of the load eccentricity during the tests.

Another important feature of this device is the presence of three 2.2 kN load cells placed on the non transparent vertical wall, for the direct measure of the out-of-plane stress. Note that this stress is not measured in some previous versions of the apparatus (e.g. Drescher et al., 1990), thus limiting the information on the stress state evolution during the test.

In addition to the above sensors, one HAENN piezoresistive transducer, located outside the confining pressure cell, is used to measure the pore water pressure within the sample. The global volume change of fully saturated specimens can be measured by means of a control panel for standard triaxial test.

2.2 Loading system

The plane strain apparatus and its instrumentation are accomodated inside a cylindrical cell, filled with nonconducting DowCorning 200/10cst silicon oil. The confining pressure and the back pressure are applied by means of a control panel for standard triaxial tests. The supply pressure is given by means of a PARISE RC24sact air compressor having a volume of 24 l for mantaining a maximum pressure of 883 kPa.

The assembled cell is placed on the platen of a Wykeham Farrance 250 kN test machine for carring out displacement-controlled compression tests.

2.3 Data acquisition system

The base of the confining pressure cell is equipped with fourteen LEMO FVN sockets for EVN high-pressure watertight plugs. Four-pin cables connect the displacement transducers and the load cells to a data acquisition system designed and assembled at the Politecnico di Milano geotecnical laboratory. This system consists of an IBM AT-bus personal computer equipped with a Data Acquisition Process (DAP) 800/3 board produced by Microstars Laboratories. In addition to the usual analog/digital conversion and multiplexing functions, the 8-channel, 12-bit resolution DAP can process the experimental data by means of an on-board processor and core memory, operating under the multitasking operating system DAPL. Hence, data averaging and filtering can be performed before transferring them to the host computer for displaying, disk logging and subsequent manipulations.

A multiplexer MSXB 021-01, expanding from 8 to 32 the analog input lines, is mounted in a rack housing also the signal conditioning board and two Elind QL100 "open case" power supplies. They provide 10Vdc power to the transducers and to the load cells, and 5Vdc power to seven 5B30 ANALOG DEVICES modules used for conditioning the output signal of the load cells.

The data acquisition process is governed by a specifically developed VisualBasic program. The displacement transducers and load cells signals, or the corresponding strain and stress components, can be plotted on the computer monitor during tests. This allows a real time qualitative control of the test progress. Finally, the row output voltages from the instruments and the processed data are stored in real time on disk for the subsequent analysis of results.

3. INFLUENCE OF "IMPERFECT" BOUNDARY CONDITIONS

The experimental results can be influenced by a possible poor attainment of the plane strain condition during the early stages of the test. A similar effect exits, for instance, in triaxial compression tests where an apparent looking of the stress-strain curve could be introduced by an imperfect contact between loading caps and sample.

To illustrate this influence, let represent in the octahedral plane the stress paths from "ideal" and "imperfect" plane strain tests on a linear elastic specimen (fig.1).

In the ideal case a perfect contact exists between sample and rigid vertical walls during the entire test. At the beginning of the loading stage the in-plane stresses σ_1 and σ_3 coincide with the cell pressure σ_c, while the out-of-plane stress σ_2 is lower than the cell pressure and depends on Poisson ratio ν

$$\sigma_2 = 2\sigma_c \, \nu/(1-\nu) \tag{1}$$

The vertical stress σ_1 increases during the loading stage, the cell pressure $\sigma_c = \sigma_3$ remains constant and σ_2 can reach intermediate values between σ_1 and σ_3. As a consequence, the stress path (a) in fig.1 crosses the σ_1 axis.

The extreme "imperfect" case would be reached when no contact exists between sample and rigid lateral walls throughout the test. In this case an isotropic stress state is induced by the cell pressure σ_c and the stress path during loading coincides with the one of conventional triaxial compression test, i.e. with the σ_1 axis (line b in fig.1).

A different stress path would be obtained if the gap between sample and rigid walls is eliminated after the cell pressure is applied. In this case the stress state at the beginning of the loading stage is represented by a point on the octahedral axis ($\sigma_1 = \sigma_2 = \sigma_3 = \sigma_c$) and the stress path correspond to line (c).

