Primary Consolidation and Creep of Clays

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Administration

To begin with…..

- This study was motivated by the core theme of 1st CREBS workshop held in Oslo in 2006.

- In CREBS II (Pisa, 2007) a need for in-depth study, e.g. in form of a PhD study, was stressed by Adjunct Professor Hans Petter Jostad.

- This study was then initiated and conducted at Norwegian University of Science and Technology (NTNU) (2007–2011) in collaboration with Norwegian Geotechnical Institute (NGI) and Chalmers University of Technology.

- Researchers who are directly involved in this work are acknowledged as
  - ✓ Hans Petter Jostad (NGI)
  - ✓ Gustav Grimstad (NTNU)
  - ✓ Steinar Nordal (NTNU)
  - ✓ Mats Olsson (Chalmers and NCC)
  - ✓ Peter Hedborg (Chalmers)

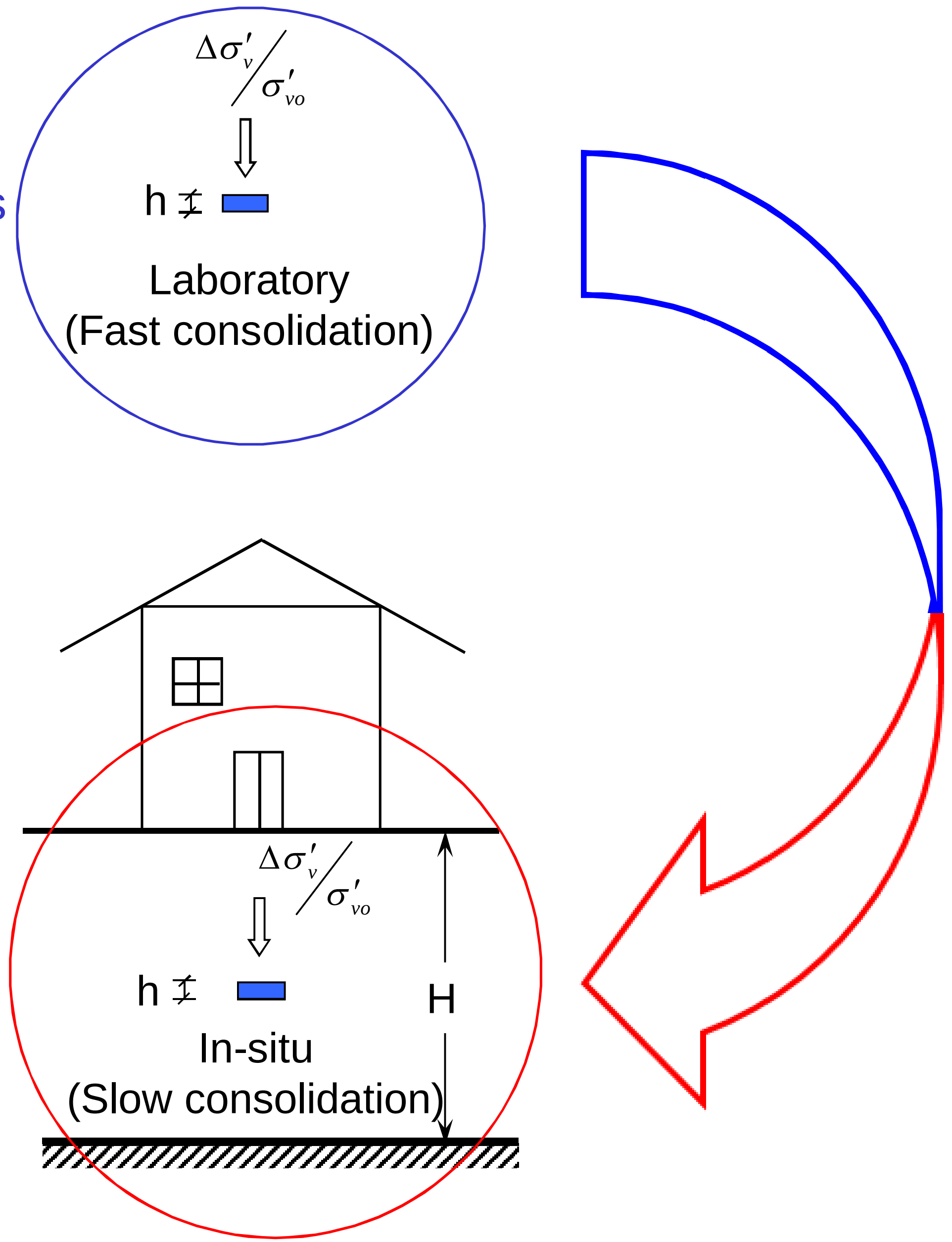
- The work has also benefited from valuable feedbacks, discussions and review critics by several other researchers.

General

Measurements

Significantly different consolidation times

Prediction



Two hypotheses on role of creep during primary consolidation

- Proposed by Ladd et al. (1977). "*Does creep act as a separate phenomenon while excess pore pressures dissipate during primary consolidation?*"

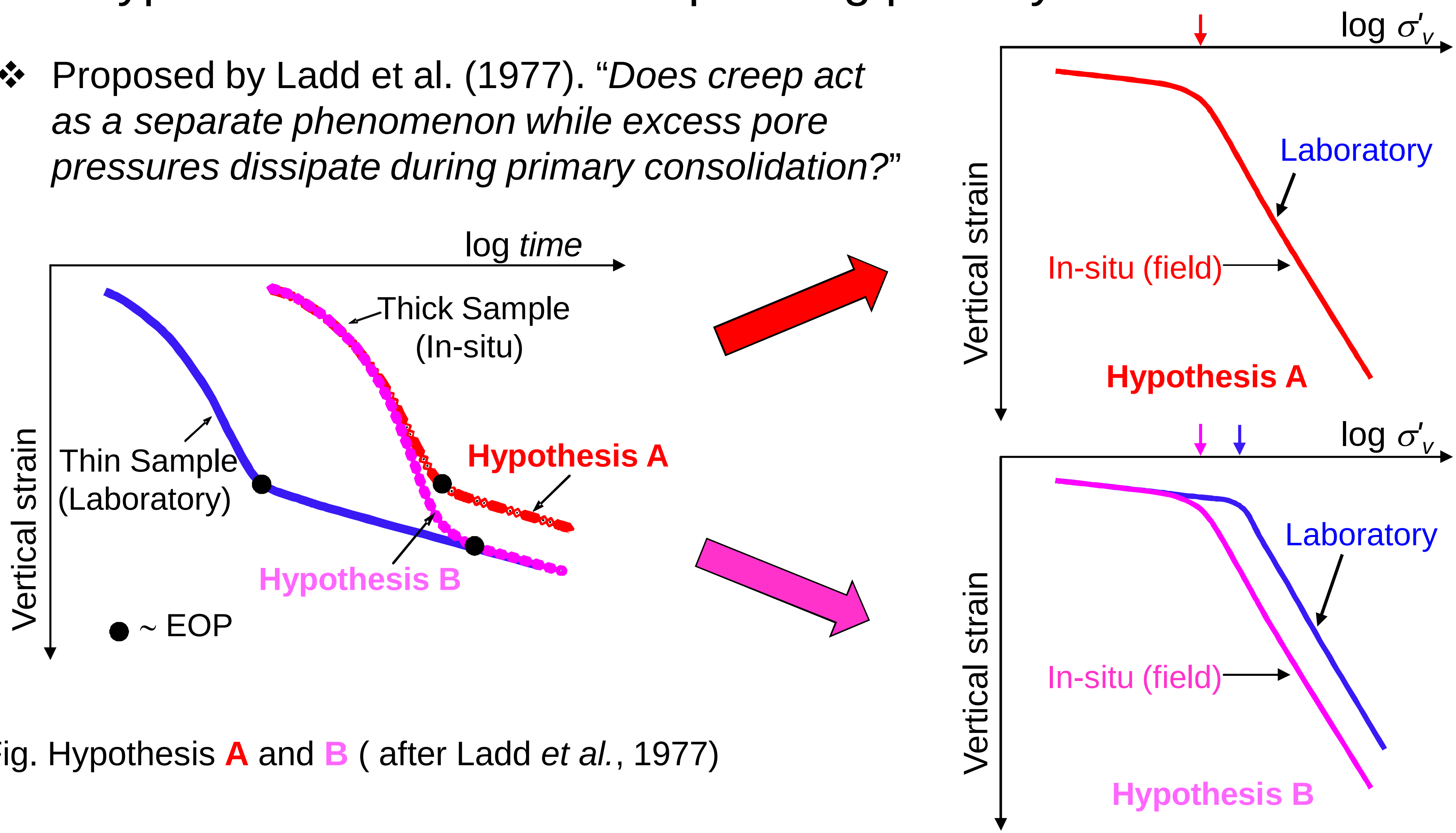


Fig. Hypothesis **A** and **B** (after Ladd *et al.*, 1977)

