Formation and Propagation of Localized Deformation in marine clays under plane strain condition

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Introduction

- Submarine slides are a direct potential threat to sub-sea infrastructure and may generate tsunamis

- Stability analysis is usually performed using the classical limit equilibrium theory based calculation methods like “method of slices” (Bishop and Morgenstern, 1960, Janbu 1973) or based on infinite slope theory.

- These calculation are based the assumption that soil behaviour is “perfectly-plastic”.

- While realizing that **marine clays are sensitive in nature, thus can be categorized as strain-softening material**. From this angle one can always conclude that the classical theories have limited validity.

Introduction

- The classical theory fail to explain the vast area of seeming stable slopes being engaged in submarine slides that may be trigger by some local disturbing factors

- These slides can be explained by **progressive failure mechanism which is a direct consequence of strain-softening behaviour**

- **The storegga slide is probably the best documented example of this kind (Kvalstad et al. 2005)**

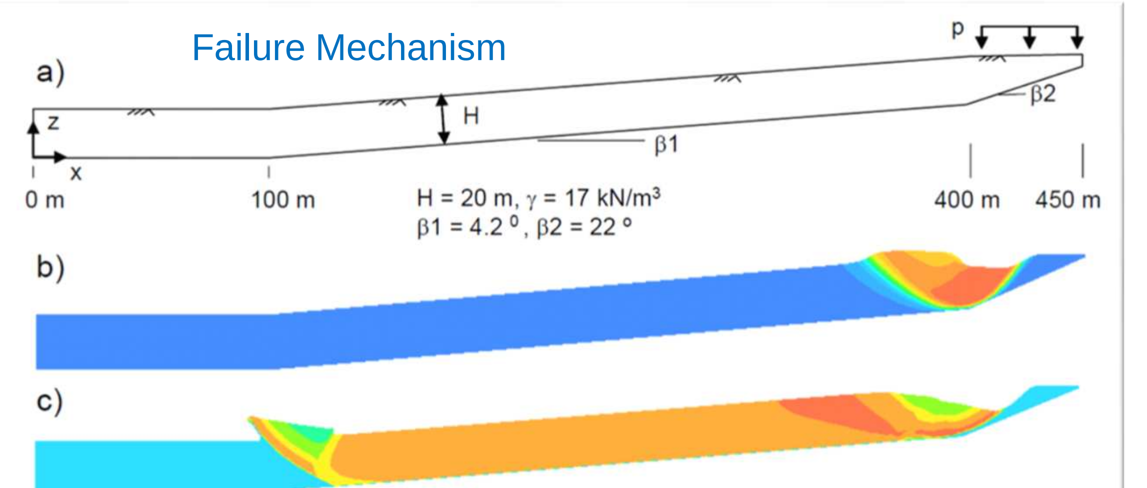
Introduction

- The classical theory based stability calculation over-predicts the factor of safety of submarine slopes.

A long natural submarine slope

Classical Theory based Solution

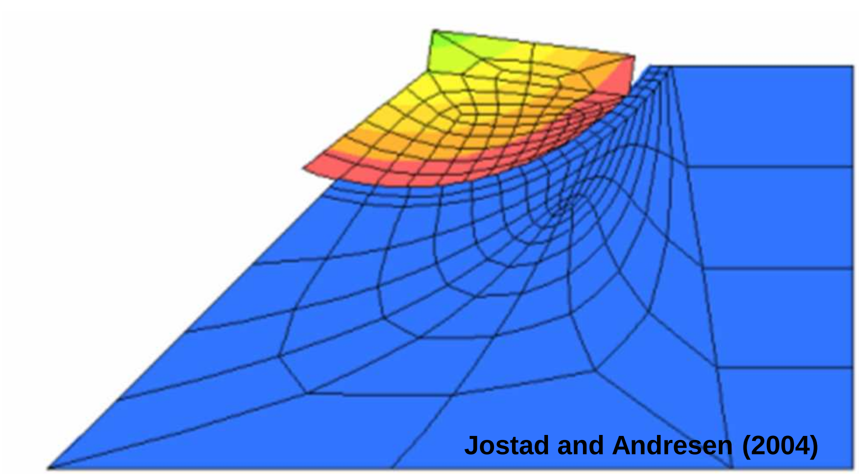
Progressive Failure

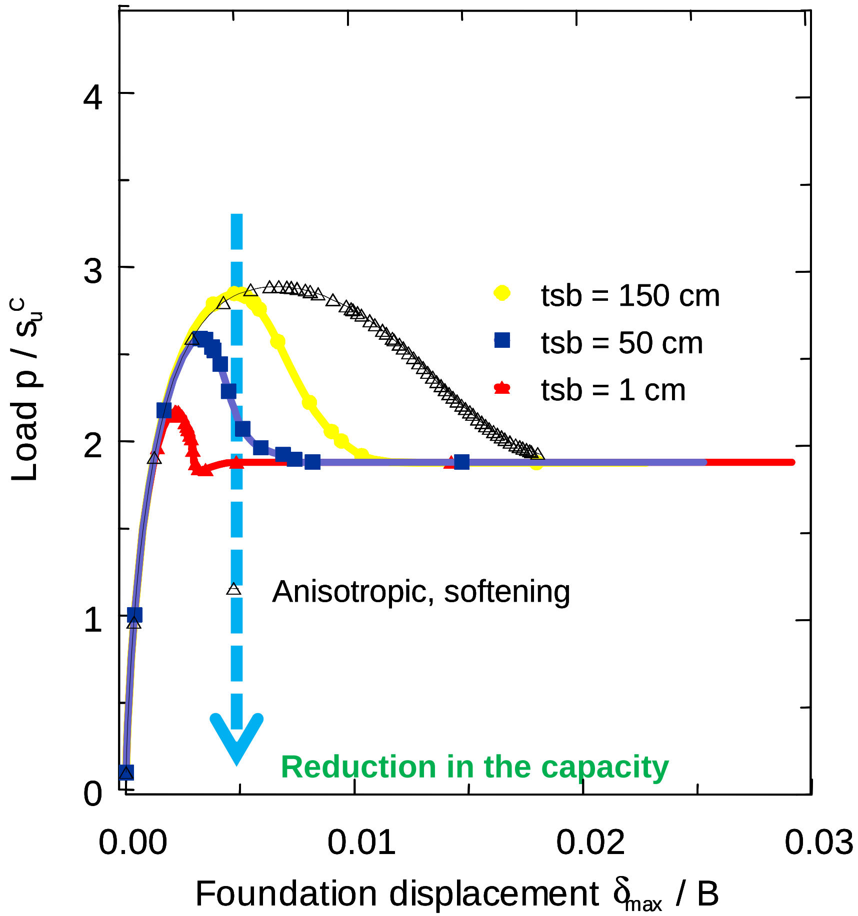


Andresen and Jostad (2008)

