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The legacy of Ioannis Vardoulakis to Geomechanics

Introduction to the school

Jean Sulem, Cino Viggiani

30th Alert Doctoral School , 3-4 Oct. 2019

Ioannis Vardoulakis

A leading scientist,
An engineer with innovative ideas,
A devoted and inspiring teacher

Large scientific culture
Taste for challenging problems
Innovative, unconventional, and pioneering ideas

Curiosity, Inspiration, Talent, Enthusiasm, Energy, Passion, Generosity …

Scientific approach

Let's take an example of I. Vardoulakis pioneering achievements

I. Vardoulakis PhD subject as proposed by Prof. G. Gudehus (Univ. of Karslruhe,):

« Post-failure slope stability in a strain softening soil »

How to address such an 'impossible' (mathematically ill-posed) problem in the 70's

INTERNATIONAL JOURNAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS, VOL. 2, 99–128 (1978)

FORMATION OF SHEAR BANDS IN SAND BODIES AS A BIFURCATION PROBLEM

I. VARDOULAKIS, M. GOLDSCHEIDER AND G. GUDEHUS
Institute of Soil Mechanics, University of Karlsruhe, West Germany

« *This paper is a partial result of the PhD dissertation of the first author (I. Vardoulakis) under the supervision of the two other authors (M. Goldscheider and G. Guhehus)* »

FUNDAMENTALS

- Go beyond classical limit analysis as used in geotechnical engineering
- Consider mathematical concepts of uniqueness and bifurcation for studying failure of materials

Vardoulakis, I. (1976). Equilibrium theory of shear bands in plastic bodies. *Mechanics Research Communications*, 3(3), 209–214.

References

1. J.Hadamard, Lecons sur la propagation des ondes, Paris, 1903 (Chp.VI, in particular).
2. R.Hill, J.Mech.Phys.Solids, 20, p. 1-16 (1962).
3. J.R.Rice, in Plasticity and Soil Mechanics (edited by A.C. Palmer), Cambridge Univ.Engr.Dept., Cambridge, 1973, p.263.
4. J.W.Rudnicki and J.R.Rice, J.Mech.Phys.Solids, 23, p.371-394 (1975.)
5. R.Hill and J.W.Hutchinson, J.Mech.Phys.Solids, 23, p.239-264 (1975.)

THEORY – Modes of deformation

Detailed analysis of the various modes of deformation
Boundary loads: Dead load / Follower load