- Advocates of the two different creep hypotheses have *independently* presented voluminous laboratory and field data to substantiate their opinions.

Experimental substantiation of the two hypotheses, e.g.

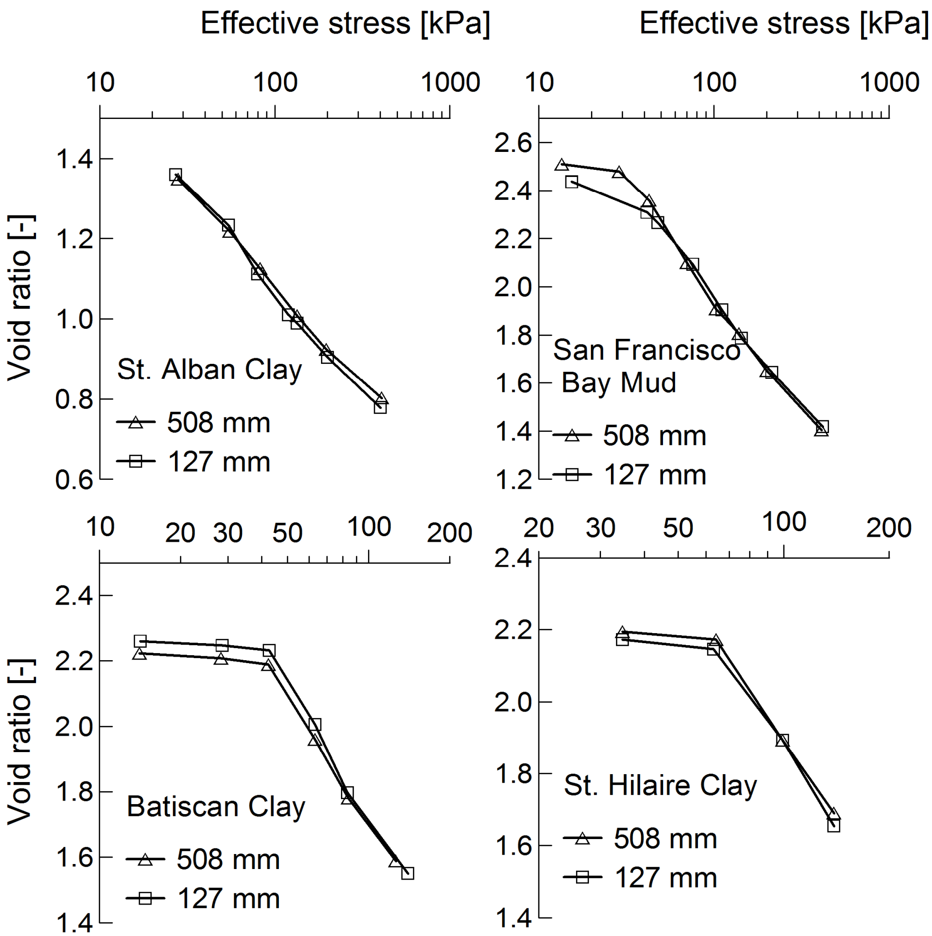


Fig.: EOP laboratory tests supporting **hypothesis A** (after Choi, 1982; Feng, 1991)

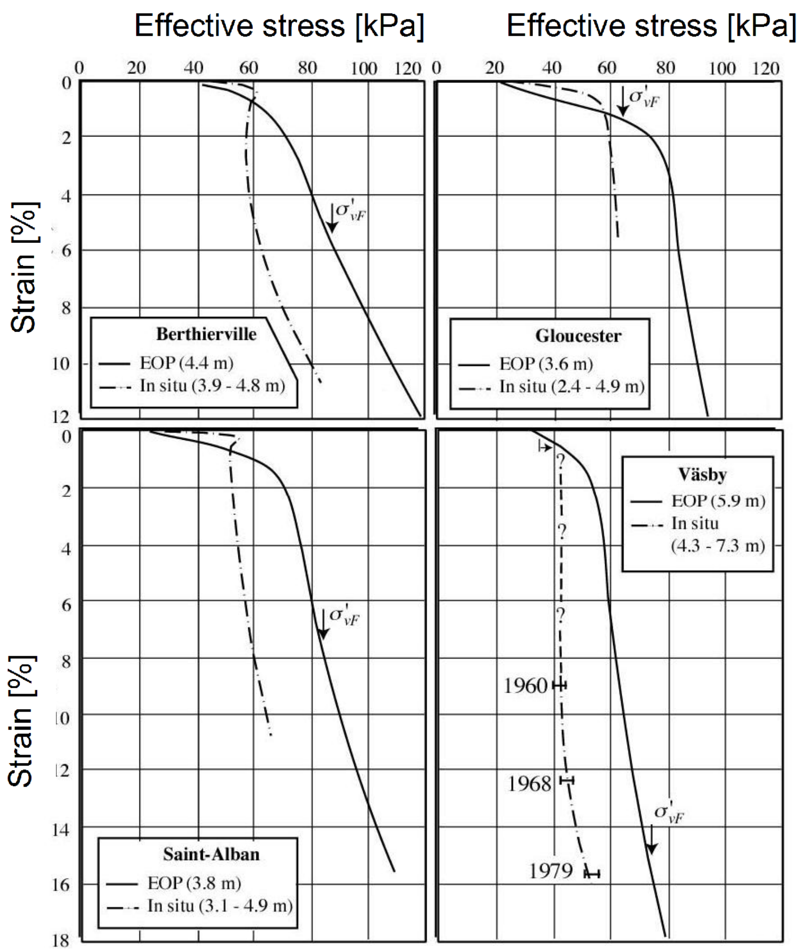


Fig.: In-situ and EOP laboratory tests that support **hypothesis B** (after Kabbaj *et al.*, 1988)

Numerical substantiation of the two hypotheses, e.g.