Effect of shear band thickness

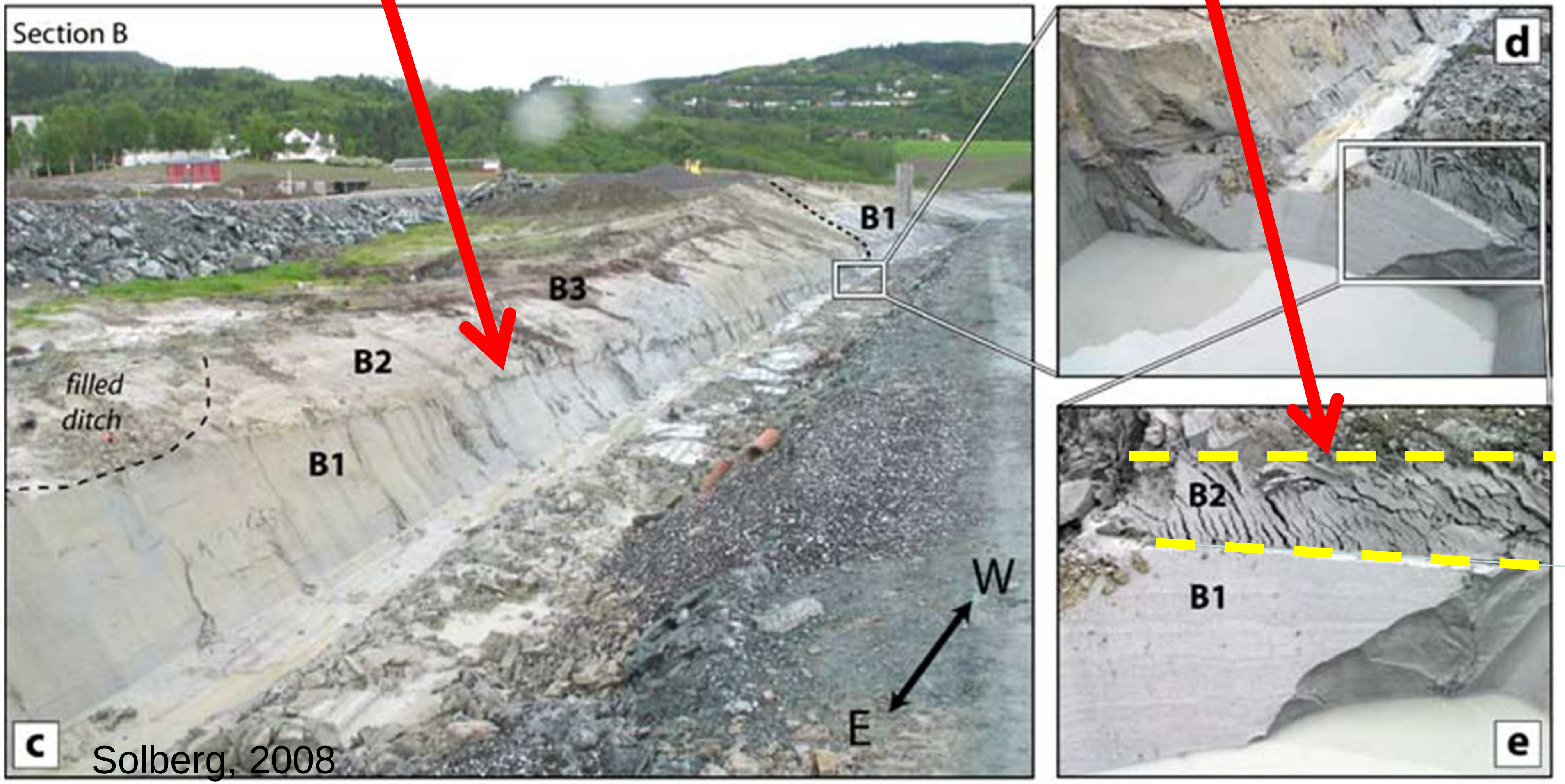
- Maximum load before completely develpoed failure mechanism
- Dependency on the thickness of shear band
- Placement of elements may influecne the orientation of shear bands





Shear band observed in a marine clay

Shear band in order of several centimeters



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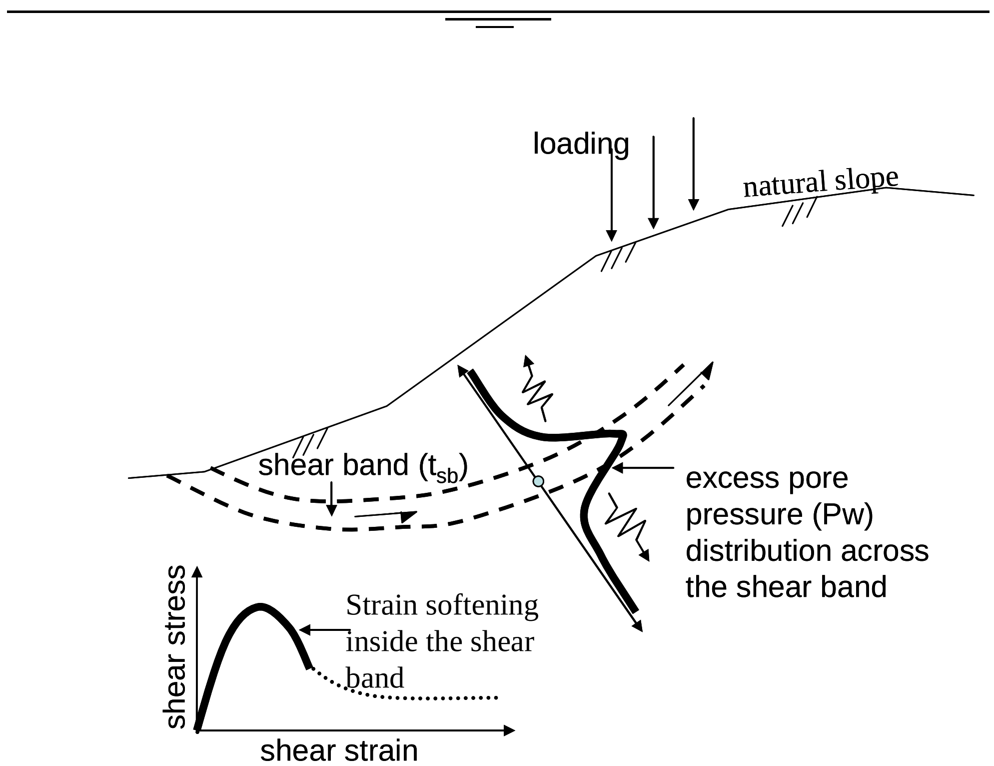
Failure in marine clays in presence of pore pressure

Viggiani et al. (1994) states: “*The analysis of the onset and propagation of shear bands in porous media such as saturated clays poses a formidable problem, because of coupled effects relating to fluid flow in the soil mass and in the localized zone which have to be taken into account*.”



Physical thickness of shear band is a key input in progressive failure modelling

Laboratory study on the physical thickness of shear bands in a marine Clay

- A collaboration between L3SR-Grenoble and NTNU-Trondheim
- Plane Strain testing at L3S-R, Grenoble
- Samples were collected from a location in Trondheim

Plane Strain Apparaturs

- The apparatus at the Laboratory 3S-R was originally Desrues (1980)
- The apparatus allows for free shear band formation in a soil specimen.
- 34 mm thick prismatic sample can be tested
- Measurement of local pore water pressure
- No measurement of the intermediate stress
- It was possible to measure volume changes in a sample during drained test

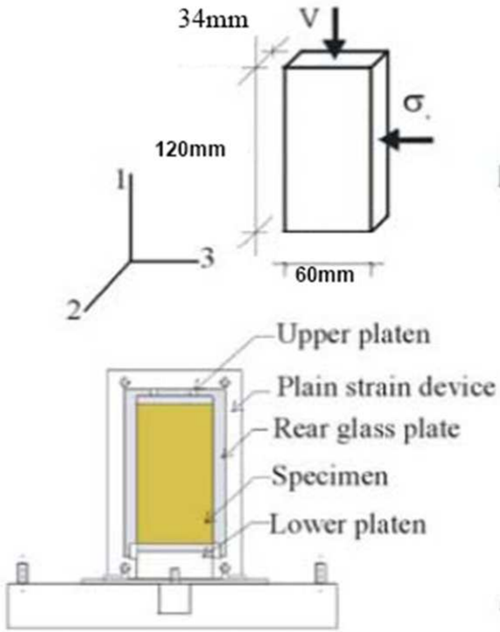
Plane Strain Apparatus

Demo film

A plane strain test on sand [Courtesy L3S-R]

Apparatus

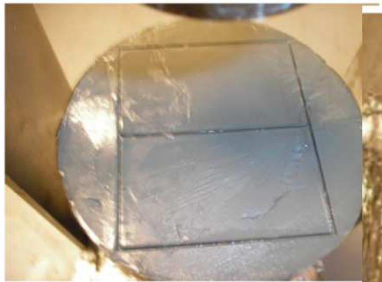
Schematics



Plane strain device
and specimen

The test material

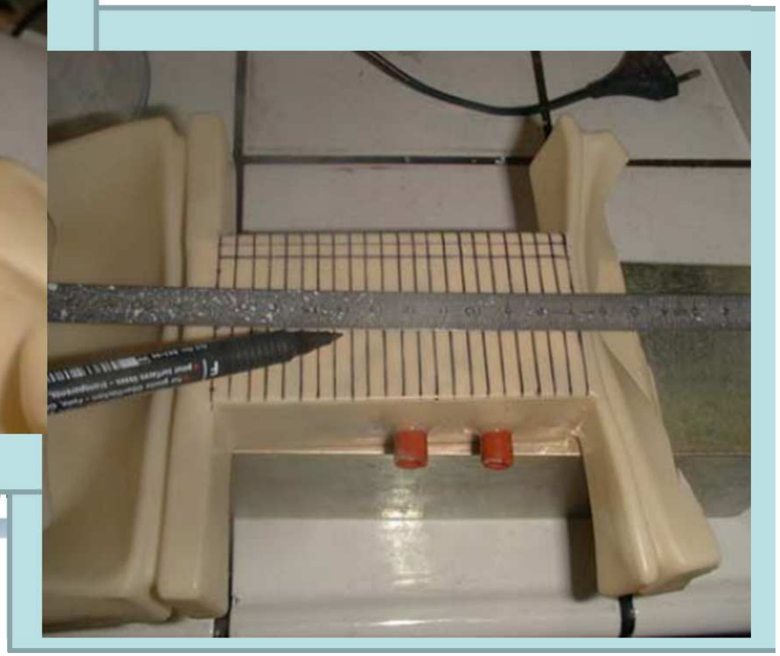
Marine Clay: Size 60mmx120mmx34mm extracted from 95 mm dia samples