The last stress path corresponds to the case in which the mentioned gap is eliminated during the loading stage. The specimen undergoes axisymmetric compression when the cell pressure is applied and then lateral expansion with increasing σ_1 until the gap between it and the walls is eliminated. Subsequently it is subjected to plane strain condition. The resulting bilinear stress path is indicated by line (d) in fig.1

The above observations show that a reliable determination of the out-of-plane stress is necessary in order to control the actual attainment of the plane strain condition during the test.

4. EXPERIMENTAL RESULTS

As previously metioned, the main part of the experimental investigation consists of a series of consolidated drained plane strain tests on Ticino sand and on overconsolidated kaolin (Devoti & Simonetta, 1996).

The axial, ϵ_1, and horizontal, ϵ_3, strains were evaluated on the basis of the initial height and width of the specimen and of the average values of the vertical and horizontal displacements obtained, respectively, by the two vertical transducers and by the four horizontal LVDTs. Vertical, σ_1, and out-of-plane, σ_2, stresses are obtained as the average values of the corresponding data obtained by the three vertical and horizontal load cells.

To represent the experimental results in a compact form, the states of stress and strain will be represented by means of the first stress and strain invariants, I_σ and ϵ_{vol},

$$I_\sigma = \sigma_1 + \sigma_2 + \sigma_3 \quad , \quad \epsilon_{vol} = \epsilon_1 + \epsilon_2 + \epsilon_3 \tag{2a,b}$$

and by means of the square root of second invariant of

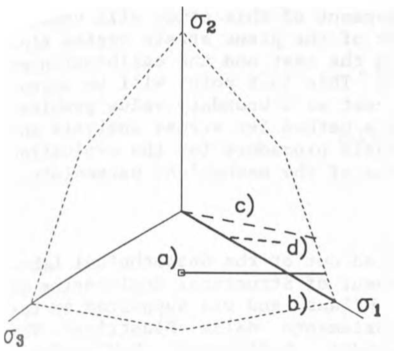

Fig.1 Stress paths from (a) "ideal" plane strain test, (b) triaxial compression test, (c,d) "imperfect" plane strain tests.

the deviatoric stresses and strains, J_σ and J_ϵ,

$$J_\sigma = [\frac{1}{2}\sum_1^3 s_i^2]^{1/2} \quad ; \quad J_\epsilon = [\frac{1}{2}\sum_1^3 e_i^2]^{1/2} \qquad (3a,b)$$

where

$$s_i = \sigma_i - I_\sigma/3 \quad \text{and} \quad e_i = \epsilon_i - \epsilon_{vol}/3 \qquad (4a,b)$$

Here, σ_i and ϵ_i represent the principal effective stress and strain components, while s_i and e_i are the corresponding deviatoric components.

After preparation, the samples were gently secured between the two vertical walls without adopting particular provisions, like e.g. the application of an out-of-plane pre-stress (Yumlu & Obzay, 1995; Labuz et al. 1996), for ensuring plane strain condition at the early stages of the test. For completeness, these results are compared with those obtained from conventional tests on axisymmetric specimens (Meroni, 1997).

4.1 Tests on Ticino sand

Medium dense specimens, with two relative densities, have been used in the investigation. The samples with an average relative density Dr of 70% have been prepared by moist tamping, compacting seven 2 cm thick layers of wet sand (water content of about 4%) in a plexiglas mold. The second set of samples, with relative density of 50%, was prepared in layers by pluviating dry sand from a costant height.

Then gaseous carbon dioxide and de-aired water were percolated to remove air bubbles and back pressure of 150 kPa was applied. The confining pressure of 200 kPa was then increased in steps in undrained conditions, obtaining values of the Skempton's pore pressure parameter B greater than .98. After allowing complete dissipation of the excess pore water pressure, the compression tests were carried out at a costant displacement rate of .08 mm/min.

