HKIE Geotechnical Division: 6 November 2007

The magic of sands

David Muir Wood
University of Bristol, England

(20th Bjerrum Lecture: Oslo: November 2005)

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David Muir Wood

1949-1950	Folkestone
1950-1970	Beaconsfield
1967-1987	Cambridge
1975	Oslo
1978	Hong Kong
1986	Boulder
1987-1996	Glasgow
1995-	Bristol
2000	Minneapolis
2003	Tokyo

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The magic of sands

- Introduction: context: WAC Bennett Dam
- Particle-continuum duality
- Mohr-Coulomb model
- Elastic properties
- *Critical states*
- Severn-Trent sand
- Grading state index
- Conclusion

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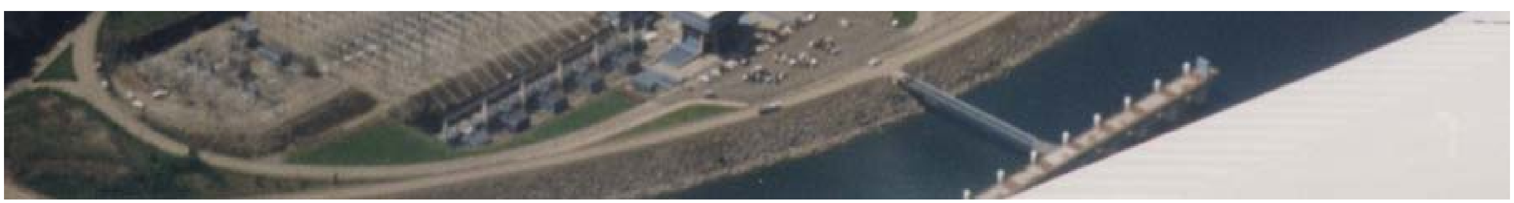

BC hydro

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WAC Bennett Dam

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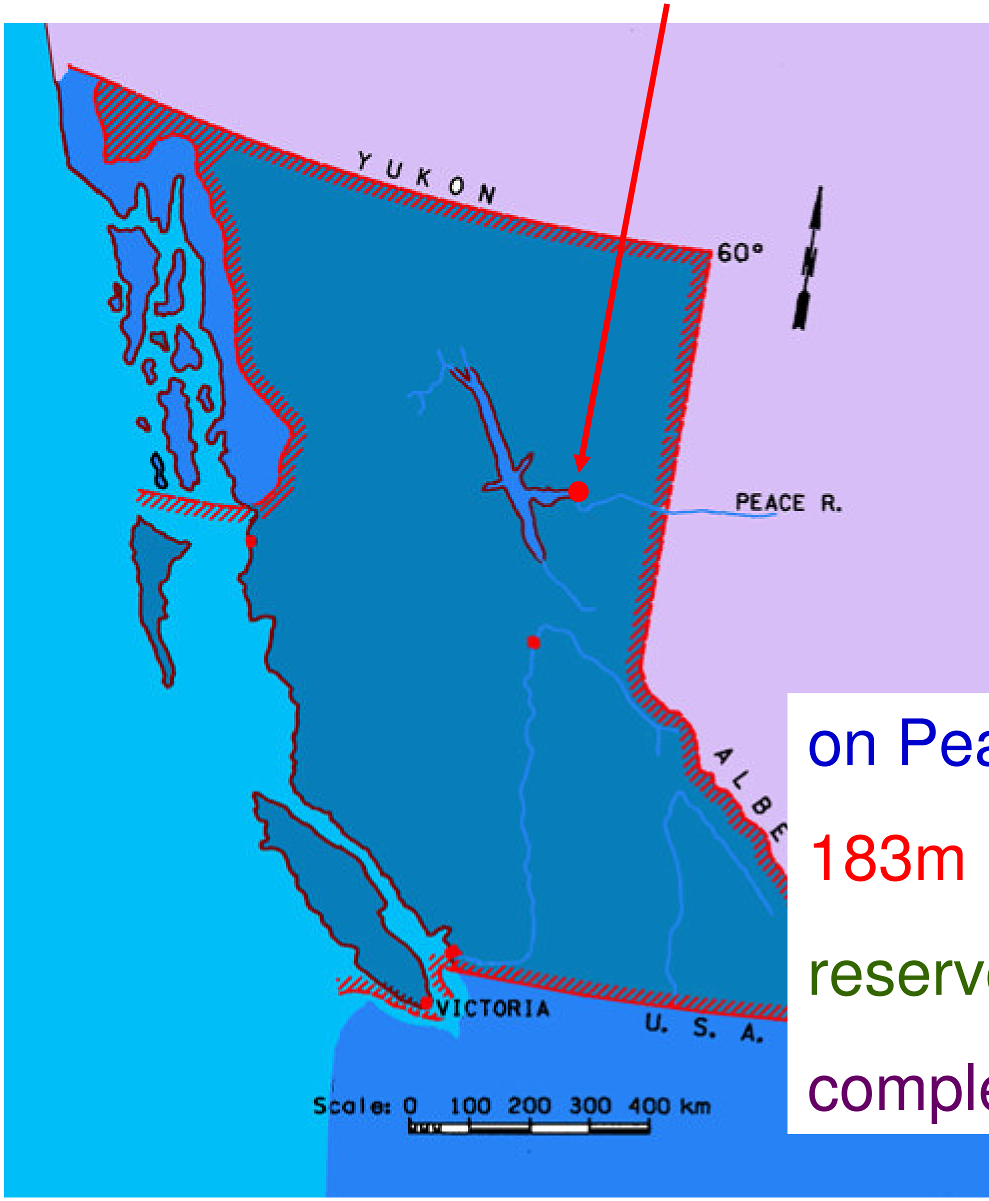

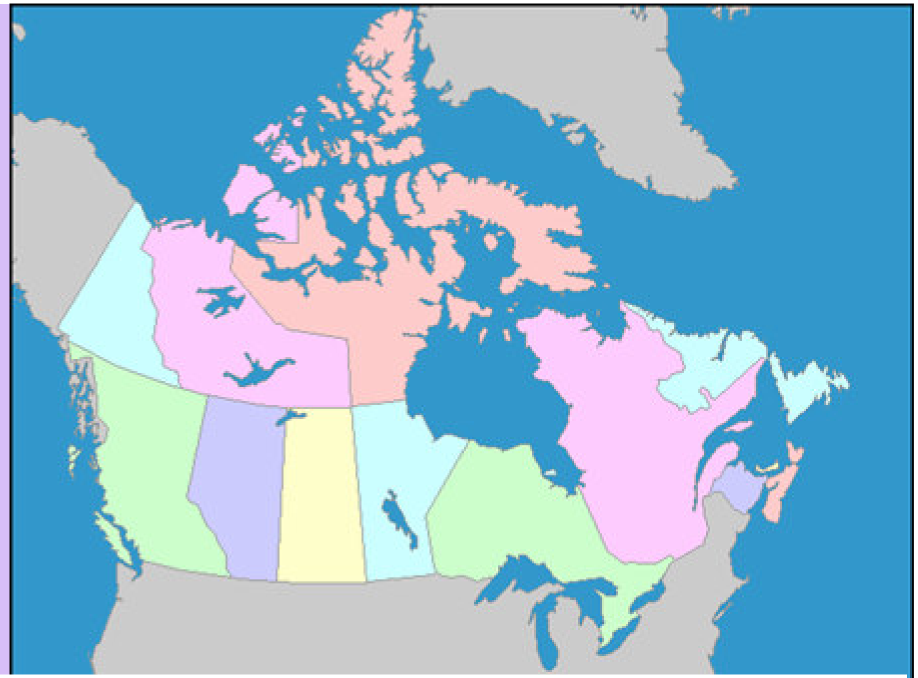

on Peace River, NE British Columbia

183m high, 2km long

reservoir $70 \times 10^9 m^3$; 2.73GW

completed 1968

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WAC Bennett Dam

BC hydro

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sinkhole 1: June 1996

WAC Bennett Dam: sinkhole incident 1996

spillway flow 3000m^3/s (> Canadian Niagara Falls)

fall in reservoir level: 2m in 7 weeks

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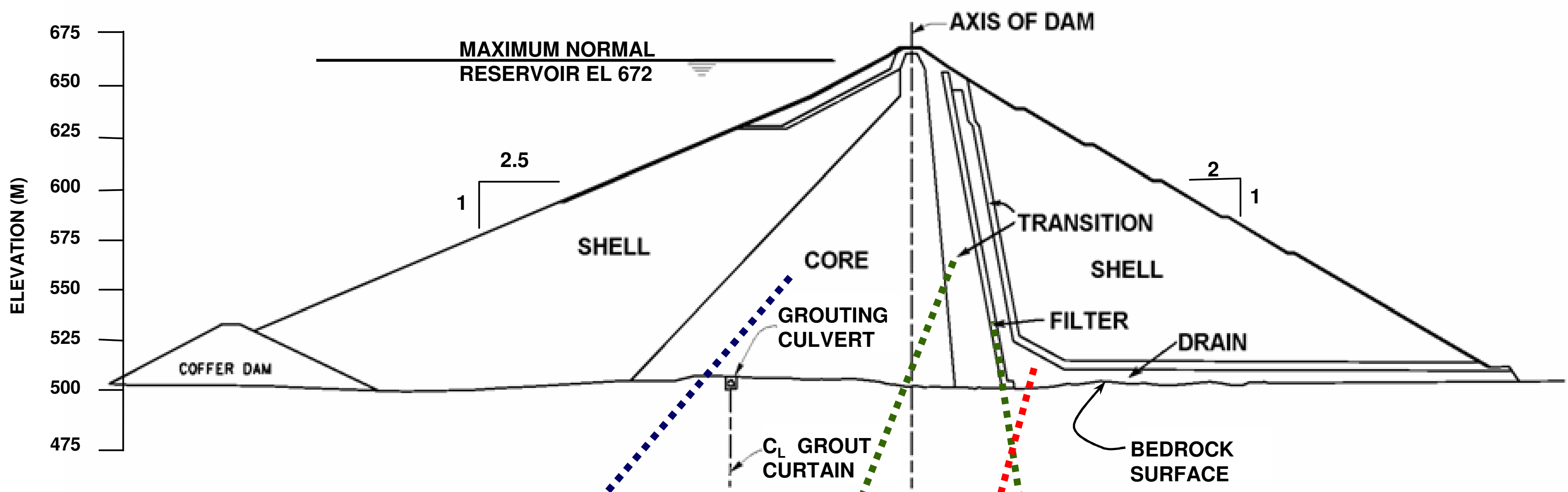
WAC Bennett Dam: cross section



zoned earthfill dam

blended 'till-like' core

well-graded transition and filter

high capacity drain

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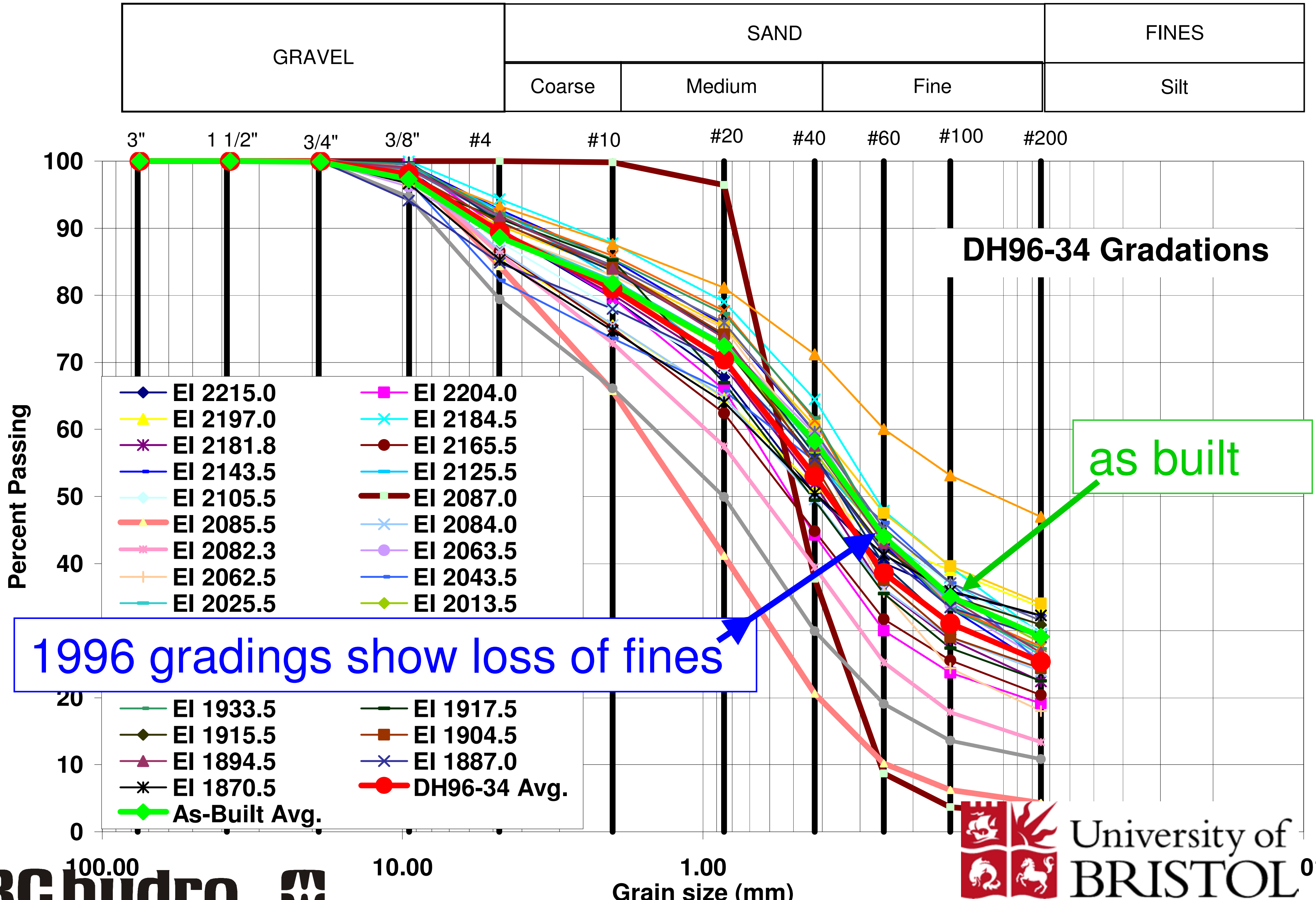
Core material (Sinkhole 1)



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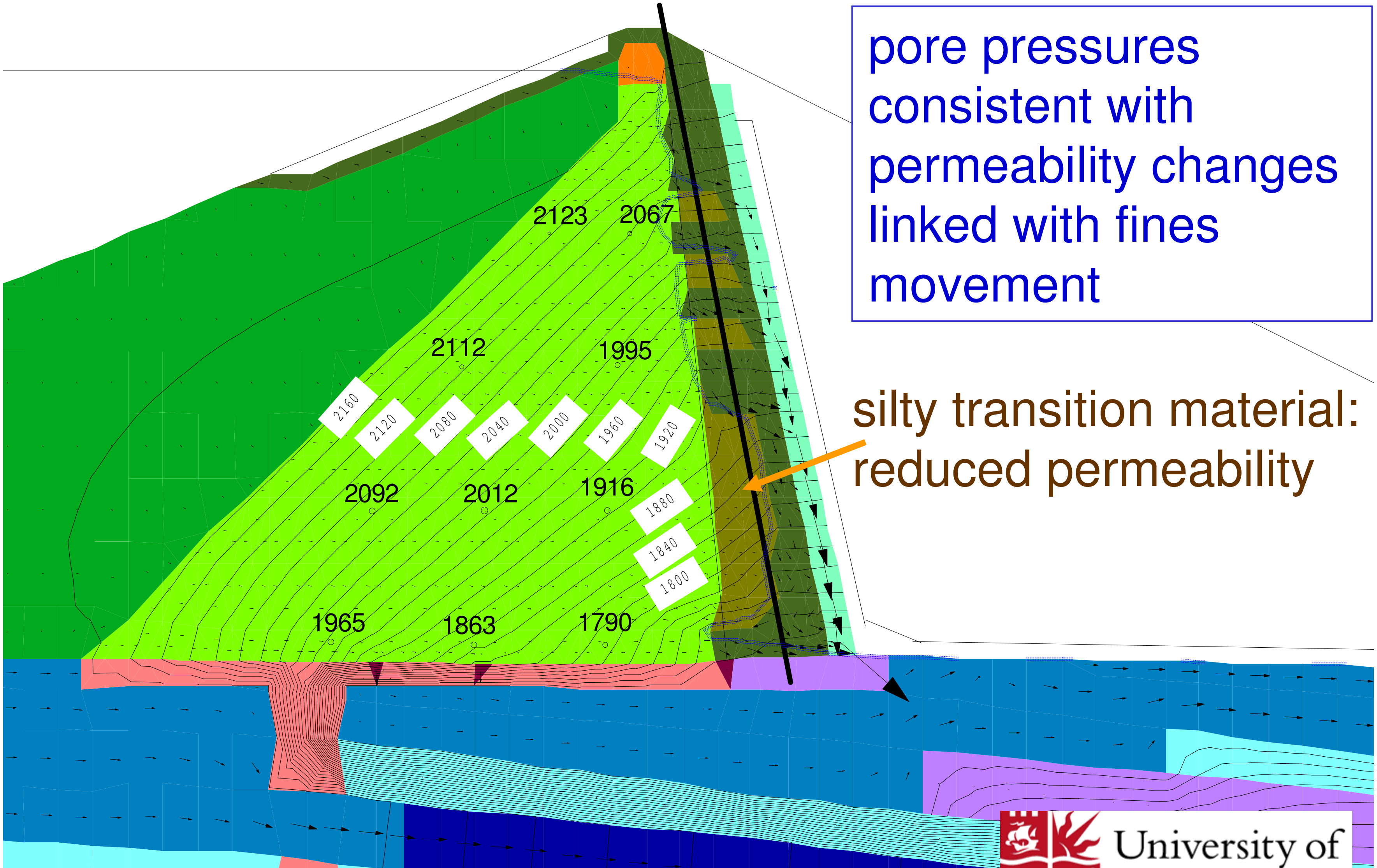
Canyon section: 2003 seepage model



pore pressures consistent with permeability changes linked with fines movement

silty transition material: reduced permeability

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WAC Bennett Dam: statement of problem

non-plastic material with changing granulometry and density

- what are consequences for mechanical response of dam?
- potential for future deformations?