Soil Parameters	This study	Sandven (1990)
Natural water content [%]	33-40	30-40
Specific gravity [-]	2.8	2.8
Unit weight [kN/m^3]	18.4-18.7	18.3-18.7
Liquid limit [%]	24-26	22-26
Plastic limit [%]	18	19-23
Plasticity index [%]	6-8	3-5
Undrained shear strength [kPa]	18-25	15-25
Remoulded shear strength [kPa]	0.1-0.3	0.1-0.3
Sensitivity S_t[-]	83-180	84-950

Preparation -1

Membrane preparation



Preparation -2

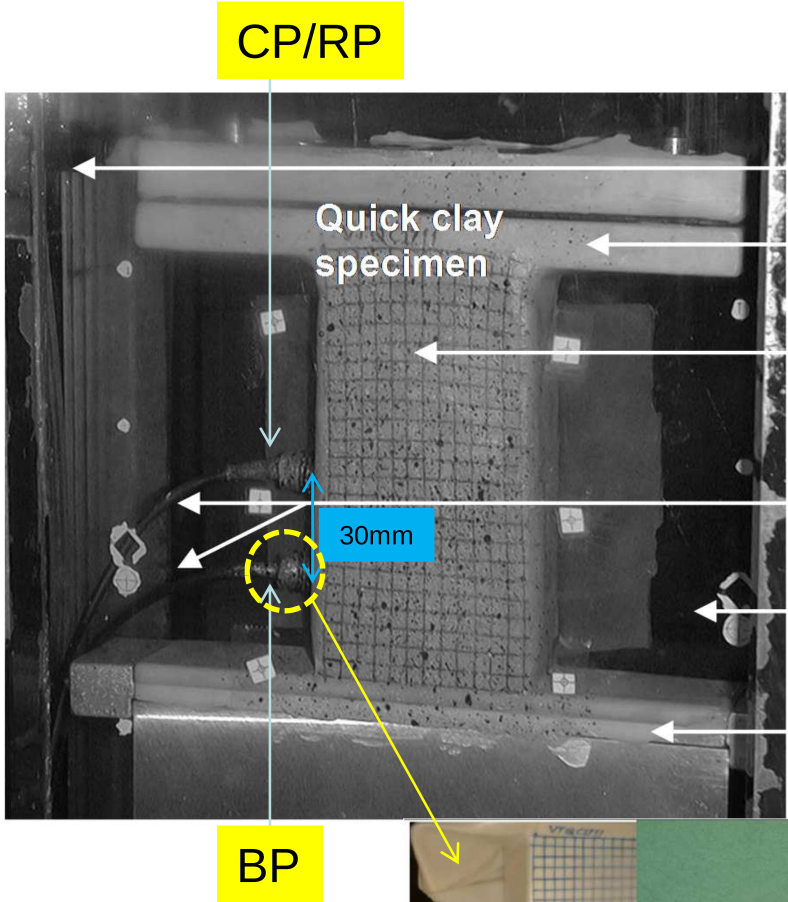
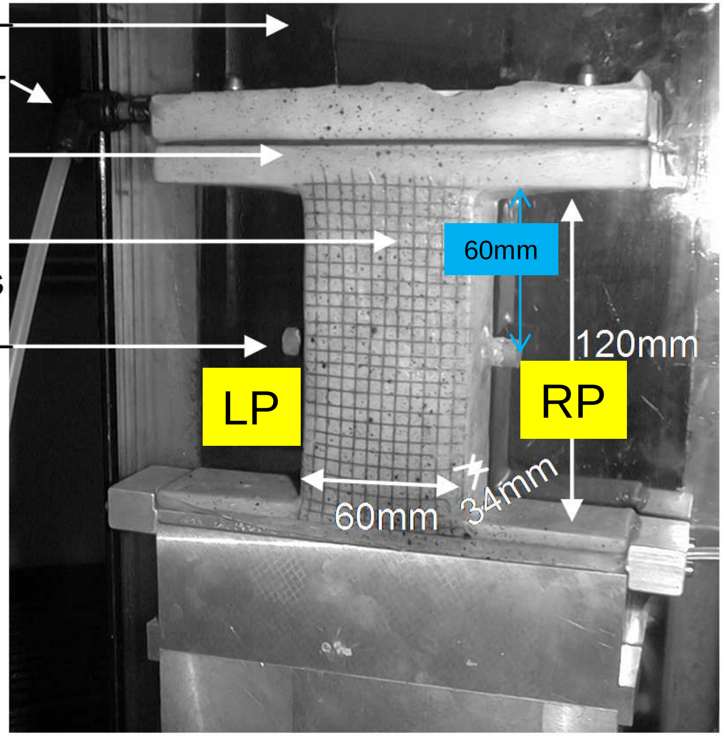
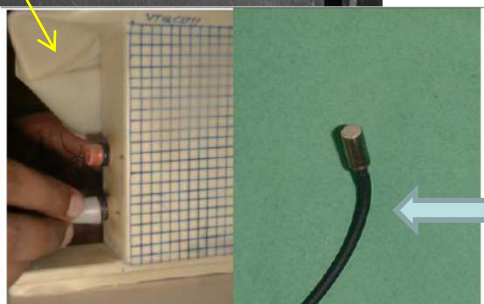
Sample holder

Inner Shell (sample)

Outer Shell (membrane)

SPECIMEN PREPARATION

The final assembly

Test Plan

Test *Consolidated* *Undrained shearing*	Deformation rate mm/min	Cell pressure (kPa)	Placement of the probes
T1	0.06	70	LP and RP
T2	0.06	60	CP and BP
T3	0.06	65	CP and BP
T4	0.06	63	CP and BP
T5	0.006	60	CP and BP
T6	**0.006**	**70**	**CP and TP**

0.06 mm/ min = 3%/hr strain rate
0.006 mm/ min = 0.3%/hr strain rate

A typical result from the consolidation stage

Observations

1. The probes were sensitive to capture even a small variation in pore pressure response.

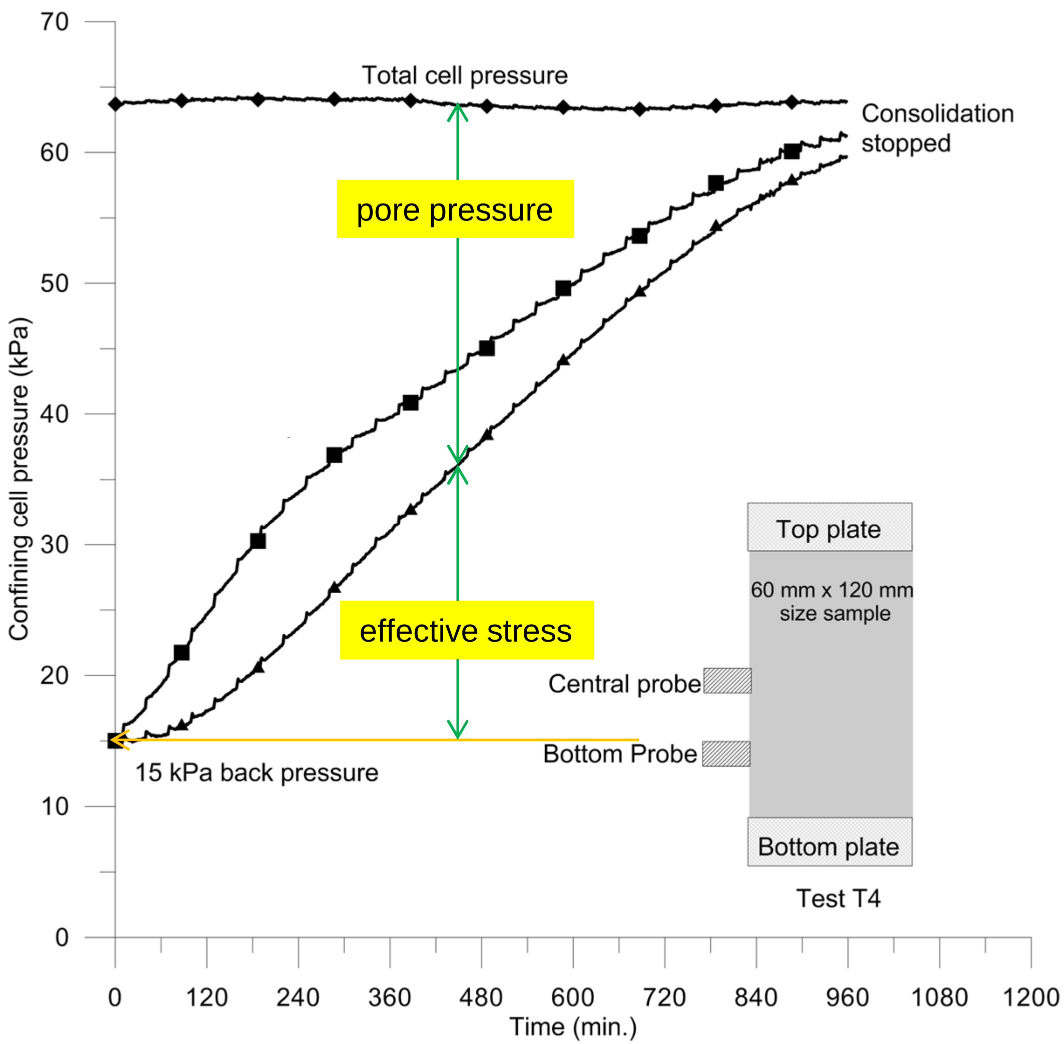
2. 50% consolidation
   - 6-8 hrs.