Plane strain and triaxial results on samples with Dr=70% are compared in fig.2. As observed in other studies (see e.g. Oda et al., 1978; Lee, 1970) the plane strain test leads to a peak resistance higher than that obtained in triaxial conditions, while the strain at failure is lower (fig.2a). After peak, the plane strain specimen undergoes a significant loss of strength reaching a residual friction angle of about 33° which is close to the value of 32° determined from direct shear tests (Badiani & Zavanella, 1996).

Unexpectedly, the volume variation in plane strain condition was larger than that observed during the triaxial test (fig.2b).

Fig.3 shows the variation of the horizontal strain ϵ_3 measured at the upper and lower parts of the sample with increasing deviatoric strain J_ϵ. The same figure reports the displacement of the sled. It can be observed that at the beginning of the test the upper and lower horizontal strains almost coincide, hence the sample is subjected to an homogeneous deformation. Subsequently, the strain in the lower part increases more rapidly than that in the upper part, indicating that a failure surface has formed within the sample. The formation of a shear band is confirmed by the sled movement, that takes place immediately after the peak load is reached (cf. fig.4).

A similar behaviour was shown by the sample having a lower density (Dr=50%). Fig.5 shows the stress path of the test in the octahedral plane. The first part of the stress path (segment AB) almost coincides with the σ_1 axis, indicating that an actual plane strain condition is reached only during the loading stage of the test. Point C corresponds to the peak state and the dots (CD) represent the post-peak data.

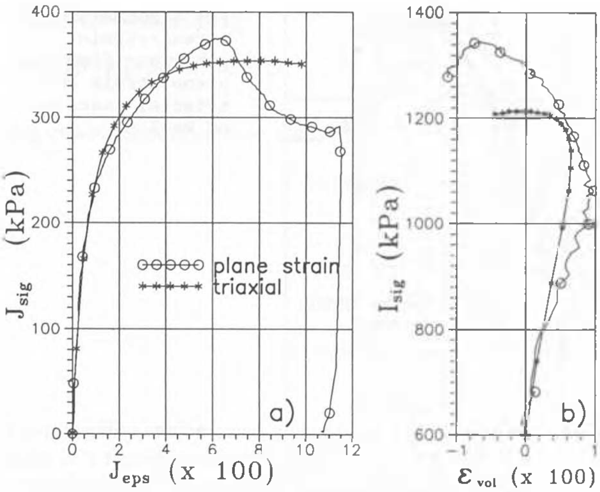

Fig.2 Comparison between plane strain and triaxial test results for Ticino sand (Dr=70%): (a) deviatoric and (b) volumetric stress-strain responses.

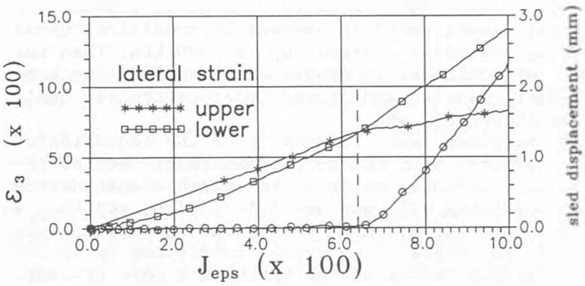

Fig.3 Evolution of the lateral strain in a plane strain test on Ticino sand (Dr=70%).

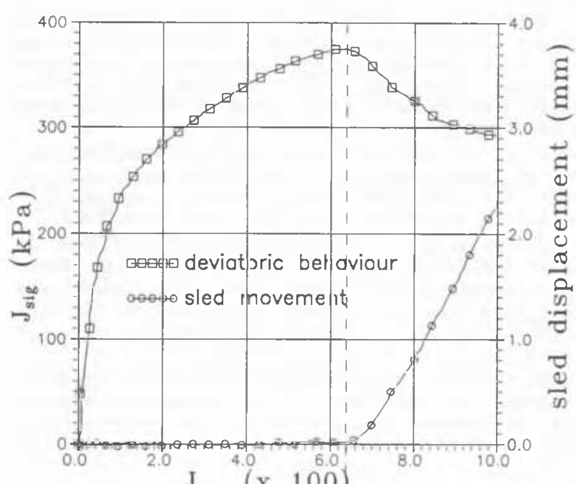

Fig.4 Sled movement during a plane strain test on Ticino sand (Dr=70%).