need model of soil behaviour which can incorporate changes in density and grading of the soil

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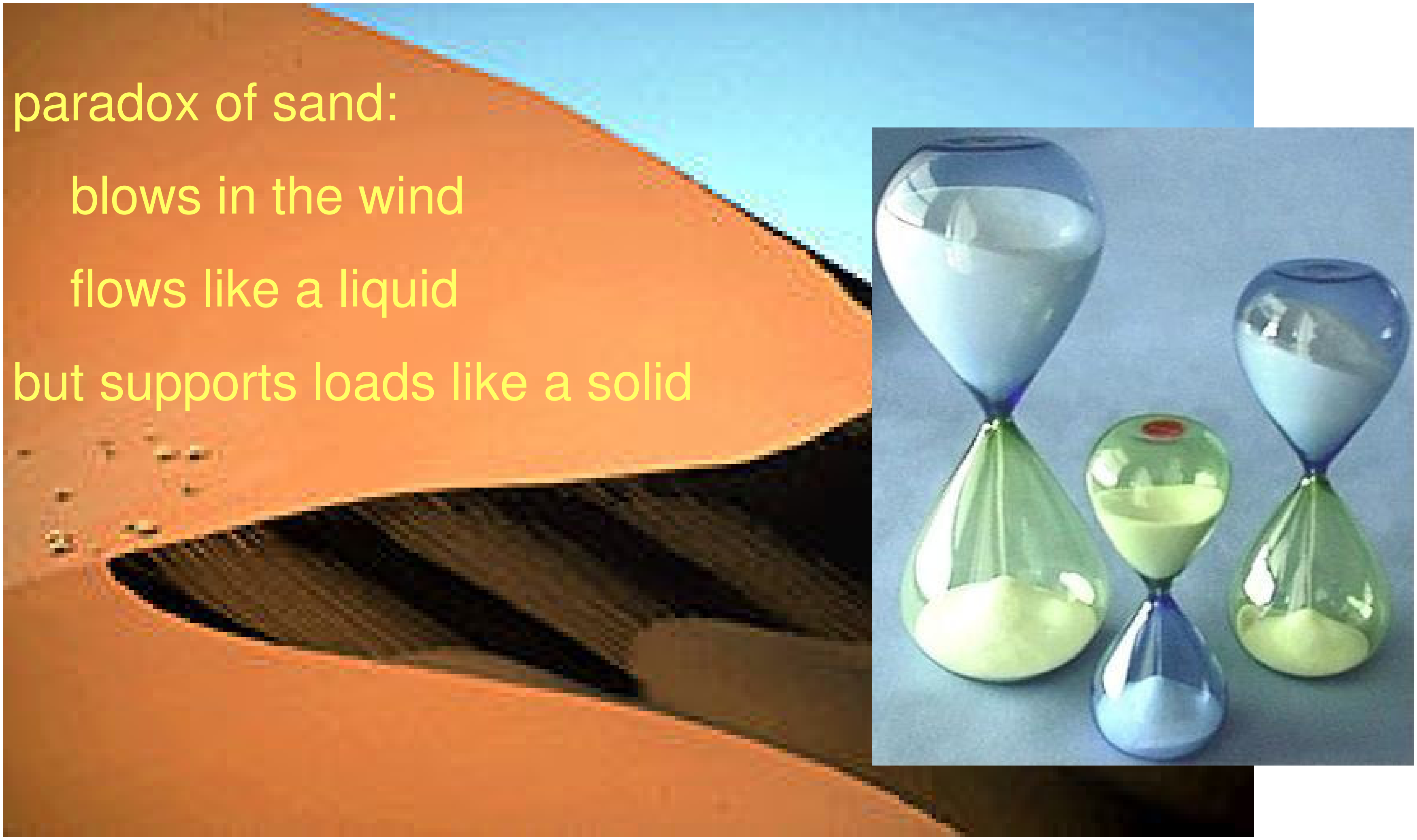
Particle-continuum duality

paradox of sand:

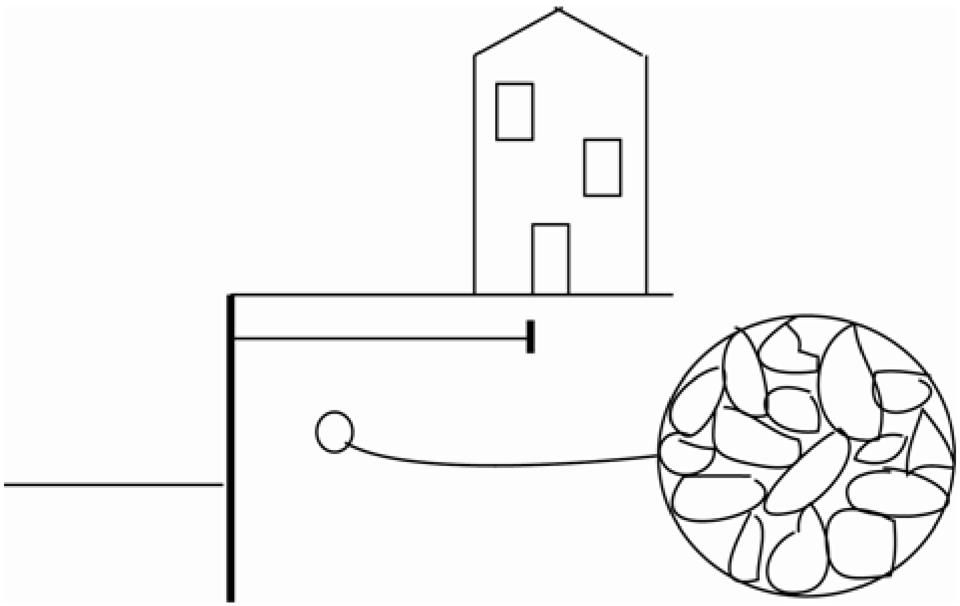
blows in the wind

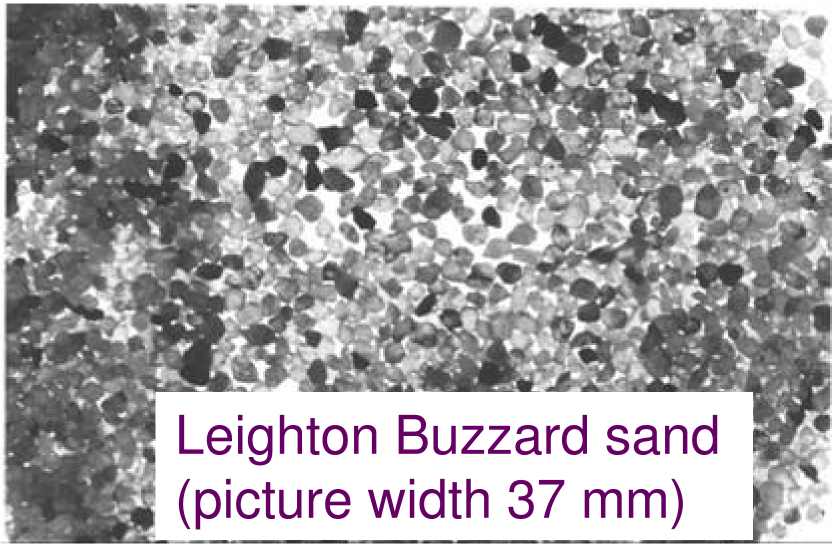
flows like a liquid

but supports loads like a solid



Particle-continuum duality





for analysis we need to treat soil as a continuum (stress, strain)

… but its properties emerge from its particulate nature

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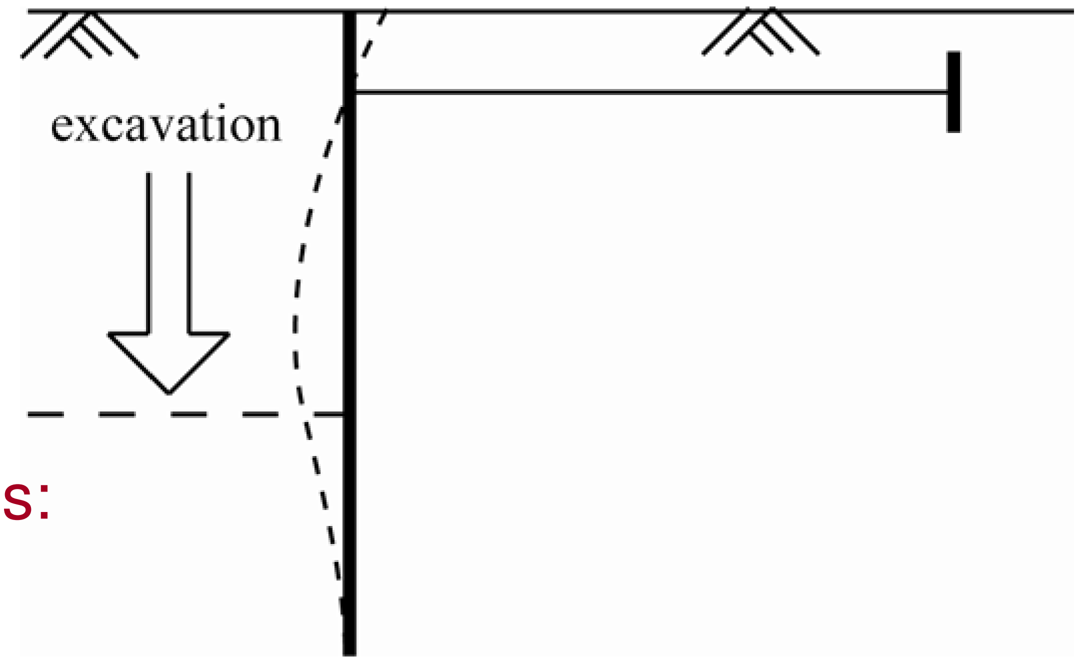
Mohr-Coulomb model

model = appropriate simplification of reality



modelling for working loads:

•serviceability limit states

•deformations of geotechnical systems

usually requires numerical analysis:

•for example, finite element, finite difference

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Mohr-Coulomb model

equilibrium

stresses

compatibility of deformations

strains

stress:strain relationship

constitutive model

eg Mohr-Coulomb

constitutive model: central element of numerical modelling

linking *change* in stress with *change* in strain

generalised evolving incremental stiffness

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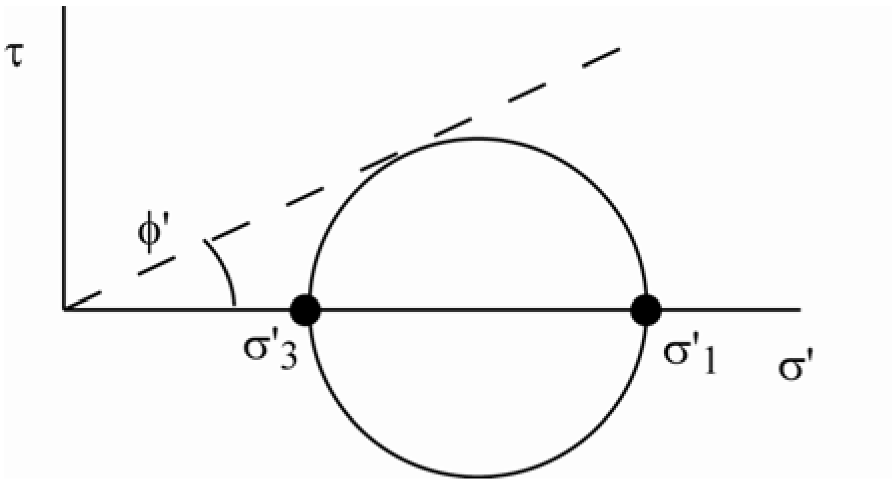
Mohr-Coulomb model: failure

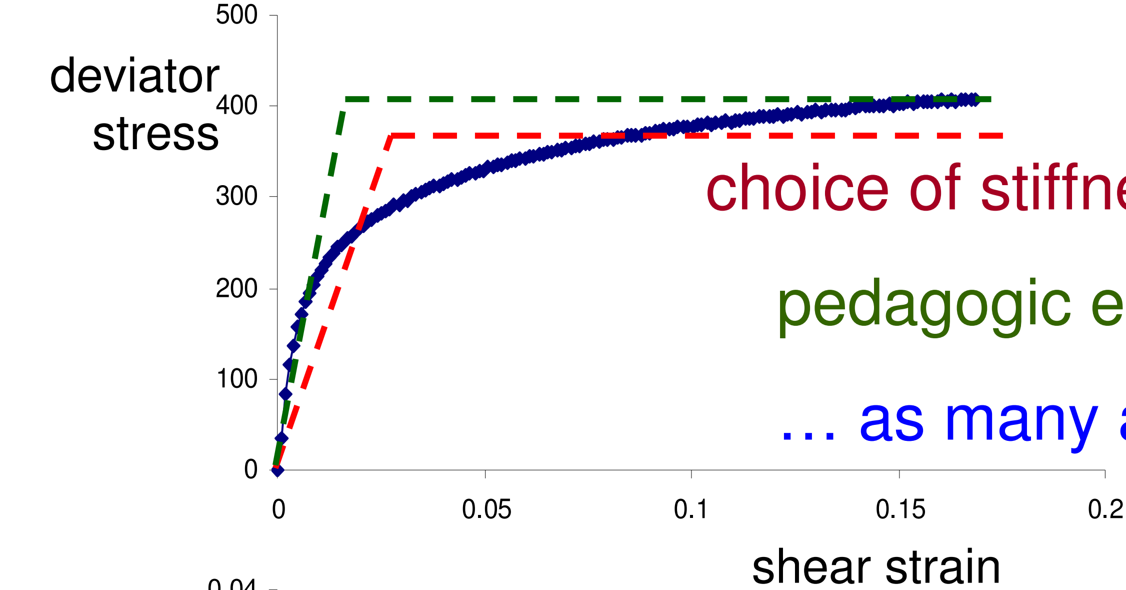
Mohr-Coulomb familiar as strength/failure model

limiting stress ratio characterised by frictional strength ϕ' (ignore cohesion)



drives laboratory and *in situ* investigation of soil properties

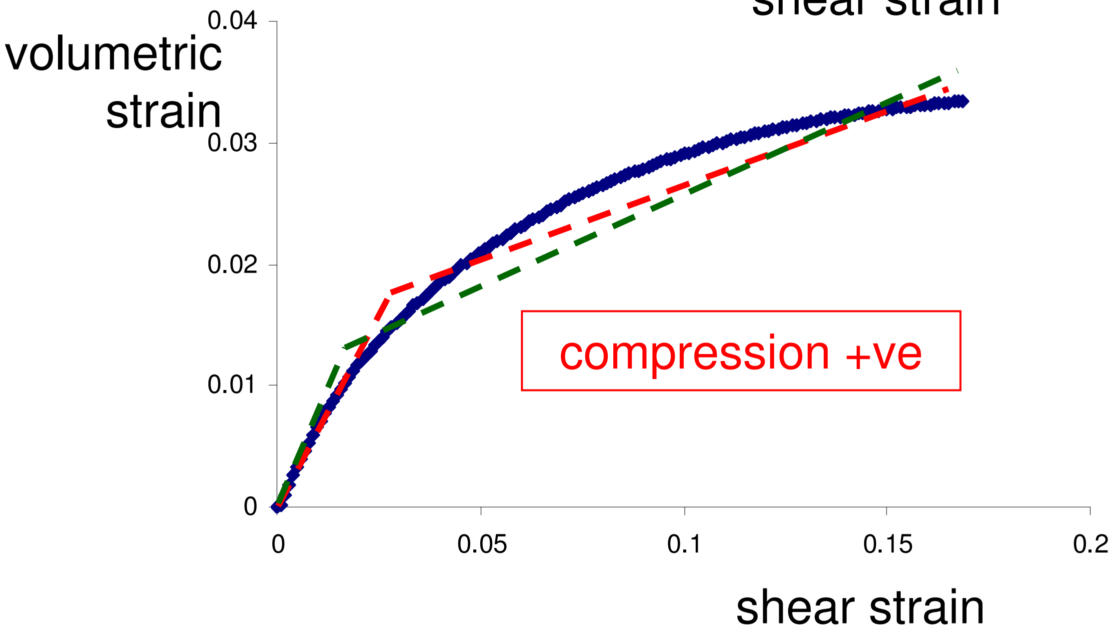
Mohr-Coulomb model: parameter selection



choice of stiffness, strength, dilatancy

pedagogic exercise

… as many answers as people!