3. 90% consolidation
   - 15-16 hrs.

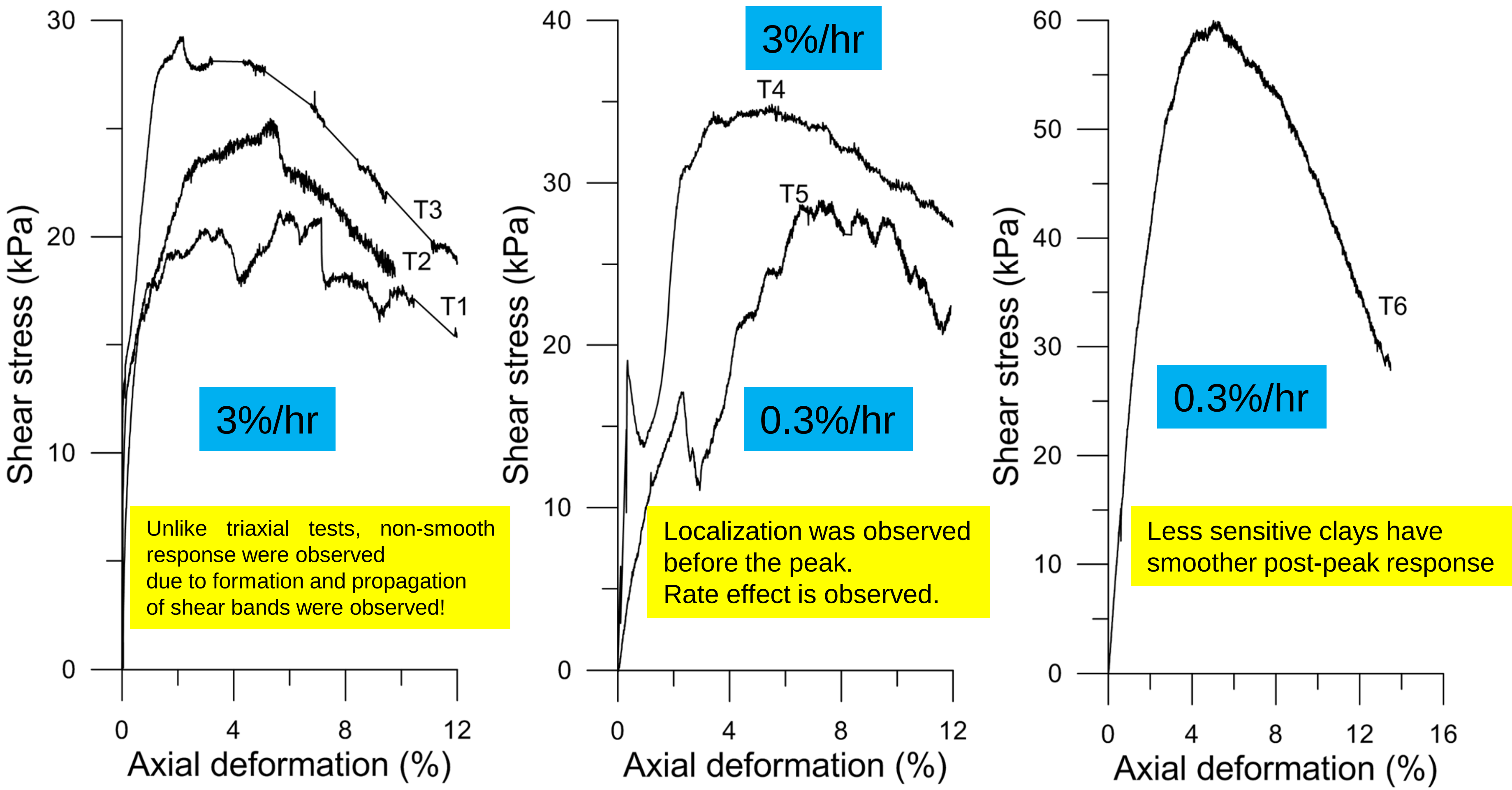
4. Some residual pore pressure in the middle of sample.

5. Plane strain condition was created before the consolidation phase. This also implies that the consolidation was somewhere in between isotropic and Ko-condition.

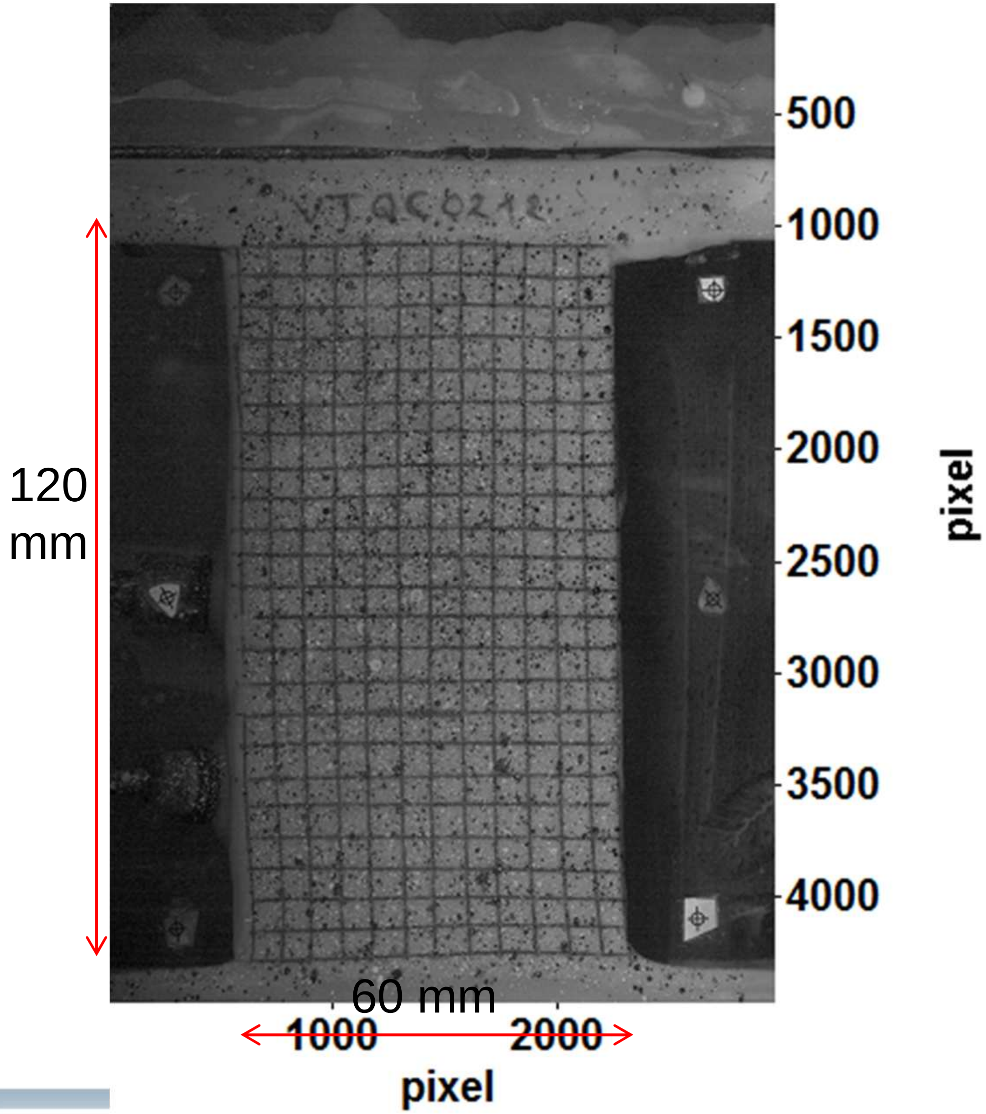
6. Silicon oil was used as the cell fluid. The oil avoids the errors due to the refractions while taking images