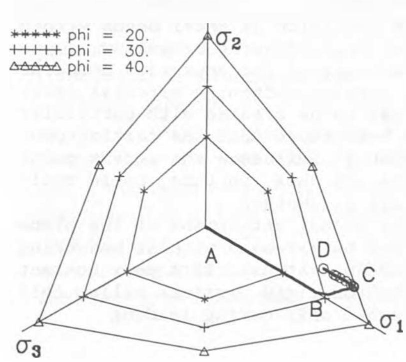

Fig.5 Stress path from plane strain test on medium dense sand (Dr=50%).

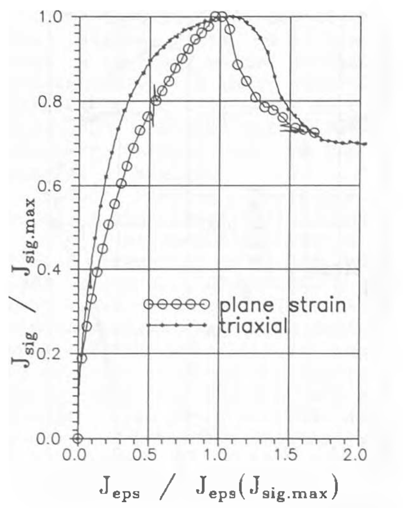

Fig.6 Normalized stress-strain behaviour from plane strain and triaxial tests on OC kaolin.

4.2 Tests on kaolin

The index properties of the Speswhite kaolin used in these tests are: LL=59%, PL=30%, G=2.64, A=.354. The kaolin was remoulded at a water content of 1.5*LL. The slurry was consolidated in oedometric conditions under increasing vertical stress up to 1600 kPa. Then the kaolin was unloaded in steps, extruded from the consolidometer, sealed and stored under controlled humidity for subsequent use.

Each specimen was trimmed from the consolidated block, covered with the rubber membrane, secured between the vertical walls of the plane strain device and the confining cell was assembled. After applying a back pressure of 150 kPa, the confining pressure was increased in steps in undrained conditions up to 200 kPa, obtaining values of the Skempton's pore pressure parameter B greater than .96. After complete dissipation of the excess pore water pressure, the drained compression tests were carried out at a constant displacement rate of .002 mm/min.

The deviatoric stress-strain data obtained from both plane strain and triaxial tests show softening effects, even though in plane strain conditions the peak stress occurs at strain smaller than that observed in the triaxial test. These data are compared in non dimensional form in fig.6.

The loss of shear resistance, expressed as percentage of the peak load, is of the same order of magnitude for the two tests. However a marked difference exists in the pre- and post-peak behaviour.

The stress-strain curve from the triaxial test is initially "stiffer" than the plane strain one. Then, it tends smoothly to the peak point. After peak, the residual condition is gradually attained and the corresponding strain is almost twice than the value at the peak point.

On the contrary, the plane strain curve presents a sharp change in curvature at the peak point and the residual resistance is reached after a relatively small increment of strain.

5. CONCLUDING REMARKS

This preliminary experimental investigation indicates that the plane strain apparatus is suitable for a detailed analysis of the formation of shear bands within samples of soils presenting softening behaviour.

A possible important use of the apparatus concerns the calibration of strain softening material laws. However, this point has to be treated with particular care. In fact, it has been shown that the testing procedure could appreciably influence the stress paths obtained from the tests and this, in turn, could modify the sought mechanical parameters.

In particular, the actual attainment of the plane strain condition cannot be assessed without measuring the out-of-plane principal stress. If a poor contact exists between sample and rigid vertical walls, this condition could be reached only during loading.

The future development of this study will concern an accurate attainment of the plane strain regime since the early stages of the test and the calibration of strain softening laws. This last point will be approached viewing the test as a boundary value problem, analizing it through a method for stress analysis and adopting a back analysis procedure for the evaluation of the "optimal" values of the mechanical paremeters.