loose Hostun sand

Benahmed, 2001

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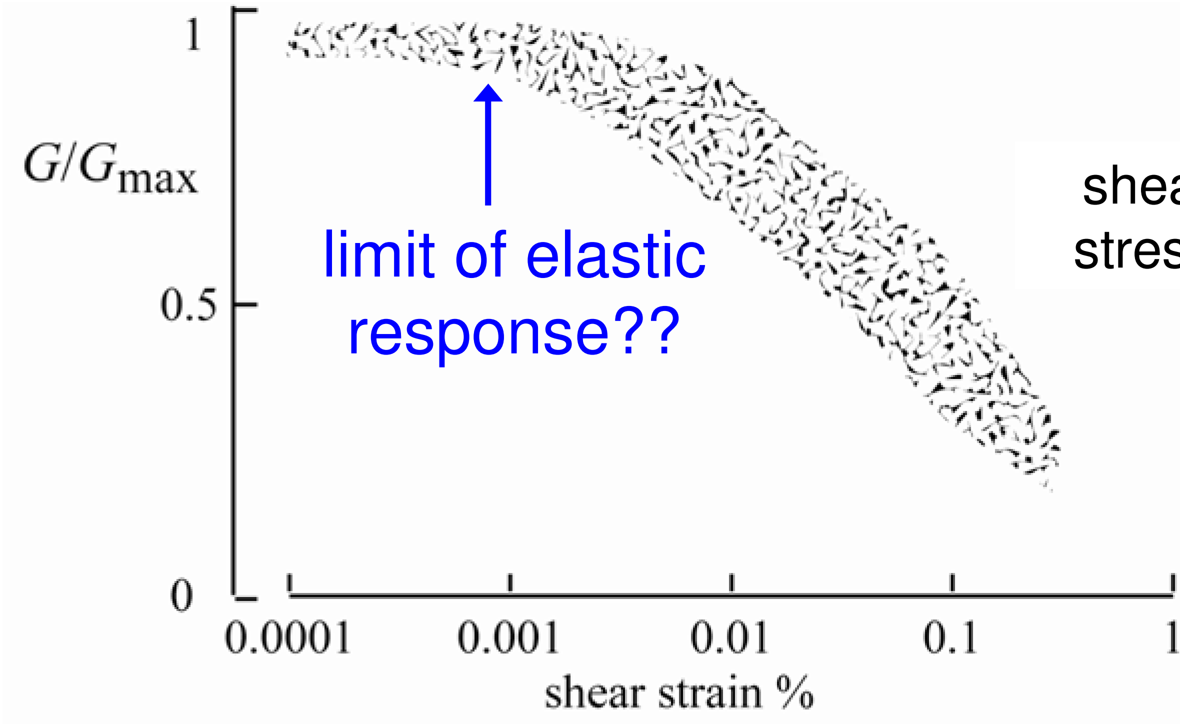
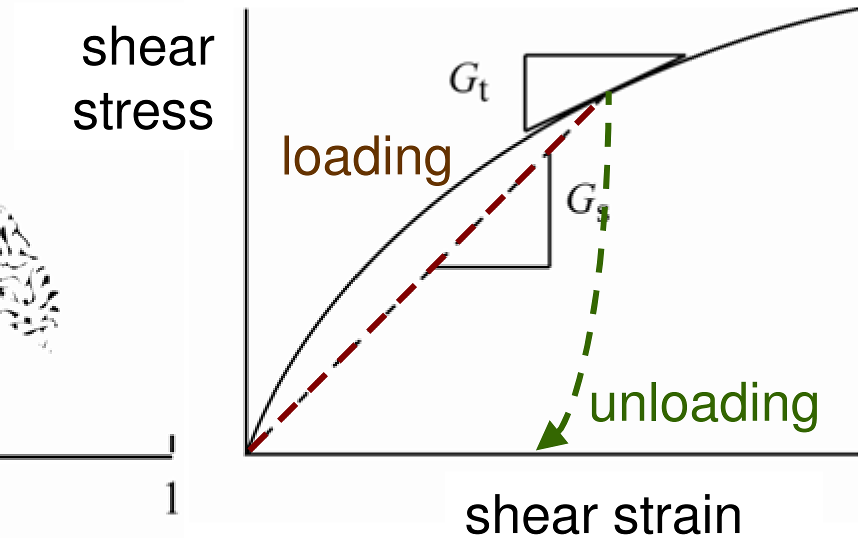
Elastic properties





stiffness does not imply *elasticity* (recoverable deformations)

fall of stiffness ⇒ *plasticity* (permanent changes on unloading)

… hence need for constitutive models

Quiou sand (LoPresti *et al.*, 1997)

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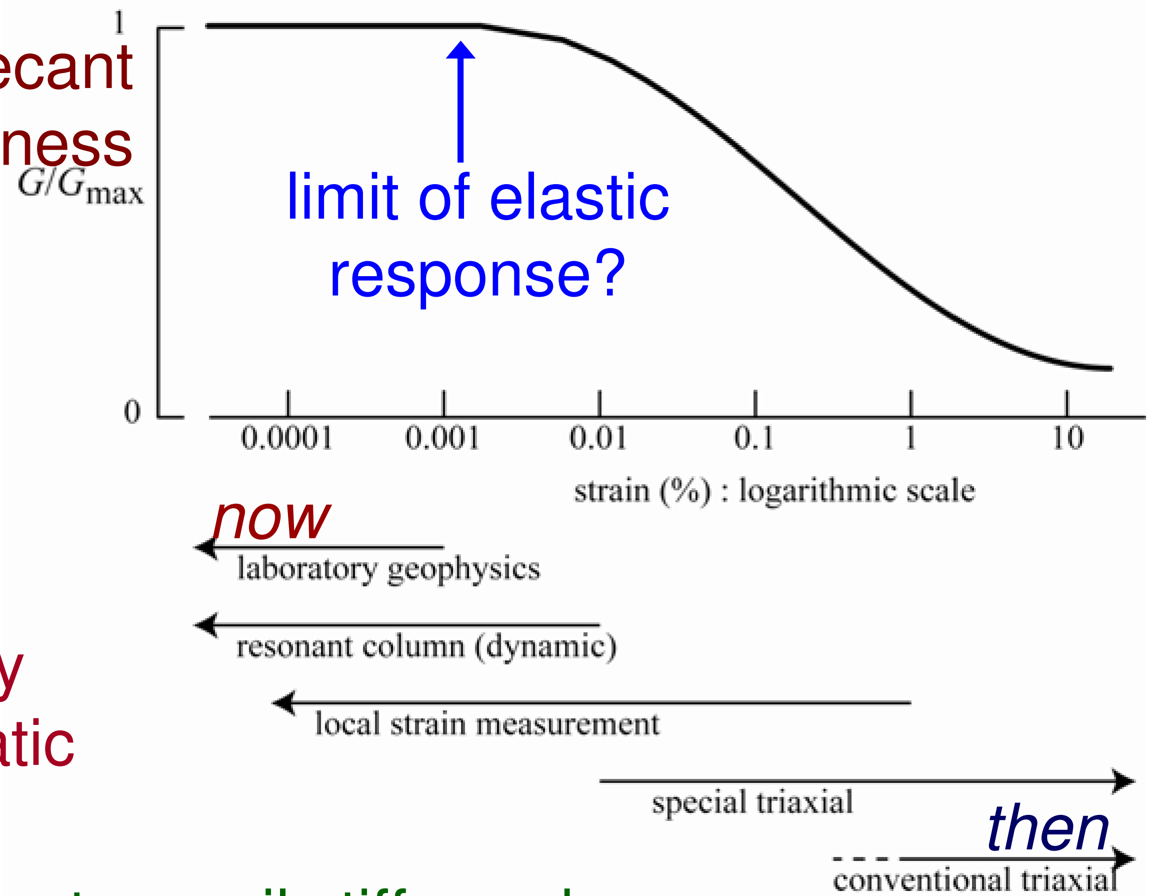
Elastic properties



then … paradox of low laboratory stiffness – high in-situ stiffness

now … consistency of dynamic and static measurements

perceptions of laboratory soil stiffness have changed as instrumentation for measurement of deformations has improved

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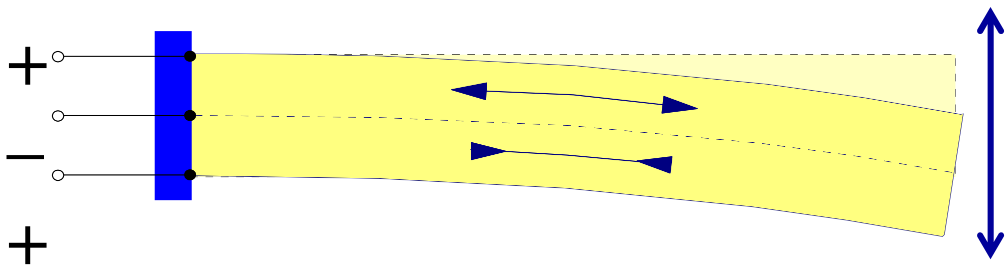
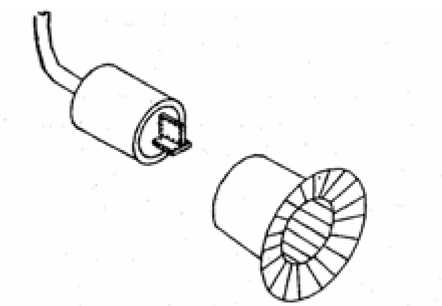
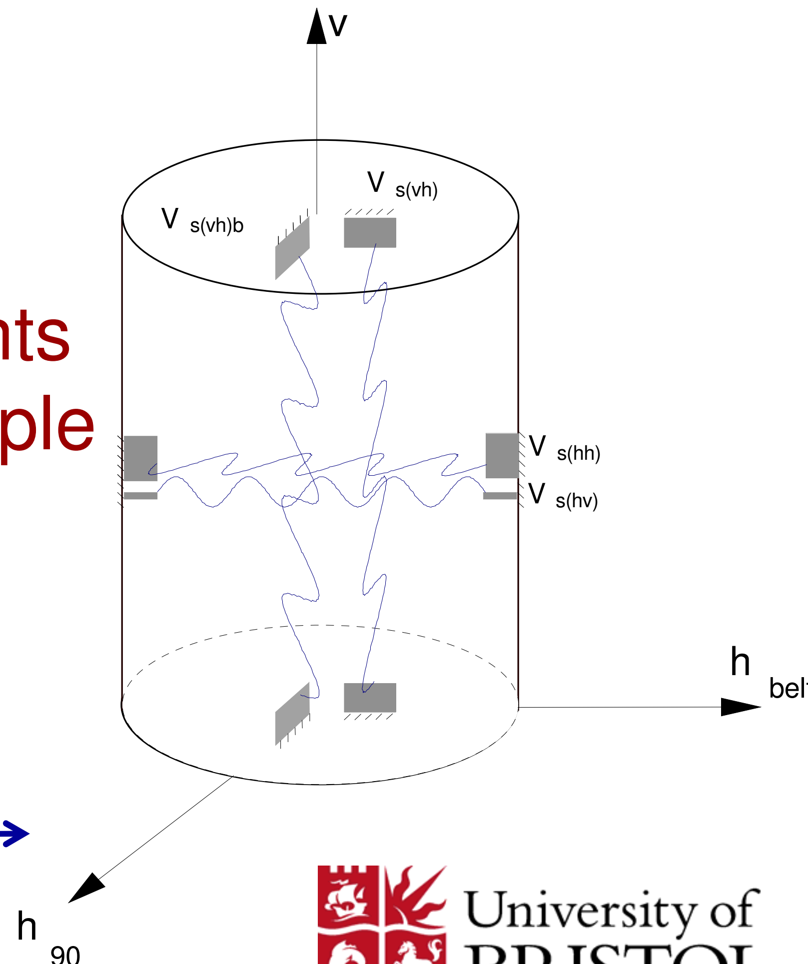
laboratory geophysics: piezoceramic elements

bender element (*s*-waves)

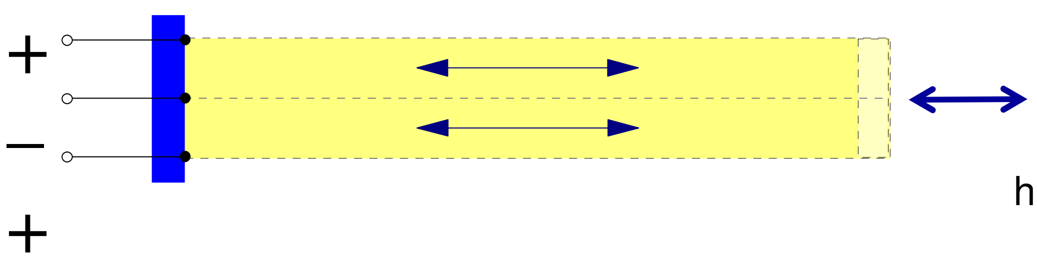




bender elements on triaxial sample



extender element (*p*-waves)



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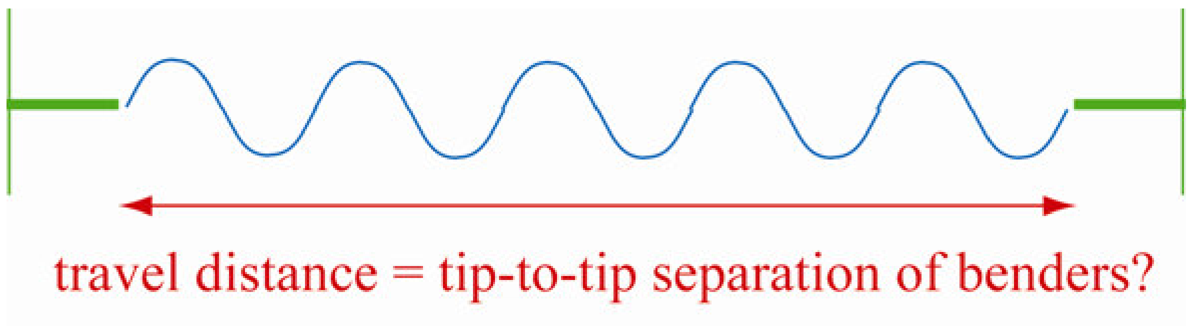
deduction of elastic stiffness

elastic stiffness deduced from shear (or compression) wave velocity $G = \rho\, v_s^2$

velocity = distance/time



arrival time? complex (attenuated) received signals – reflections, dispersion

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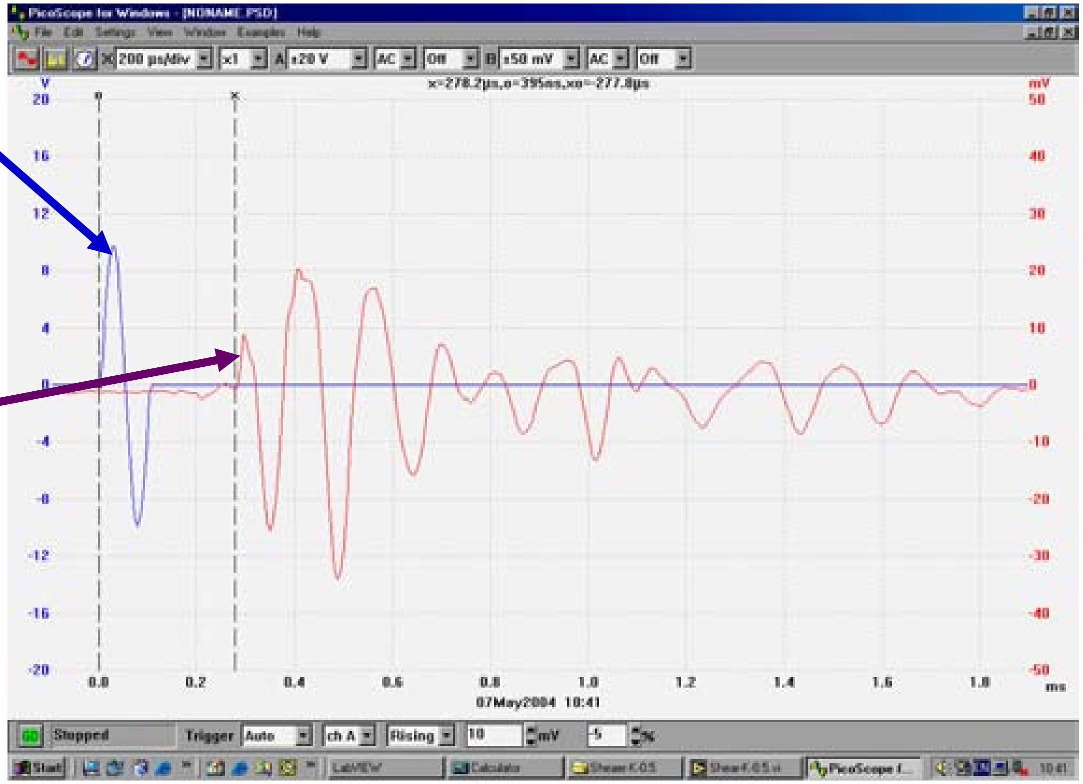
the problem:

input signal: single sine pulse!!



output signal: complex

arrival time?