- Analysis of field cases using constitutive models based on the two hypotheses

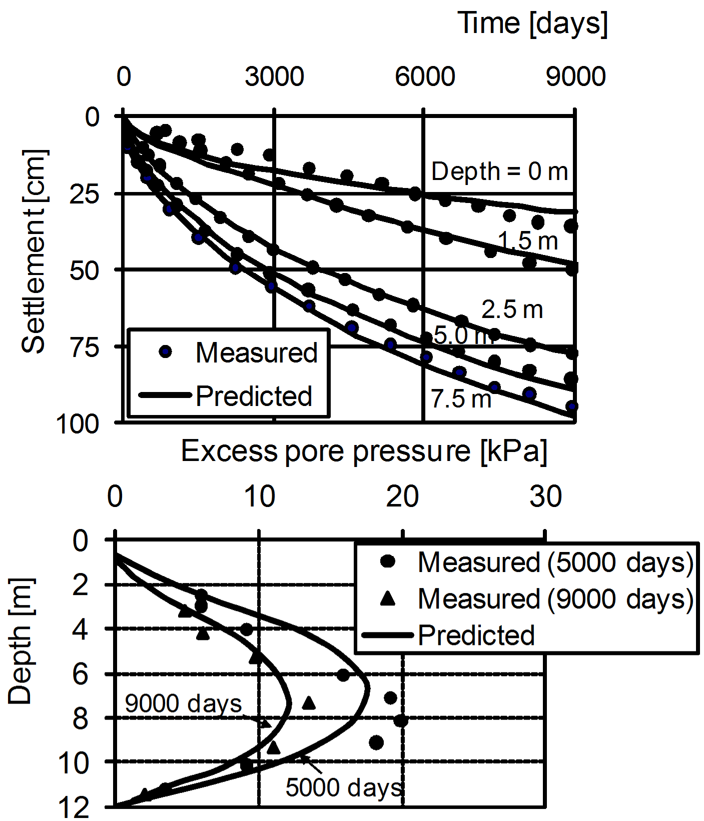


Fig. : Measurement Vs. predictions at Skå-Edeby test fill using **hypothesis A** model (after Mesri and Lo, 1989)

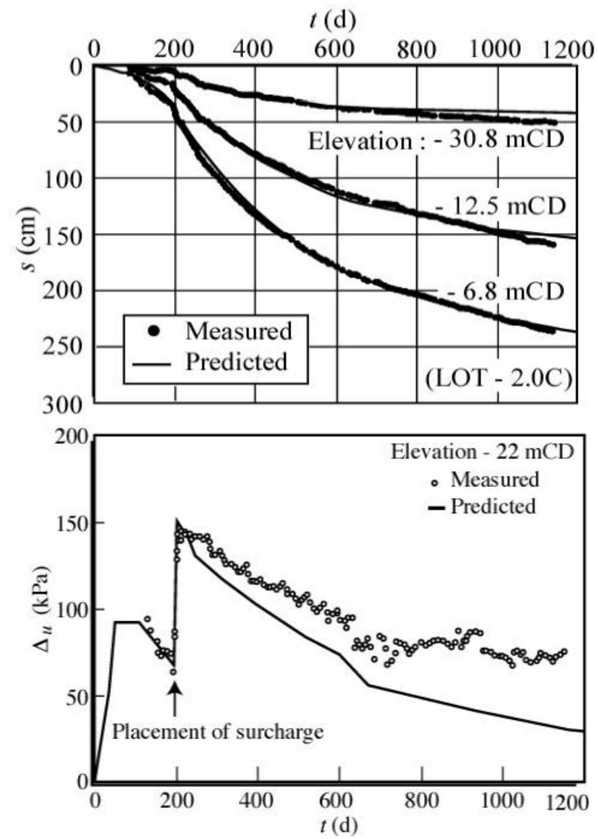


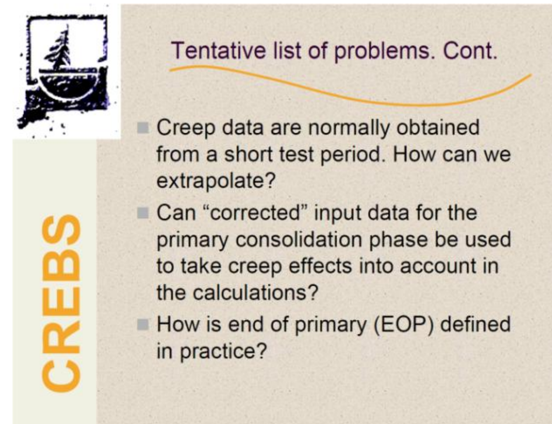
Fig. : Measurements Vs. predictions at Changi Airport using **hypothesis B** model (Cao *et al.*, 2001)

More on the two creep hypotheses

- With an inclination to hypothesis A, Ladd *et al.* in 1977 concluded that "*little definitive data exists to show which of the two hypotheses is more nearly correct for the majority of cohesive soils*".
- Ever since, the topic became a topic of active debate and discussion and remained to be an issue that needed to be resolved.
- This discussion was re-started by NGI in 2006 at 1st CREBS workshop, where advocates from both sides as well as others have attended.
- In 2007, this study was initiated and carried out at NTNU, NGI and Chalmers with additional funding from ICG (International Center for Geohazards).

Main motivation and objectives – CREBS I

- How to extrapolate creep from short time observation to long term predictions ?
- The two conflicting hypotheses are well substantiated with laboratory and field data. Why ?
- Constitutive models based on the two hypotheses are seen to produce acceptable field predictions. Study and evaluate the models based on field cases.
- To increase understanding on time- and stress-compressibility of clays during primary consolidation.
- To produce the most convincing creep hypothesis and a numerical tool that can consistently explain laboratory and field observations.



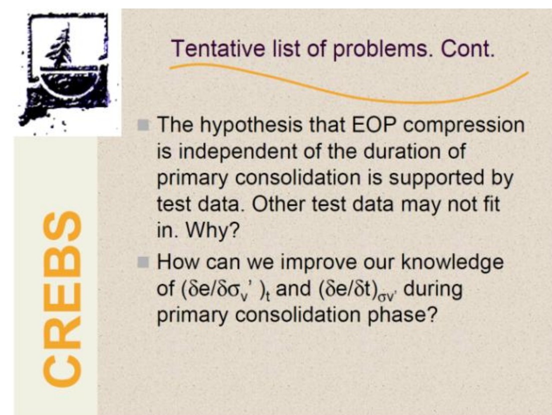


Fig. : Tentative list of problems as presented in the 1st CREBS workshop (Jostad, 2006)

Outline of the presentation

- Laboratory studies
  - Part I: Specimens of varying thicknesses
  - Part II: Soil element compressibility (varying consolidation duration)

- Field studies

- Present the hypotheses for a specific case
  - A look at the relevant laboratory tests
  - Numerical studies

Laboratory studies I: Creep hypotheses for varying soil layer thicknesses

- EOP strain-effective stress relationships: the creep hypotheses

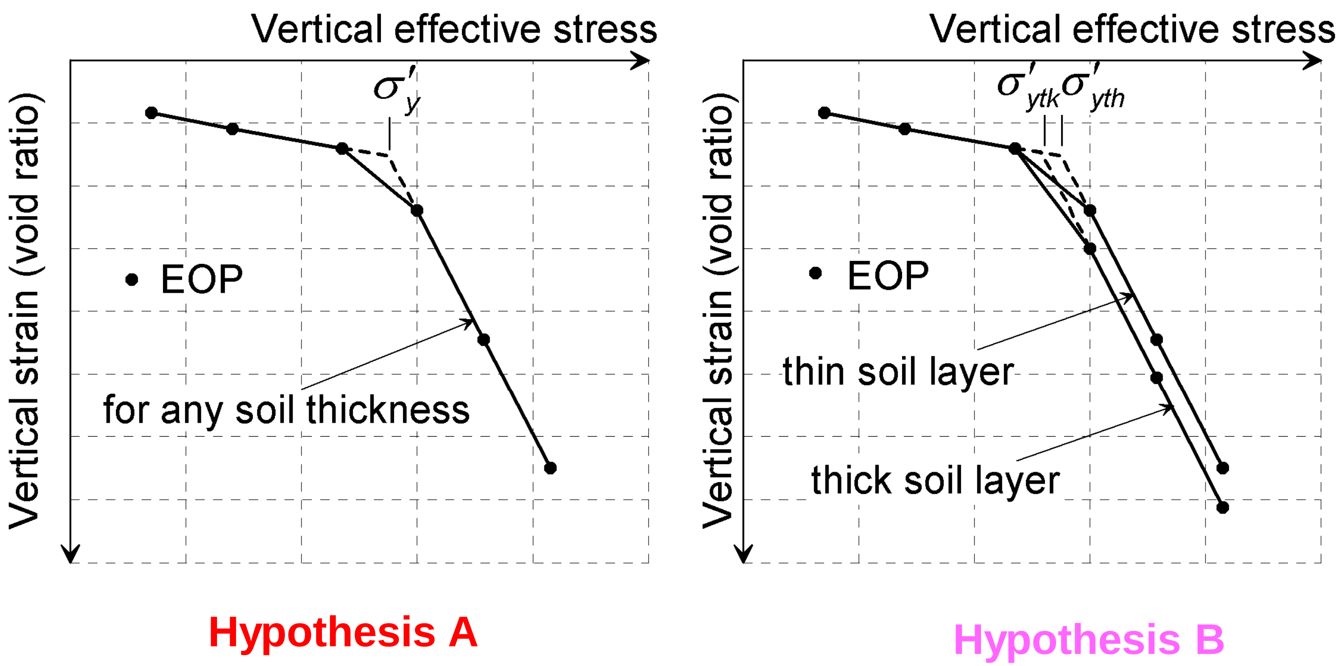


Fig.: Principle sketch of the two creep hypotheses for varying soil layer thicknesses

- EOP strain-effective stress relationships: laboratory tests

- End effects (testing problem) ?

