Stability Analysis On Natural And Artificial Slopes Under Earthquake Loading Based On Non-Linear Material Models

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis

Institute of Soil Mechanics and Rock Mechanics (IBF), KIT

Contents

- ULS and SLS issues on stability analysis of slopes
- Pseudo static analysis with non-linear constitutive laws
- Non-linear material behaviour (attractor states, anisotropy) for cyclic loading
- Constitutive laws on cyclic behaviour of soils
- Diffraction effects on artificial slopes consisting of materials with different stiffnesses

Questions raised to ULS and SLS for natural and artificial slopes under seismic loads

Seismic effects on slopes: :

- Induction of mass acceleration on the slope stability (is the static limit analysis still possible?).
- Reduction of the shear resistance due to accumulation of pore water pressure.

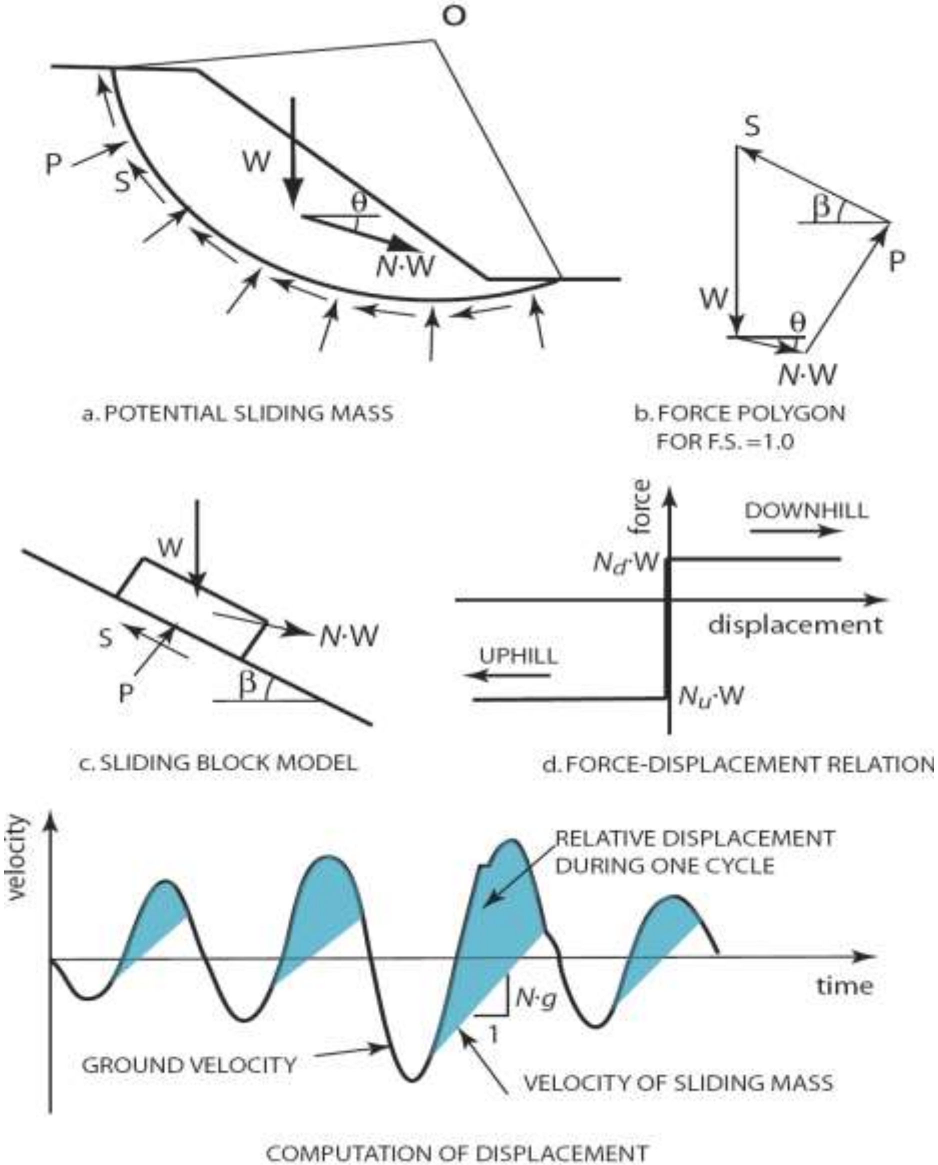
  $\tau_f = c + (\sigma - u\uparrow) \tan\varphi$

- Failure due to large deformations (cyclic mobility) or desintegration of the soil structure due to the degradation of the contact forces (partial liquefaction) leading to instable particle system

- Separation of the material phases (solid, air, water) - (phase separation, lateral spreading)

14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

System failure of slopes



Pseudo static or dynamic analysis (without desintegration)

- Hynes-Griffin Method (sliding block analysis NEWMARK) Excess of energy not absorbed by friction is transfered to block movement (kinetic energy) on the inclined plane.

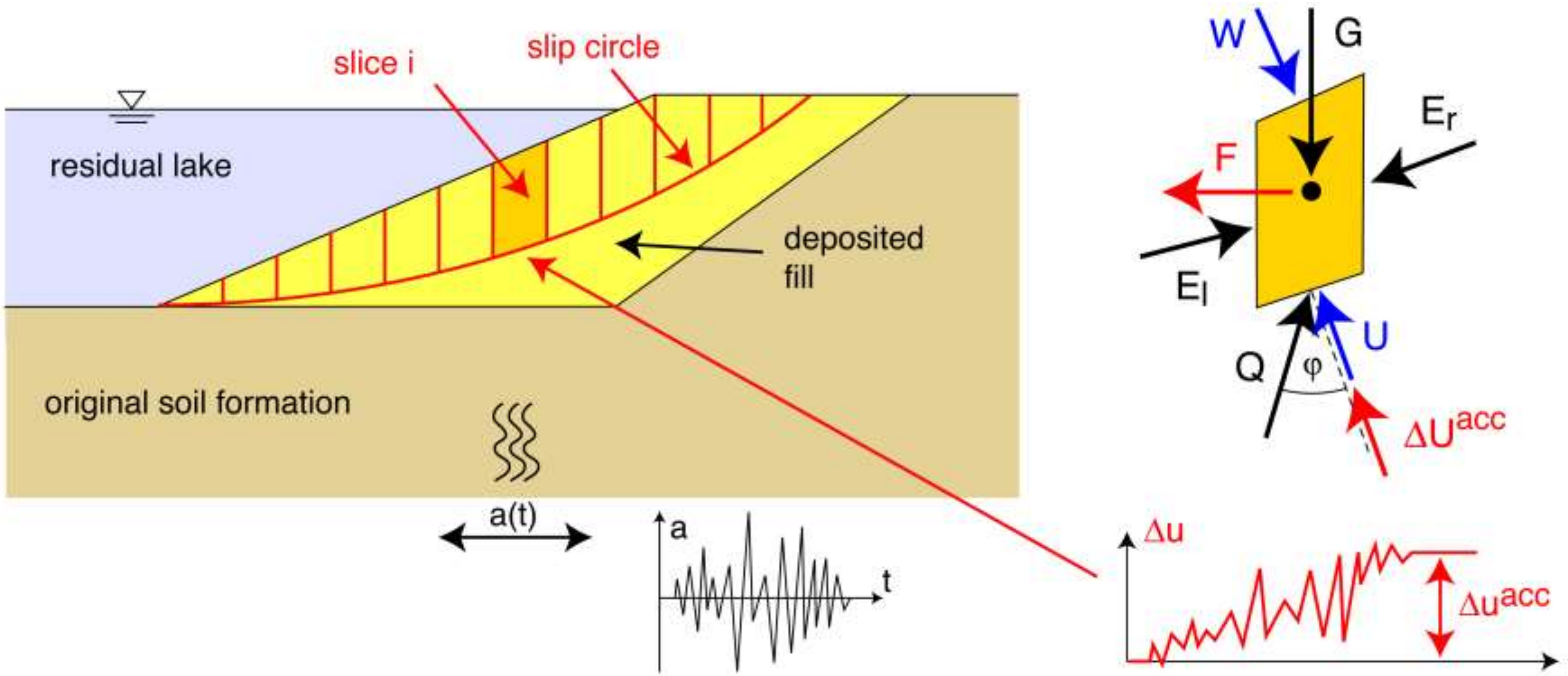
How large is the allowable movement until failure occurs? Equilibrium states below the global FOS = 1.0 are possible (permanent deformations)

Performance based design!!

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Failure mechanism in a quasi-static analysis

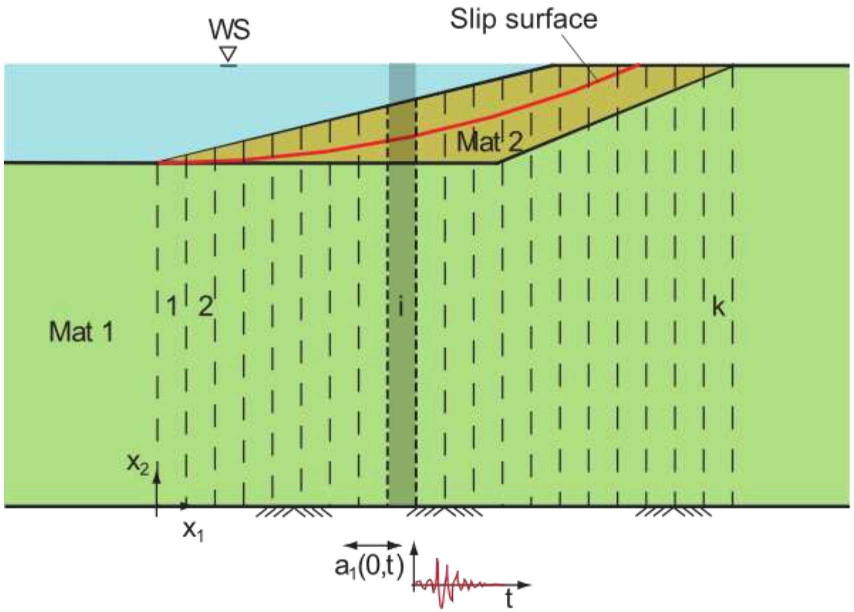
Pseudostatic analysis

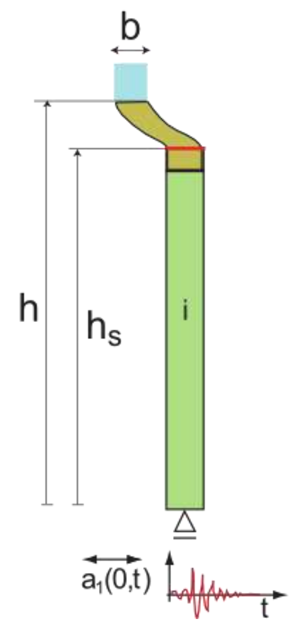


- Bishop method (vertical slices)
- Inertia forces acting on the slices $\bar{F} = m\chi a_{\max}$
- (m: mass, a_{max}: maximum acceleration, pseudo-static coefficient χ

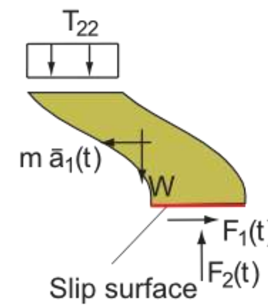
21.12.2016
14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Scheme for the computation of χ from 1-d analysis





$$\dot{\mathbf{T}} = \mathbf{f}(\mathbf{T}, \mathbf{D}, e, \mathbf{s})$$
$$\dot{p}_w = -K_w \mathrm{tr}\mathbf{D}$$



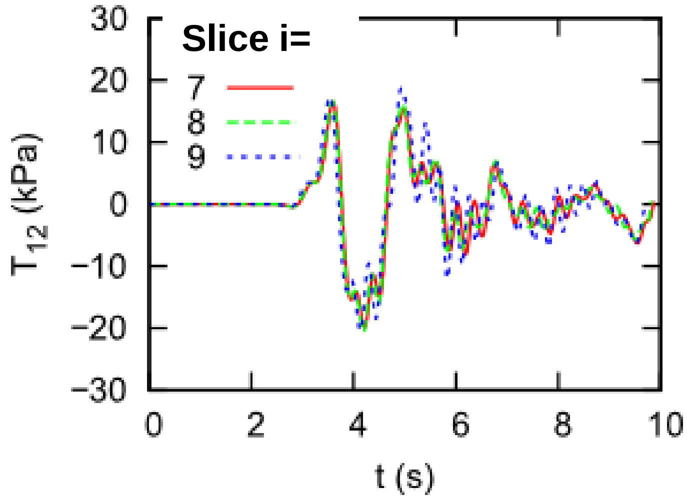
Impulse balance: $\dfrac{\partial T^i_{12}(x_2,t)}{\partial x_2} = \rho a^i_1(x_2,t)$ Integration from $x_2 = h_s$ to $x_2 = h$

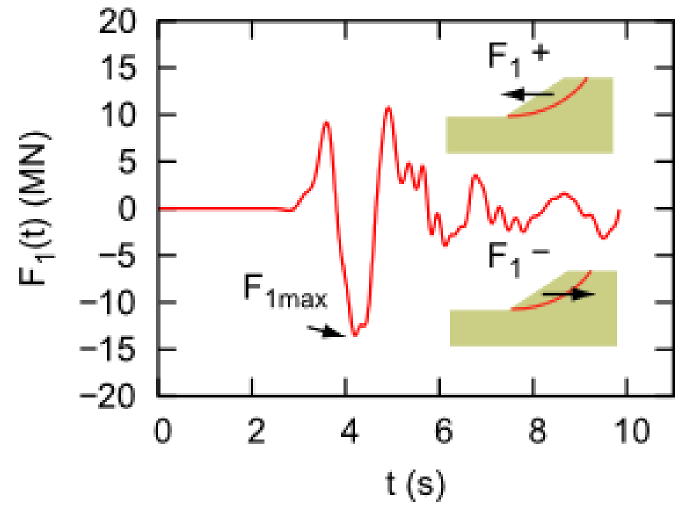
$$F^i_1(t) = b\int_{h_s}^{h} \frac{\partial T^i_{12}}{\partial x_2}\,\mathrm{d}x_2 = b\rho\int_{h_s}^{h} a^i_1\,\mathrm{d}x_2 = m^i\bar{a}^i_1(t)$$

$$F^i_1(t) = b[\overbrace{T^i_{12}(h,t)}^{=0} - T^i_{12}(h_s,t)] = -bT^i_{12}(h_s,t) = m^i\bar{a}^i_1(t)$$

14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Scheme for the determination of χ





The forces $F_1^i(t)=b\,T^{\,i}_{12}(t)$ at time *t* will be added over the entire number *k* of slices

$$F_1(t) = \sum_{i=1}^{k} F_1^i(t) \qquad \text{and from that} \qquad F_{1\,\max} = \max(|F_1(t)|)$$

With the mass *m* of the sliding body we can compute

$$\chi = \frac{F_{1\,\max}}{\max(|a_1(h=0,t)|)\cdot m} \quad \text{or} \quad \chi^{PGA} = \frac{F_{1\,\max}}{PGA\cdot m}$$

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Material failure: Liquefaction due to cyclic loading (Deterioration of the grain skeleton structure)

Examples

Christchurch, New Zeeland, 2016

Christchurch, New Zeeland, 2011

Material failure: Liquefaction due to cyclic loading (Deterioration of the grain skeleton structure)

Resistance of the grain skeleton against deterioration due to cyclic or dynamic loading depends upon:

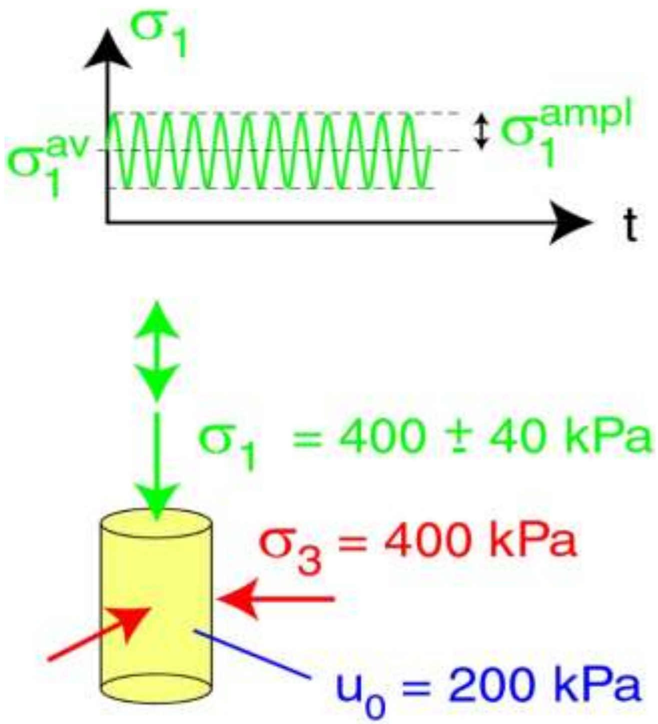
- Grain size distribution (including fines content) and grain morphology
- Relative density
- Deposition method (artificial slopes) or genesis (natural slopes)
- Preloading (static or dynamic) due to pre-seismic activity
- Empirical relations between CPT or SPT resistance (pressure dependent) or correlations of the pressure dependent shear velocity versus the resistance CRR as indicator for possible liquefaction (laboratory tests on undisturbed samples)