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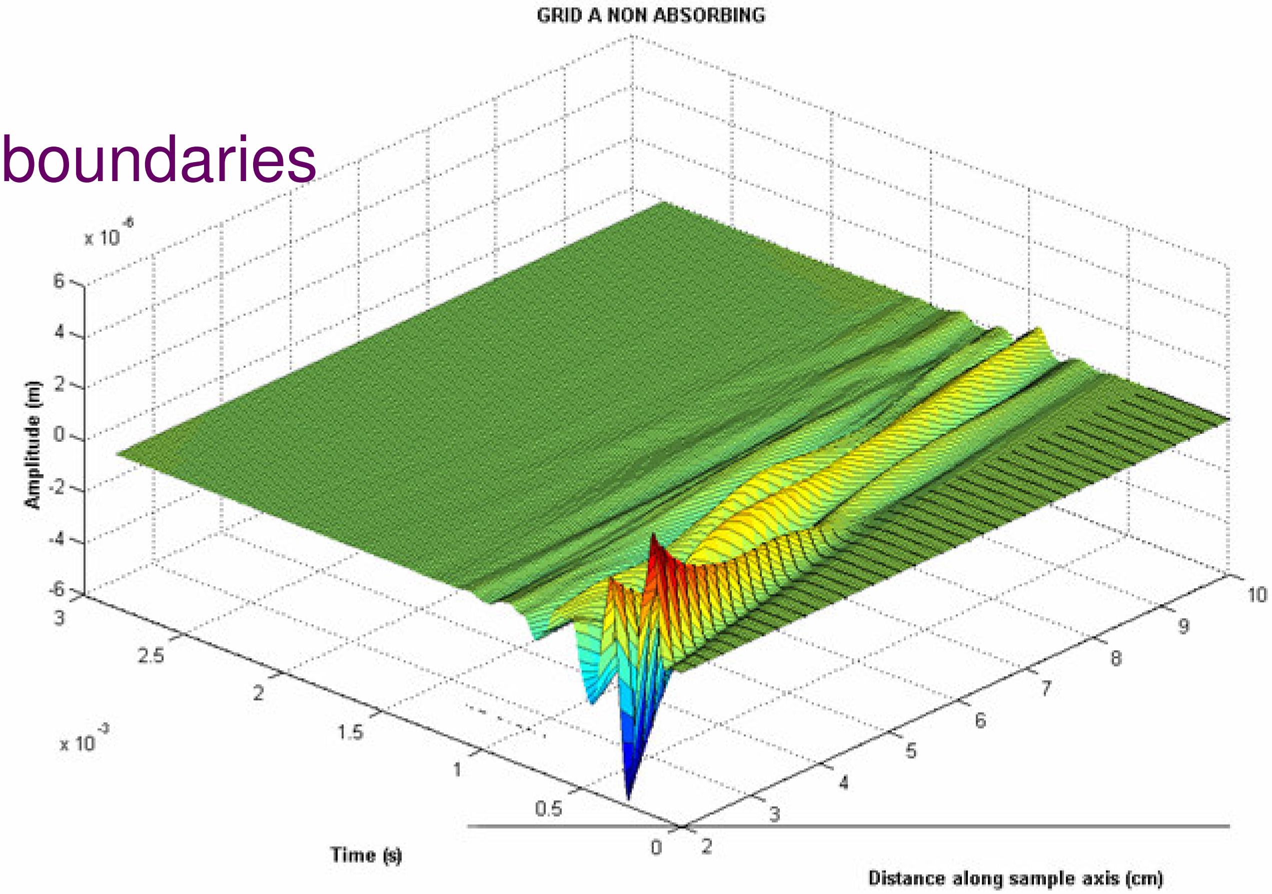
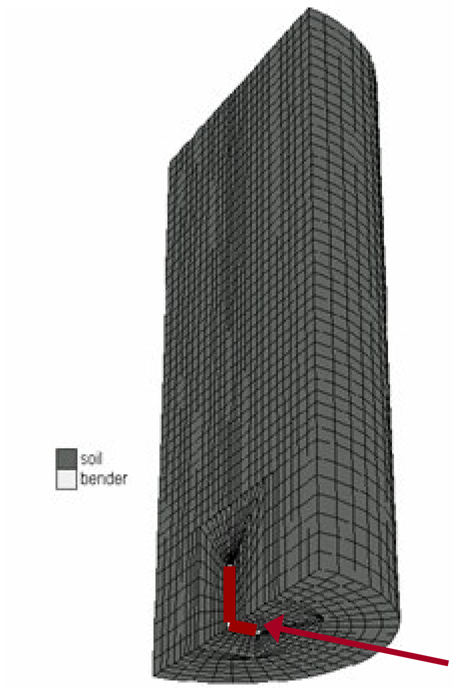
elastic properties: numerical simulation

non-absorbing boundaries



FLAC-3D grid

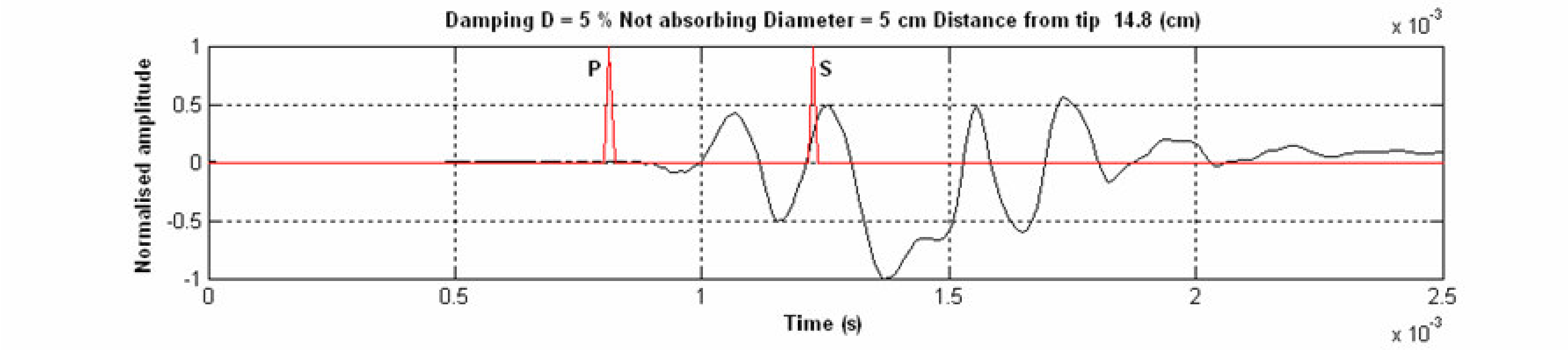


reflection at boundaries

conversion of *s*-wave to *p*-wave energy

bender element

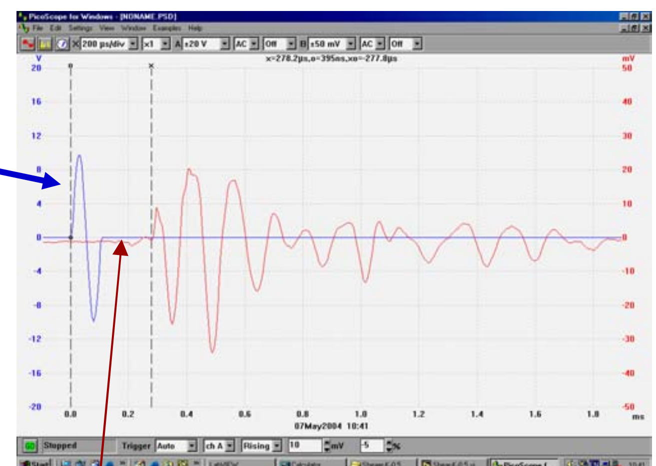
interpretation of numerical simulations



numerical simulation: objective deduction of arrival time??

input signal: single sine pulse!!

compare theoretical *p*-wave and *s*-wave arrival times



experimental observation: note *p*-wave arrival in *s*-wave trace

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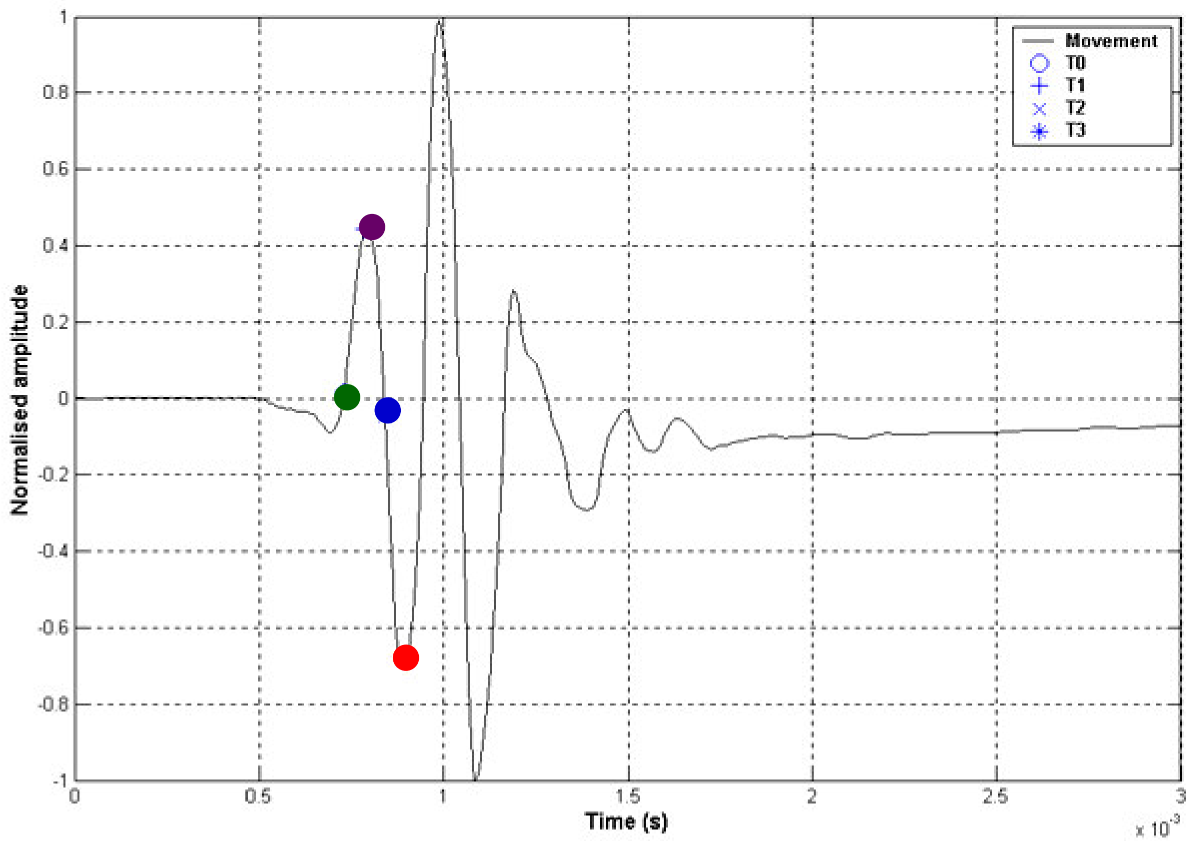
interpretation of numerical simulations



typical choices for arrival time from inspection of received signal

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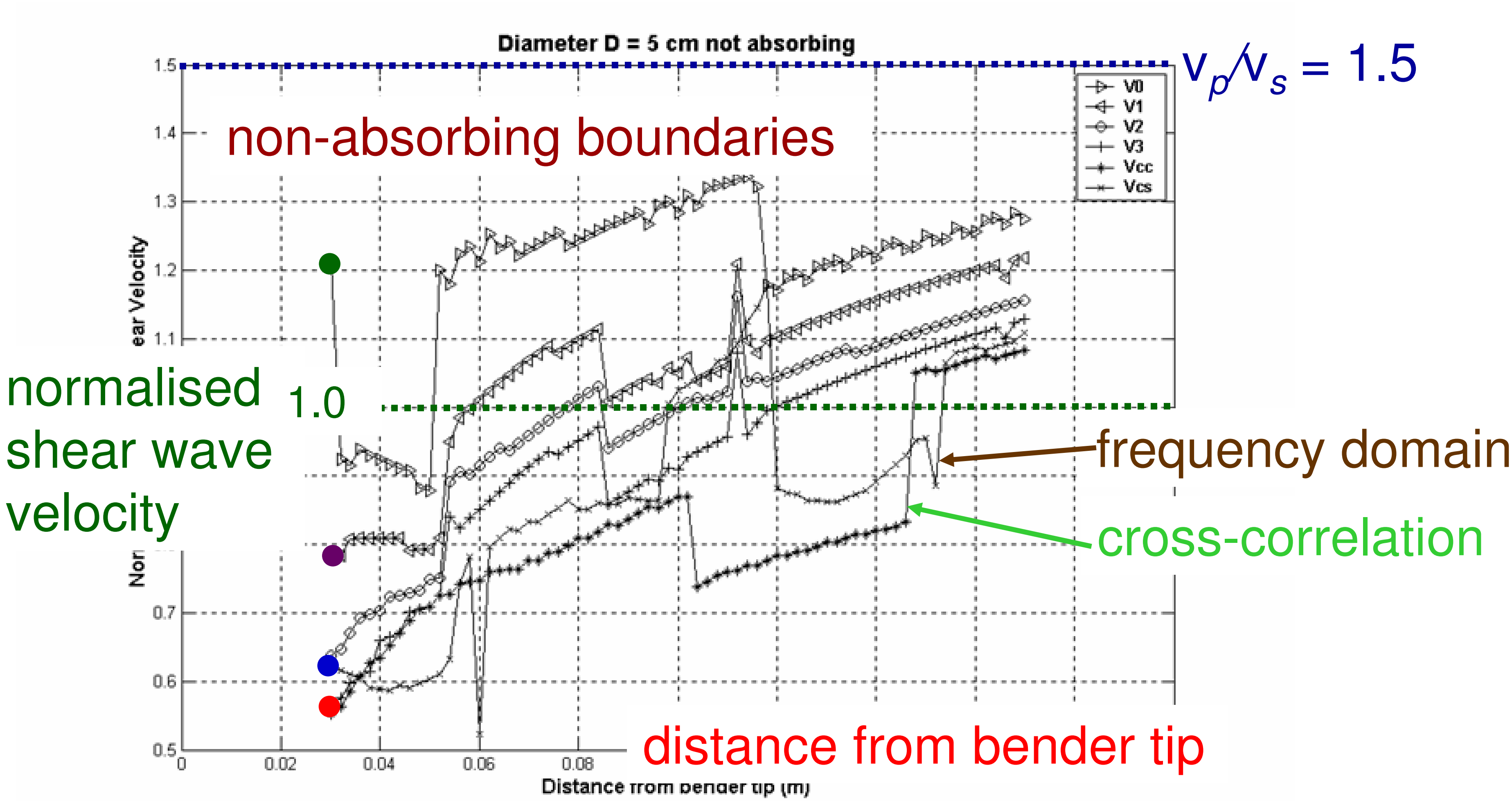
interpretation of numerical simulations



no clear trends?

p-wave dominating with distance

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Severn-Trent sand

Severn – river adjacent to Bristol

Trent – Alessandro Gajo, Italy

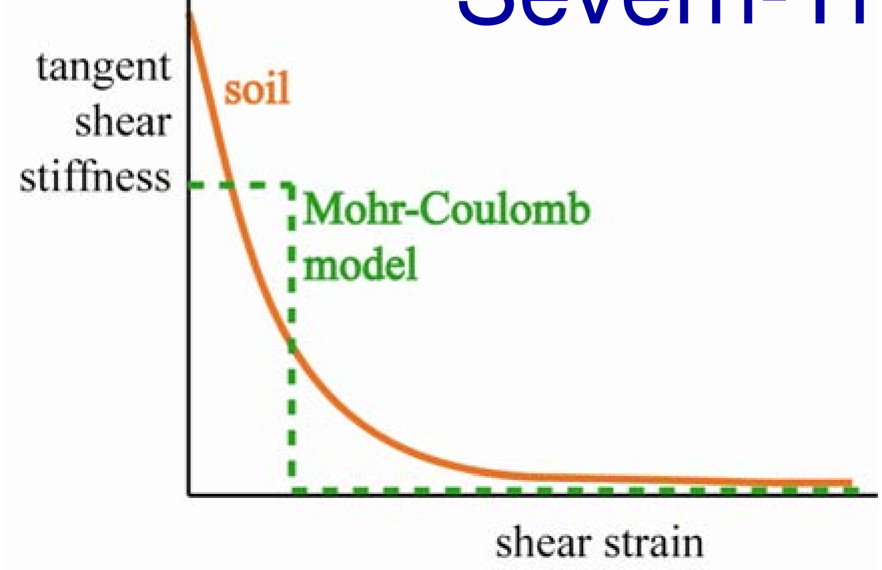
- Introduction: context: Bennett Dam
- Particle continuum duality
- Mohr Coulomb model
- properties