- Strain rate effects ?

✓ Evaluate the 508 mm thick specimen (the action and the reaction)

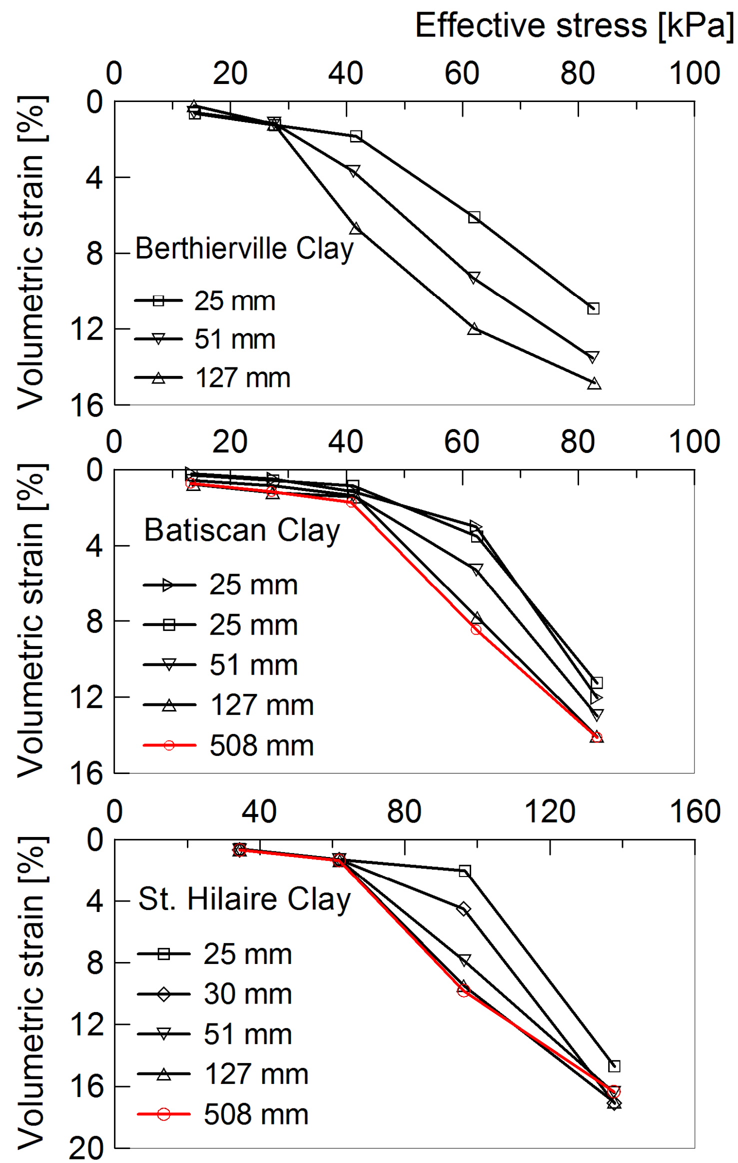


Fig. : EOP ΔV/Vo–σ′ relationships for various thicknesses (after Feng, 1991)

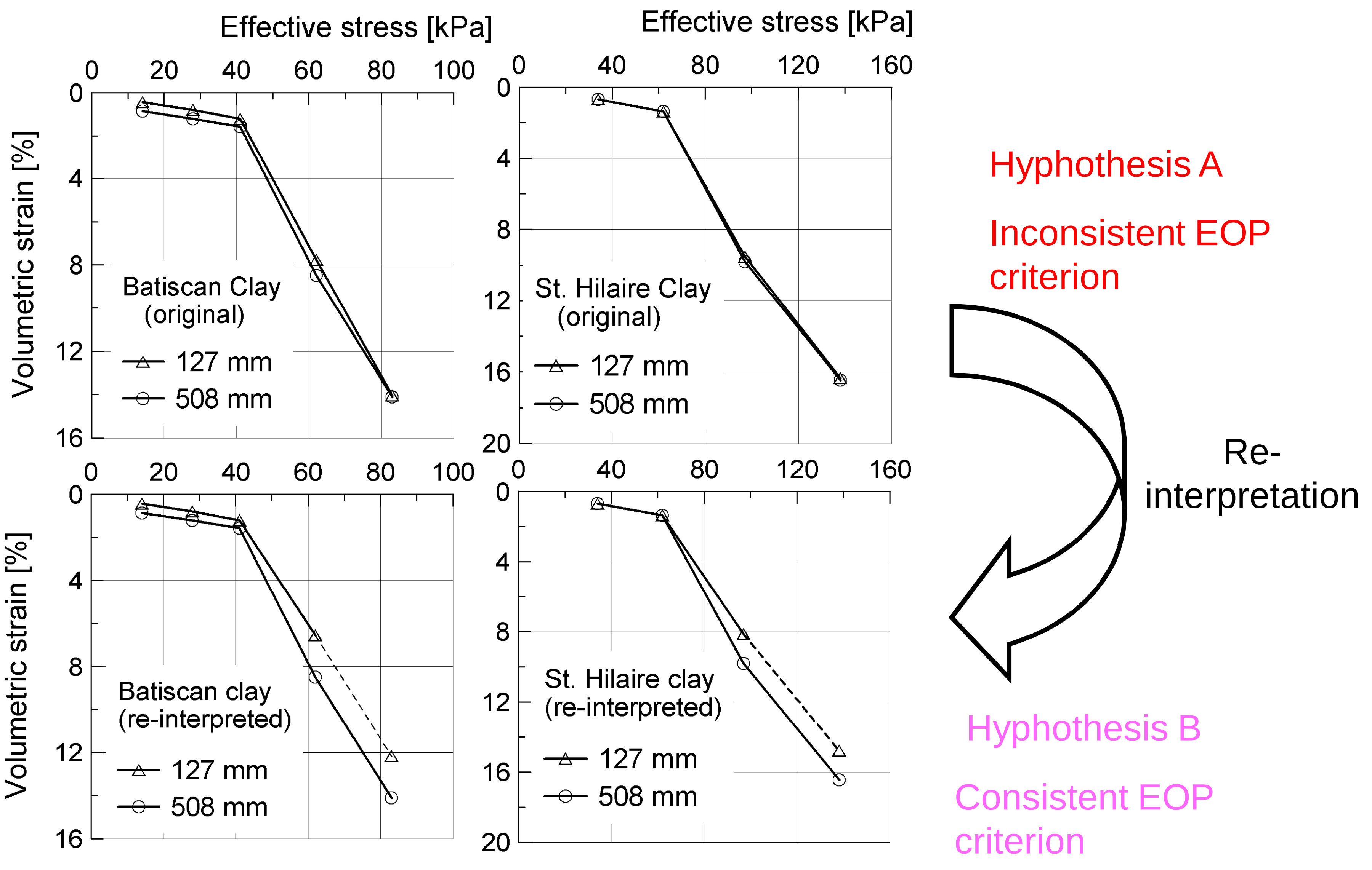


Fig.: Original and re-interpreted volumetric strain–effective stress relationships