  CRR = f (Density, N:number of cycles, fabric)
- Material laws have to account for: limit and attractor states, historiotropy

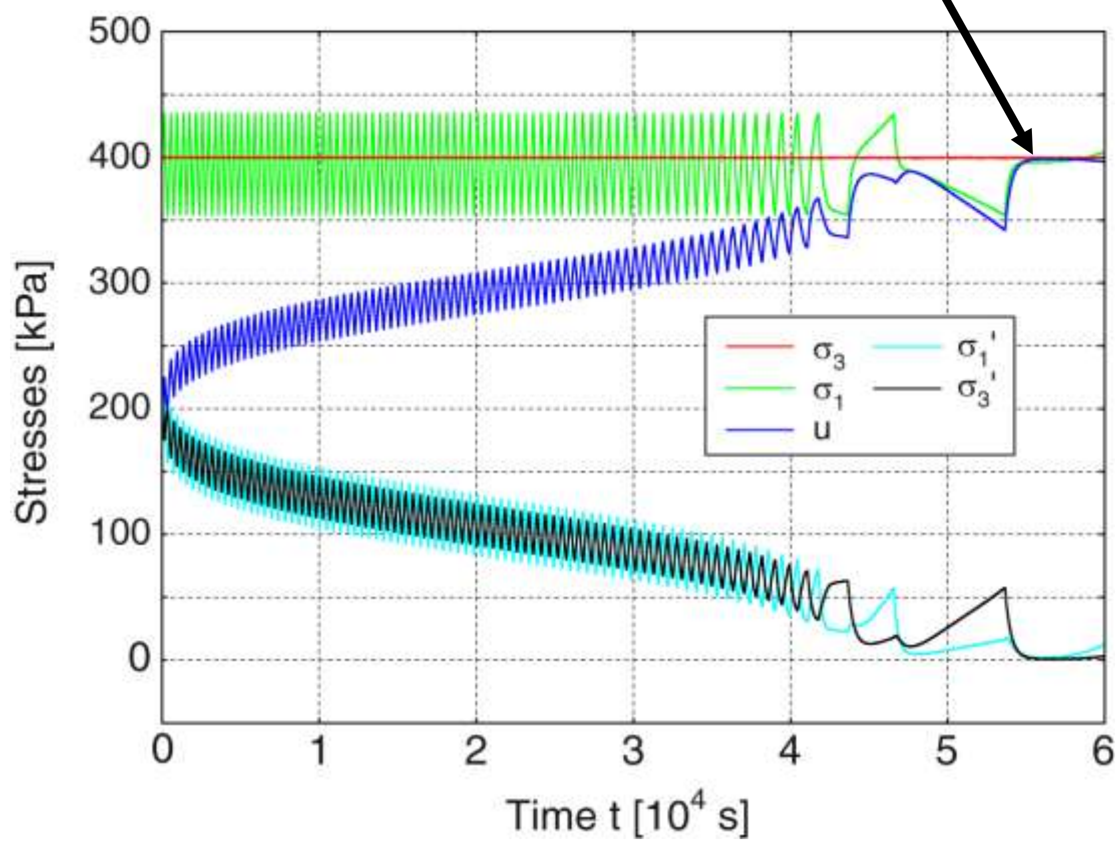
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Undrained material behaviour

IBF-tests on a fine sand $I_D \approx 0.65$):



“initial liquefaction“



 21.12.2016 14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)

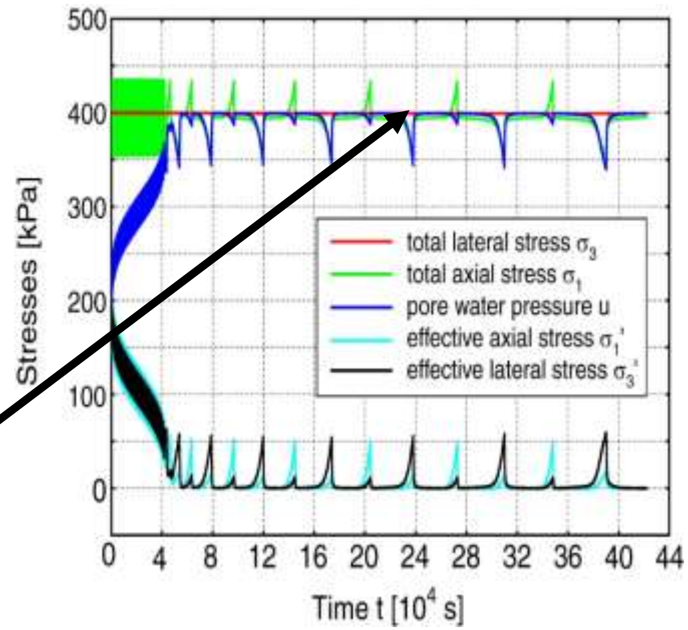
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

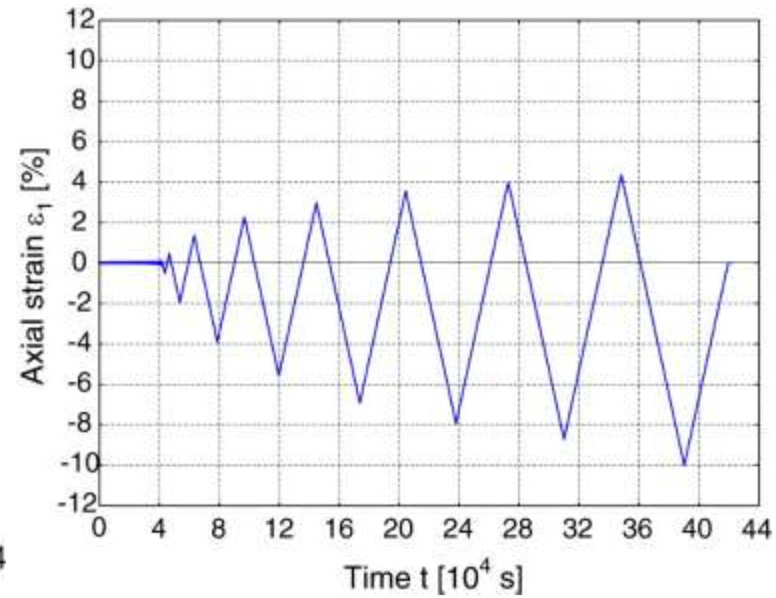
Undrained material behaviour

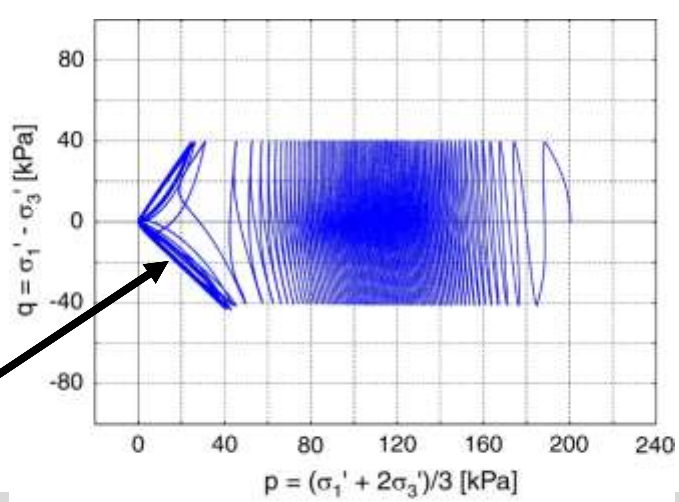
IBF tests on a fine sand :

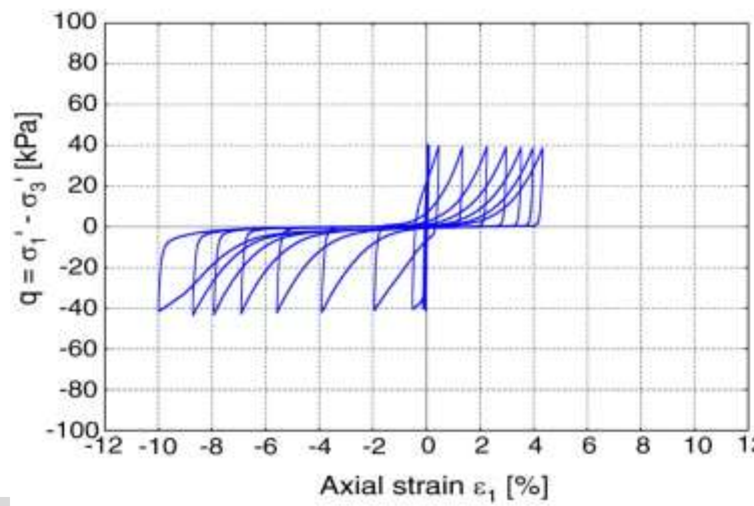
“partial liquefaction“

„cyclic mobility“





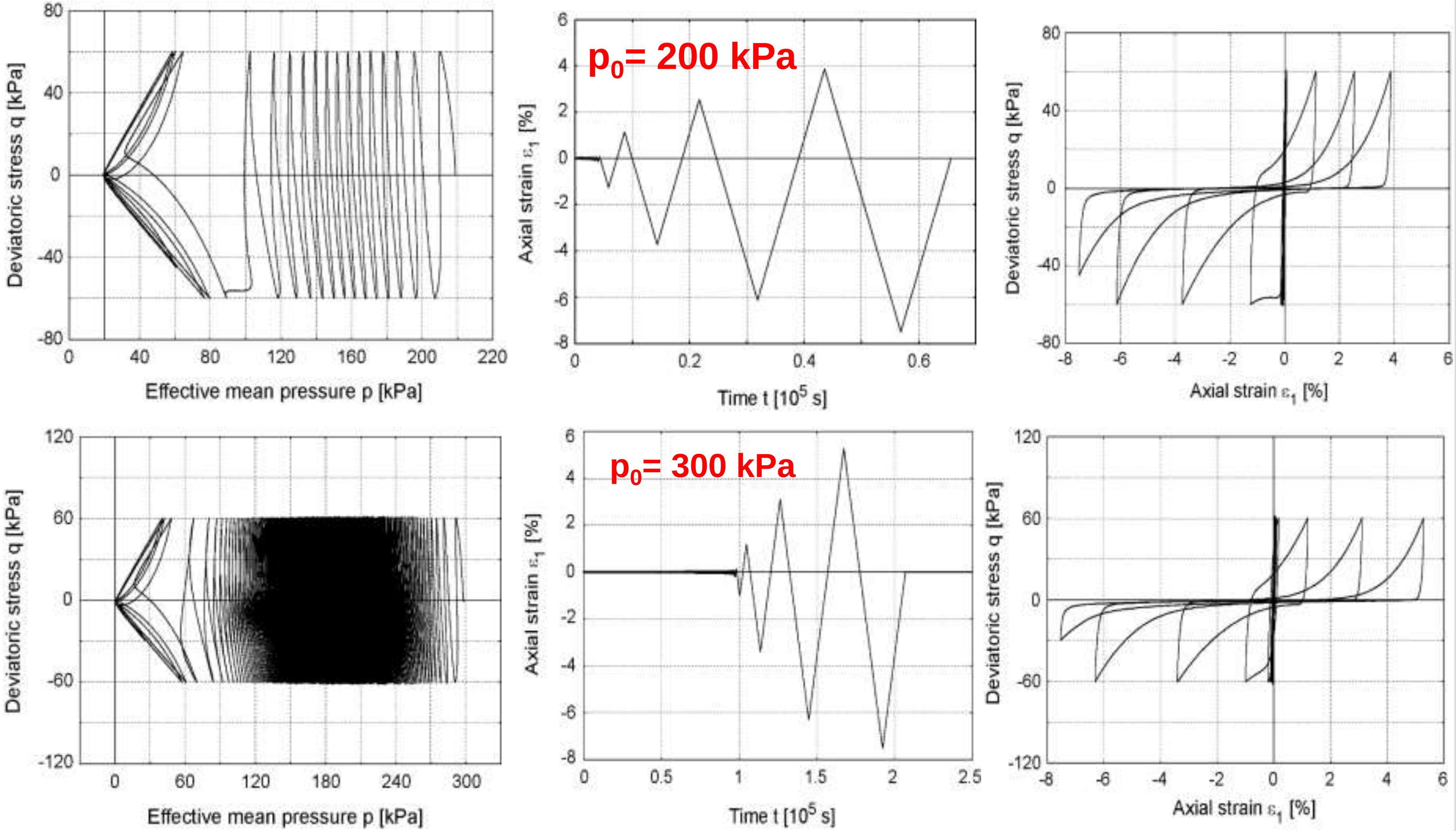




Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Undrained cyclic shearing - Attractors

Medium dense fine sand I_{d0}= 0,59 -0.55, q^{ampl} = 60 kPa, at different pressures p_0



14 -17 December 2016, Hong Kong International Geotechnics Symposium cum
International Meeting of CSRME 14th Biennial National Congress (IGSIM)

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF),
Germany

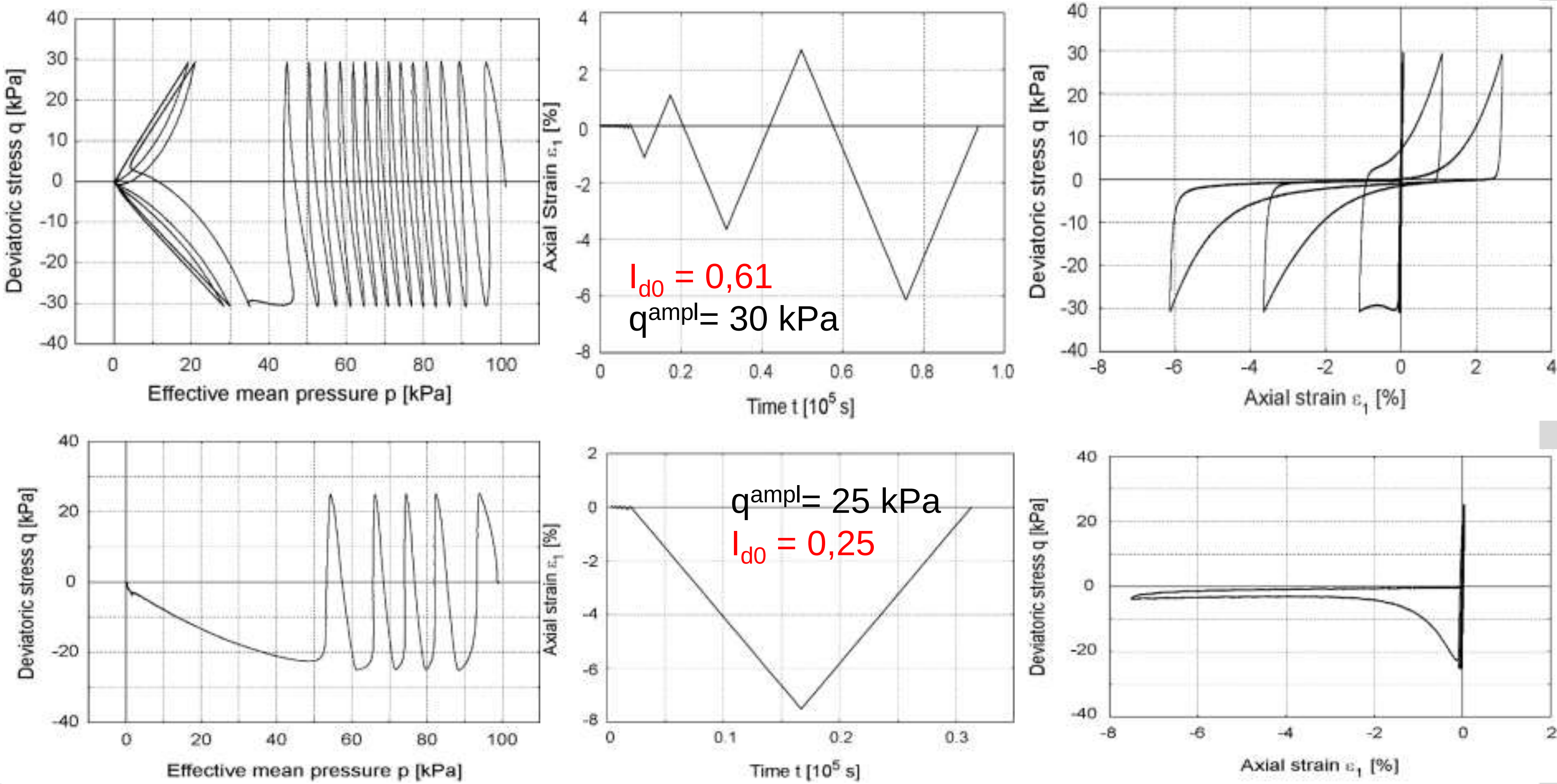
Undrained cyclic shearing - Attractors

Tests on the same initial pressure (p_0 = 100, q^{ampl} = 25/30 kPa, but with different densities)