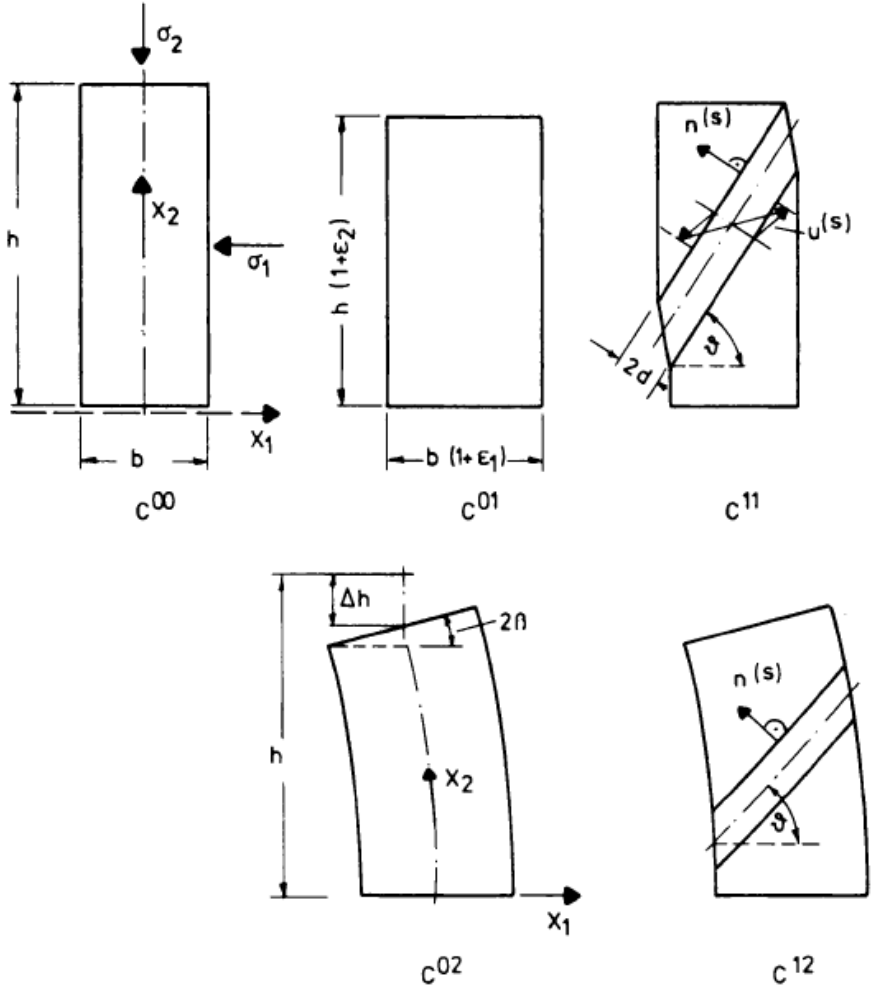


Figure 1. Configurations considered as bifurcation modes

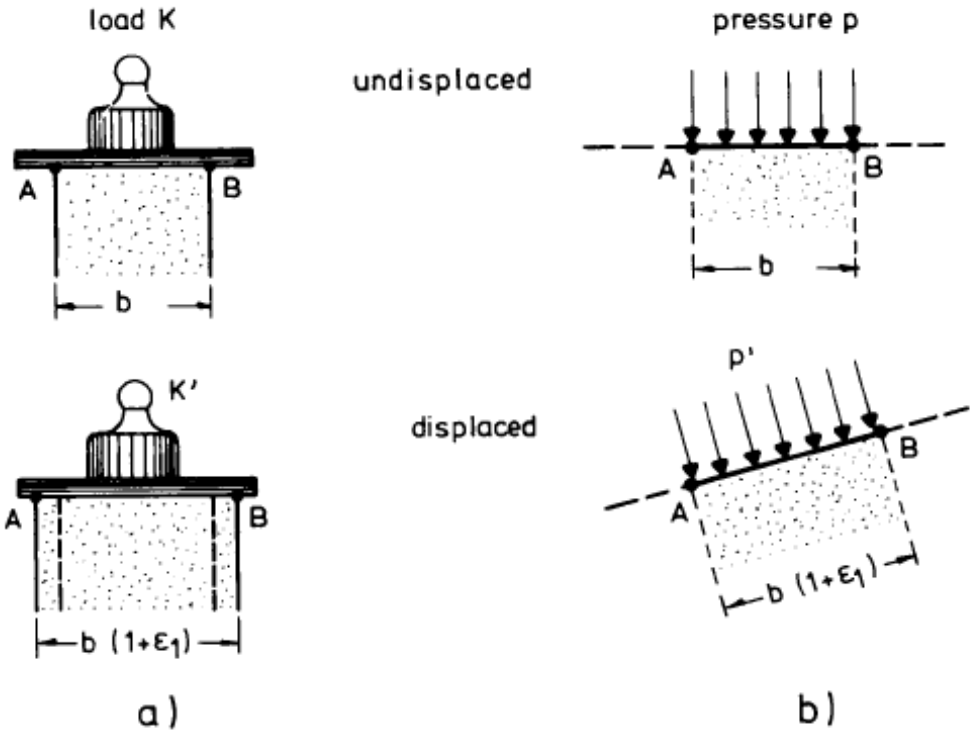


Figure 2. Configuration dependent boundary loads (a) a dead load, (b) a follower load