Numerical study of raw experimental data with hypothesis B model

- Similar load sequence and duration adopted from the actual test.
- Identical set of soil parameters for the thin and thick specimen
- Three load increments with respect to p'_c

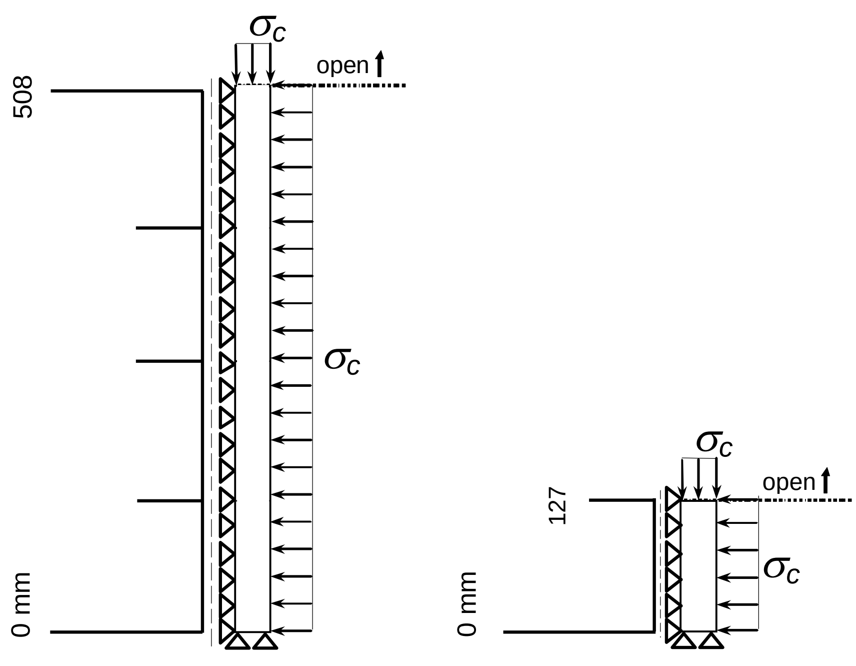


Fig.: Axisymmetric FE-model of the triaxial specimens

- Numerical study of raw experimental data with hypothesis B model

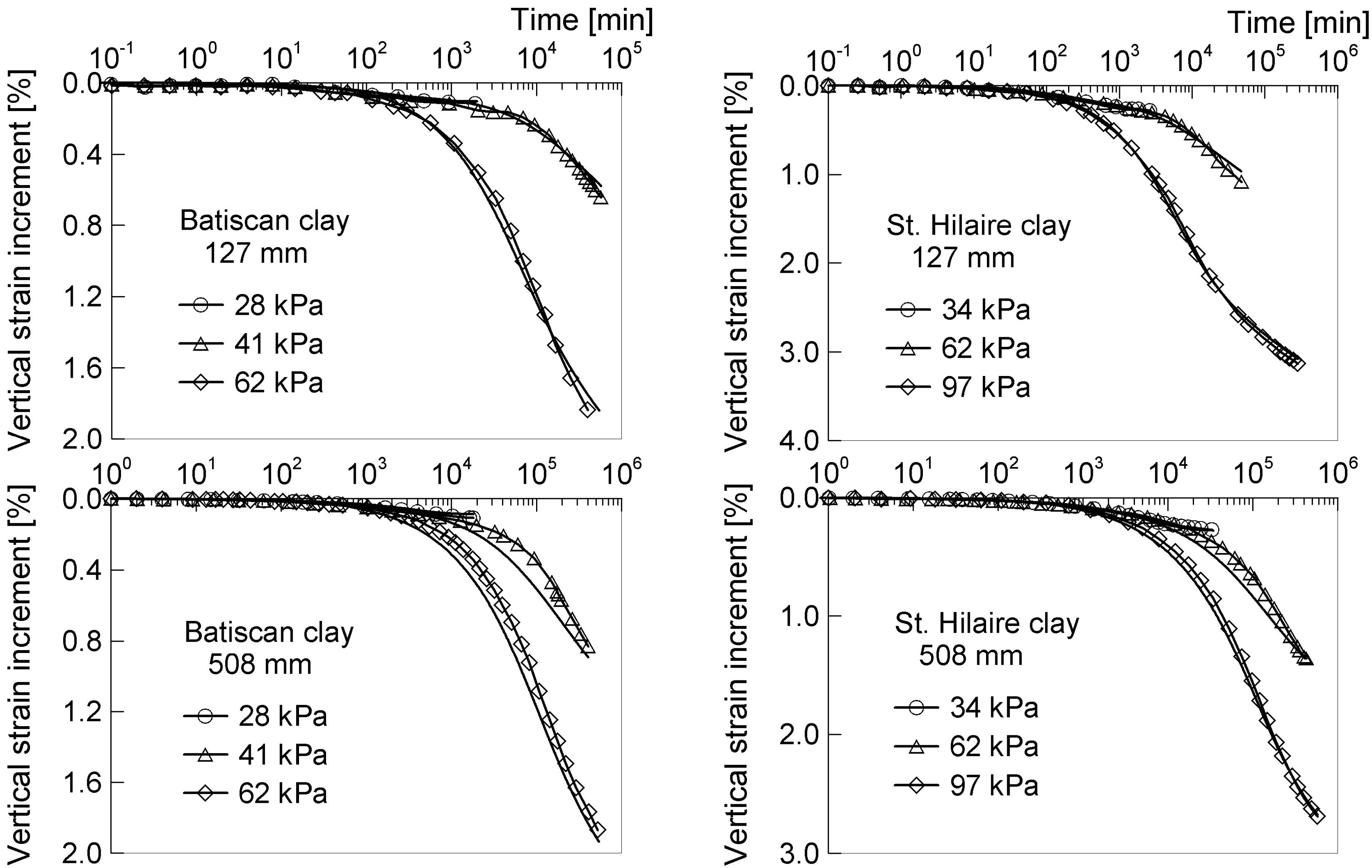
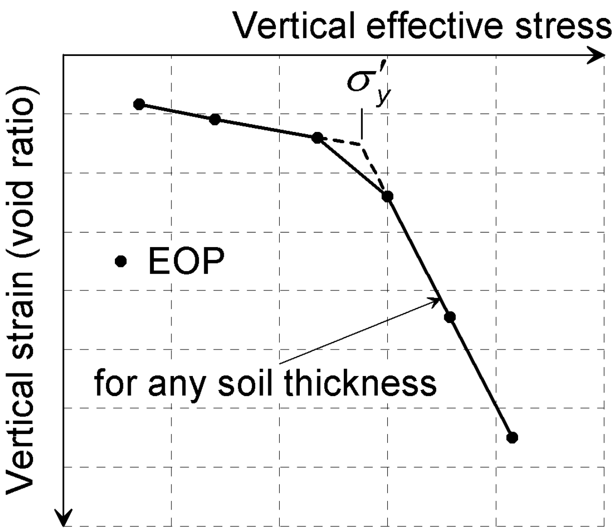


Fig.: Numerical simulation (smooth lines) vs. measurements (lines with symbols)