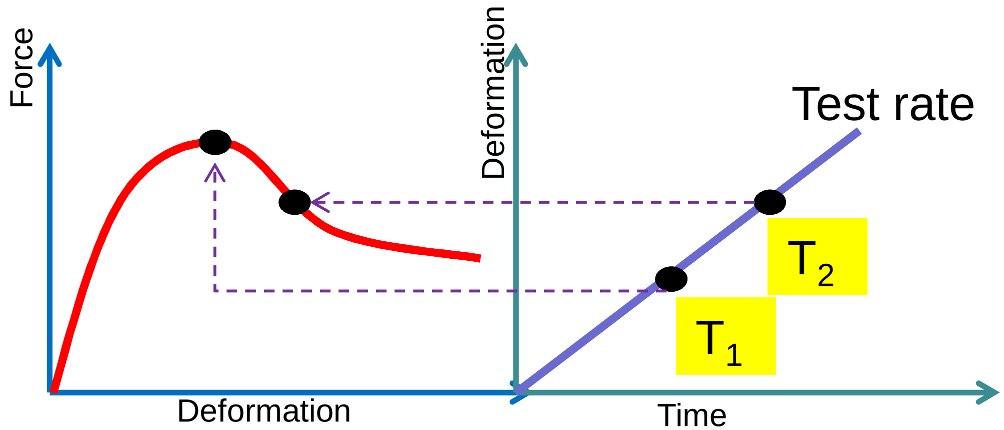
The observed stress-strain response



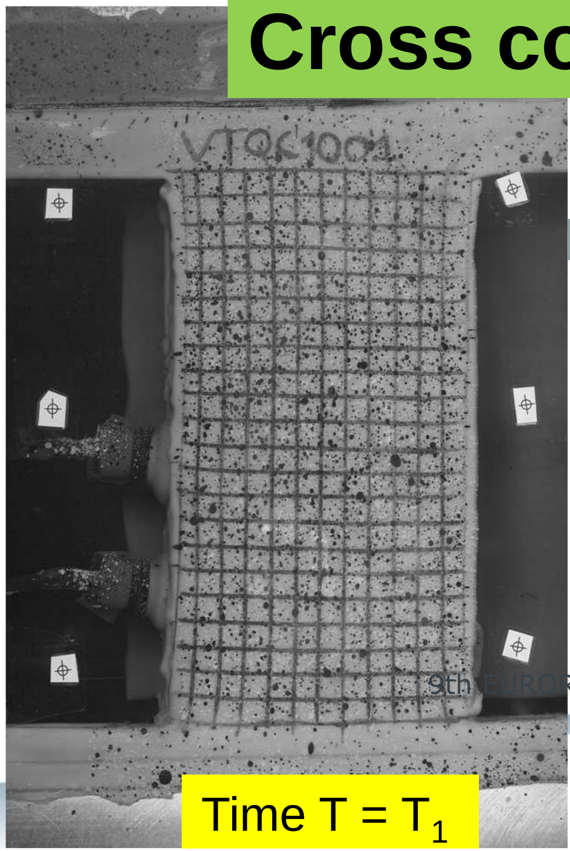
A Marine clay sample during the Plane-strain testing



Partical Image Velocimetry analysis

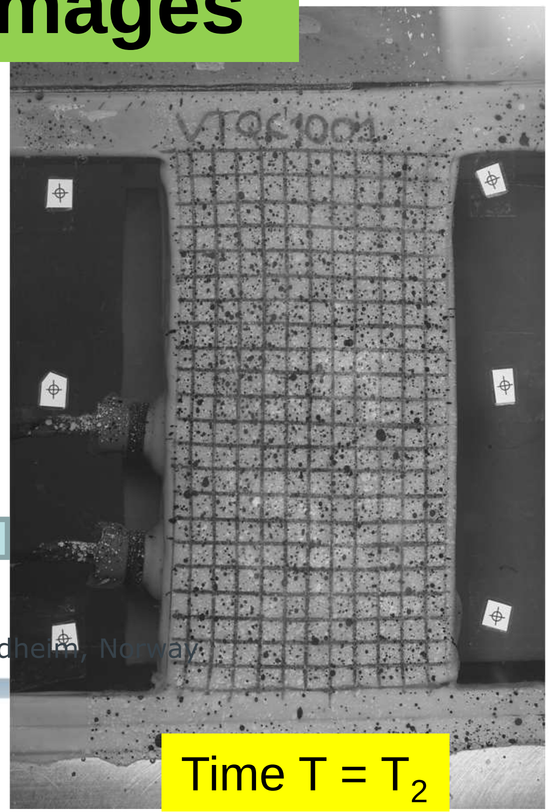


Cross correlation of two images



Davis LaVision Software

2D correlation



Test T2

Observations

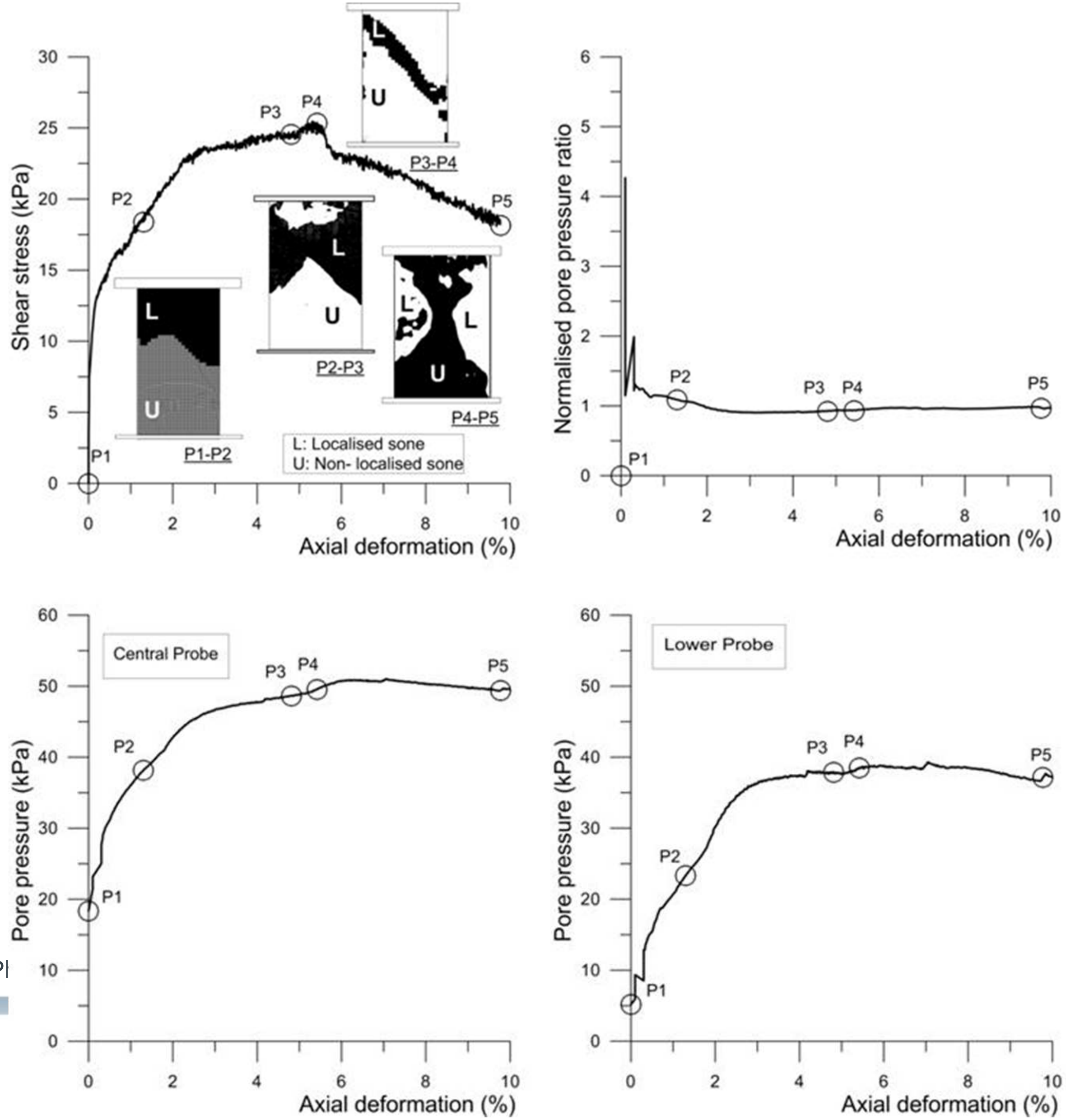
1. Non-uniform deformation was observed before the peak.