THEORY – Governing equations

Constitutive relations, Equilibrium solutions, Bifurcation modes

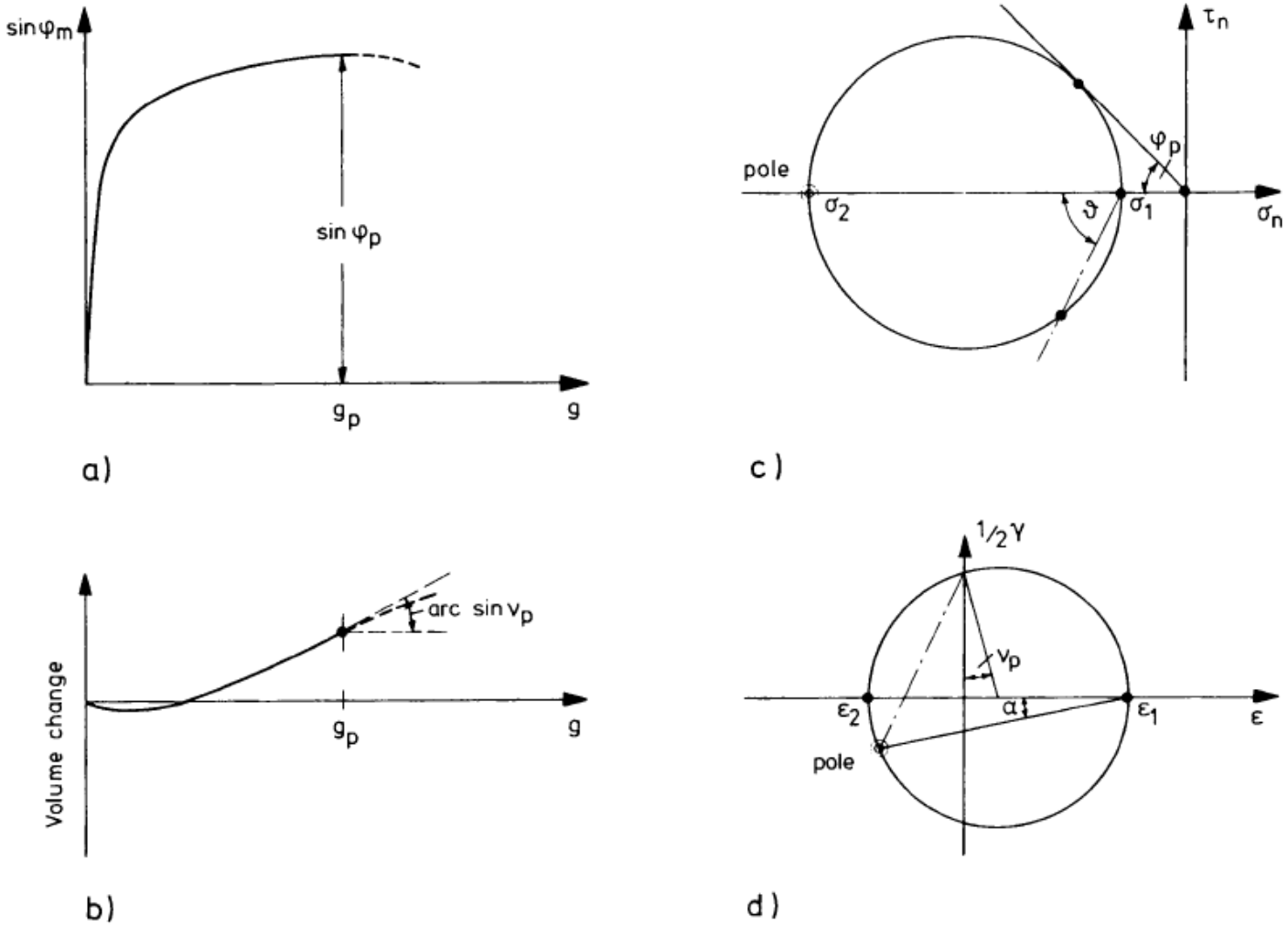


Figure 3. Behaviour of dry sand assumed (a) hardening under rectangular stretch (b) volume change under rectangular stretch and constant mean pressure (c) peak stressed state under non-rectangular stretch (d) peak infinitesimal strains under non-rectangular stretch

EXPERIMENTS - Design

Testing procedure

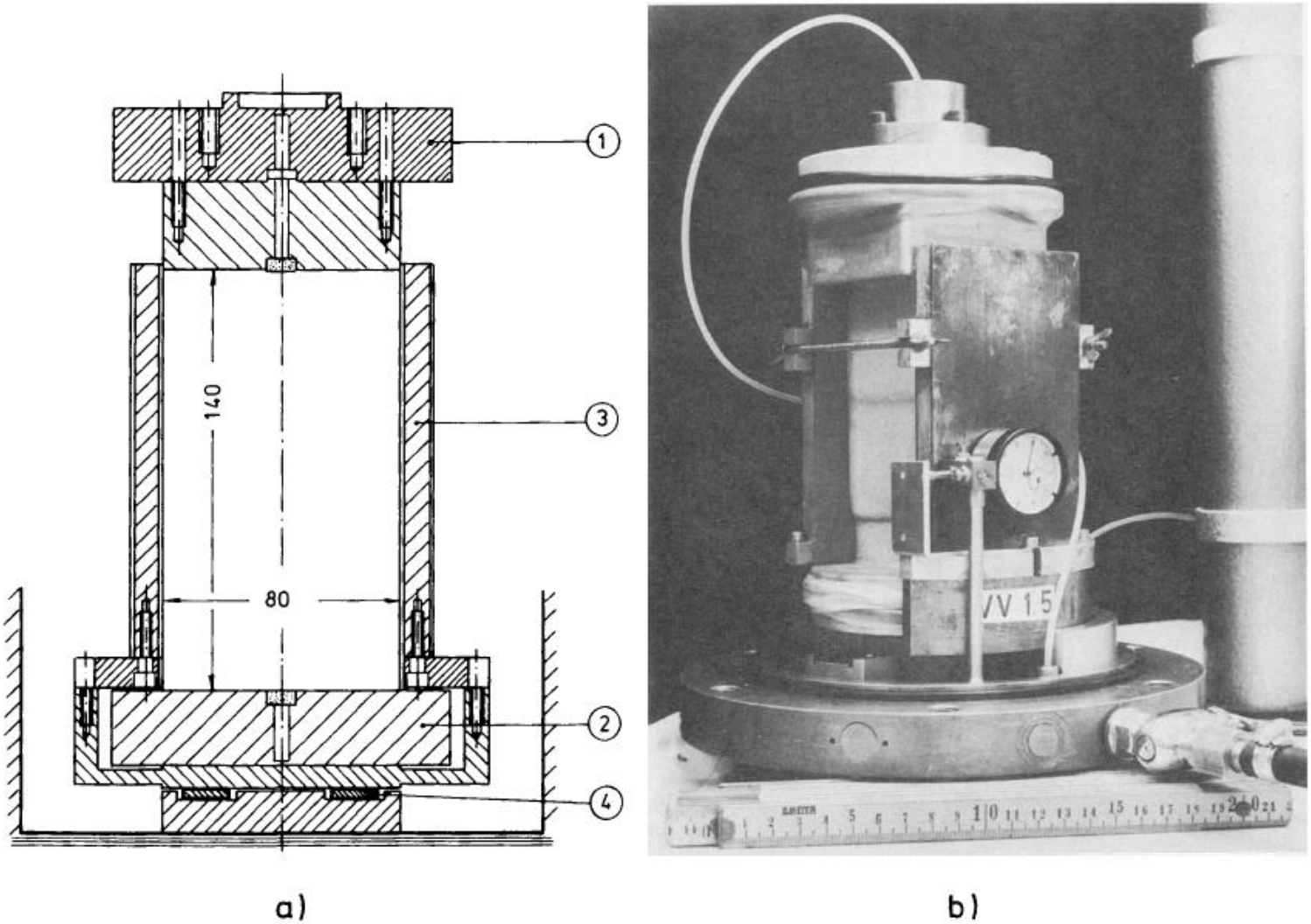


Figure 4. The biaxial apparatus, (1) top plate, (2) base plate, (3) side plates, (4) roller bearing