Strain-time relationships: the creep hypotheses

- Hypothesis A



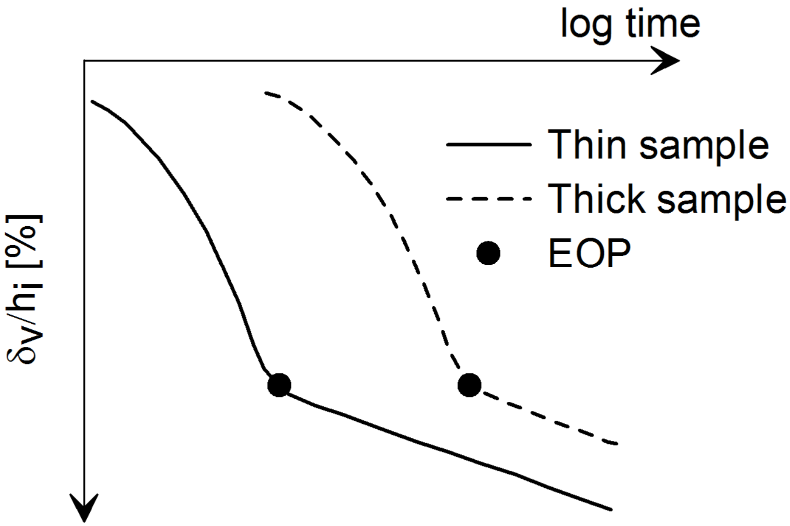


Fig. : Principle sketches of action–response relationships according to hypothesis A

- Hypothesis B

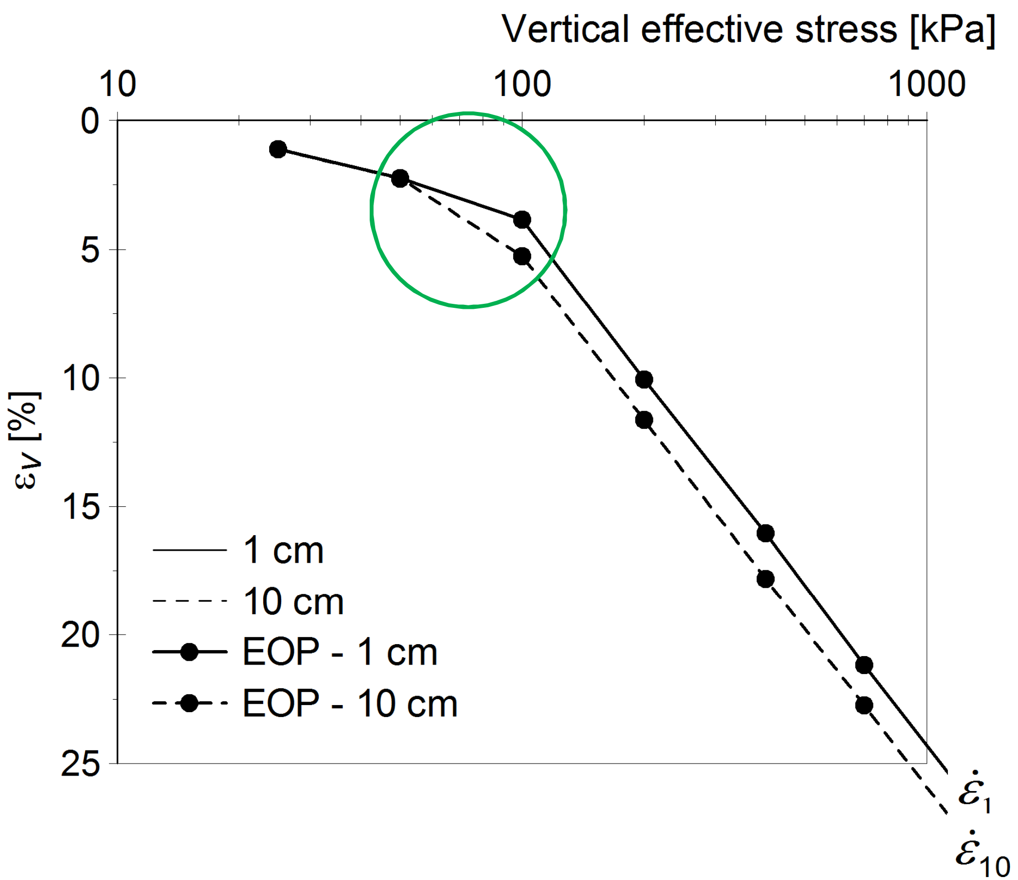


Fig.: Effective stress–Strain and Strain-Time relationships according to hypothesis B

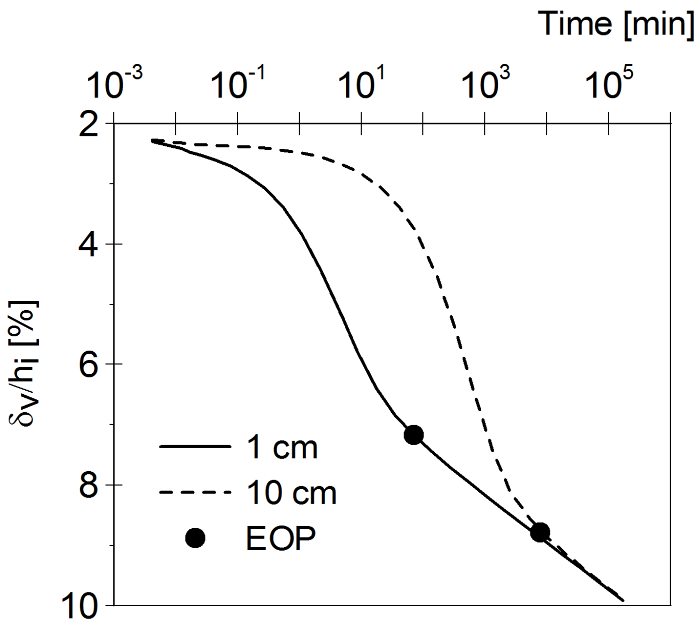


Fig. : $\Delta\sigma'$ = 50–150 kPa, p'_c = 100 kPa (allowed to creep at 150 kPa for 100 days)