Effective stress path

Axial strain

Deviator stress versus axial strain



14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

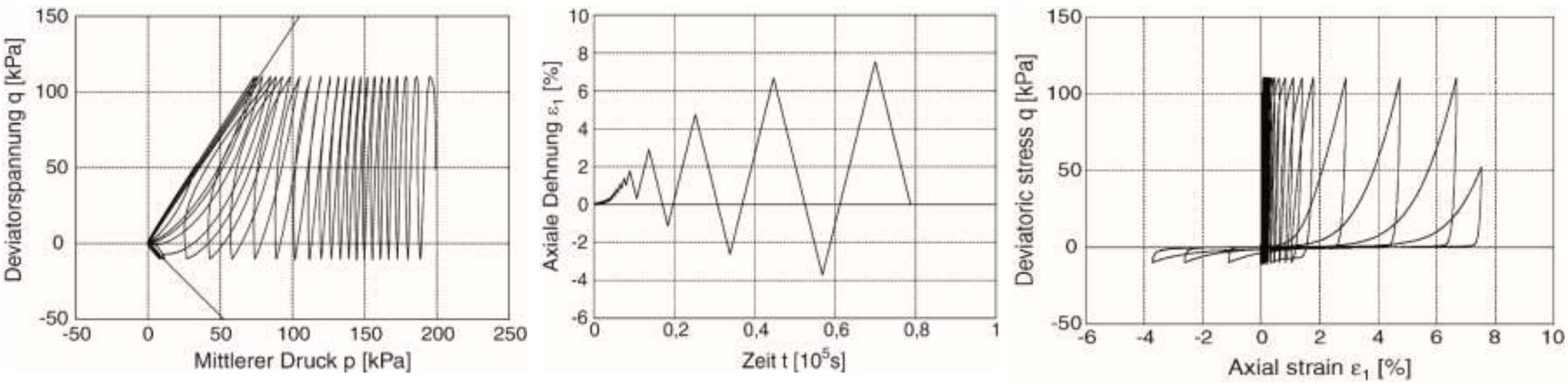
Undrained cyclic shearing with anisotropic shear stress - Attractors

Tests with anisotropic initial stresses
(q_{min}< 0, I_{d0}= 0,53, q^{ampl}=60 kPa):

Effective stress path

Axial strain

Deviator stress versus axial strain



Cyclic mobility attractor for anisotropic initial stress lead to an asymmetric butterfly attractor (for q_{min}<0 , p = 0 is often reached !!!!)

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

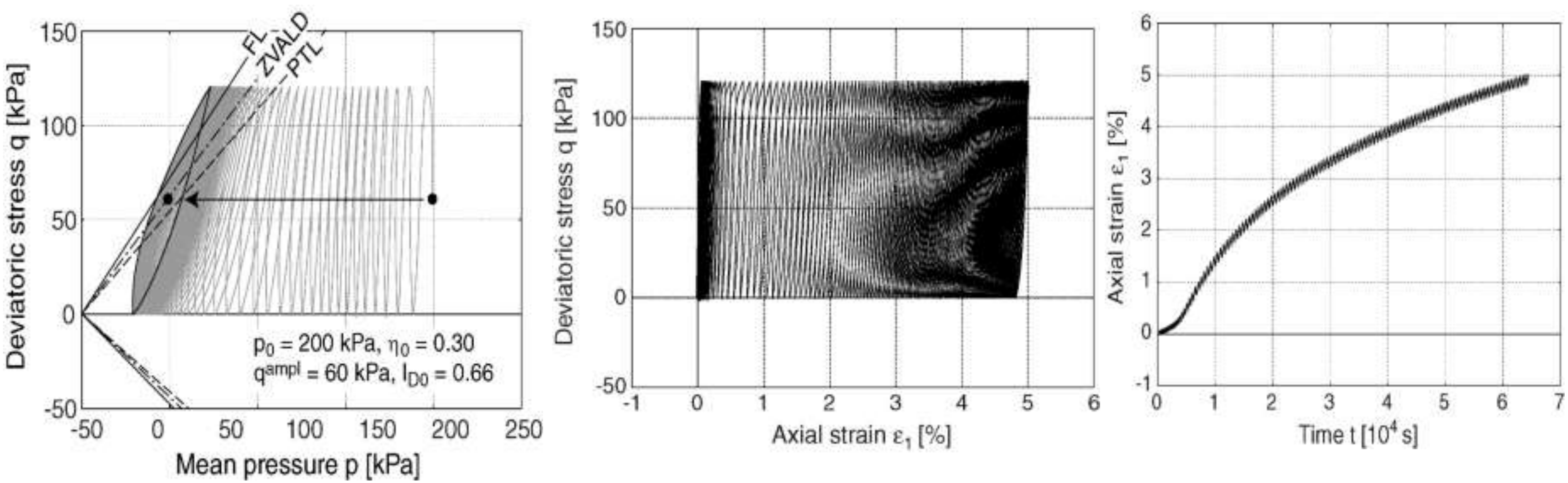
Undrained cyclic shearing with anisotropic shear stress - Attractors

Tests with anisotropic initial stress state and pulsating stress ($q_{min} = 0$) :

Effectiv stress path

Deviator stress versus axial strain

Axial strain



Limit cycle has the form of a lense not of a butterfly!!

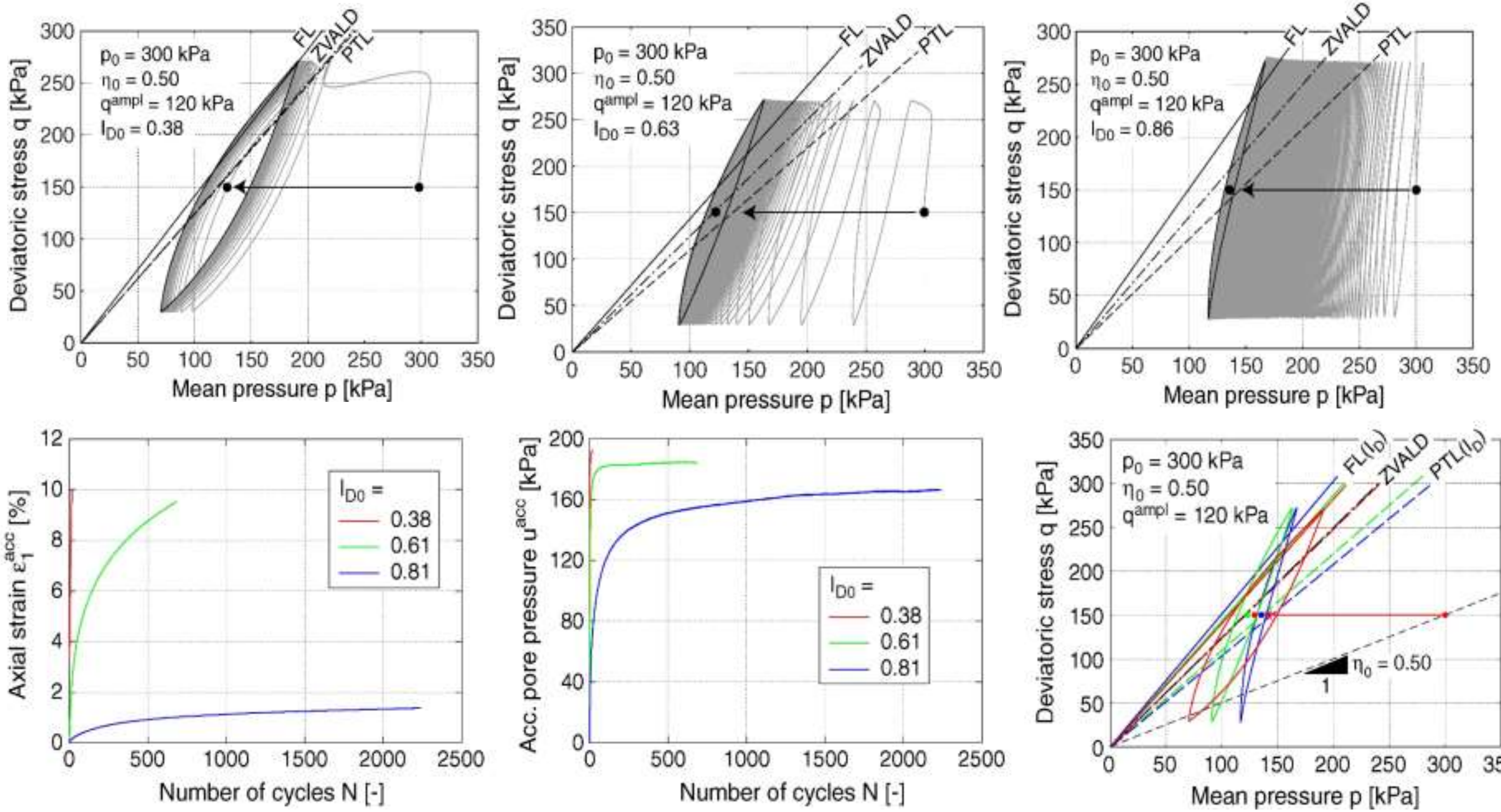
With increasing number of cycles N the accumulation rate became smaller!!

p= 0 is never reached but a limit stress p ≠ 0!!

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Undrained cyclic shearing with anisotropic shear stress - Attractors

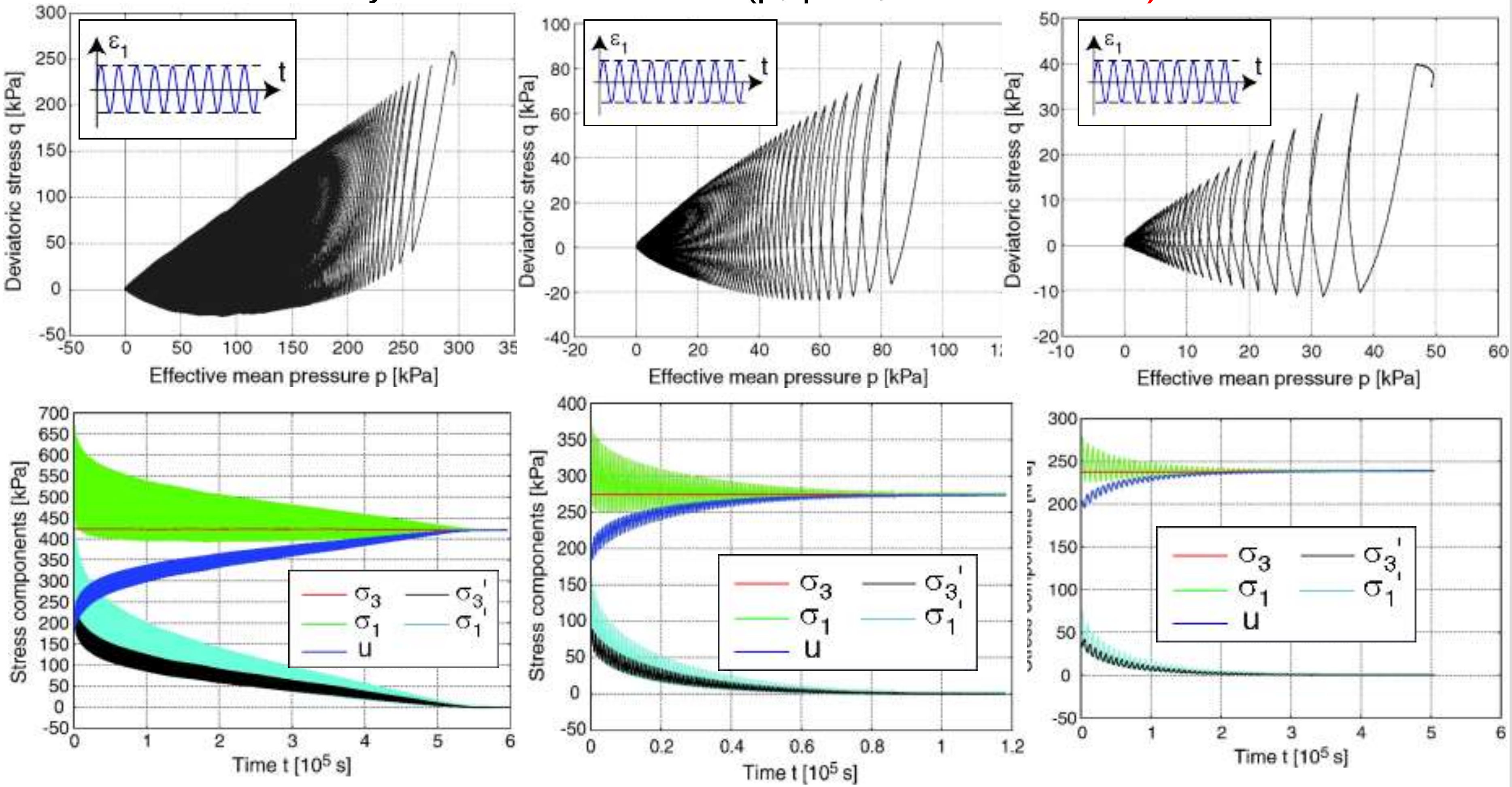
Influence of the density under the same initial stress regime ($q_{min} > 0$), and the same cyclic stress amplitude (lose: I_{d0} = 0,38, medium dense I_{d0}= 0,63 and dense: I_{d0}= 0,86)



14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

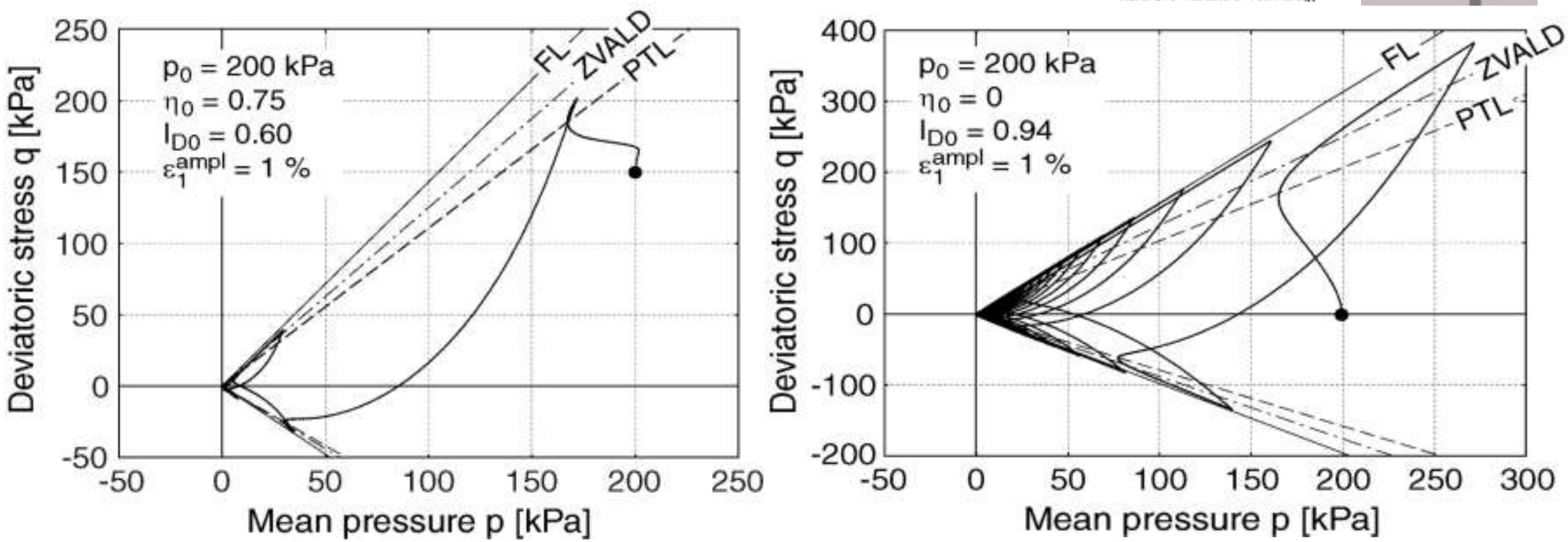
Undrained shearing with strain control - Attractors

Effective stress paths for the same initial stress ratio η=0,75, density and strain amplitude ε_1 = $6 \cdot 10^{-4}$ but different isotropic stress. Relaxation of the effective stress with the number of cycles towards to zero (p,q = 0, Point-Attractor)



Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Strain control with larger amplitudes



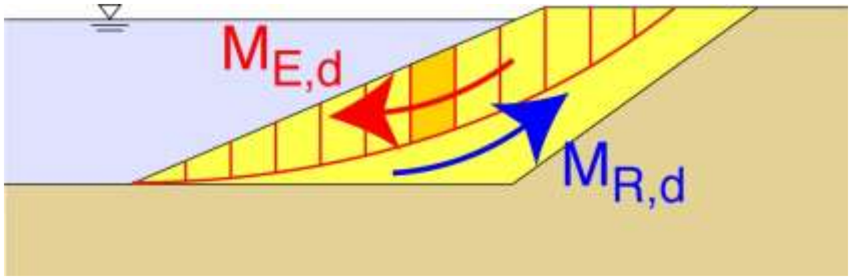
- Large cyclic strain amplitudes (in the order of 10^{-2} lead always to the butterfly effect for medium and dense sands independent from the initial values of e und σ.