EXPERIMENTS - Design

Biaxial device with roller bearing platten

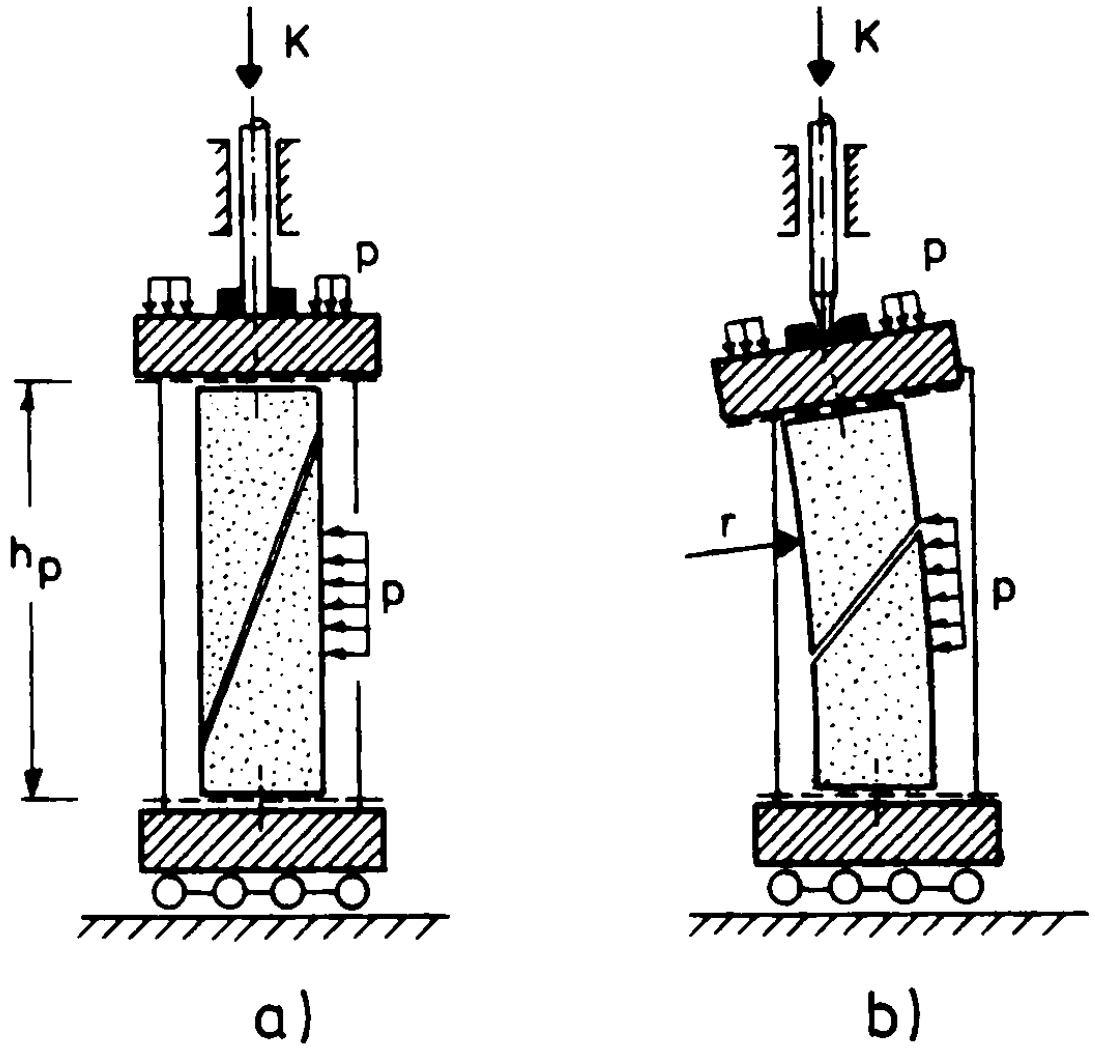
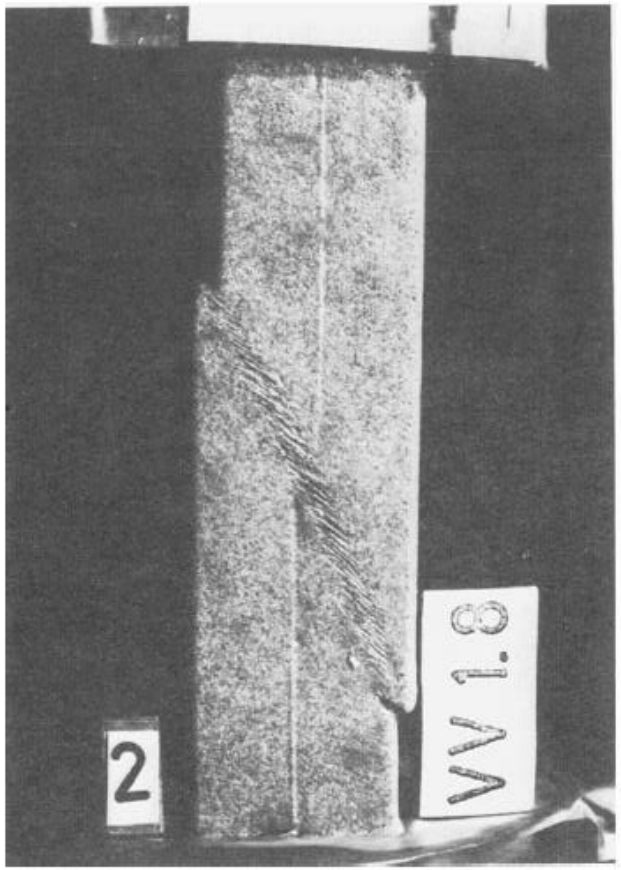