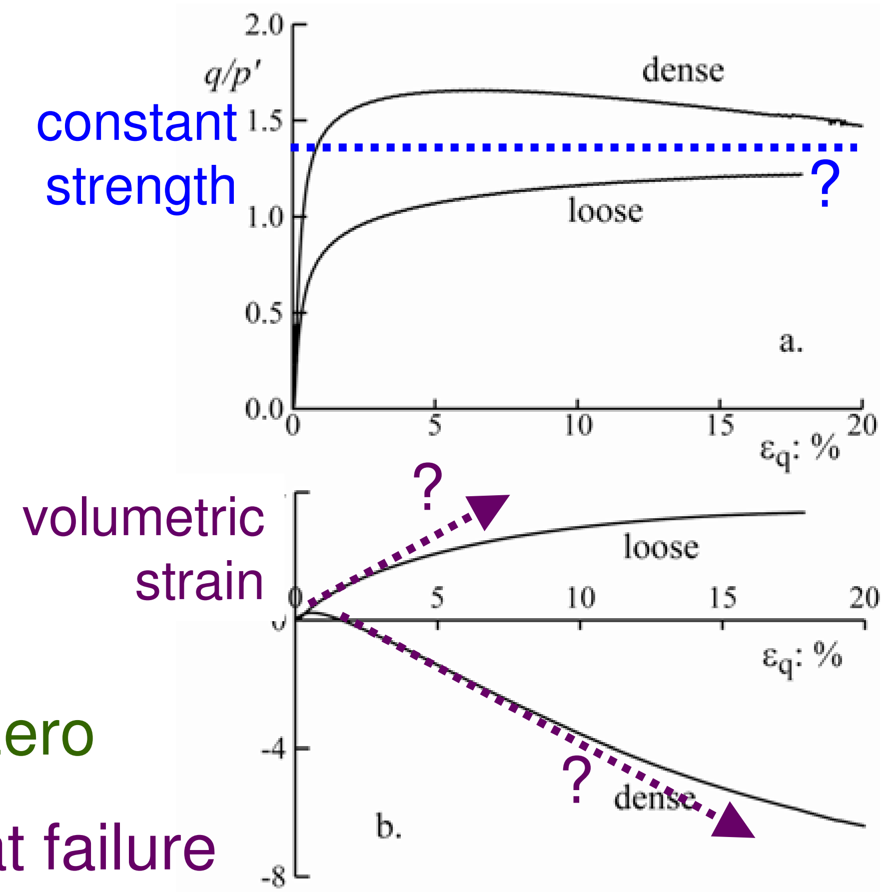
Trento

River Severn

Bristol

Severn-Trent sand





Hostun sand (Benahmed)

Mohr-Coulomb model: defects?

- incremental stiffness elastic or zero
- indefinite dilation/compression at failure
- strength chosen as soil constant

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Severn-Trent sand: strength

what is peak strength?

•property of the soil which changes with stress level, density

•*dependent* quantity

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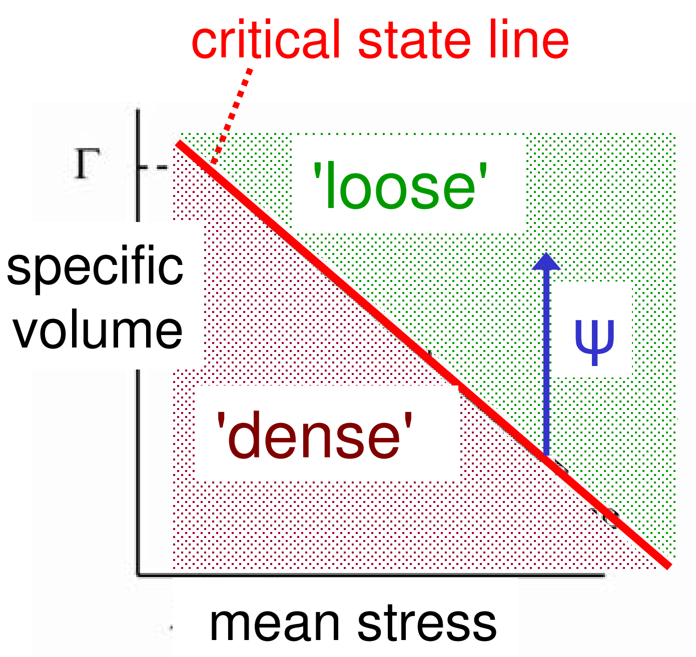
Severn-Trent sand: strength



state parameter ψ = volume distance from critical state line

function of density *and* stress level

more useful than void ratio alone – indicating effect of density *and* stress

Been & Jefferies

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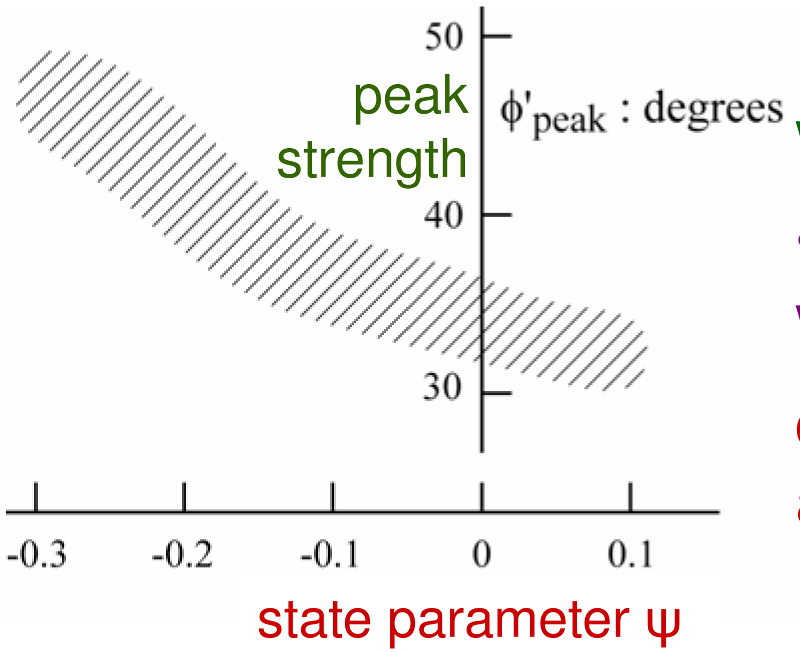
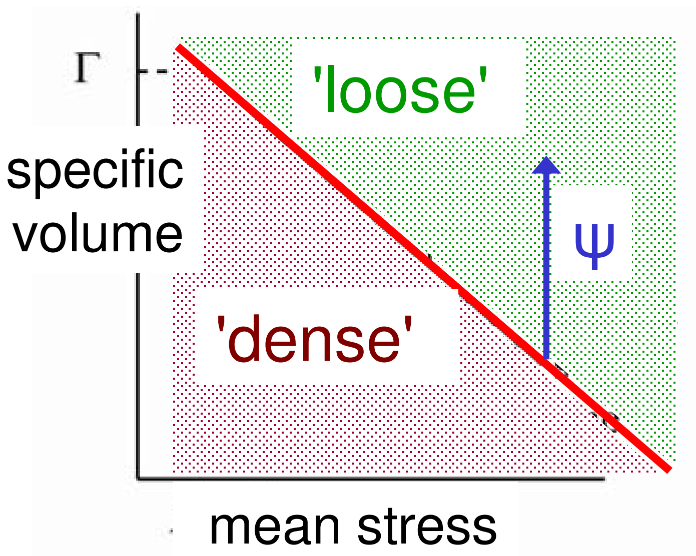
Severn-Trent sand: strength



what is peak strength?

•property of the soil which changes with stress level, density

data confirm link between strength and state parameter ψ



Mohr-Coulomb model with *current* strength dependent on *current* stress level and density

Been & Jefferies

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Severn-Trent sand: dilatancy

dilatancy: volume change during shearing

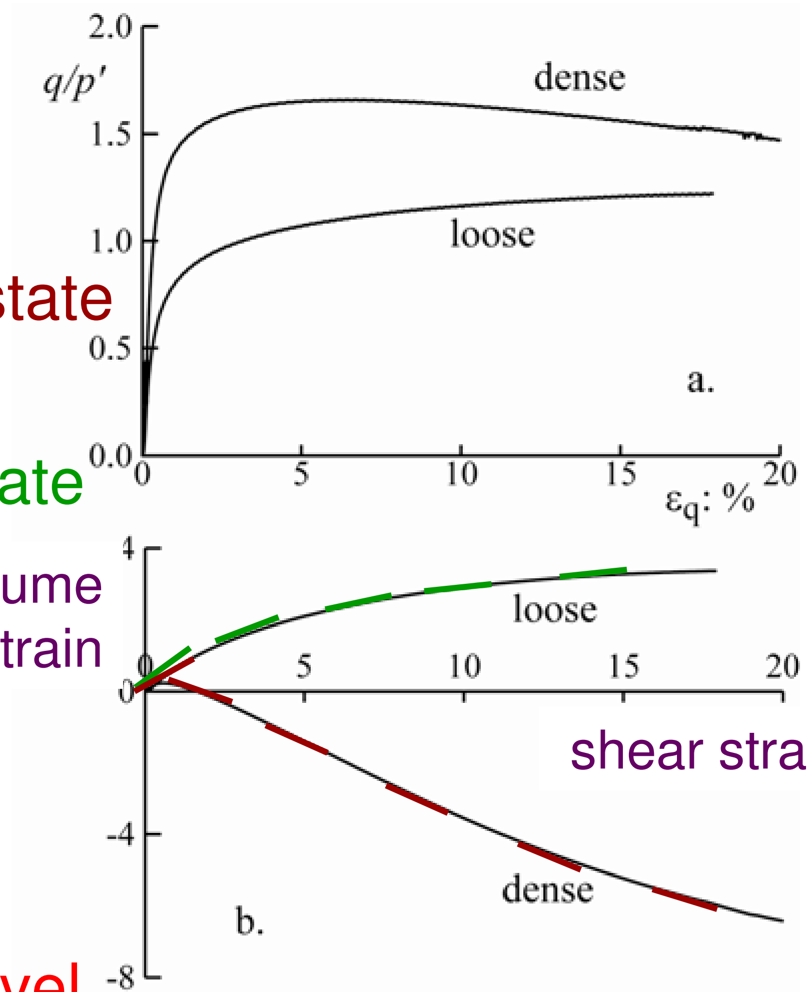
'dense' sand expands – negative state parameter

'loose' sand contracts – positive state parameter

dilatancy depends on density

dilatancy varies during test

link with state parameter (stress level and density)



Benahmed

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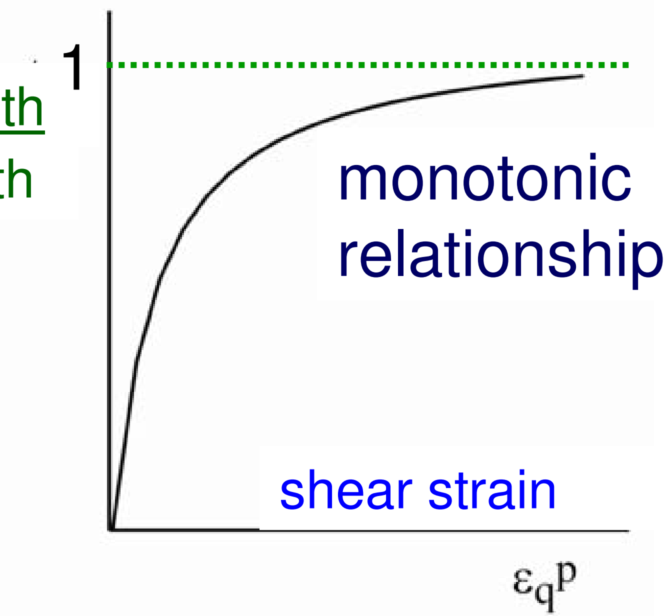
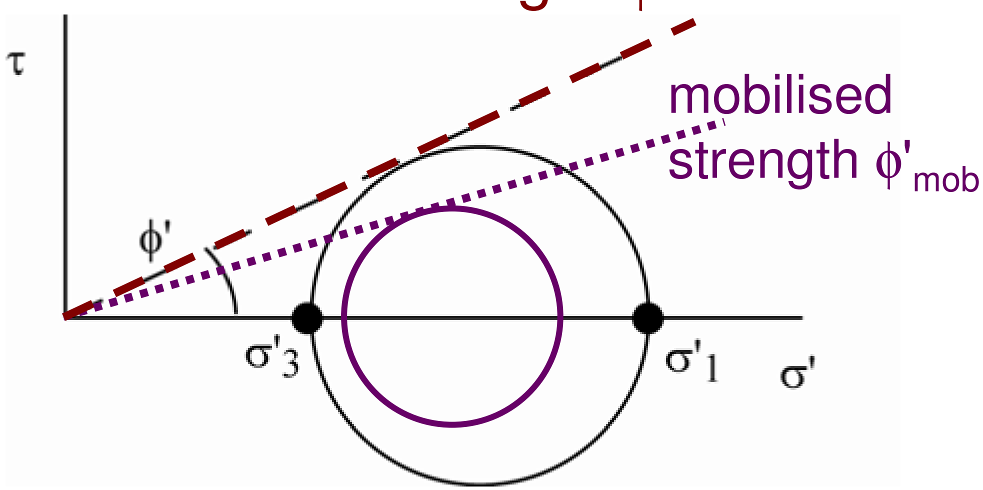
Severn-Trent sand: stiffness evolution

ratio $\frac{\textit{currently}\text{ mobilised strength}}{\textit{currently}\text{ available strength}}$



available strength φ': varies with ψ



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Severn-Trent sand

model complete

•monotonic travel towards *current* strength

•*current* strength depends on *current* density (state parameter)

•shearing leads to *change* in density (dilatancy): soil seeking critical state

•*change* in density leads to *change* in strength

etc

predicted softening for dense sand as emergent property

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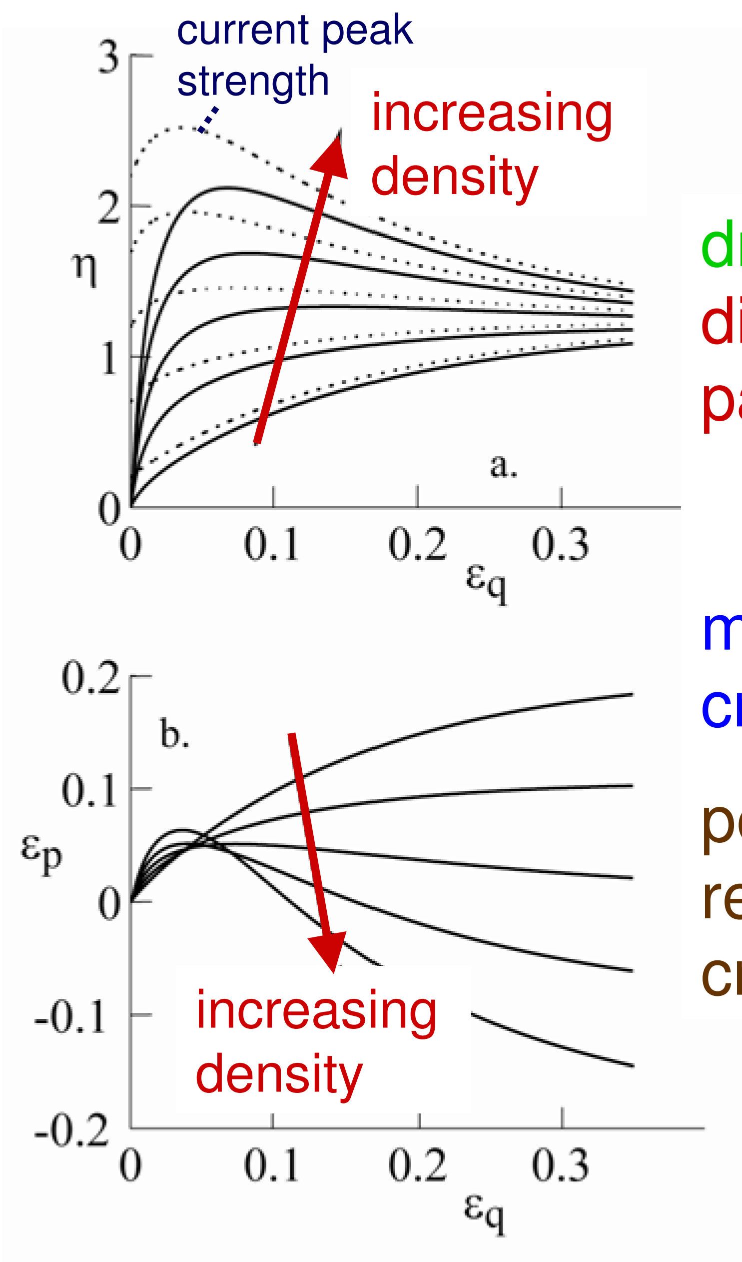
Severn-Trent sand: simulations



drained triaxial compression tests

different initial density (state parameter)

model automatically homes in on critical state

peak strength is moving target reached at infinite distortional strain – critical state