- At large strain amplitudes after a initial contractant behaviour the dilatancy takes over and forces the stress path to cross the phase-transformation line (PTL) and the material creates more space for the following contractancy after the strain reversal. This additional space is used from the material to cross the PTL-line on the extensional regime and to follow the failure with dilatant behaviour. After the strain reversal the material reaches the butterfly attractor (not the Point attractor)

Dynamic stability analysis and requirements on constitutive equations

Constitutive laws have to describe:

- All the attractor states
  cyclic mobility, lens and point attractors
- Steady state behaviour
- Dilatancy and contractancy effects
- Historiotropy effects



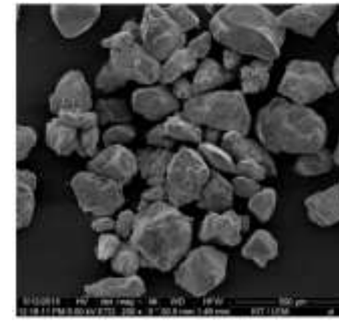
Only under principal satisfaction of the above criteria and satisfactory calibration of the material parameters a performance based design is possible.

The slope after an initial movement due to a seismic event may slide in order to find a new equilibrium state.
The amount of the permanent deformation may be checked against the serviceability of the utilities or the nearby structures (displacement or performance based design).

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

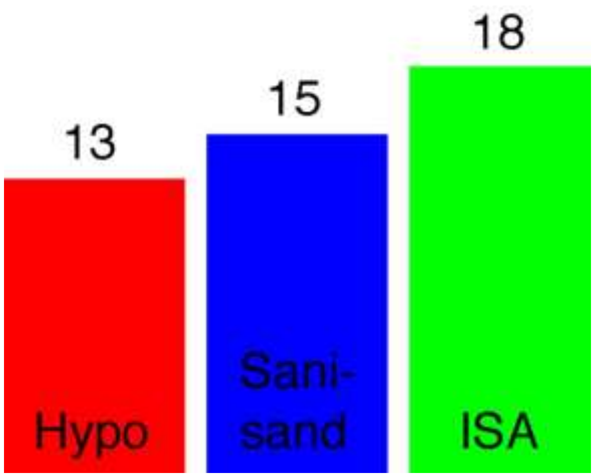
Modelling the cyclic behaviour

Only a few families of constitutive laws are suitable for the description of the cyclic material behaviour

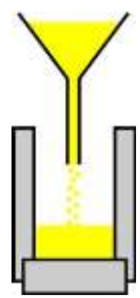


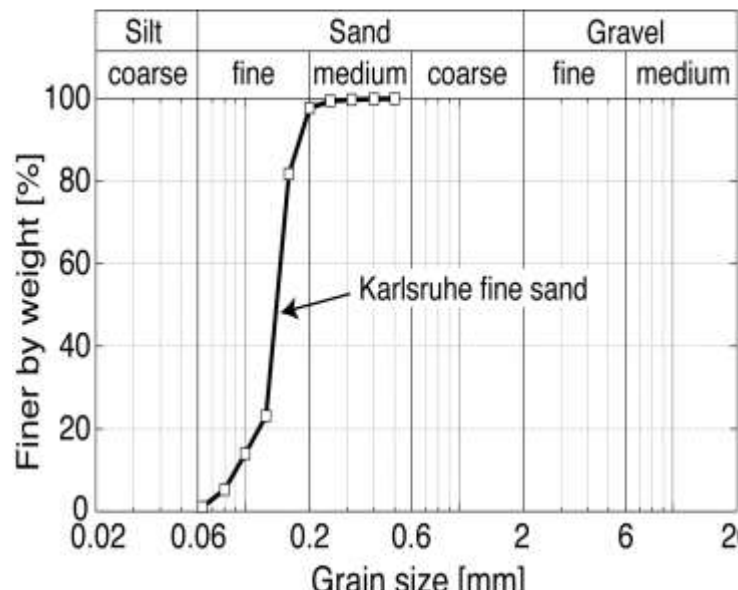
- Hypoplasticity with intergranular strain (von Wolffersdorff, 1996, Niemunis & Herle, 1997)
- Sanisand (elasto-plastic model, Dafalias & Manzari, 2004)
- ISA-Model („Intergranular Strain Anisotropy“, Fuentes and Triantafyllidis, 2015)

Number of material parameters to be determined:



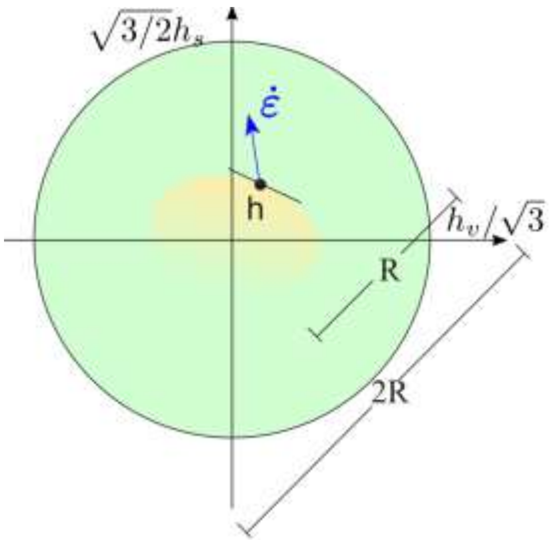
- Material tested: (Karlsruhe fine sand) d_{50} = 0,14 mm, C_u = 1,5





Schematic view of the material models

Hypoplasticity with intergranular strain (Niemunis and Herle, 1997)

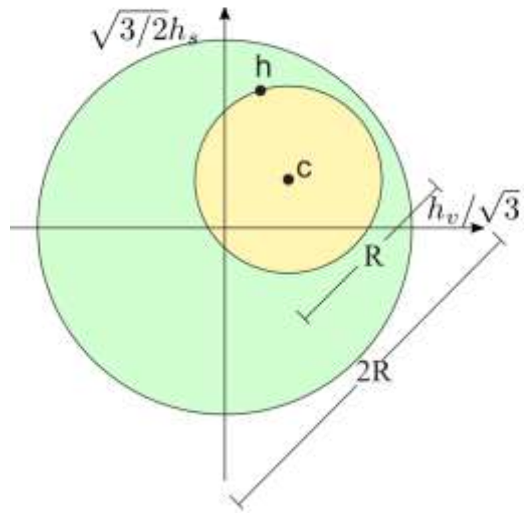


$$\dot{\boldsymbol{\sigma}} = \mathsf{E} : (\dot{\varepsilon} - Y\mathbf{m}\|\dot{\varepsilon}\|)$$

- Unloading: $\dot{\mathbf{h}} = \dot{\varepsilon}$
- Loading:

$$\dot{\mathbf{h}} = \left(\mathsf{I} - \overrightarrow{\mathbf{h}}\,\overrightarrow{\mathbf{h}}\,\rho^{\beta_r}\right) : \dot{\varepsilon}$$

ISA (Fuentes and Triantafyllidis, 2015)

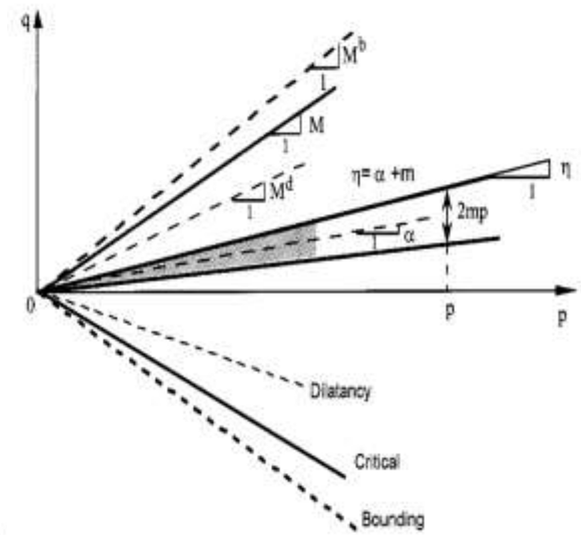


$$\dot{\boldsymbol{\sigma}} = \mathsf{E} : (\dot{\varepsilon} - Y\mathbf{m}\|\dot{\varepsilon}^p\|)$$

- Unloading: $\dot{\mathbf{h}} = \dot{\varepsilon}$
- Loading:

$$\dot{\mathbf{h}} = \dot{\varepsilon} - \dot{\lambda}(\mathbf{h} - \mathbf{c})^{\rightarrow}$$

SANISAND (Dafalias and Manzari,,2004)



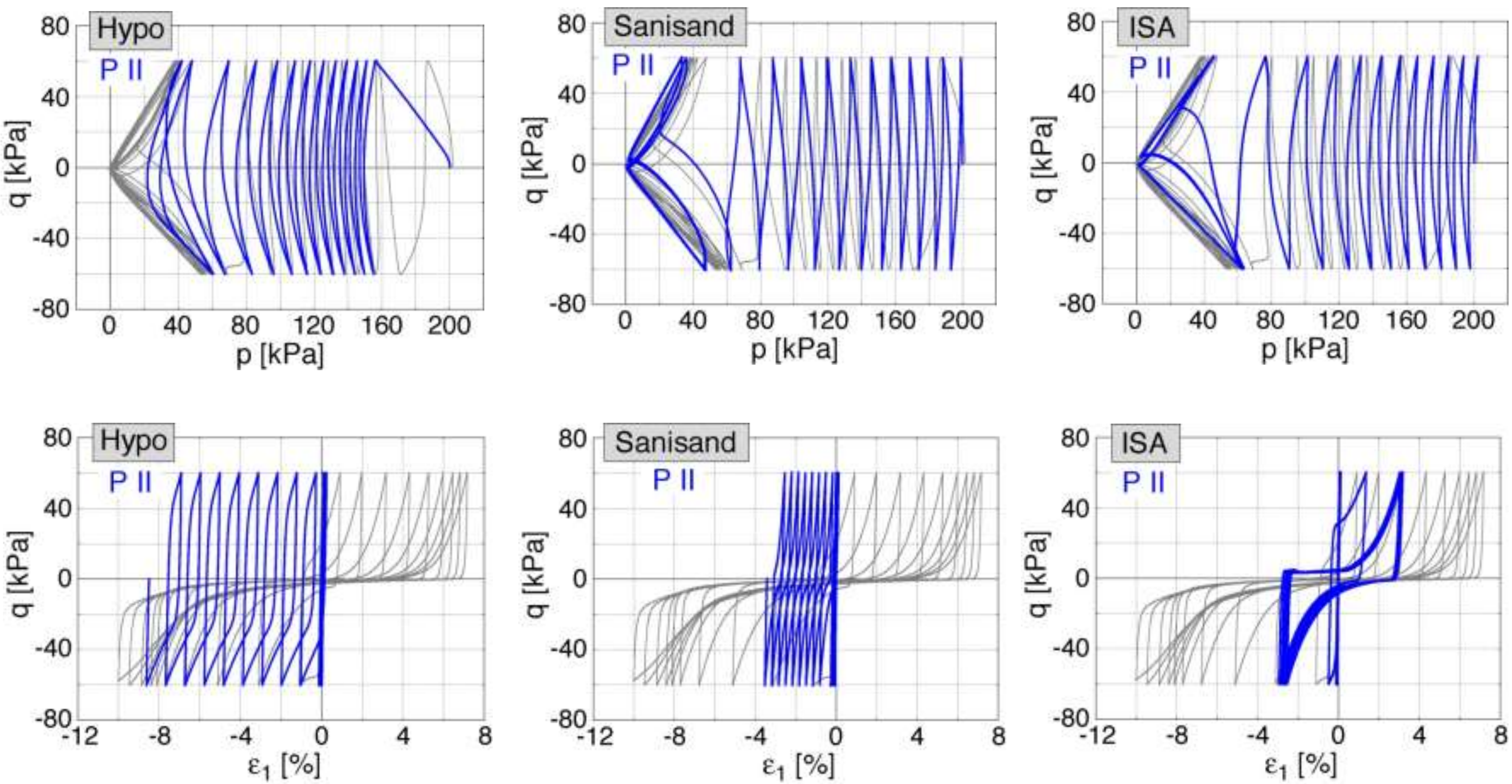
Elasto-plastic model with dilatancy and bounding surfaces)

14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Simulations of triaxial testing

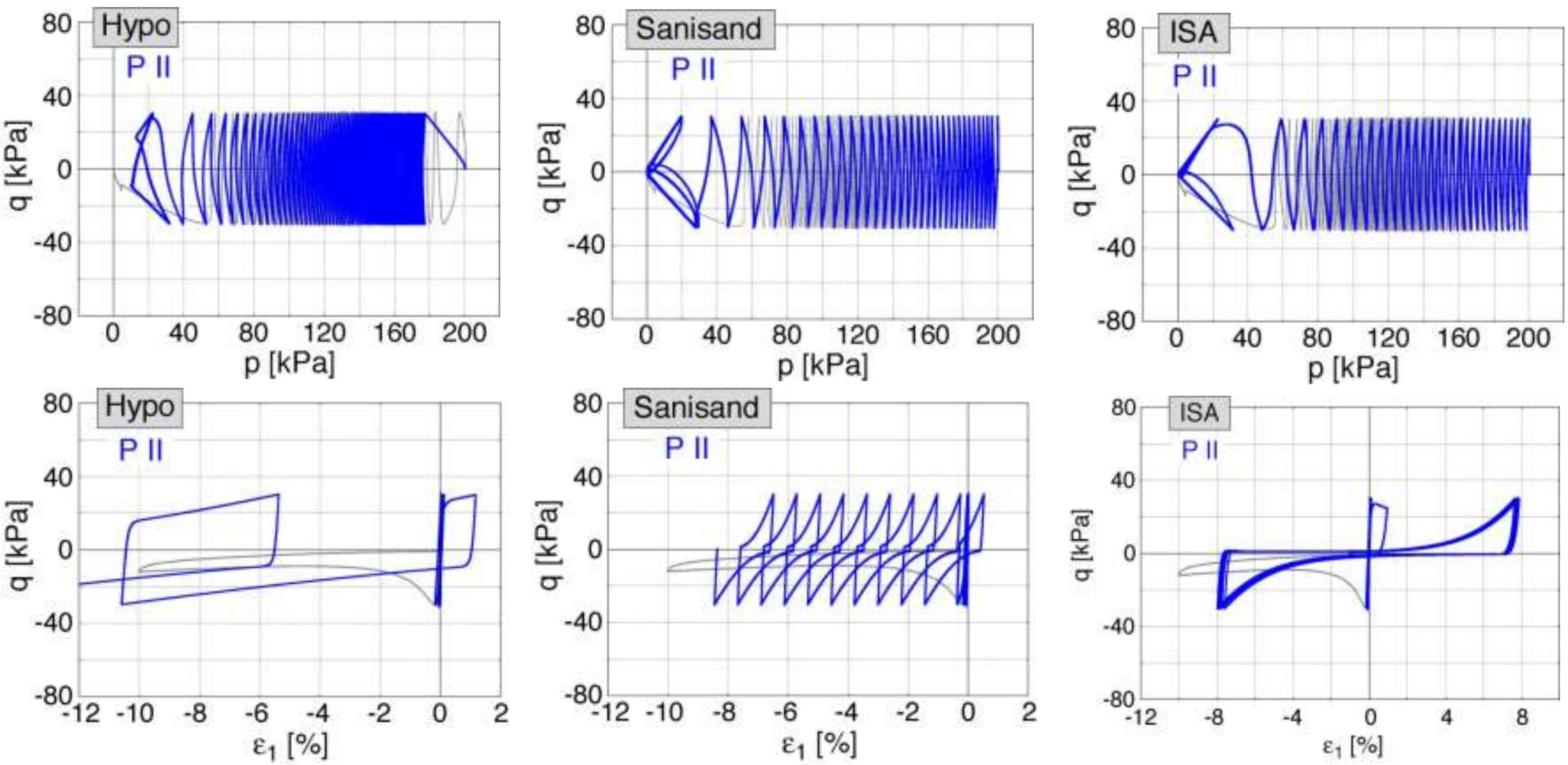
Undrained conditions with isotropic initial mean stress, stress cycles, medium dense sand (I_{D0} = 0,67)



Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Simulations of triaxial testing

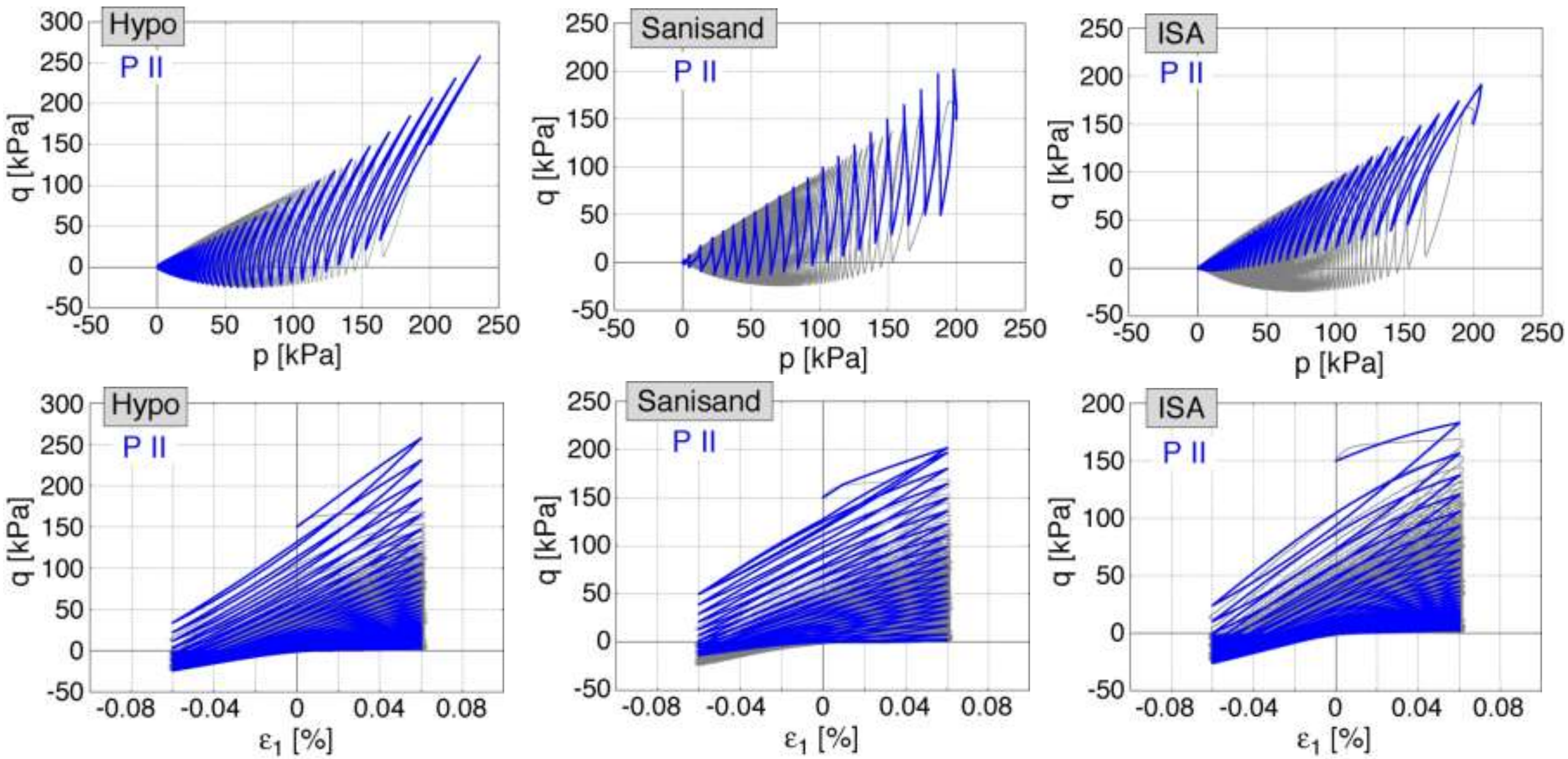
Undrained conditions, isotropic initial stress,
stress cycles, loose density (I_{D0} = 0,27)



→ Test: Failure within the first cycle on the extensional regime;
Model prognosis: either butterfly or eight-shaped effective stress path

Simulations of triaxial testing

Undrained conditions, anisotropic initial stress,
strain cycles with relatively small amplitudes $\varepsilon_1^{ampl} = 6 \cdot 10^{-4}$, dense ($I_{D0}$ = 0,64)

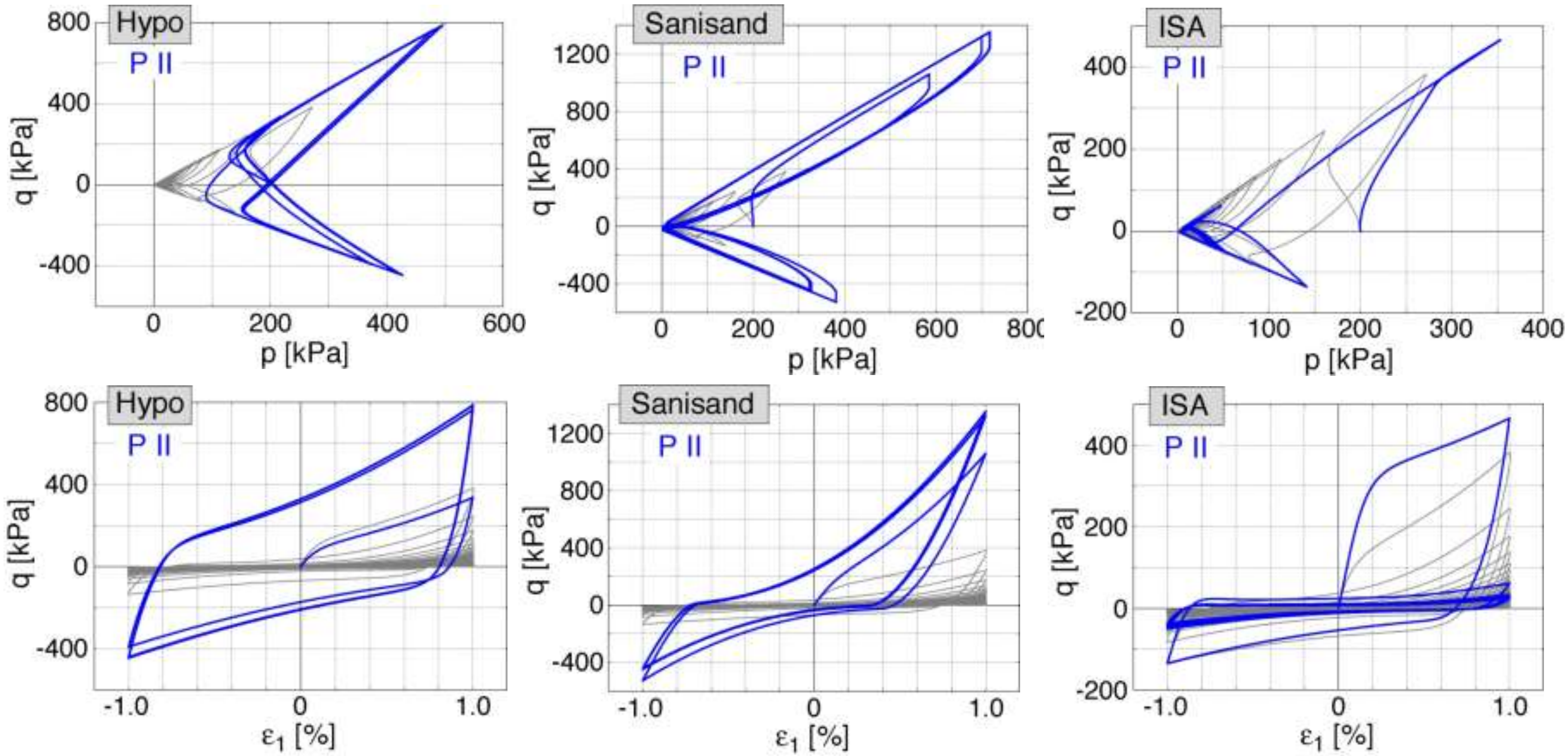


→ qualitatively good reproductivity of the test results for all the models
→ stress relaxation rate a bit to large for the sanisand model

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Simulations of triaxial testing

Undrained conditions, isotropic initial stress,
strain cycles with relatively large amplitude $\varepsilon_1^{ampl} = 1 \cdot 10^{-2}$, dense ($I_{D0}$ = 0,94)

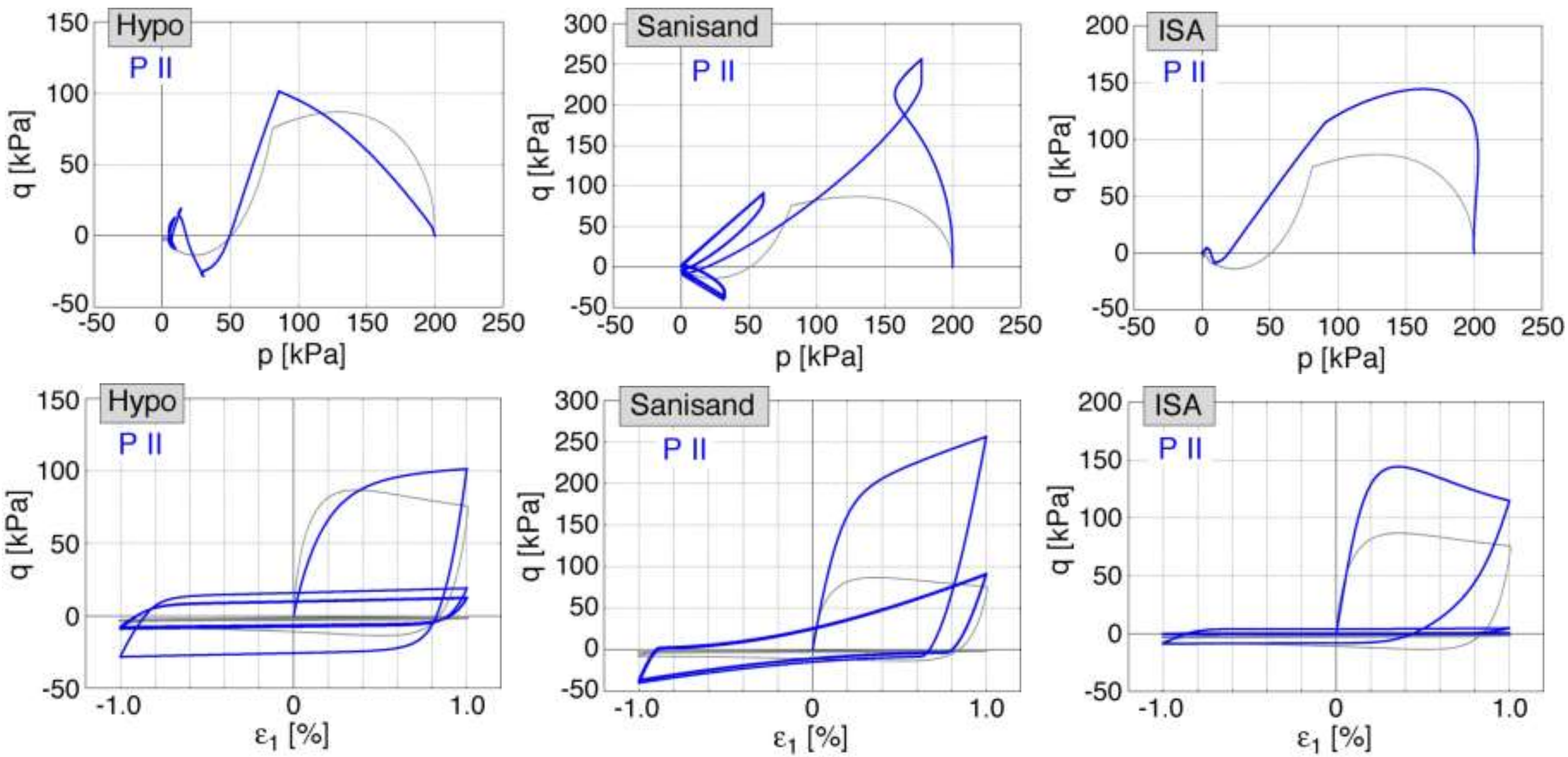


→ Test ended at p = q = 0, model prognosis either as an eight shaped stress (Hypo) or large (Sanisand) or small (ISA) „butterfly“ attractor

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Simulations of triaxial testing

Undrained conditions, isotropic initial stress,
strain cycles with relatively large amplitude $\varepsilon_1^{ampl} = 1 \cdot 10^{-2}$, loose ($I_{D0}$ = 0,26)

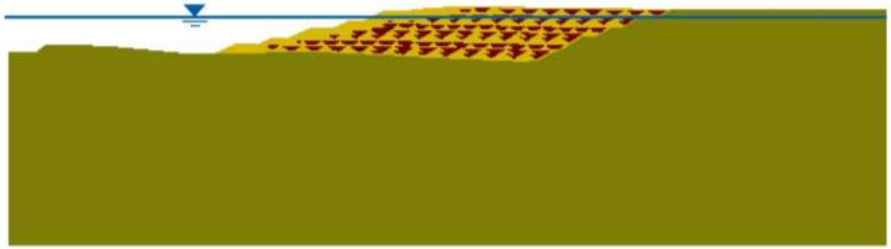


→ Test ended at p = q = 0, model prognosis as an eight shaped stress path (Hypo), „butterfly“ (Sanisand) or approx. in the stress point p = q = 0 (ISA)

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Example of a dynamic analysis on a slope in a residual lake after the lignite mining operations

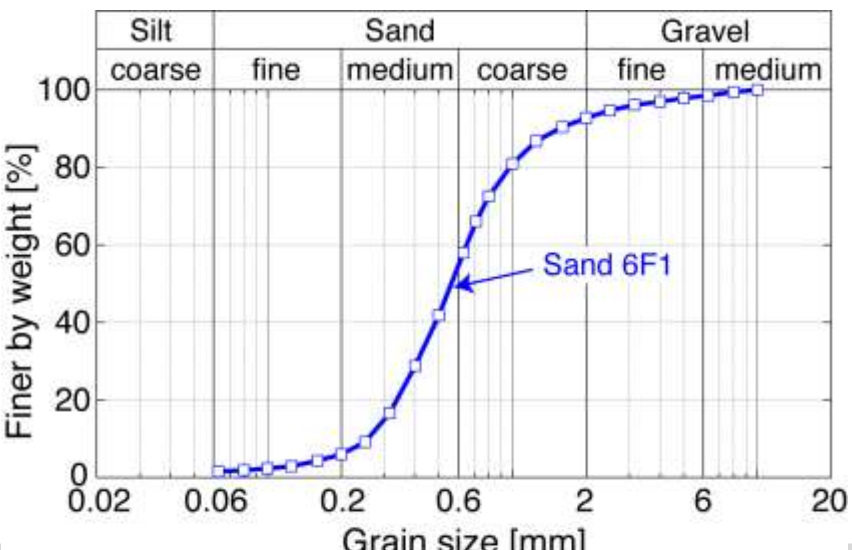
- Creation of a slope profile consisting of cohesive and non cohesive materials
- Aprox. undrained conditions under the water table especially during seismic events (conservative assumption)



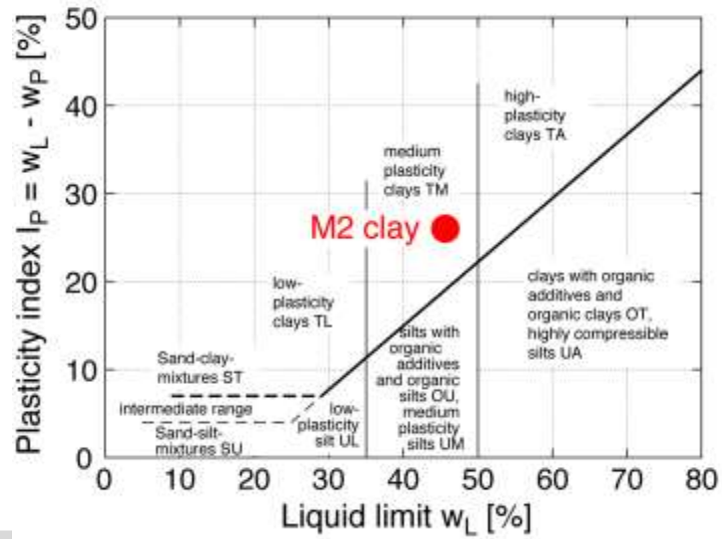
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Materials (examples)