Figure 5. Load systems for biaxial tests (a) system for mode C^{11} (b) system for mode C^{12}

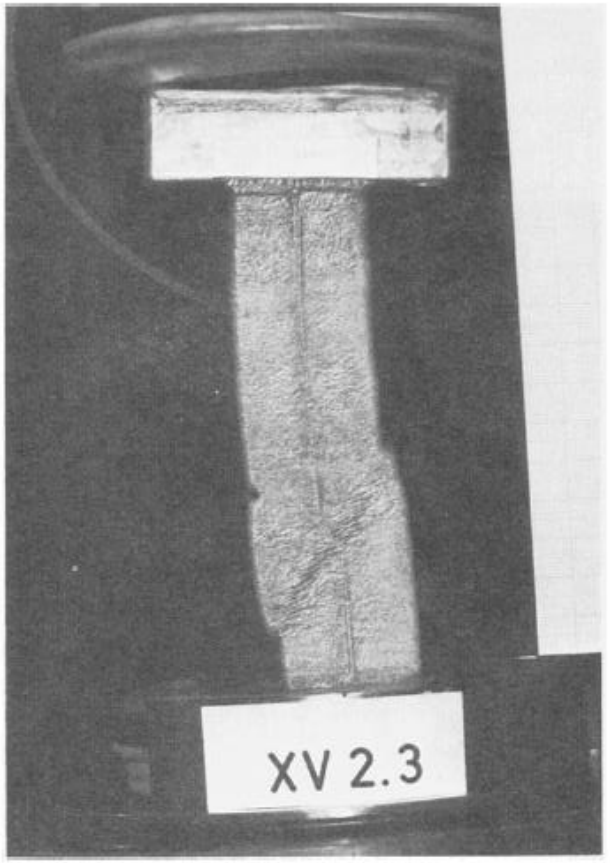
EXPERIMENTS - Observations

Pattern of shear bands



(c)

Figure 6. 'Type 1' shear band patterns



(b)

Figure 7. 'Type 2' shear band patterns

EXPERIMENTS - Analysis

Combining innovative ideas and simple engineering concepts

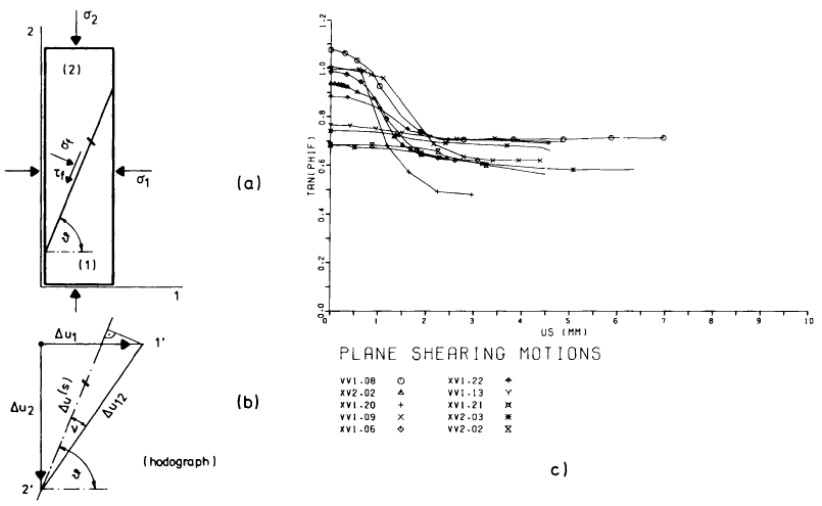
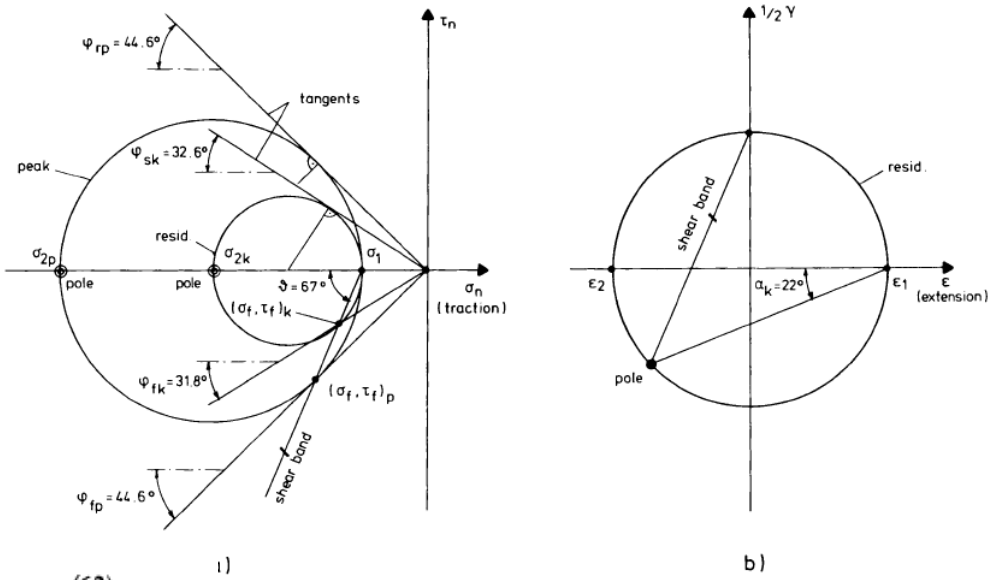