ACKNOWLEDGEMENTS

This study was carried out at the Geotechnical Laboratory of the Department of Structural Engineering of the Politecnico di Milano and was supported by the "Fondo per il Potenziamento della Didattica". The assistance of E.Iscandri, P.Simonetta, M.Meroni and L.Locatelli is gratefully acknowledged.

REFERENCES

Badiani B. & L.Zavanella 1996. Studio sperimentale su un modello di opera in terra rinforzata, Tesi di laurea, Dept.Civil Engin., Universita' di Brescia.

Budhu M., 1988. A New Simple Shear Apparatus, Geotechnical Testing Journal, 11, pp. 281-287.

Cividini A., G.Garigali & V.Manassero, 1996. A numerical interpretation of the observed behaviour of an unstable slope. Proc.Int.Symp. Prediction and Performance in Rock Mech. and Rock Engin., Torino.

Cividini A. & G.Gioda, 1992. A finite element analysis of direct shear tests on stiff clays. Int.J. Numer. Anal.Methods in Geomechanics, 16, 869-886.

Cornforth D.H., 1964. Some experiments on the influence of strain conditions on the strength of sand, Geotechnique, 15, pp.143-167.

Desrues J., J.Lanier & P.Stutz, 1985. Localization of the deformation in tests on sand sample, Engineering Fracture Mechanics, 21, pp.909-921.

Devoti M. & P.Simonetta, 1996. Apparecchiatura per prove triassiali in condizione piana nelle deformazioni, Tesi di Laurea, DIS Politecnico di Milano.

Drescher A., I.Vardoulakis & C.Han, 1990. A biaxal apparatus for testing soils, Geotechnical Testing Journal, 13, pp.226-234.

Finno R.J., W.W.Harris, M.A.Mooney & G.Viggiani, 1996. Strain localization and undrained steady state of sand. ASCE GT, 122, pp.462-472.

Hambly E.C., 1972. Plane strain behaviour of remoulded normally consolidated kaolin, Geotechnique, 22.

Labuz J.F., S.-T.Dai & E.Papamichos, 1996. Plane-strain compression of rock-like materials, Int.J. Rock Mech.Min.Sci. & Geomech.Abstr., 33, 573-584.

Lee K.L., 1970. Comparison of plane strain and triaxial tests on sand, ASCE SM3, 96, pp.901-923.

Marachi N.D., J.M.Duncan, C.K.Chan & H.B.Seed, 1981. Plane-Strain Testing of Sand, In 'Laboratory Shear Strength of Soil' ASTMSTP740 (Yong & Townsend Eds).

Meroni M. 1997. Comportamento di materiali geotecnici in prove triassiali piane ed assialsimmetriche, Tesi di Laurea, Dept.Struct.Eng., Politecnico Milano.

Oda M., I.Koishikawa & T.Higuchi, 1978. Experimental study of anisotropic shear strength of sand by plane strain test, Soils and Foundations 18, 25-38

Sterpi D., A.Cividini & M.Donelli, 1995. Numerical analysis of a shallow excavation, Proc. 8th Int. Conf. on Rock Mechanics, Tokyo, Vol.2, pp.545-549.

Sterpi D., 1997. Influenza del fenomeno di localizzazione delle deformazioni sulla stabilita' di aperture sotterranee. Doctoral dissertation. Dept. Structural Engin., Politecnico di Milano.

Tatsuoka F., M.Sakamoto, T.Kawamura & S.Fukushima, 1986. Strength and deformation characteristics of sand in plane strain compression at extremely low pressures, Soils and Foundations, 26, pp.65-84.

Vaid Y.P., R.G.Campanella, 1974. Triaxial and Plane Strain Behaviour of Natural Clay, ASCE GT3, 100.

Yumlu M. & M.Ozbay, 1995. A study on the behaviour of brittle rocks under plane strain and triaxial loading conditions, Int.J.Rock Mech.Min.Sci.Geom.Abstr.