- Sand

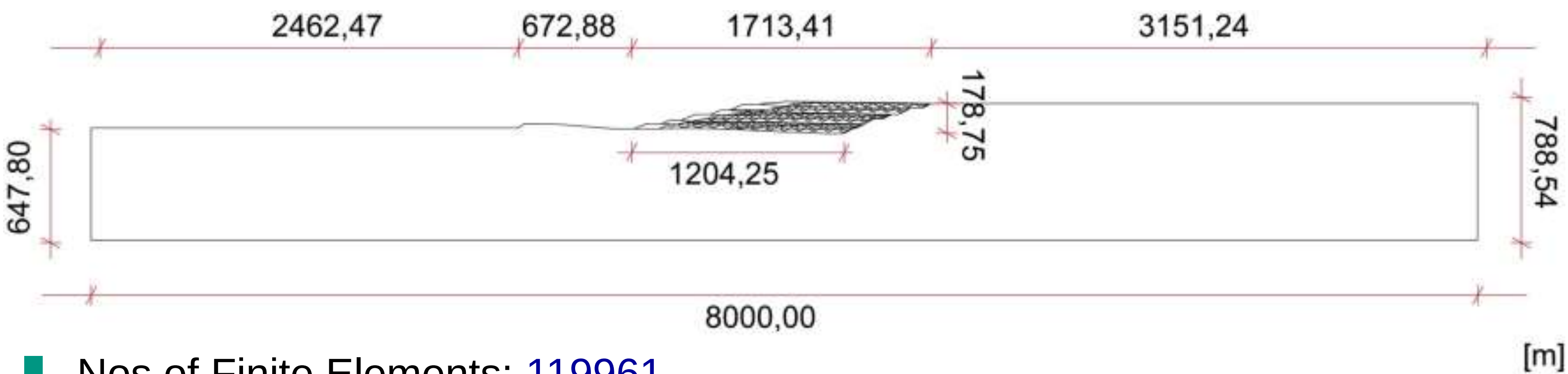


- M2 -Clay



14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Slope simulation model

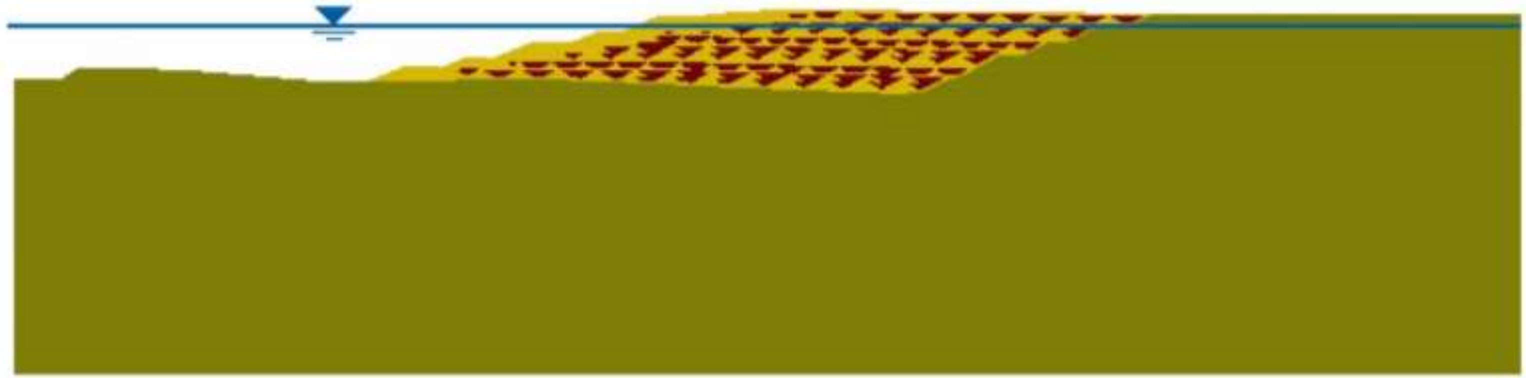


- Nos of Finite Elements: 119961
- Element type: CPE4R und CPE3 (ABAQUS)
- Element size: in the slope 2x2 m, beneath the slope up to 7x7 m, and close to the side boundaries up to 50x50 m
- Stress dependent initial void ratio distribution in the slope (I_{D0}=0,3) and in the underlain undisturbed soil (I_{D0}=0,7)

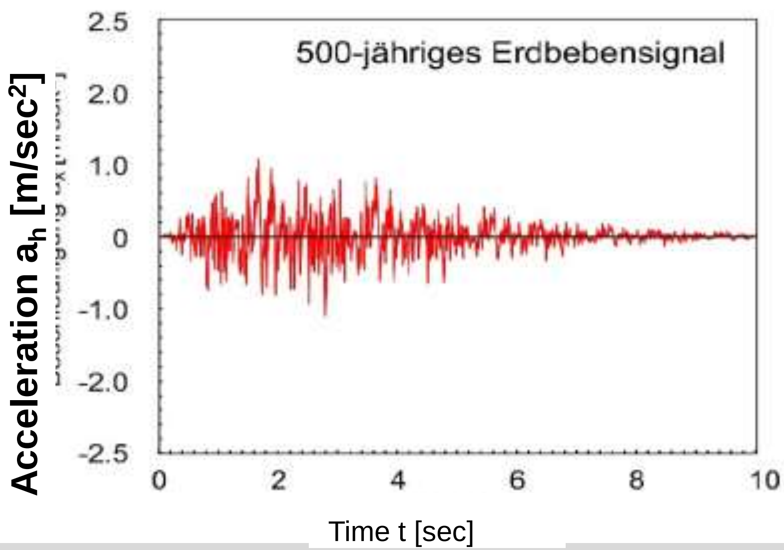
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

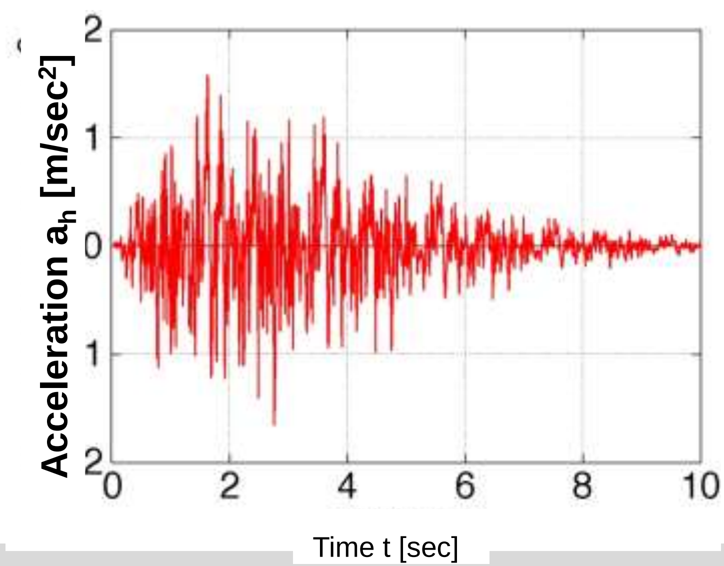
Deformation behaviour of one slope under seismic excitation: FE-Simulation results

Model



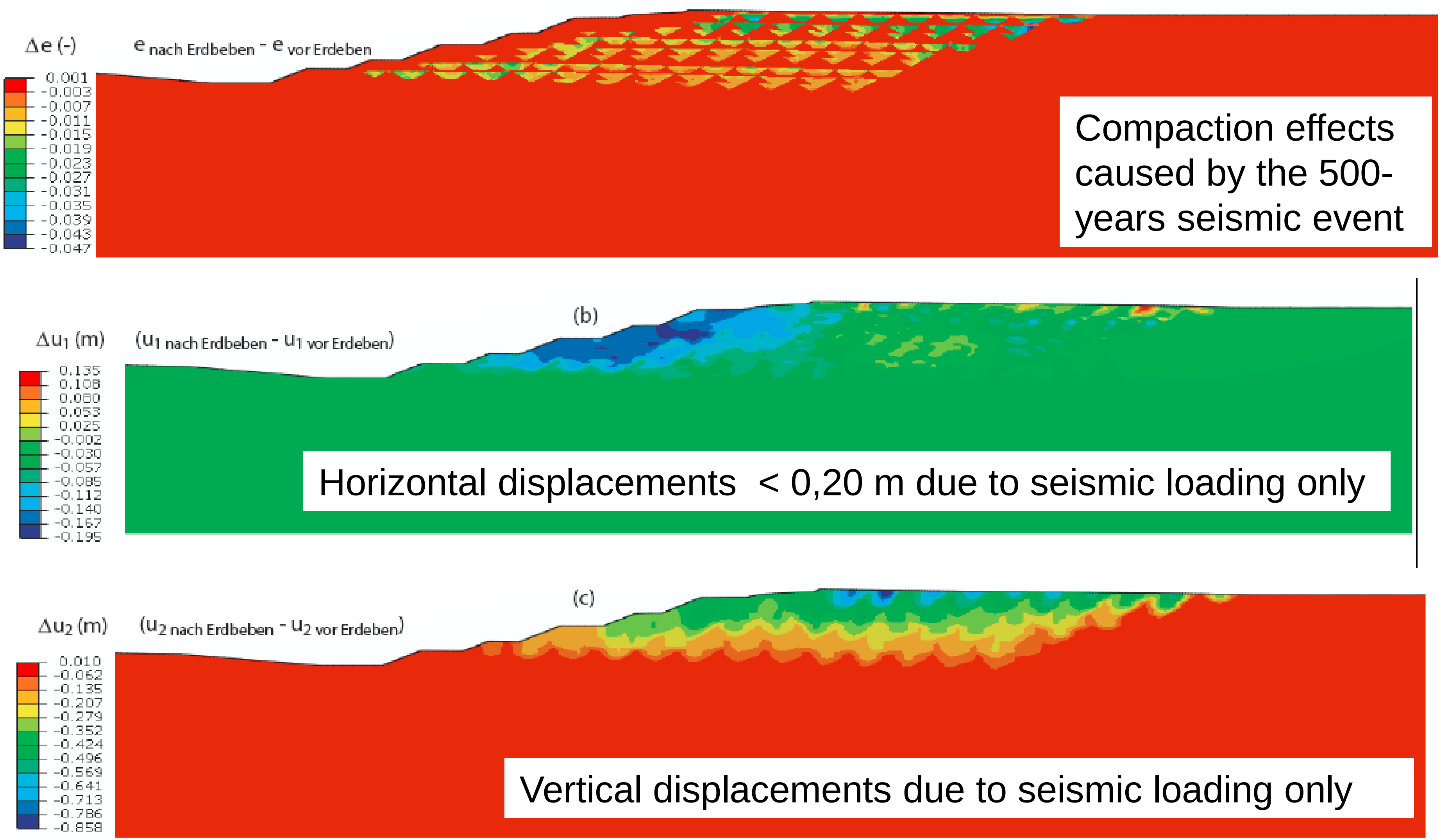
Synthesized seismic accerelogramms for the lower Rhine river basin based on the recurrence return period of 500-years (without water) and of 2500-years (WL 10 m below GL) with the magnitude M 6 on the basis of the FE – model (rock surface)



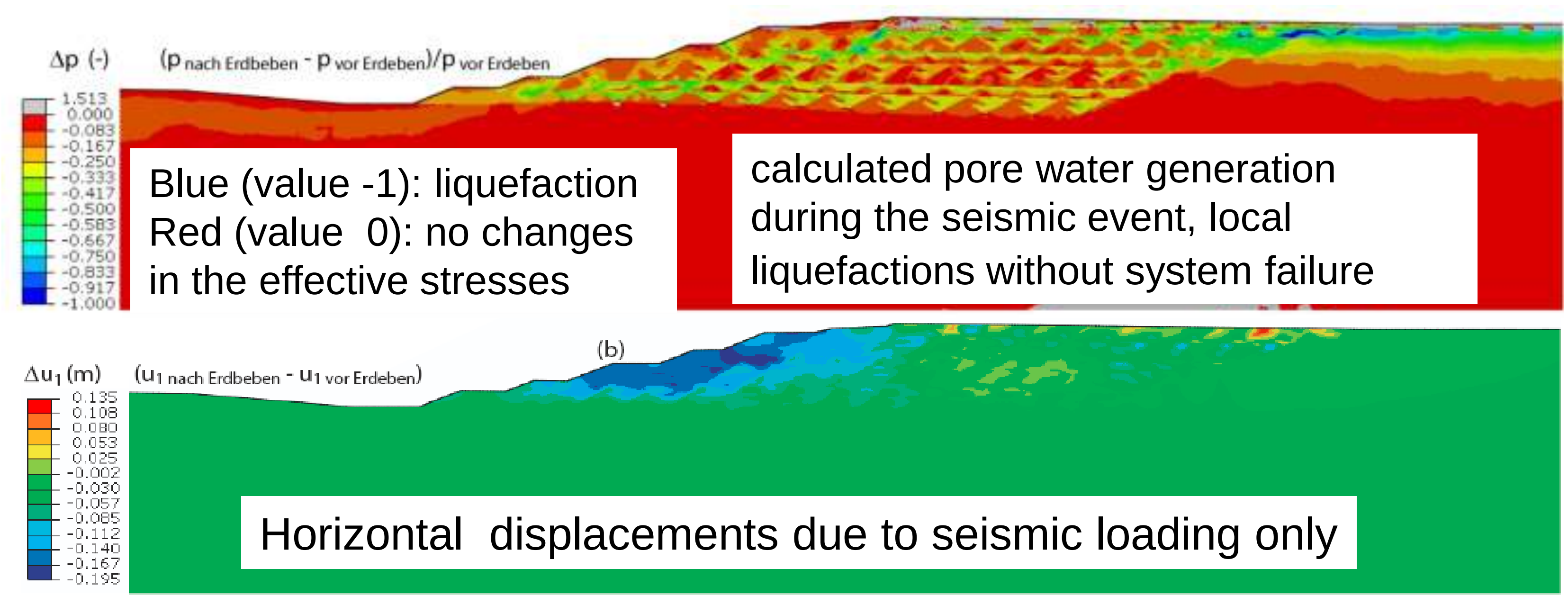


Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

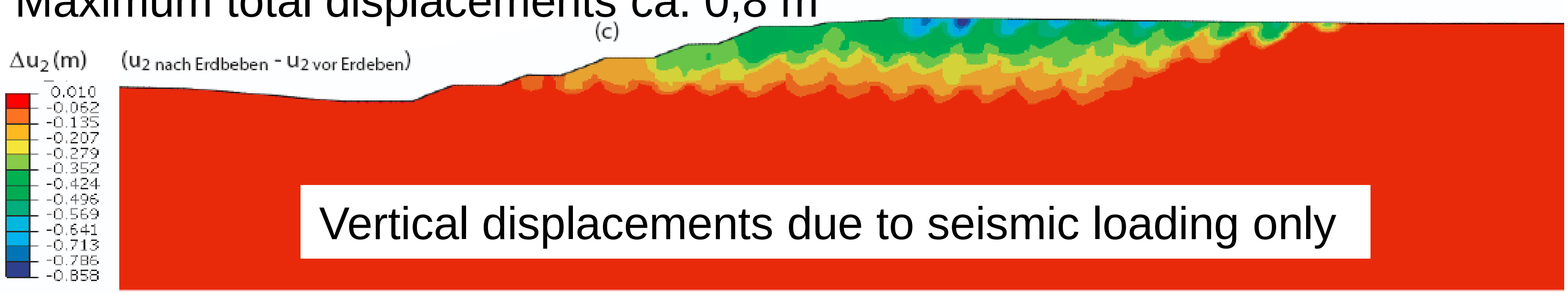
Deformations due to the 500-years seismic event



Deformations of a residual lake slope under a 2500-years excitation: Results of the FE-Simulations