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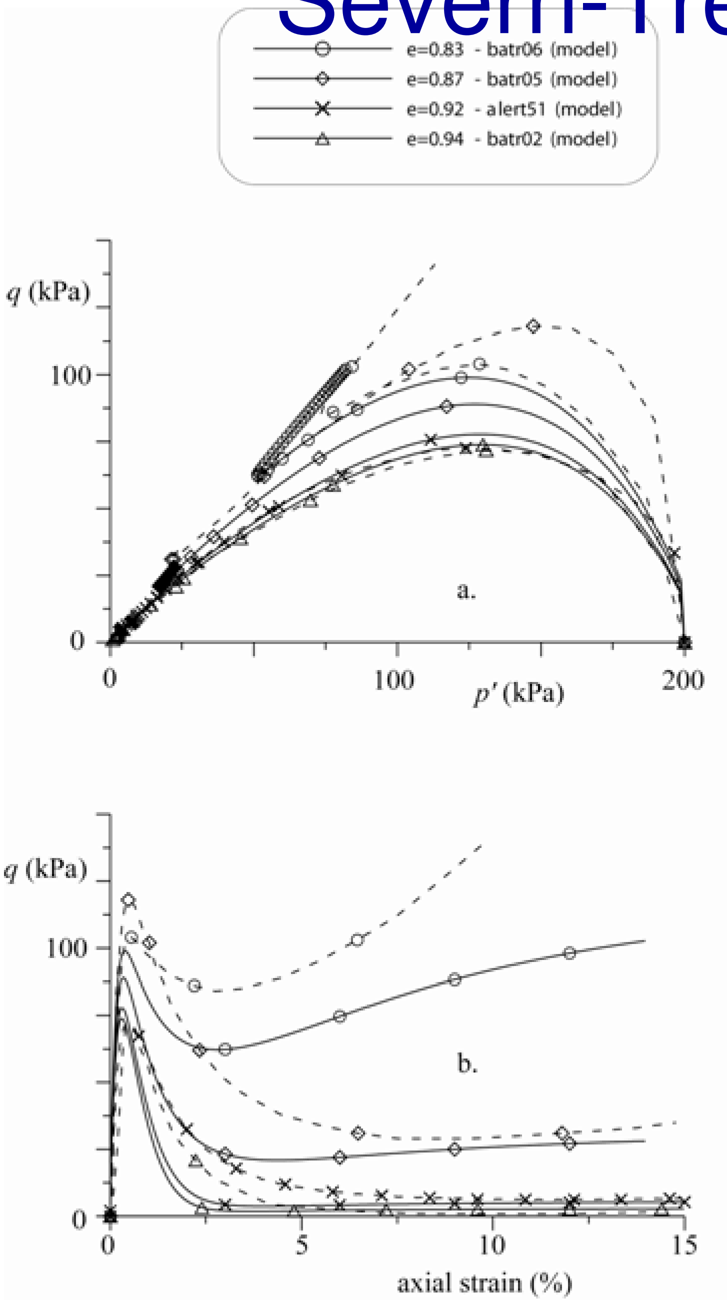
Severn-Trent sand: calibration



calibrated against triaxial test data for Hostun sand

undrained triaxial compression

effect of different initial density automatically described

Gajo & Muir Wood, 1999

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Severn-Trent sand

Mohr-Coulomb model with extra features

building on familiar foundations

- central role of state parameter
- feedback through dilatancy
- rich patterns of response simulated

mathematically elegant

economical in demand for soil parameters

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- **Grading state index**
- Conclusion

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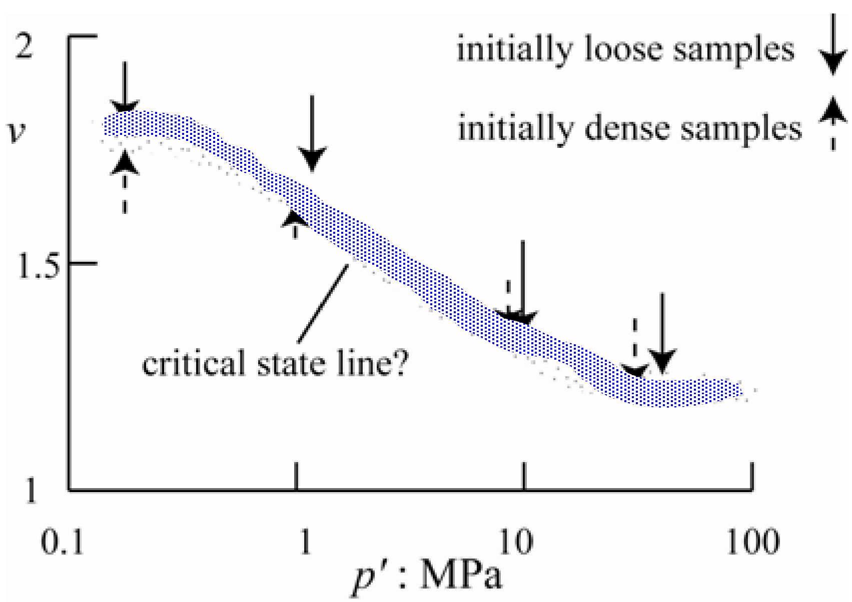
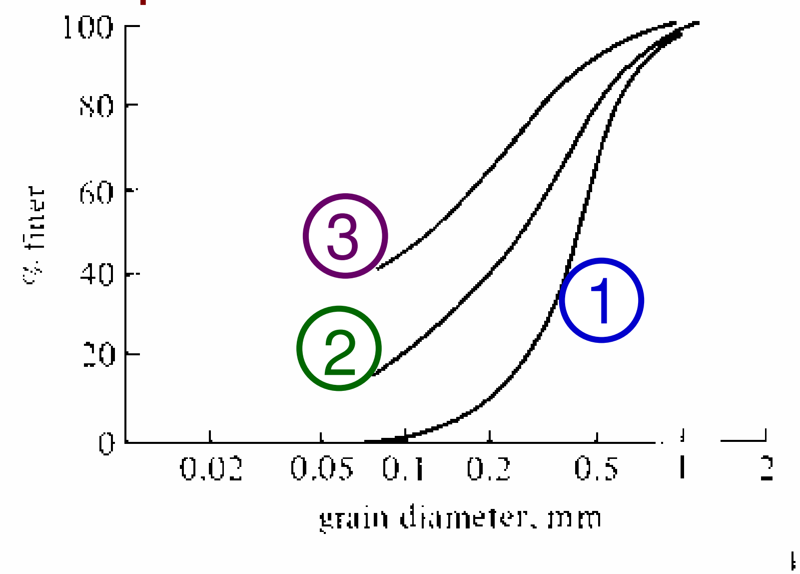
Grading state index



particle size distribution



occurrence of crushing

change in grading

irreversible

1: before testing

2: after compression to 6.21MPa

3: after triaxial compression

Chattahoochee River sand

Vesic & Clough, 1968

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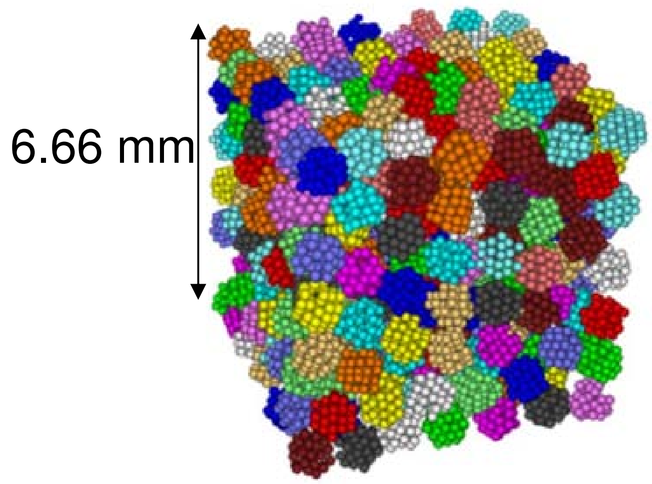
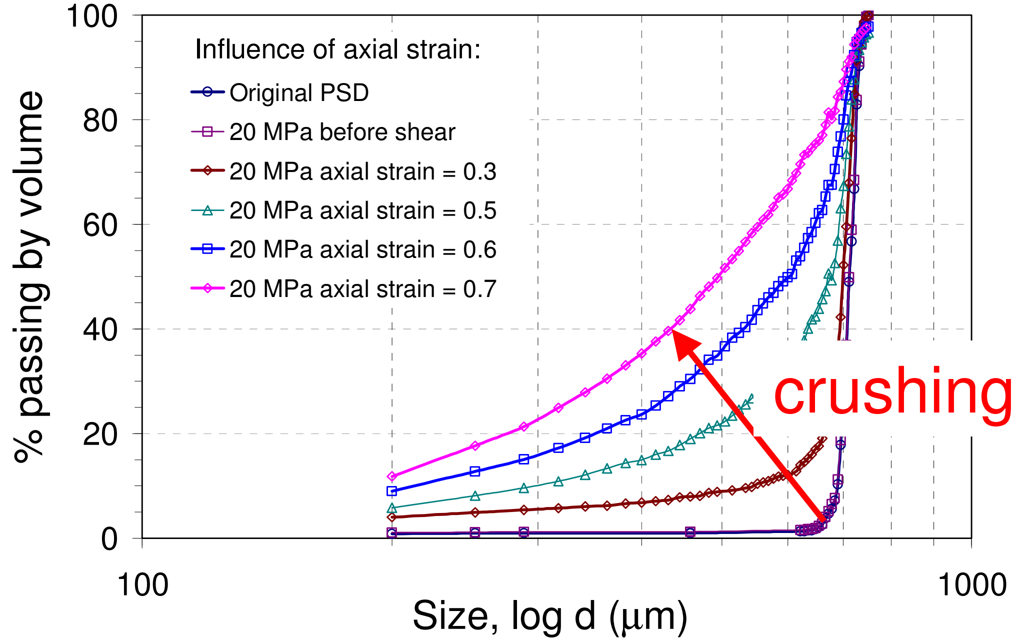
Grading state index



Cheng 389 agglomerates



numerical simulations – compression and shearing of assembly of agglomerates

gradings tend to *self similar* 'fractal' grading

continuous 'fractal' grading: every void space filled with progressively smaller particles

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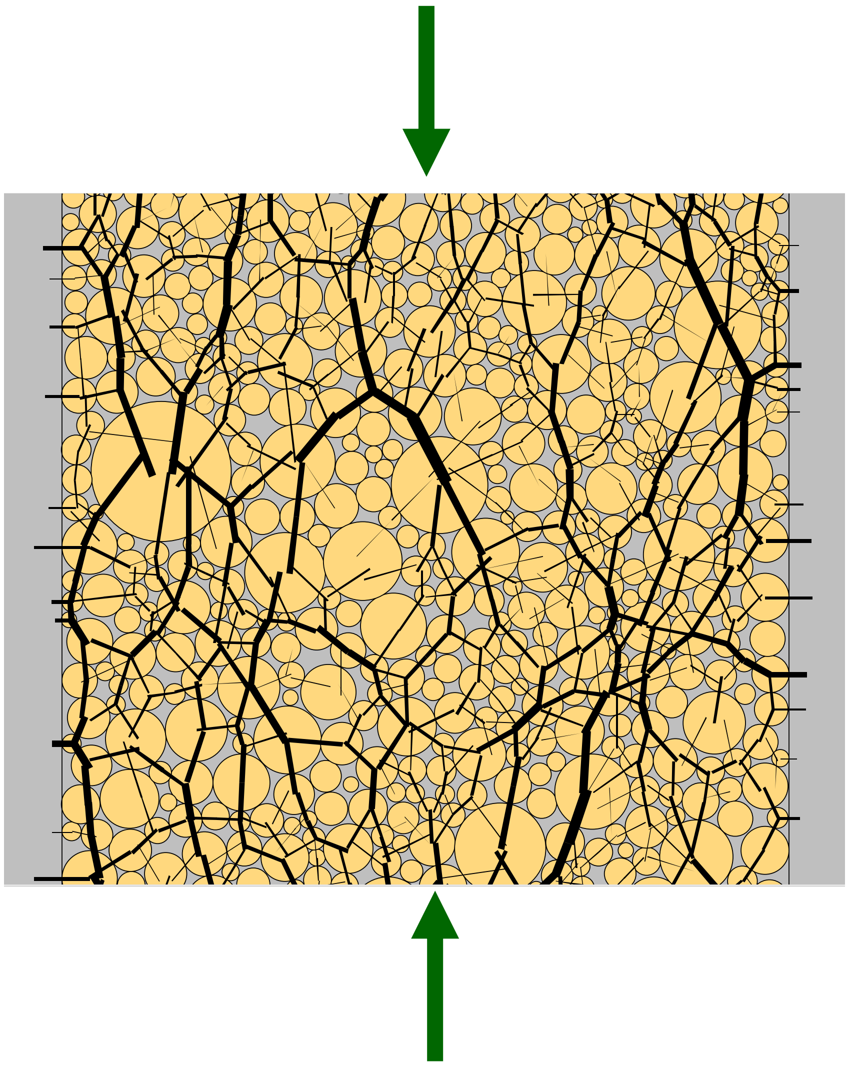
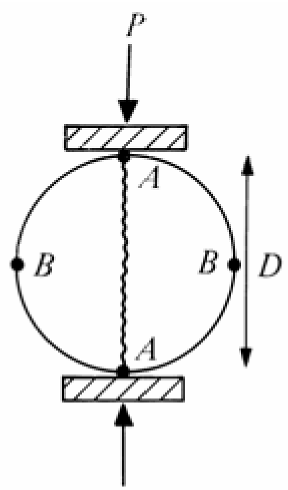
Grading state index: crushing



crushing?

coordination number (number of contacts) larger for larger particles

smaller particles tend to crush



Brazil cylinder test: *tensile* strength of concrete

Maeda (2005)

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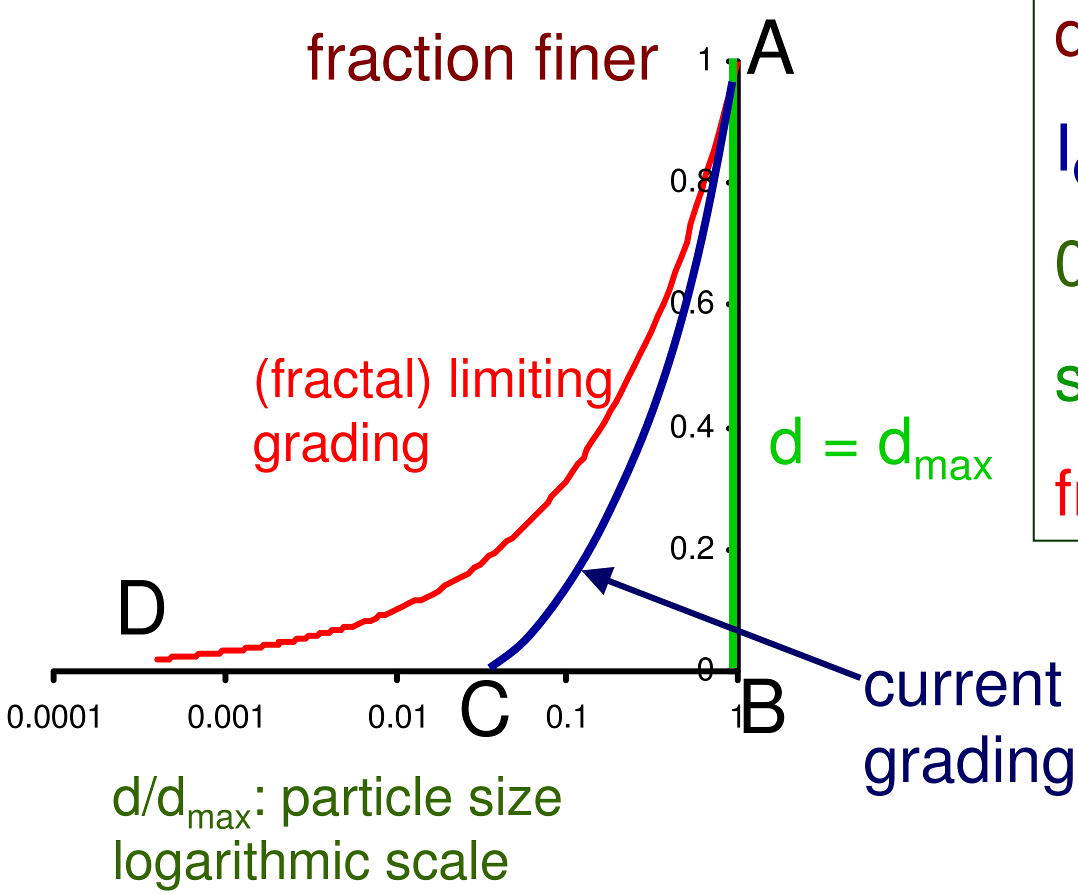
Grading state index I_G: definition



definition of I_G?