- Hypothesis B

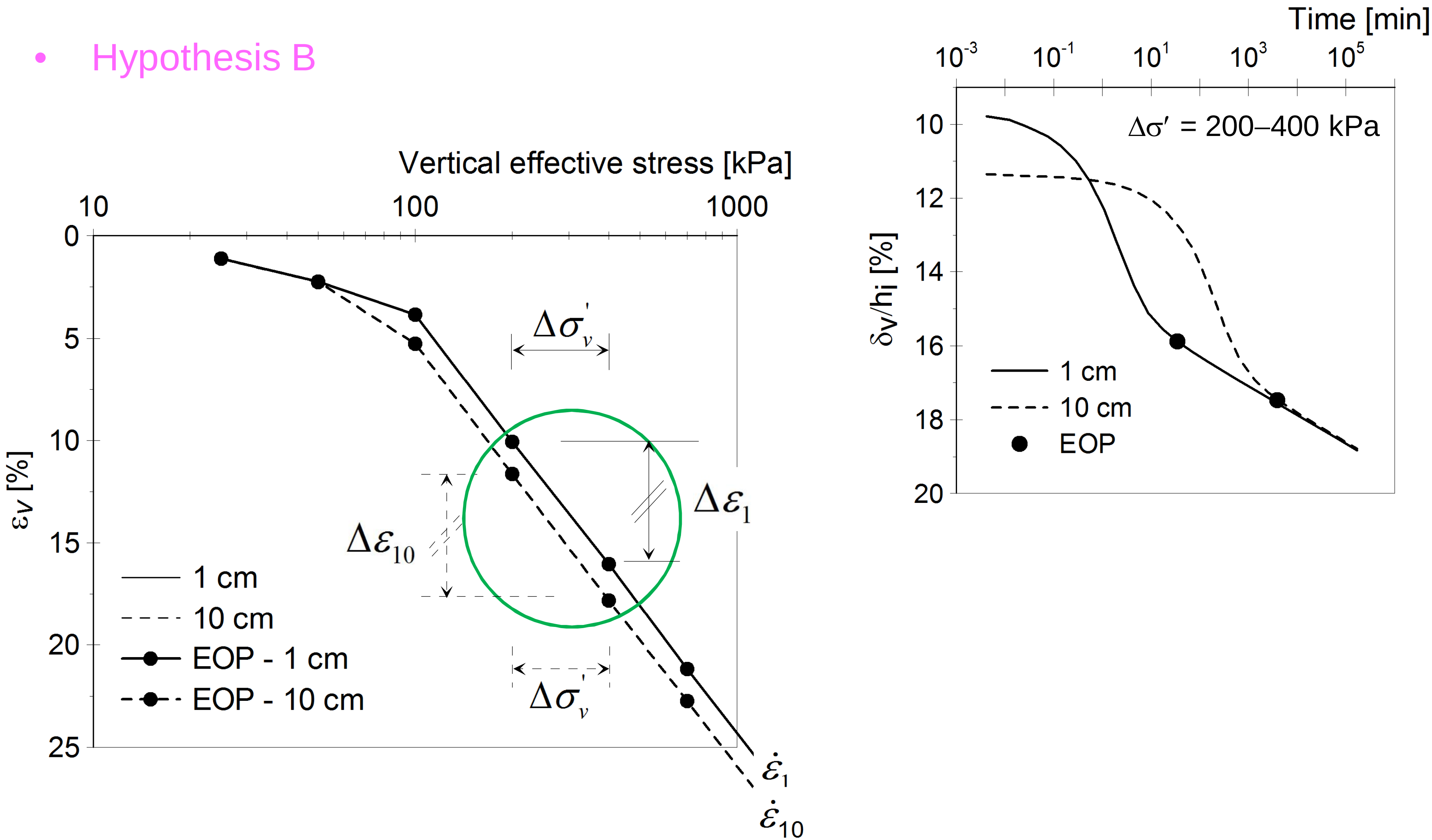
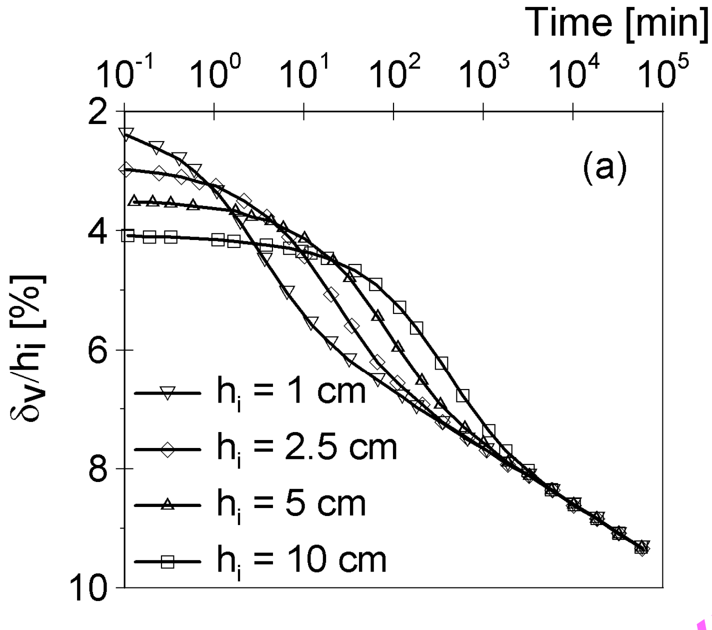


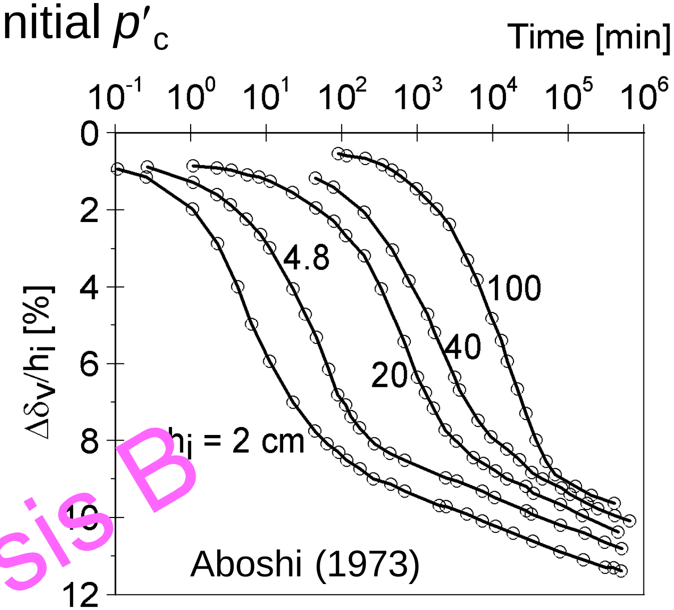
Fig.: Effective stress–Strain and Strain-Time relationships according to hypothesis B

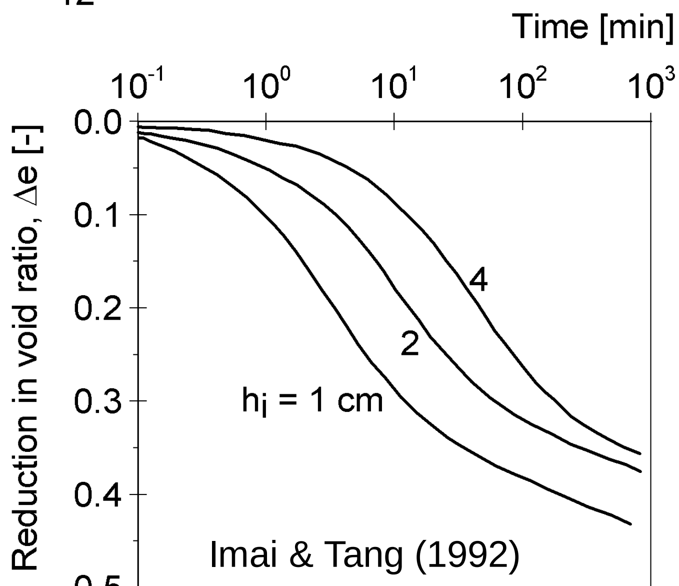
Some typical experimental observations

- Single load increment tests after exceeding initial p'_c



Konovalov & Bezvolev (2005)





Hypothesis B

(Degago et al. (2011), *Géotechnique* 61(10))

Laboratory studies I: Creep hypotheses for varying soil layer thicknesses

Final remarks

- ✓ Laboratory tests on specimens of varying thicknesses imply hypothesis B.
  - EOP strain-effective stress relationship is not unique.
  - EOP strain increases with increasing consolidation duration

- ✓ Numerical simulation results using hypothesis B model can explain experimental measurements.

Laboratory studies II: Creep hypotheses for soil element compressibility

- The two hypotheses are best differentiated by consolidation duration of soil layers than soil layer thickness