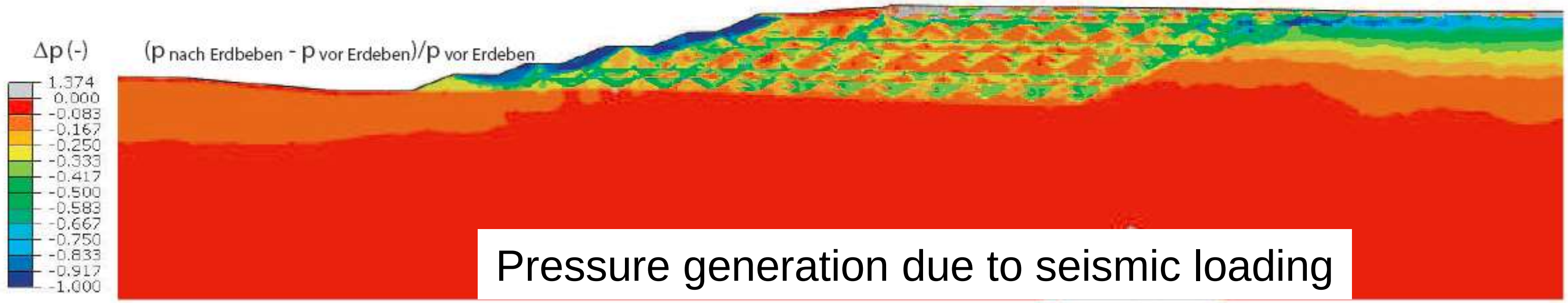
Maximum total displacements ca. 0,8 m

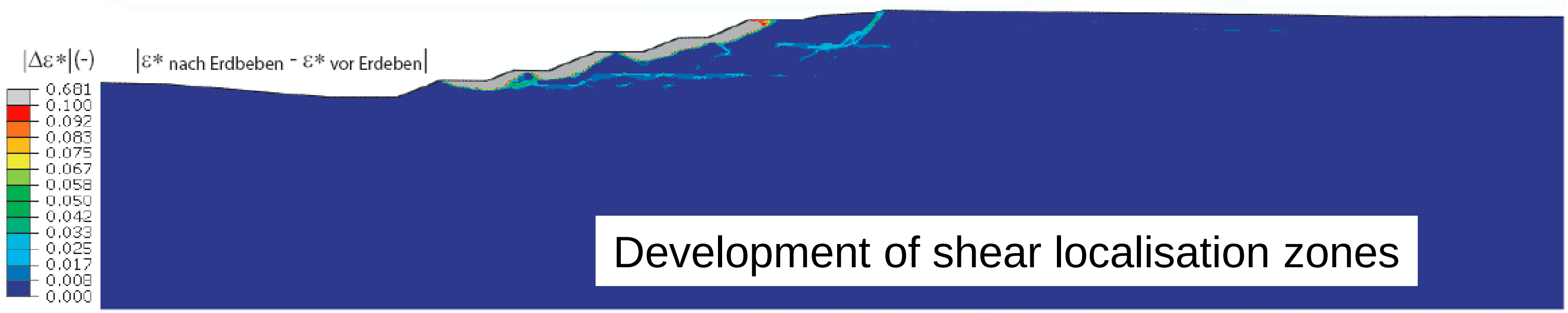


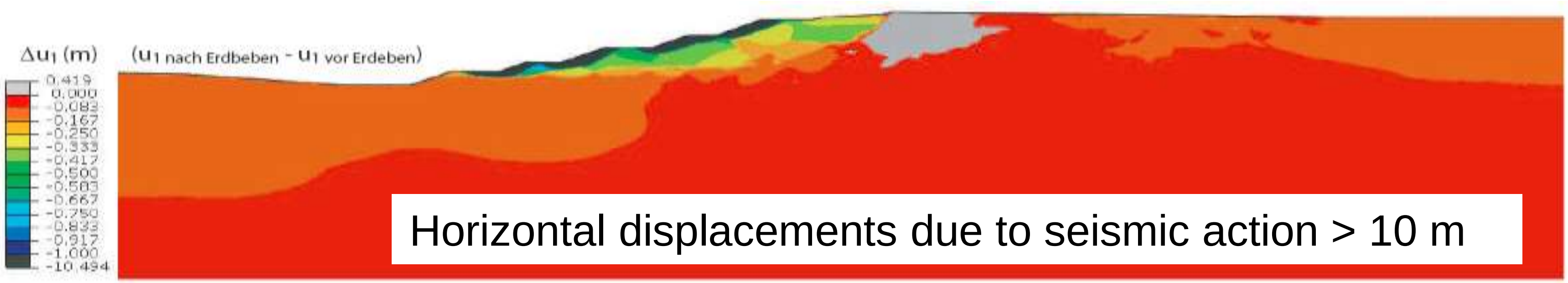
14 -17 December 2016, Hong Kong International Geotechnics Symposium cum International Meeting of CSRME 14th Biennial National Congress (IGSIM)
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

FE- Simulations for a seismic event of longer recurrence periods than 2500-years

Maximum acceleration on the underlain rock 2,1 m/s^2 (PGA ca. 0,5g)



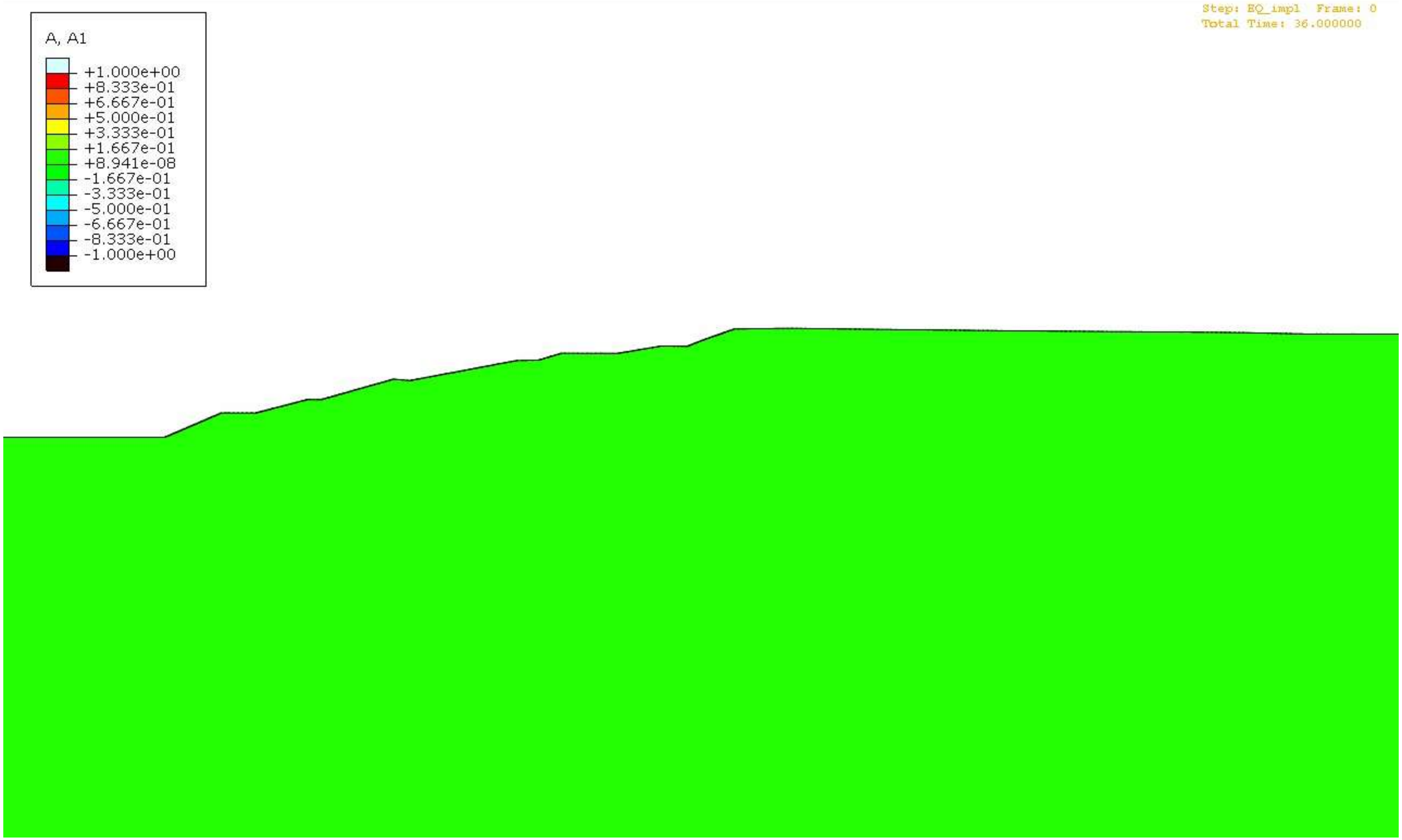




Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Deformations of a residual lake slope under a 2500-years recurence seismic excitation: FE-Simulations

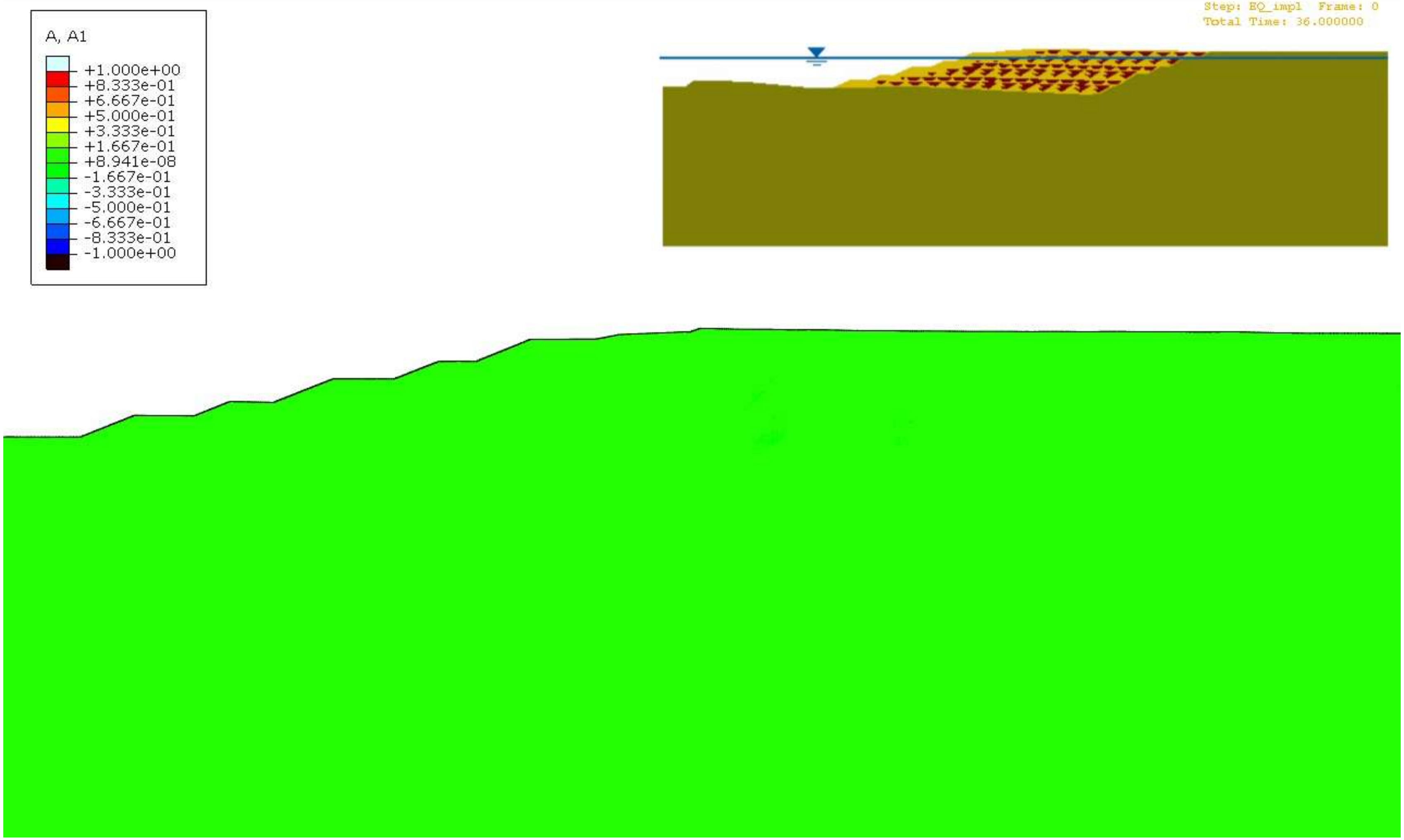
Slope consisting of sandy material only



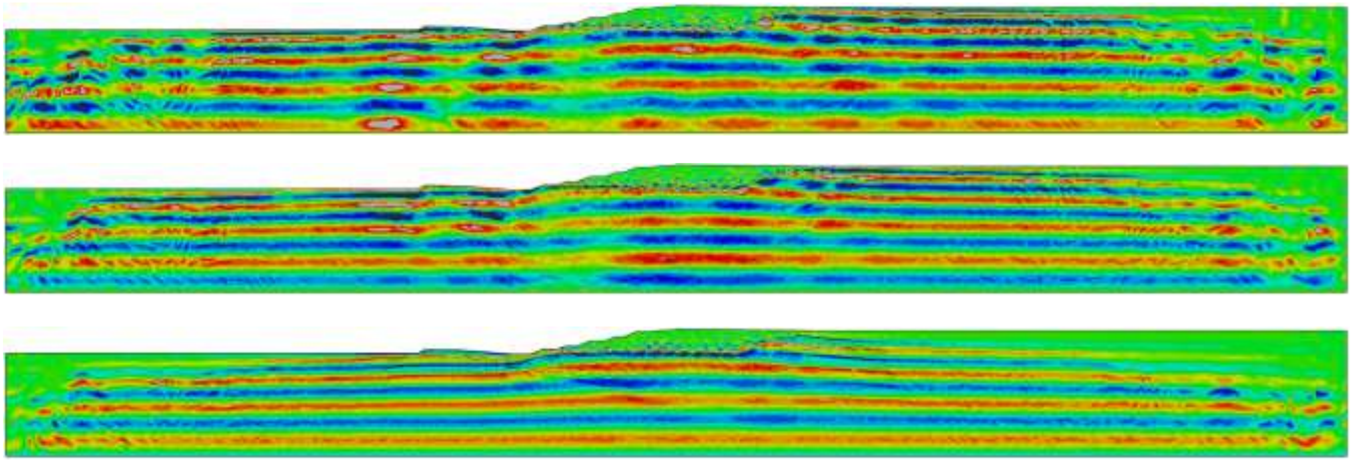
Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Deformations of a residual lake slope under a 2500-years recurence seismic excitation: FE-Simulations

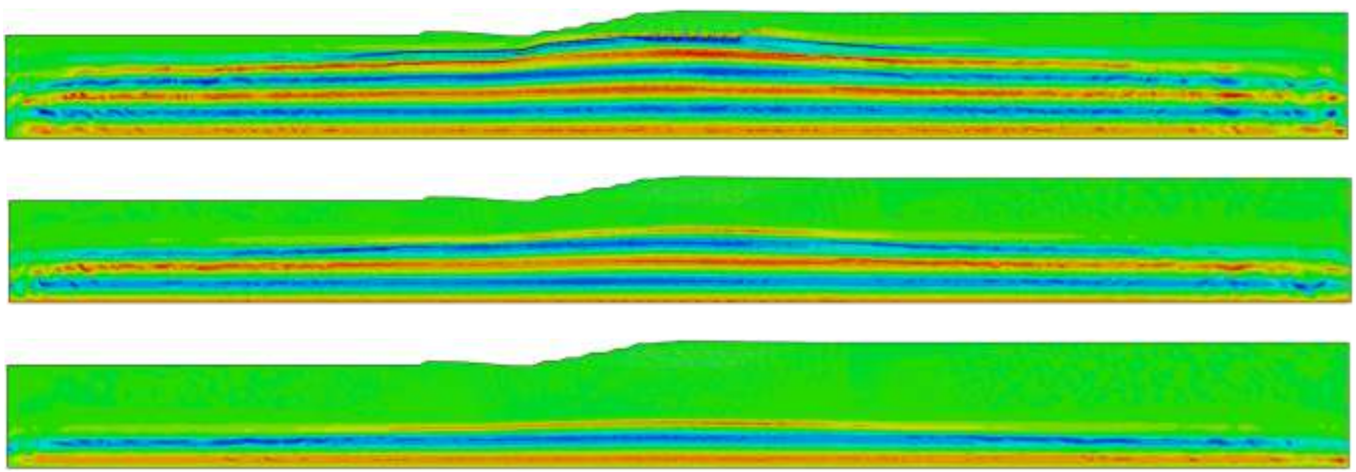
Slope with a soil profile consisting of clayey partitions and sandy material)



Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany



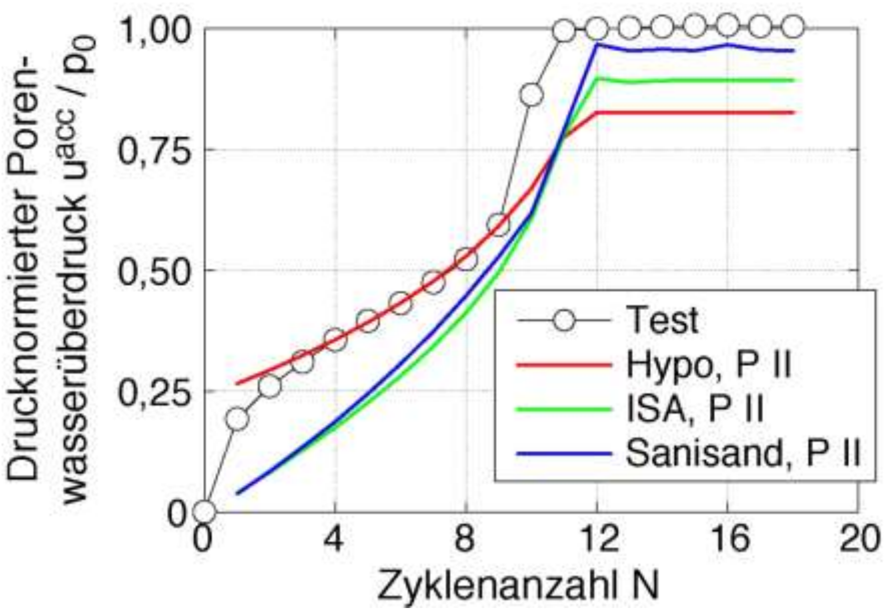
Thank you very much for your attention!