Figure 9. Post-failure stress–displacement behaviour (a) failure mechanism (b) hodograph (c) shear diagram



$$\theta_{1,2} = 45° + \tfrac{1}{4}(\phi_p + \nu_p) \qquad (62)$$

Table I shows a comparison between the measured θ-values referred to by Arthur *et al.*[1] and the theoretical predictions according to equations $(59)_1$ and (62).

$$\theta = \pi / 4 + \phi / 4 + \psi / 4$$

Table I. A comparison between measured(*) and computed shear band inclination

Apparatus (*)	Measured (*) ϕ_p	(*) ν_p	(*) θ	Computed $\theta = 45° + \frac{1}{4}(\phi_p + \nu_p)$	$\theta = \arctan\sqrt{(\lambda_p \delta_p)}$
FPSA	49°	21°	62°	62·5°	63·2°
FPSA	50°	30°	65°	65°	65·4°
FPSA	45°	22·5°	64·5°	61·9°	62·3°
FBC	46°	9°	59°	58·9°	59·6°
FBC	50°	19°	60°	62·3°	63·0°
FBC	51°	20°	64°	62·8°	63·5°
FBC	49°	23°	64°	63·0°	63·6°

(*) Data are taken from Arthur *et al.*[1]

Arthur-Vardoulakis equation for shear band orientation

Calibration of the out-of plane shear modulus

Vardoulakis, I. (1980). *International Journal for Numerical and Analytical Methods in Geomechanics*, 4 103–119.

POST FAILURE ANALYSIS
The missing link

Physical evidence: Shear bands have a finite thickness related to the grain size

Deficiency of classical continuum theories: The governing mathematical equations are ill-posed in the post-localization regime

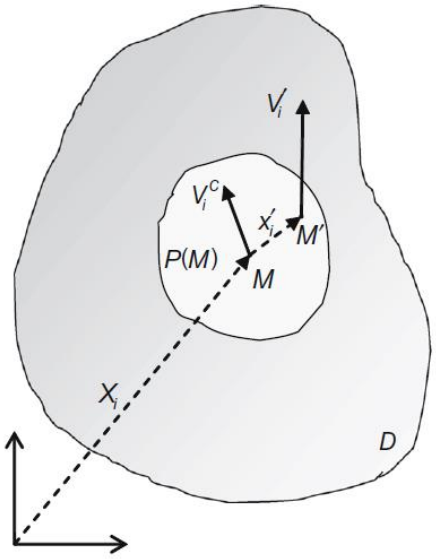
Remedy: Look at the governing mechanisms at a smaller scale

Mühlhaus, H.-B. & Vardoulakis, I. (1987). *Géotechnique* **37**, No. 3, 271–283

The thickness of shear bands in granular materials

H.-B. MÜHLHAUS* and I. VARDOULAKIS†

CONTINUUM THEORIES FOR A MATERIAL WITH MICROSTRUCTURE



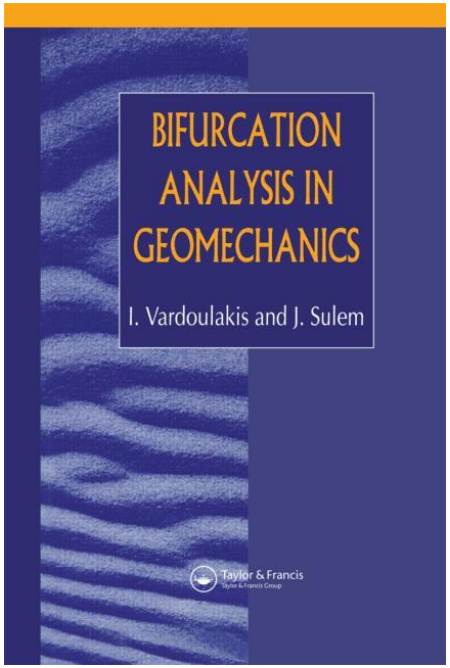
Cosserat, E. et F., 1909, *Théorie des corps déformables*, Hermann.