2. The peak capacity was around 5.5% axial strain compare to 1-3% what is often seen in the triaxial testing.

3. A distinct shear band (order of 3-5 millimetres) at the peak is observed. The orientation is 48.8º wrt. to the horizontal axis

4. There is a sharp drop in the shear stress soon after the peak. This could be an indication of a fully developed shear band.

5. Corresponding pore pressure plot also show that a sharp increase in the rate of pore pressure
6. Further discussion on the pore pressure is made later



Test T6

Observations

1. Slower rate gives smoother stress-strain response

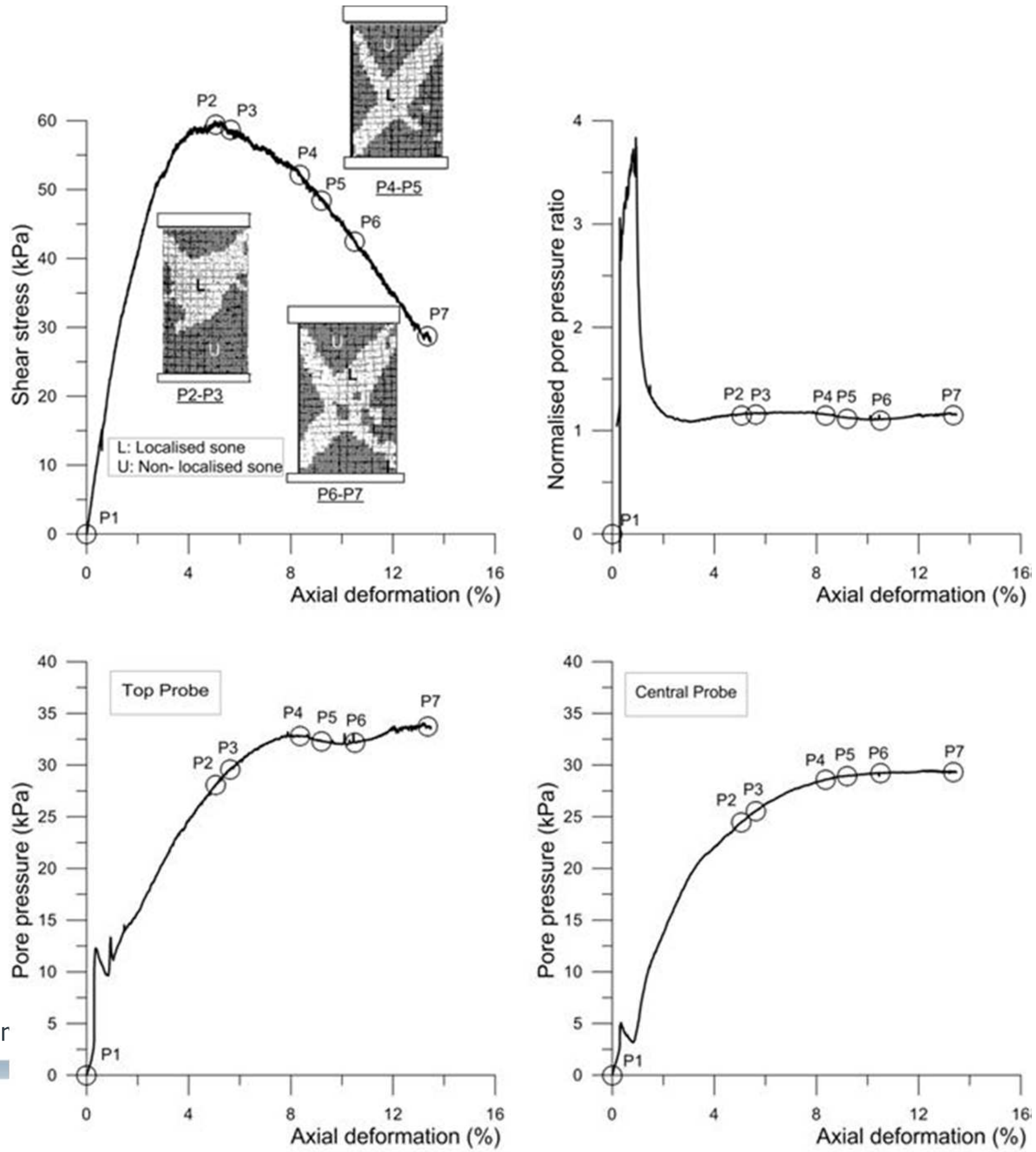
2. The peak capacity was around 4-5% axial strain compare to 1-3% what is often seen in the triaxial testing.

3. Shear band (order of 5 millimetres) has emerged at the peak.

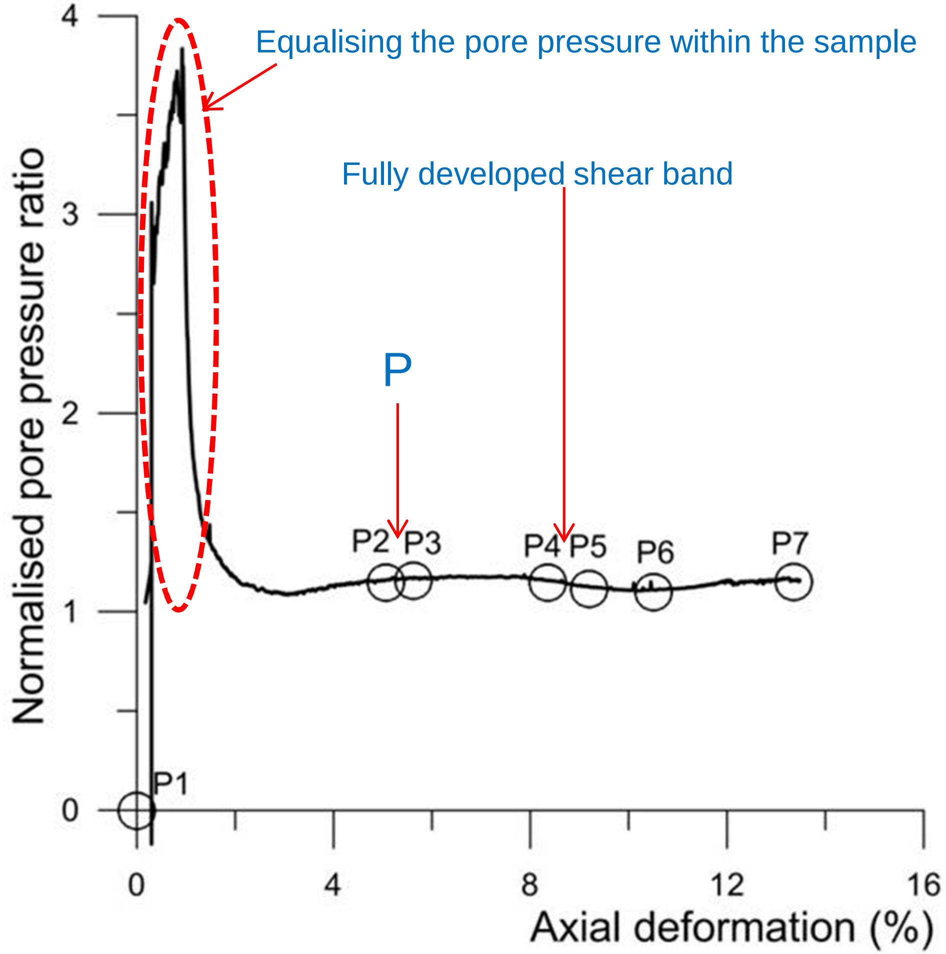
4. Shear band has fully developed, gradually, towards the post-peak softening
5. The shear band is slightly curved and has non-symmetry. It seems the shear band inclined to the right is thicker than the one inclined to the left side of the vertical axis.