I_G = area ABC/area ABD

$0 < I_G < 1$

single size AB: $I_G = 0$

fractal limit AD: $I_G = 1$

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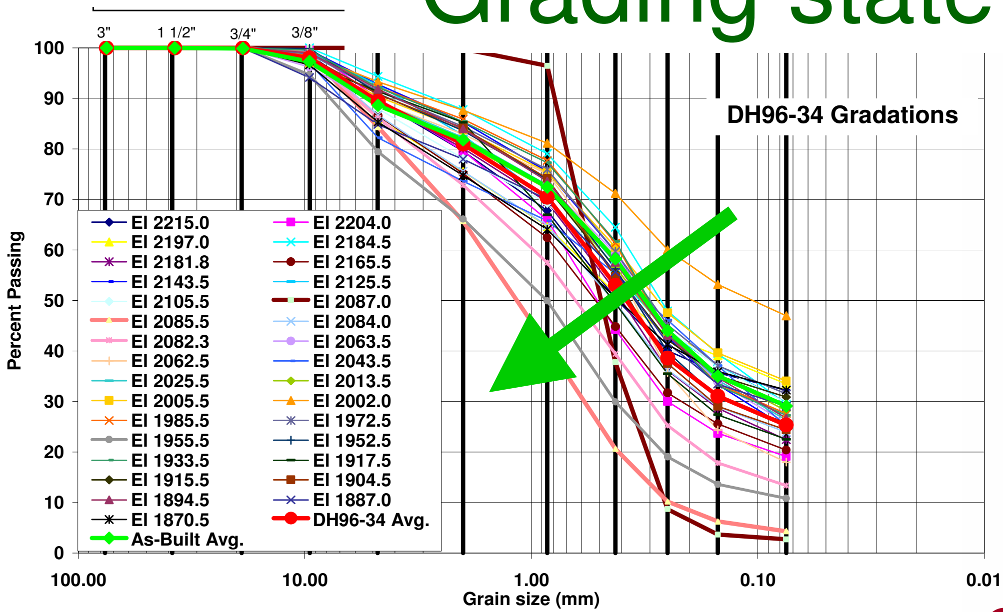
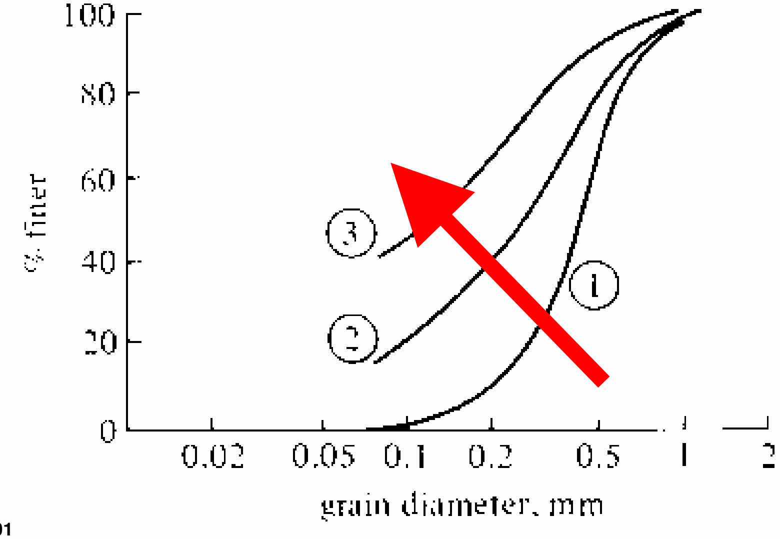
Grading state index I_G





WAC Bennett Dam core

Chattahoochee River sand

fines removal: I_G falling

grain crushing: I_G increasing

- soil grading change: erosion/transport or crushing
- material changing (irreversibly) while being studied
- effect on mechanical behaviour?

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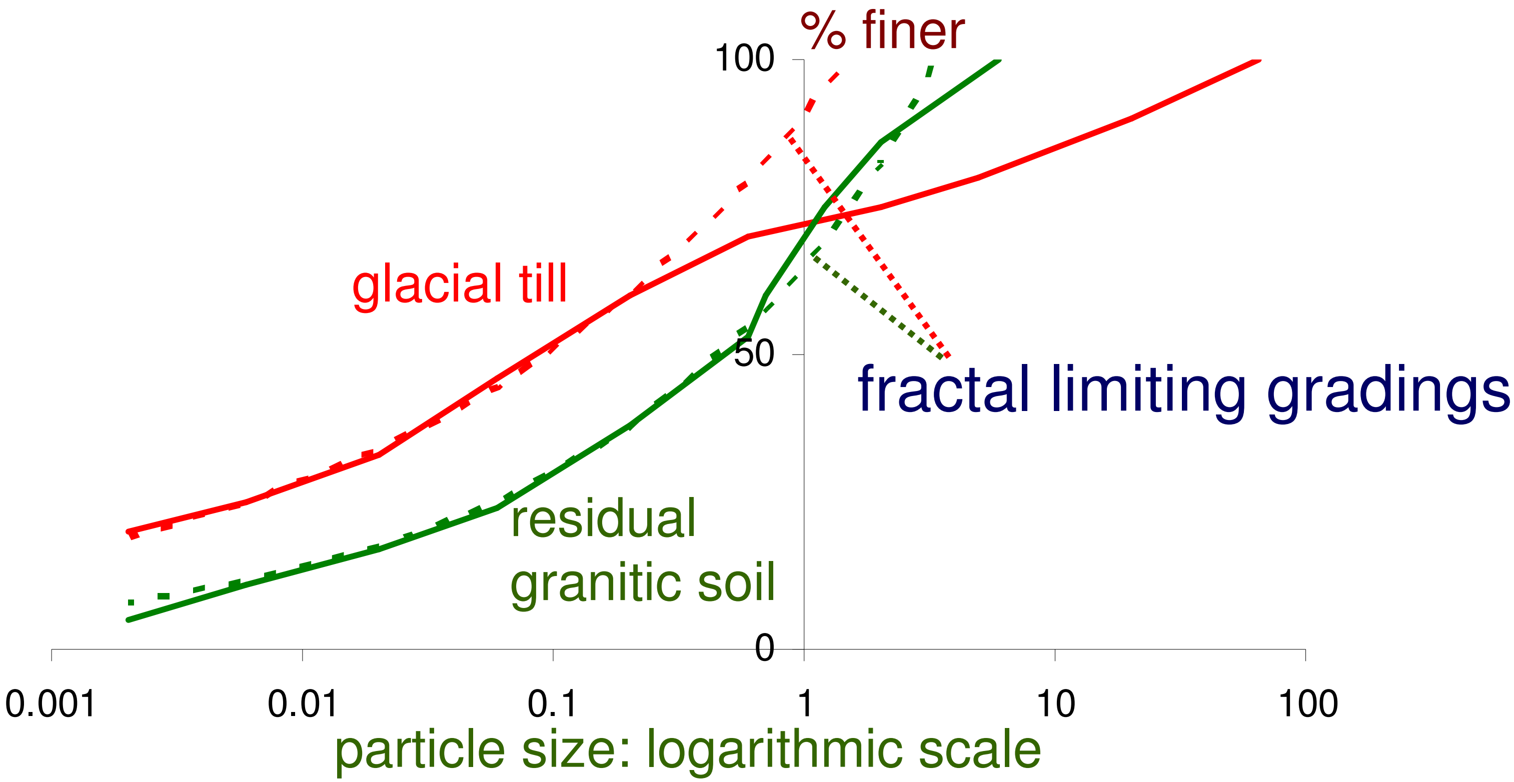
Grading state index



natural soils:

discovering fractal limiting gradings?

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Modelling grading change

- material changing (irreversibly) while being studied
- modelling requirements:
  - ❖*characterisation* of evolving grading – additional grading state index
  - ❖*evolution law* for grading state index (mass conservation, transport, crushing criteria, etc)
  - ❖*influence* of grading state index on constitutive properties (for example, critical states)
- *research in progress: add I_G influence to existing model*

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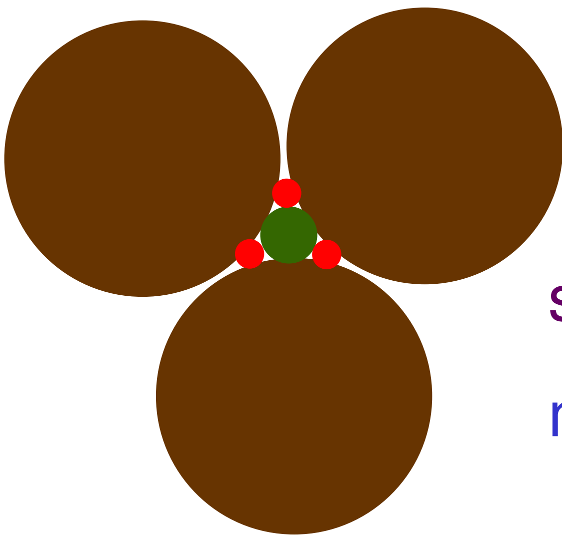
Grading state index I_G: influence

influence of grading state index on constitutive properties

•elastic properties – unchanged (first order)?

•friction/strength – unchanged (first order)?



smaller particles tending to fill gaps

maximum and minimum void ratios ↓ as I_G ↑

•critical state line – expected to change!

evidence?

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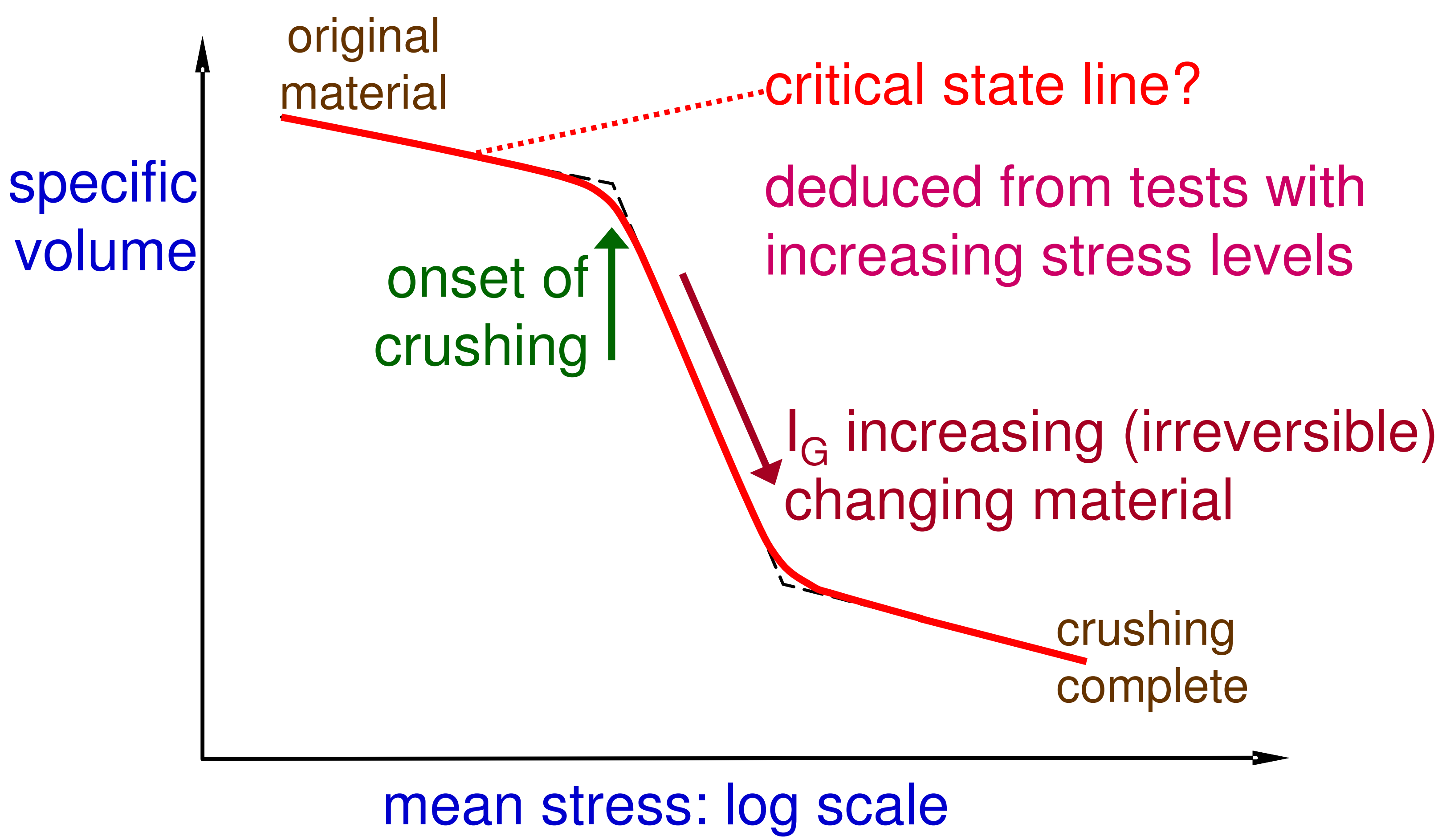
Grading state index I_G: critical states



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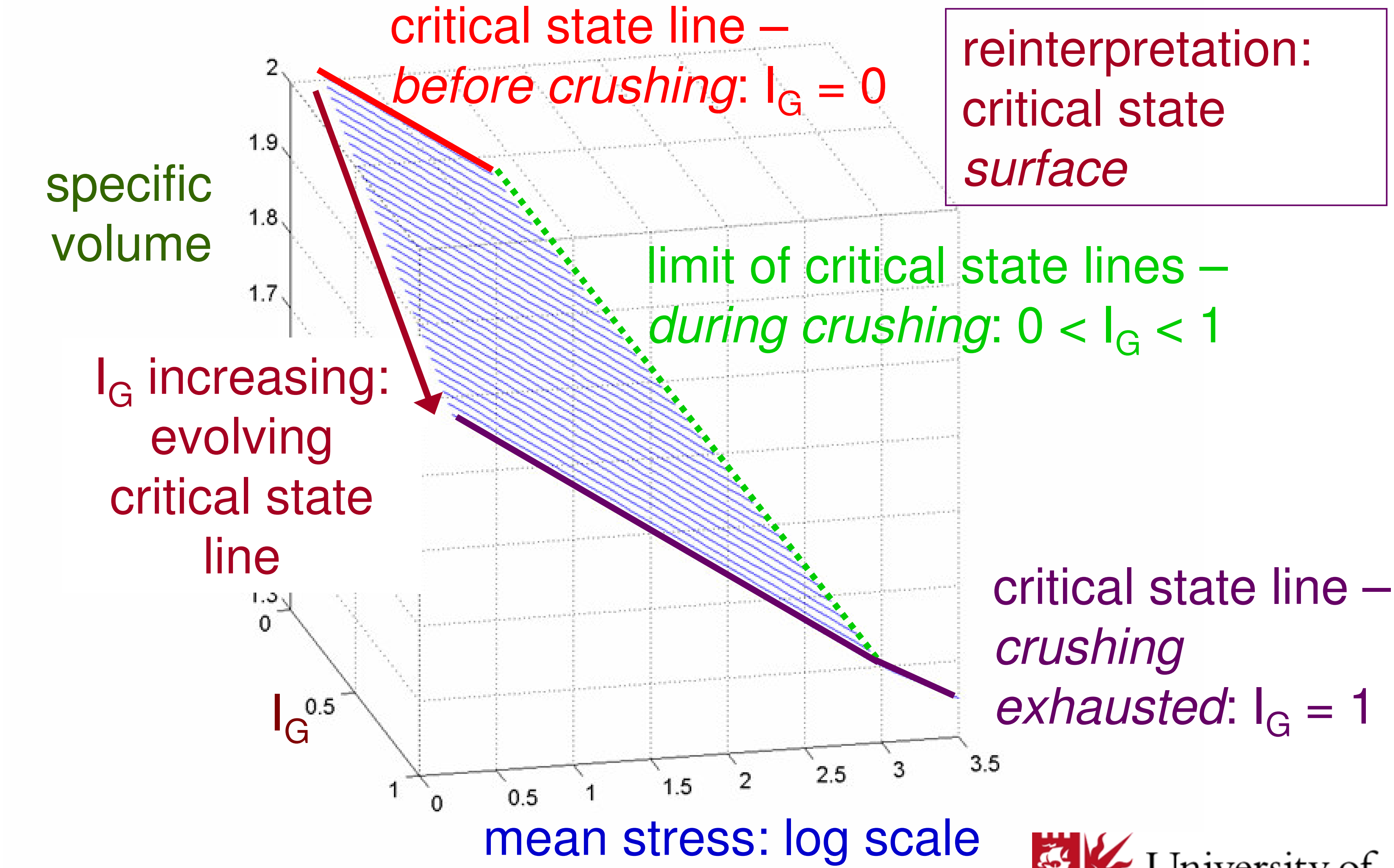
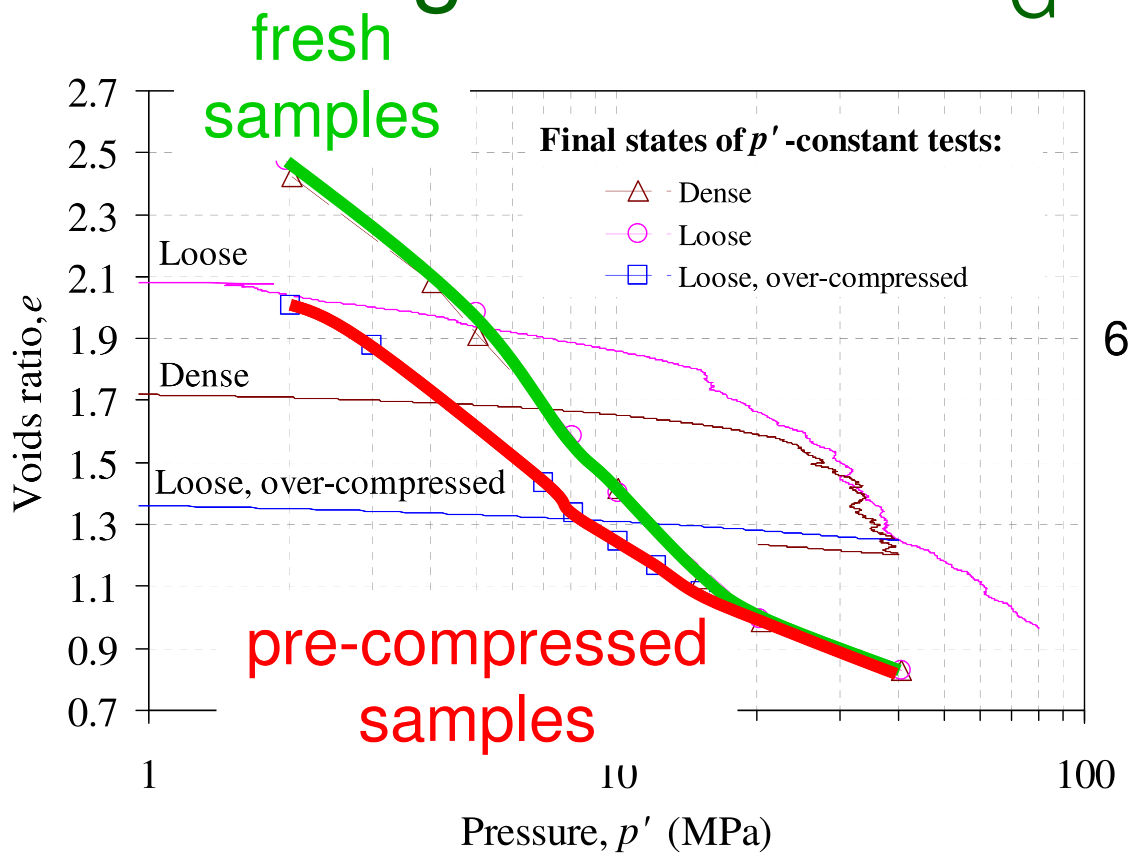
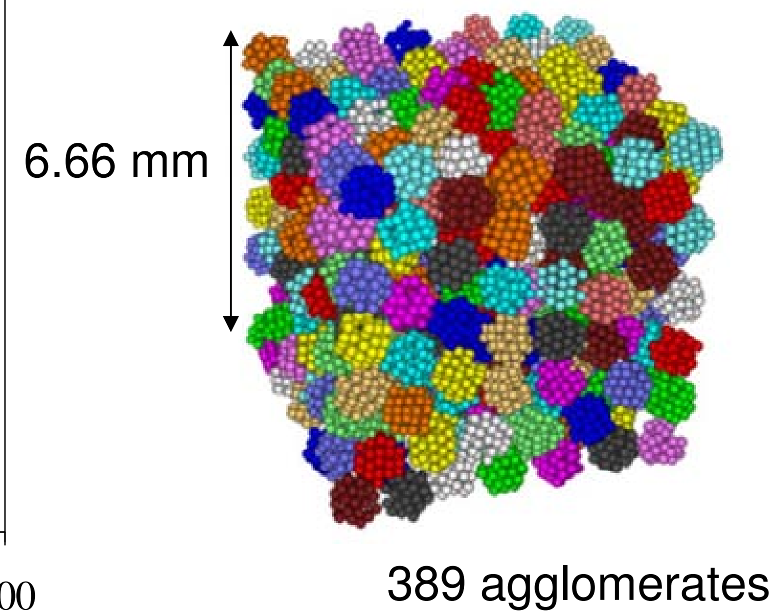
Grading state index I_G: critical states