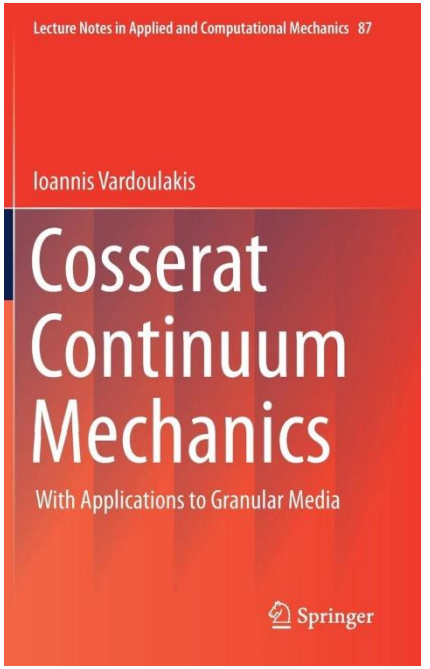
Mindlin R.D., 1964, *Arch. Rat. Mech. An.*

Germain P., 1973, *SIAM*

Vardoulakis I. & Sulem J., 1995, *Bifurcation Analysis in Geomechanics*, Taylor & Francis

Vardoulakis I, 2018, *Cosserat Continuum Mechanics with Applications to Granular Media*, Springer





ENGINEERING APPLICATIONS

Borehole stability and sand production

Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 21, No. 3, pp. 137–144, 1984
Printed in Great Britain

Rock Bursting as a Surface Instability Phenomenon

I. VARDOULAKIS*

Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 25, No. 3, pp. 159–170, 1988
Printed in Great Britain

Borehole Instabilities as Bifurcation Phenomena

I. VARDOULAKIS*
J. SULEM†
A. GUENOT‡

INTERNATIONAL JOURNAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS, VOL. 12, 379–399 (1988)

INTERNATIONAL JOURNAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS, VOL. 13, 183–198 (1989)

BIFURCATION ANALYSIS OF DEEP BOREHOLES: I. SURFACE INSTABILITIES

I. G. VARDOULAKIS
AND
P. C. PAPANASTASIOU
Department of Civil and Mineral Engineering University of Minnesota, Minneapolis, Minnesota, U.S.A.

INTERNATIONAL JOURNAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS
Int. J. Numer. Anal. Meth. Geomech., 2001; **25**:789–808 (DOI: 10.1002/nag.154)

BIFURCATION ANALYSIS OF DEEP BOREHOLES: II. SCALE EFFECT

P. C. PAPANASTASIOU AND I. G. VARDOULAKIS
Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, MN 55455, U.S.A.

INTERNATIONAL JOURNAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS
Int. J. Numer. Anal. Meth. Geomech., **22**, 749–769 (1998)

Volumetric sand production model and experiment

E. Papamichos[1†], I. Vardoulakis[2], J. Tronvoll[3] and A. Skjærstein[4]

COUPLED WELLBORE EROSION AND STABILITY ANALYSIS

M. STAVROPOULOU[1], P. PAPANASTASIOU[2,*] AND I. VARDOULAKIS[1]

ENGINEERING APPLICATIONS
Landslides

Vardoulakis, I. (2002). *Géotechnique* **52**, No. 3, 157–171

Dynamic thermo-poro-mechanical analysis of catastrophic landslides

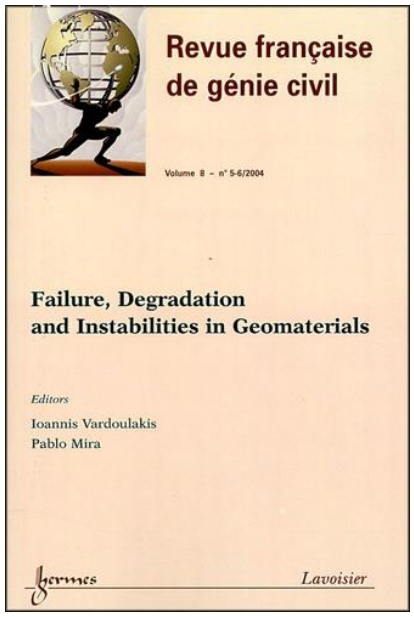
I. VARDOULAKIS*

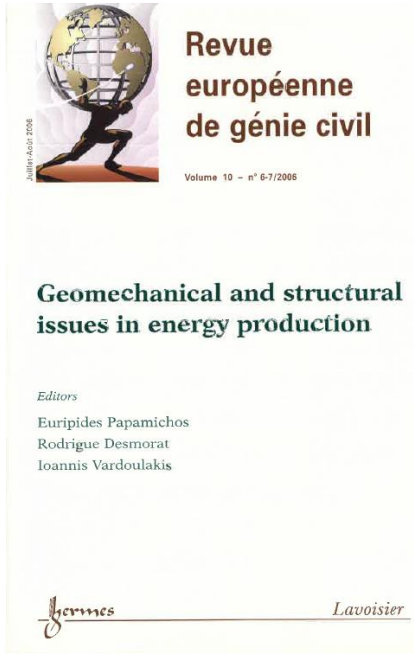
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, F03026, doi:10.1029/2006JF000702, 2007

Thermoporomechanics of creeping landslides: The 1963 Vaiont slide, northern Italy

Emmanuil Veveakis,[1] Ioannis Vardoulakis,[1] and Giulio Di Toro[2,3]

The importance of thermal pressurization of the pore fluid during rapid slip





Ioannis Vardoulakis
A devoted teacher

ALERT doctoral schools (2004, 2006)
LARAM school (2008)
CISM (2003)

http://geolab.mechan.ntua.gr/teaching/

GeoLab :: Laboratory of Geomaterials - NTUA

Teaching Material

Lecture notes

The following lecture notes are available online:

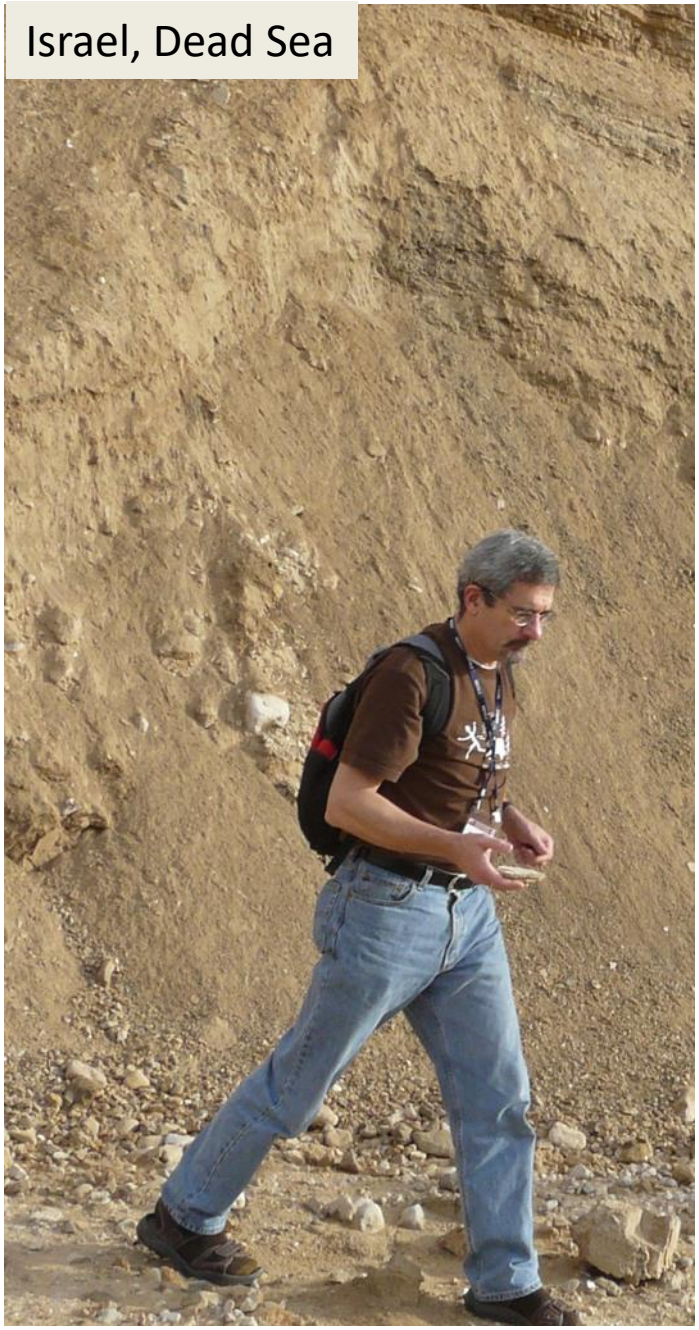
- *Cosserat Continuum Mechanics*, by prof. Ioannis Vardoulakis
- *Lecture notes from LARAM school on Geodynamics of Landslides*, by prof. Ioannis Vardoulakis
- *Lecture notes from CISM school on Degradation and Instabilities in Geomaterials*, by prof. Ioannis Vardoulakis
- *Engineering Mechanics II*, by prof. Ioannis Vardoulakis, in **greek**.
- *Engineering Continuum Mechanics*, by prof. Ioannis Vardoulakis
- *Mathematic theory of limit analysis*, by prof. Ioannis Vardoulakis, in **greek**.
- *Postgraduate course in Continuum Mechanics*, by prof. Ioannis Vardoulakis, in **greek**.
- *Introduction to Geomechanics*, by prof. Ioannis Vardoulakis, in **greek**.
- *Introduction to the Mathematical Theory of Ideally Plastic Solids*, by prof. Ioannis Vardoulakis, in **greek**.

Courses

Material for the following undergratuate courses are available online

- *Mechanics I*, by prof. Ioannis Vardoulakis,in **greek**.
- *Mechanics II*, by prof. Ioannis Vardoulakis,in **greek**.
- *Mechanics III*, by prof. Ioannis Vardoulakis,in **greek**.
- *Experimental Mechanics*, by prof. Ioannis Vardoulakis,in **greek**.
- *Continuum Mechanics*, by prof. Ioannis Vardoulakis,in **greek**.

Geolab - comments to webmaster@mechan.ntua.gr



three illustrative anecdotes

1. IV about JD work on tomography
2. IV and young(er) researchers
3. IV and teaching: pictorial, beam theory

ALERT SCHOOL

The legacy of Ioannis Vardoulakis

Some selected topics addressed by Ioannis Vardoulakis are revisited and recent developments are highlighted

STRAIN LOCALIZATION

Stability analysis, higher order regularization, multiphysics couplings, ***Ioannis Stefanou, Eleni Gerolymatou***

MECHANICS OF GRANULAR MATERIALS

Experiments – Modelling - Hydrodynamics, ***Edward Andò, Itai Einav, Holger Steeb***

GEOTECHNICAL AND PETROLEUM ENGINEERING

Landslide mechanics, Borehole stability, ***Sasha Puzrin, Euripides Papamichos, Panos Papanastasiou***


Itai Einav
Jim Rice
Ioannis Vardoulakis
Jean Sulem
Climbing the Masada, Israel