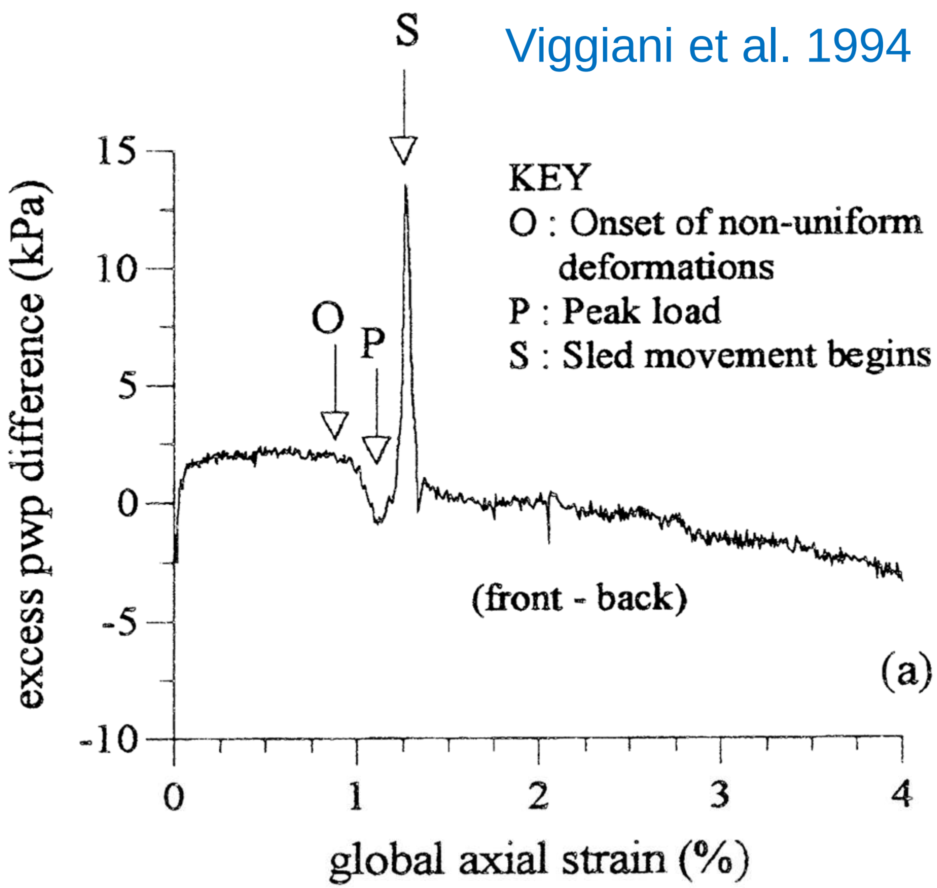
6. The shear band inclination is around 51 degrees from the horizontal axis

7. Further discussion on the pore pressure is made later

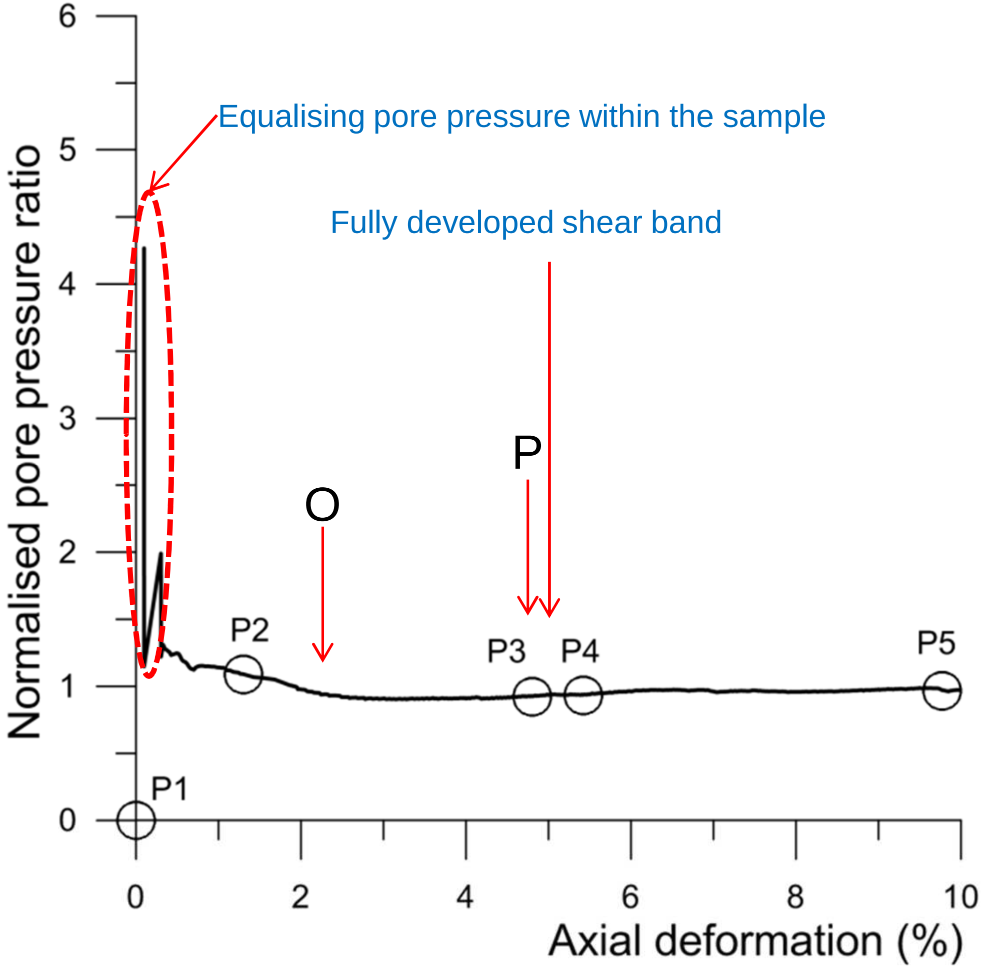


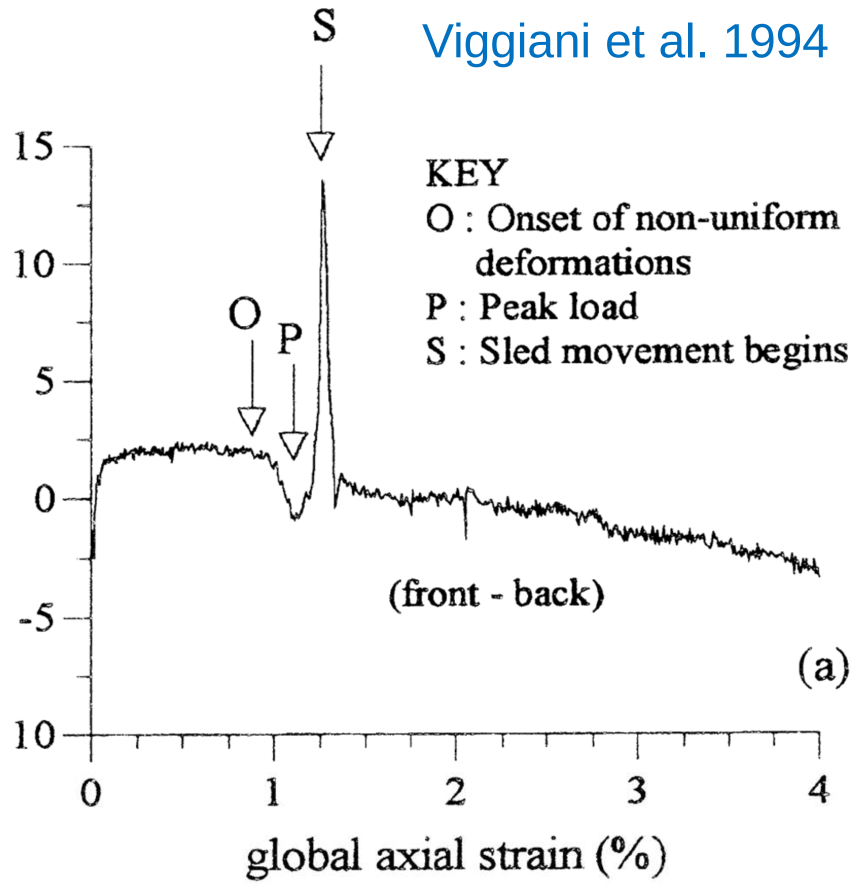
Comparison: Test T2 and Viggiani et al. 1994