Grading state index I_G: critical states





simulations for assemblies of agglomerates

critical state line *changes* with crushing

fresh samples – pre-compressed samples

Cheng, 2005

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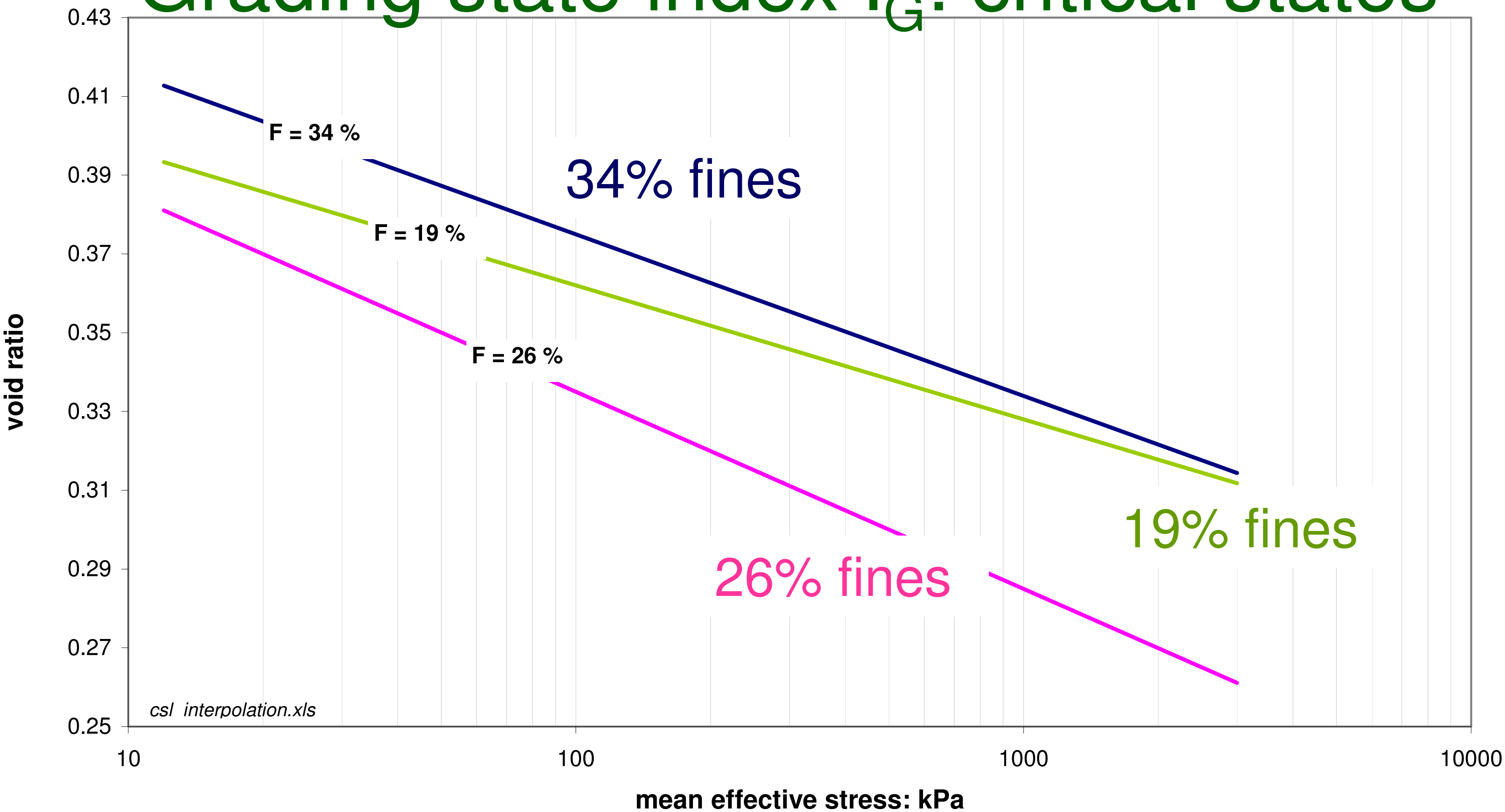
Grading state index I_G: critical states



WAC Bennett Dam: interpretation of effect of fines content on location of critical state line (triaxial tests, artificial mixtures)

non-monotonic…!?

BC hydro

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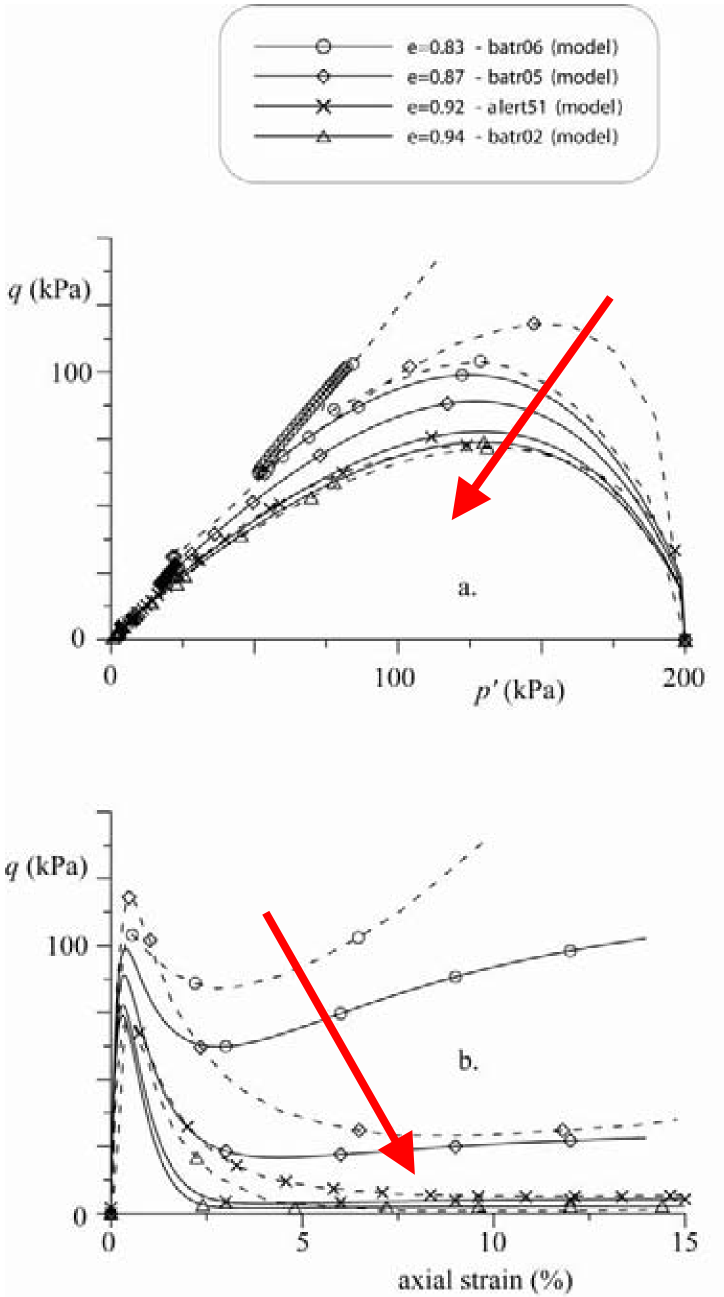
Grading state index



WAC Bennett Dam

Severn-Trent sand

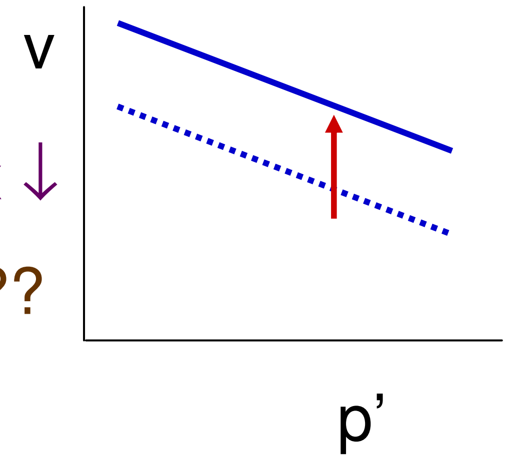
transport of fines from core

void ratio ↑

grading state index ↓

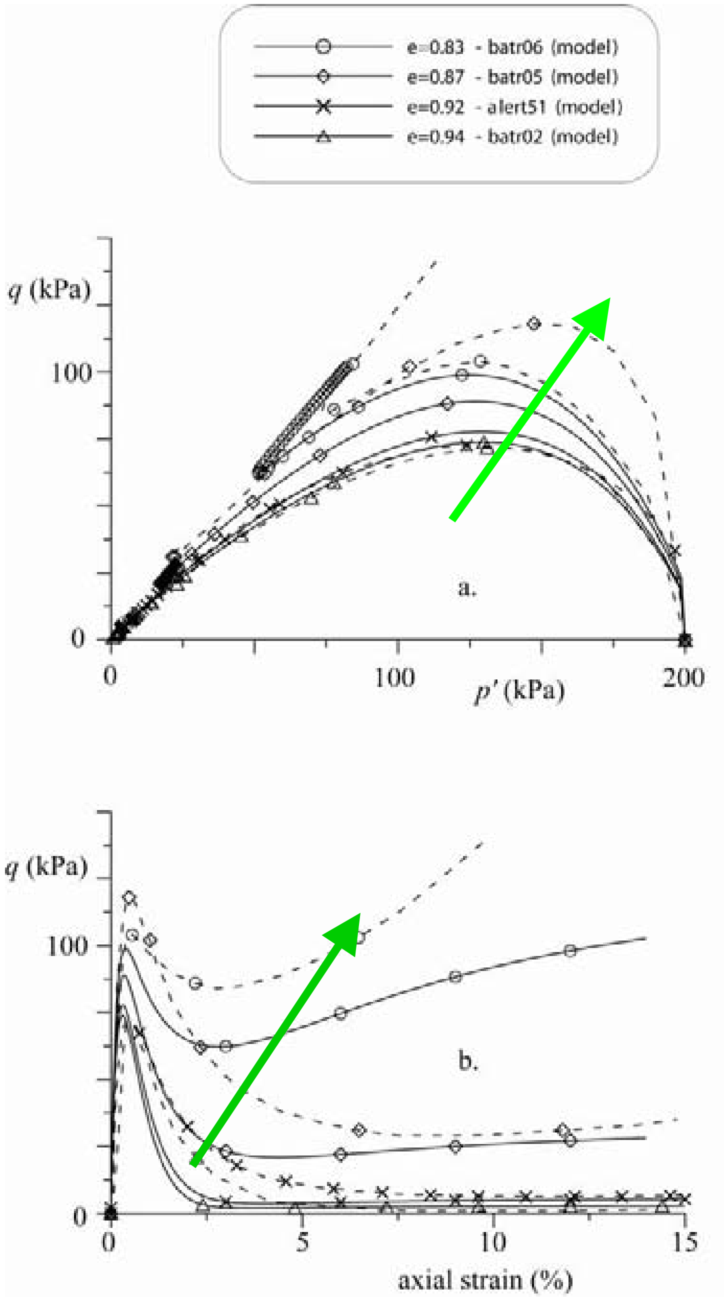
critical state line ↓??

state parameter ↑



soil feels looser ☹

Grading state index



WAC Bennett Dam

Severn-Trent sand

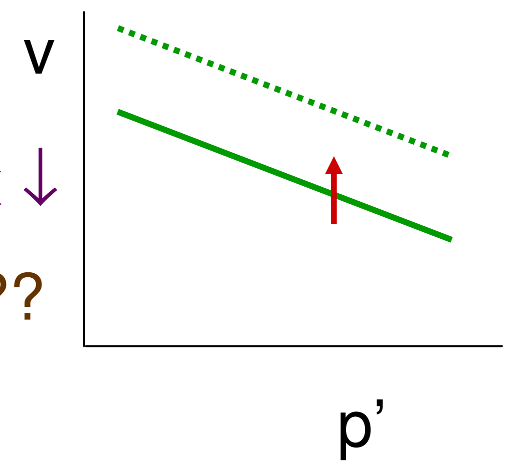
transport of fines from core

void ratio ↑

grading state index ↓

critical state line ↑??

state parameter ↓



soil feels denser ☺

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Grading state index

WAC Bennett Dam??

benefit of simple model that systematically incorporates changes in stress level *and* density *and* grading (making up *state* of soil)

model has to be honed – subtle data requirements for calibration

most testing has used artificially prepared mixtures

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The magic of sands

- Introduction: context: WAC Bennett Dam
- Particle continuum duality
- Mohr-Coulomb model
- Elastic properties
- *Critical states*
- Severn-Trent sand
- Grading state index
- Conclusion

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Conclusion

WAC Bennett Dam: Need for modelling able to include effects of density, stress *and* evolving grading.

Mohr-Coulomb model: Use as basis for development of more comprehensive models.

Severn-Trent sand: Mohr-Coulomb model with strength dependent on state parameter – softening as emergent property.

Grading state index: How does the changing grading of a soil affect its mechanical behaviour?

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Nous nous sommes nourris de la magie des sables.

We are sustained by the magic of sands.

Antoine de St Exupéry: *Terre des hommes* (1939)

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