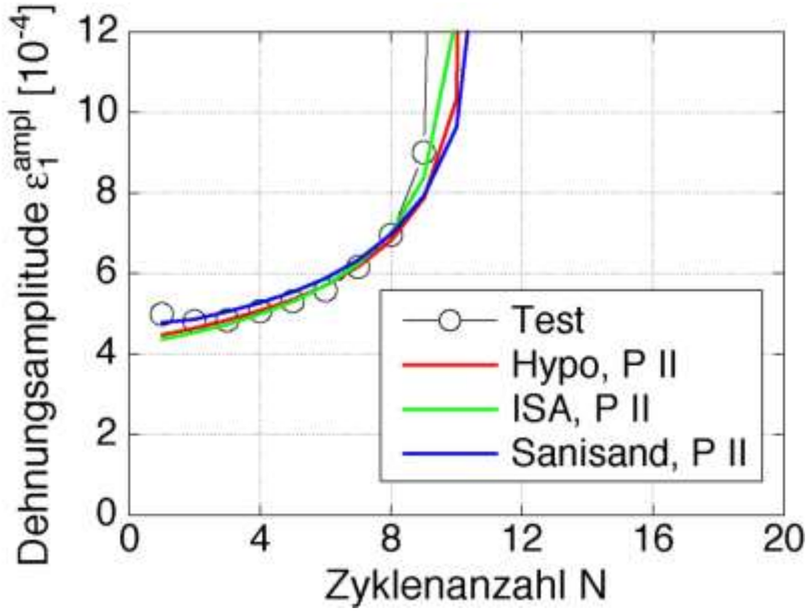


Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Simulationen: Zyklische Belastung

Undränierte Bedingungen, isotrope Anfangsspannung, Spannungszyklen, mitteldichte Lagerung (I_{D0} = 0,67)



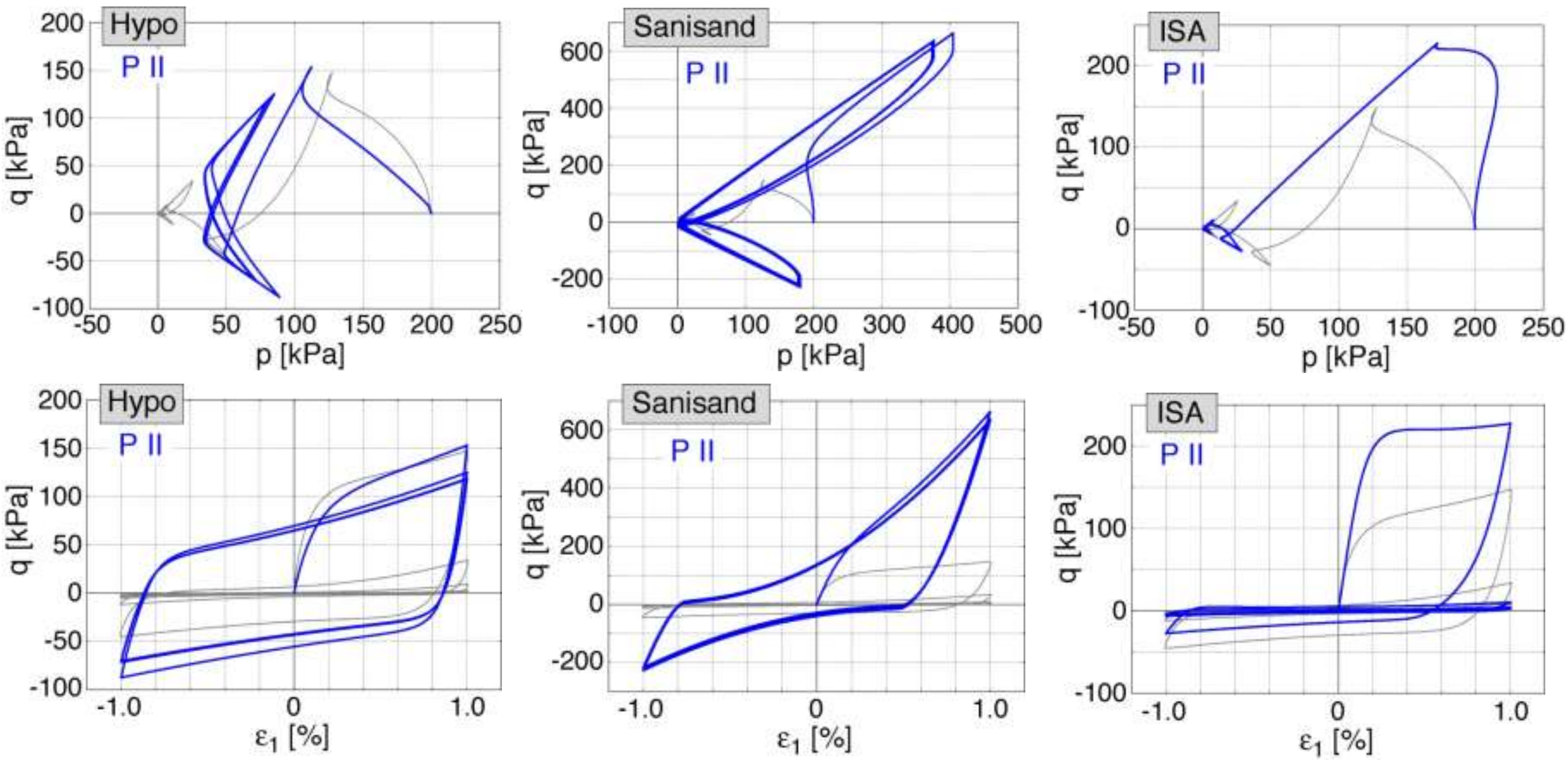


→ gute Reproduktion der gemessenen Relaxation der effektiven Spannung (= Porenwasserdruckanstieg) und der Amplitude der axialen Dehnung ε_1^{ampl}, d.h. Steifigkeit in den Zyklen

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Simulationen: Zyklische Belastung

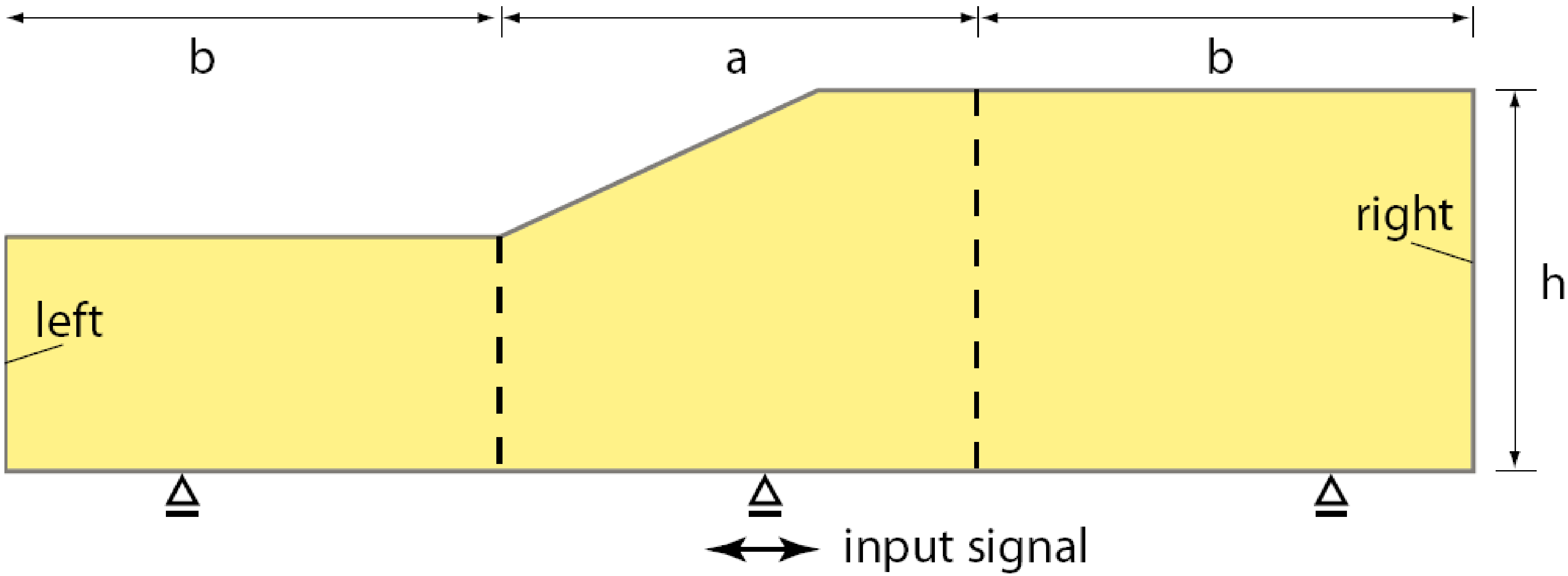
Undränierte Bedingungen, isotrope Anfangsspannung,
Dehnungszyklen mit relativ großer Amplitude $\varepsilon_1^{ampl} = 1 \cdot 10^{-2}$, mitteldicht ($I_{D0} = 0{,}66$)



→ Versuch endet bei p = q = 0, Modellprognosen in achtförmigem Pfad (Hypo) bzw. großem (Sanisand) oder sehr kleinem (ISA) „Schmetterling"

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Wahl der Modellgröße



Auf welche Kriterien ist bei der Modellgröße zu achten?

- Simulationszeit t_s < Reflexionszeit t_r einer Welle bis zum Zentrum des Gebietes:
- $t_r = (h + a/2 + 2b)/c$, wobei c die Wellengeschwindigkeit ist
- Bei nicht linearen Stoffbeziehungen mittlere Geschwindigkeit $c^* = h/t_h$ an einer Säule, bei der das gleiche Material betrachtet wird und die Welle die Zeit t_h braucht, damit sie die Oberfläche erreicht.

Simulationen: Zyklische Belastung

Entwicklung eines Parametersatzes
für jedes Modell zur besseren Reproduktion der zyklischen Versuche

- Hypoplastizität mit intergranularer Dehnung:

	φ_c [°]	e_{i0}	e_{c0}	e_{d0}	h_s [MPa]	n	α	β	R	m_R	m_T	β_R	χ
I	33,1	1,212	1,054	0,677	4000	0,27	0,14	2,5	10^{-4}	5	2	0,5	6
II										2,2	1,1	0,1	5,5

- Sanisand:

	e_0	λ	ζ	M_c	M_e	m	G_0	ν	h_0	c_h	n_b	A_0	n_d	z_{max}	c_z
I	1,103	0,122	0,205	1,34	0,94	0,05	100	0,25	4,0	0,95	1,2	0,9	2,0	1,0	100
II							130		20	0,70				20	5000

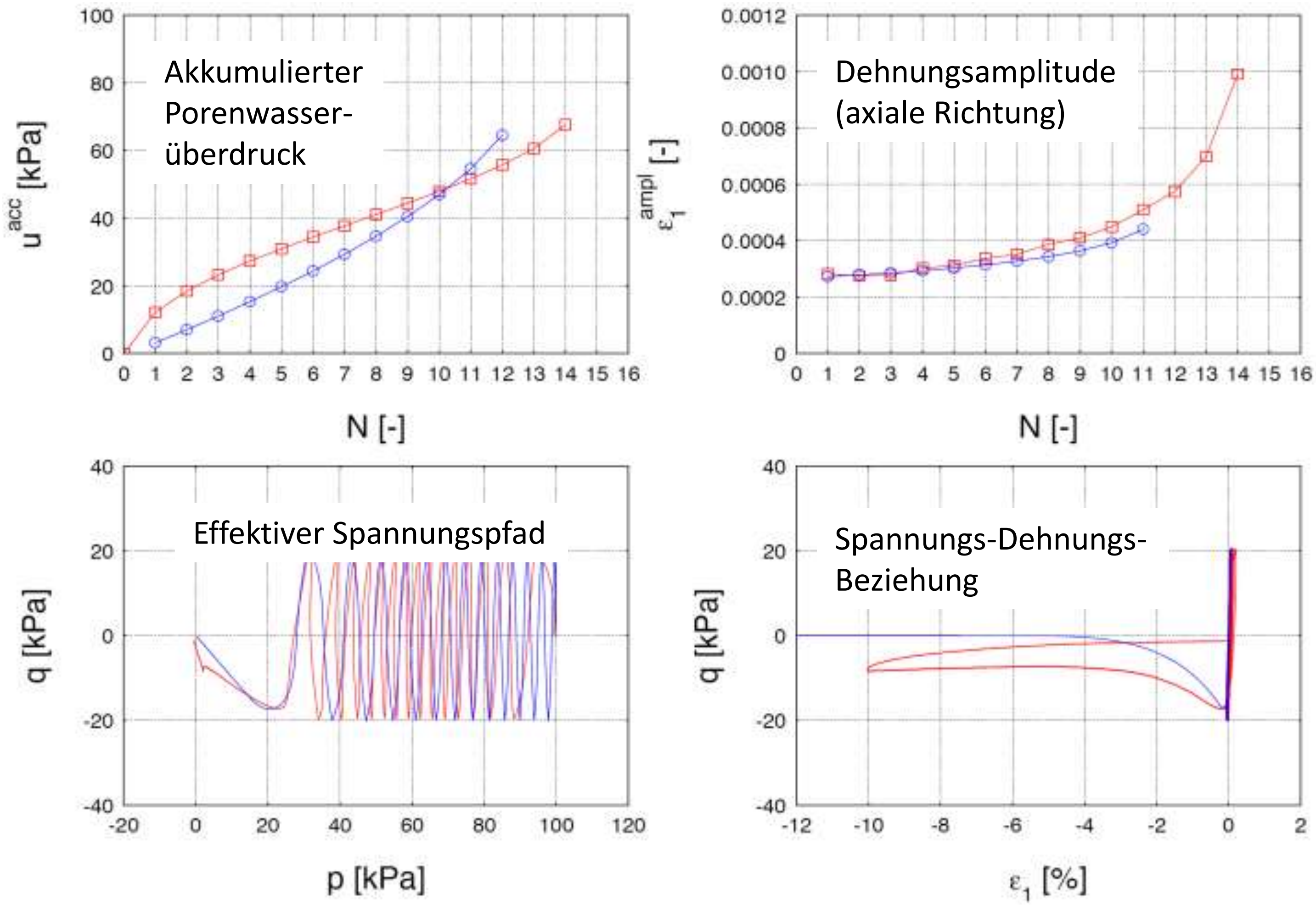
- ISA:

	e_{i0}	…	f_{b0}	R	m_R	β	χ_h	c_z	r_F
I	1,21	…	1,8	10^{-4}	5,0	1,0	7,0	5000	1,6
II					1,7	0,1	11,0	50000	

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany

Kalibration der Parameter anhand eines undränierten zyklischen Versuches am Sand Inden 6F1 mit lockerer Lagerung (I_{D0} = 0,27)

ISA-Modell (optimaler Parametersatz)



Rot = Versuch

Blau = Rechnung

Univ. Prof. Dr.-Ing. habil. Theodoros Triantafyllidis
Institute of Soil Mechanics and Rock Mechanics (IBF), Germany