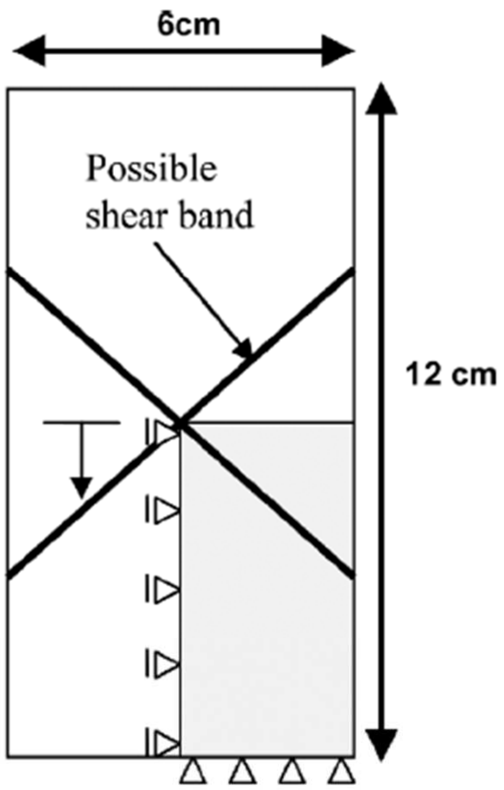
Comparision: Test T6 and Viggiani et al. 1994





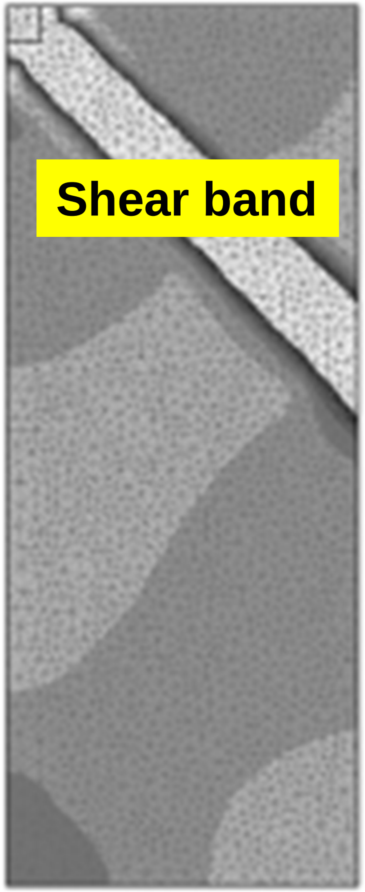
Back calculation

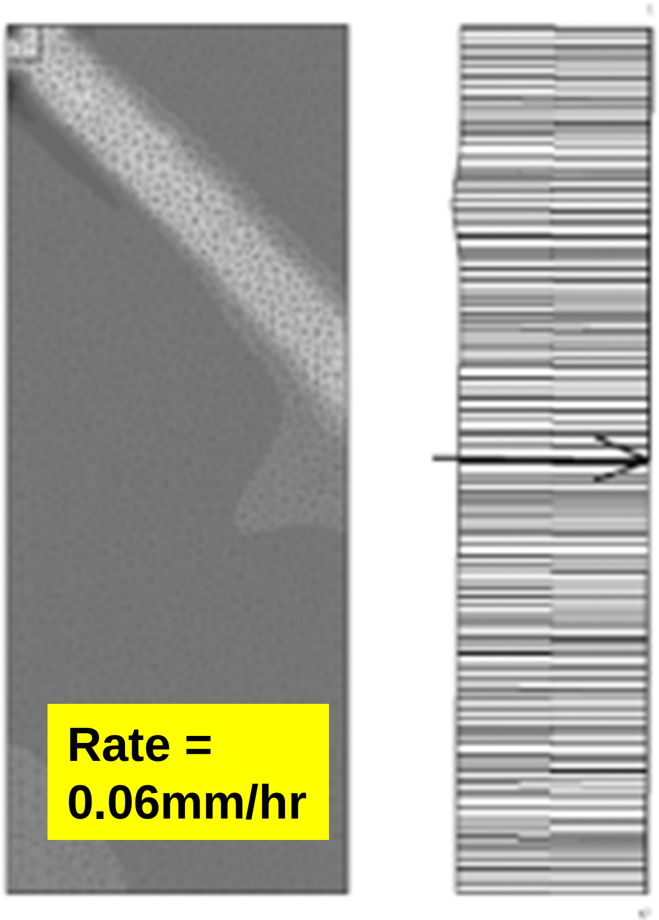
- Finite element modelling



Thakur (2011)

Rate = 0.06mm/hr





Thakur (2011)

t_{sb} = 7 element size = 3.50 mm (bigger than the size of the perturbation)

pore pressure plot

Pore pressure distribution inside and outside the shear band is nearly the same.

Closing remarks

- There was no dramatic collapse of clay structures during the plane strain testing.
- A physical thickness of shear band do exist in marine clays.
- The observed thickness is in order of a few millimetres (3 to 5.0 mm). The thickness on the images appeared to be more due to the membrane effect.
- The orientation of shear band is not necessarily be 45 degree wrt. minor principal axis.
- The orientation is influence by the local drainage of pore water pressure.
- A distinct pore pressure jump was not observed during the onset of localization for marine clay. This is mainly due to the fact that formation and propagation of shear bands in the marine clay was a smooth process.
- The adopted deformation rates were proven to be slow to create a local drained condition.
- PIV analysis provides vital information regarding formation and propagation of shear bands.

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Thank you for your kind attention!

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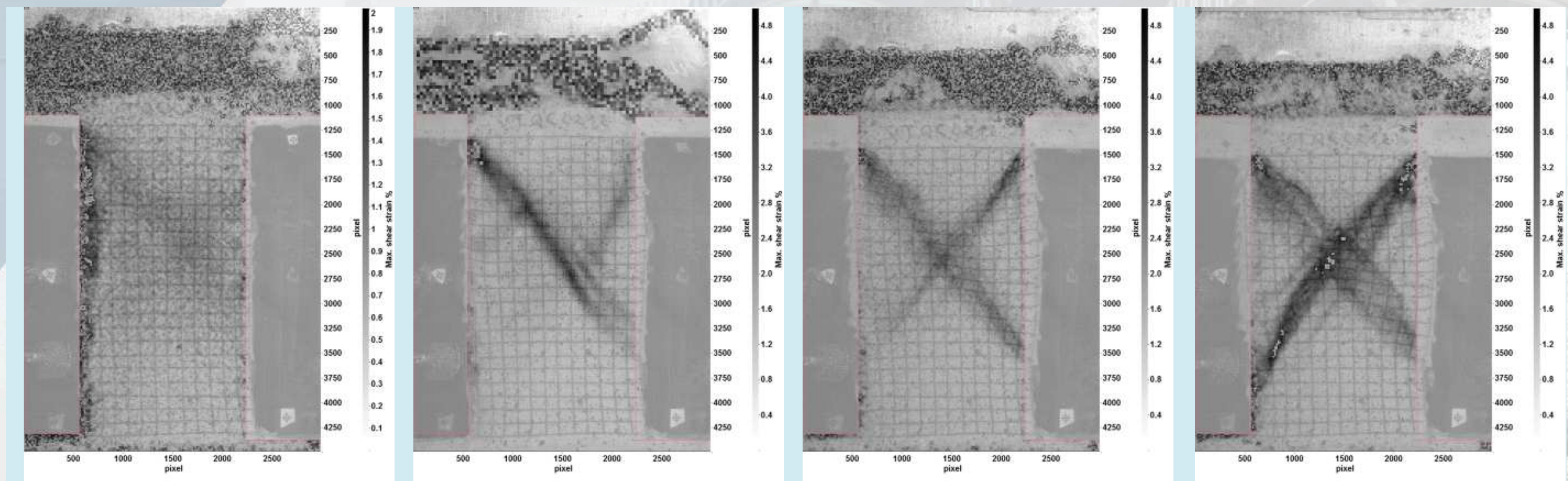

Foto: Colourbox