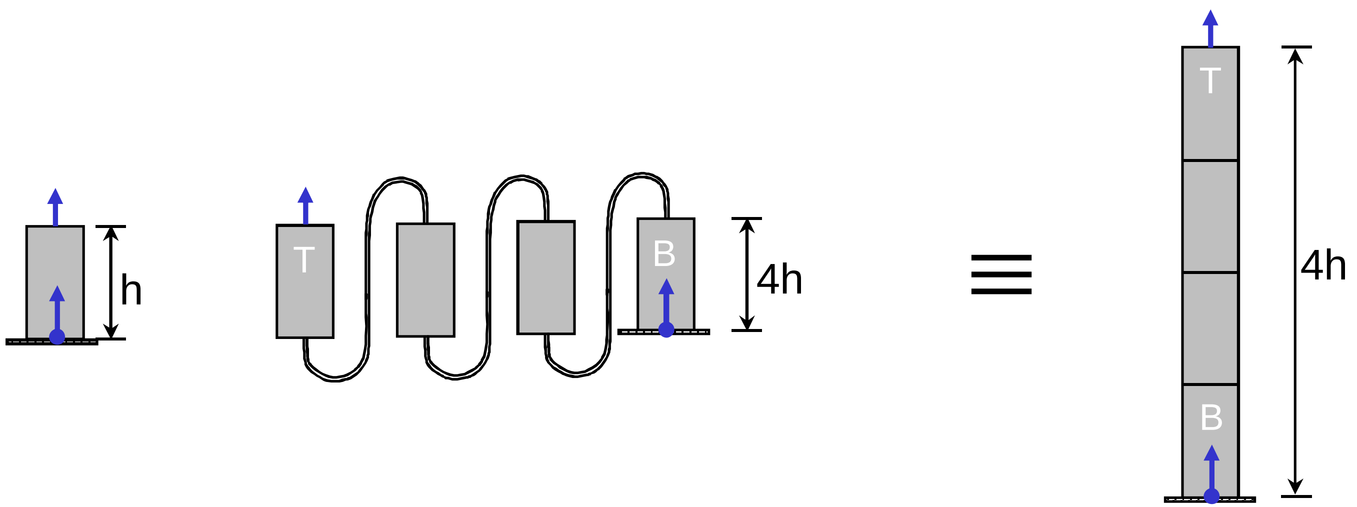


Fig.: Interconnected tests

Creep hypotheses for soil element compressibility

EOP strain-effective stress relationships: the creep hypotheses

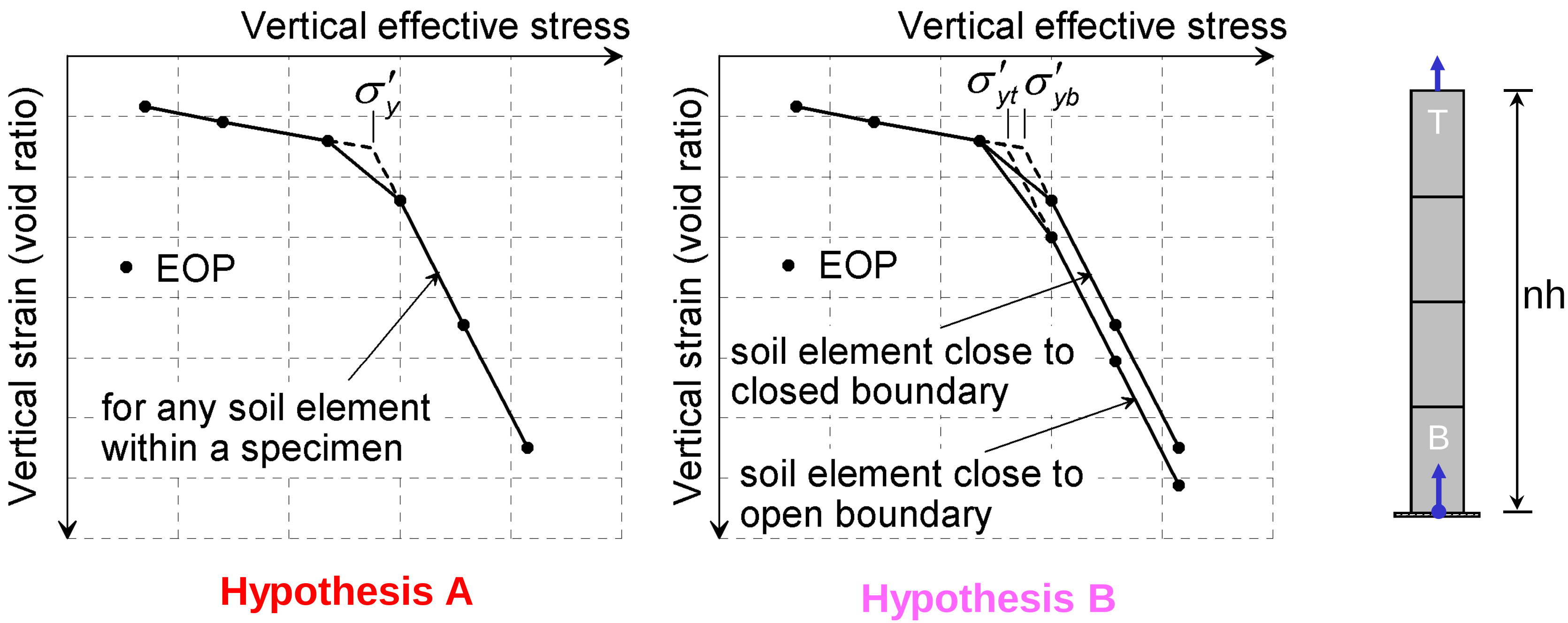


Fig.: Principle sketch of the two creep hypotheses for compressibility of soil elements within a specimen

EOP strain-effective stress relationships: laboratory test results

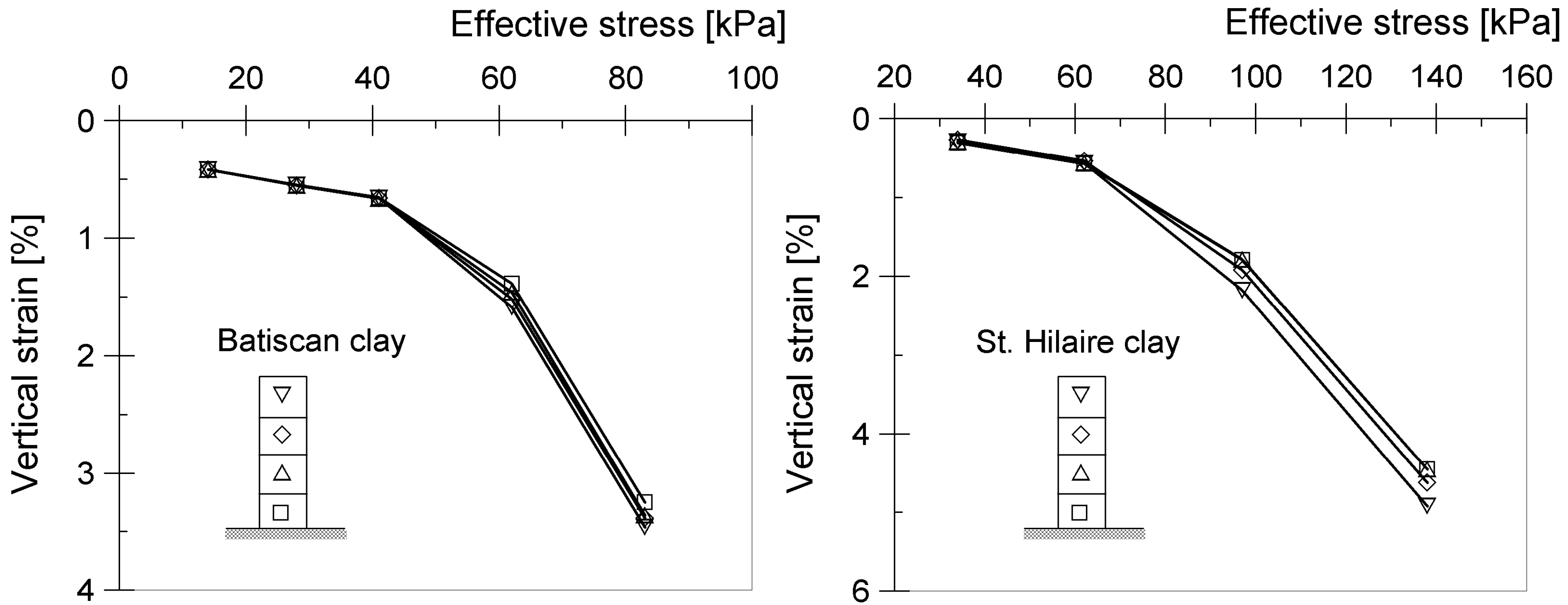


Fig.: EOP vertical strain–effective stress of sub-specimens (interpreted from Feng, 1991)

- Hypothesis B

Strain-time relationships: the creep hypotheses

Hypothesis A

- At EOP, the strain-time relationships of all sub-specimens converge to the same point

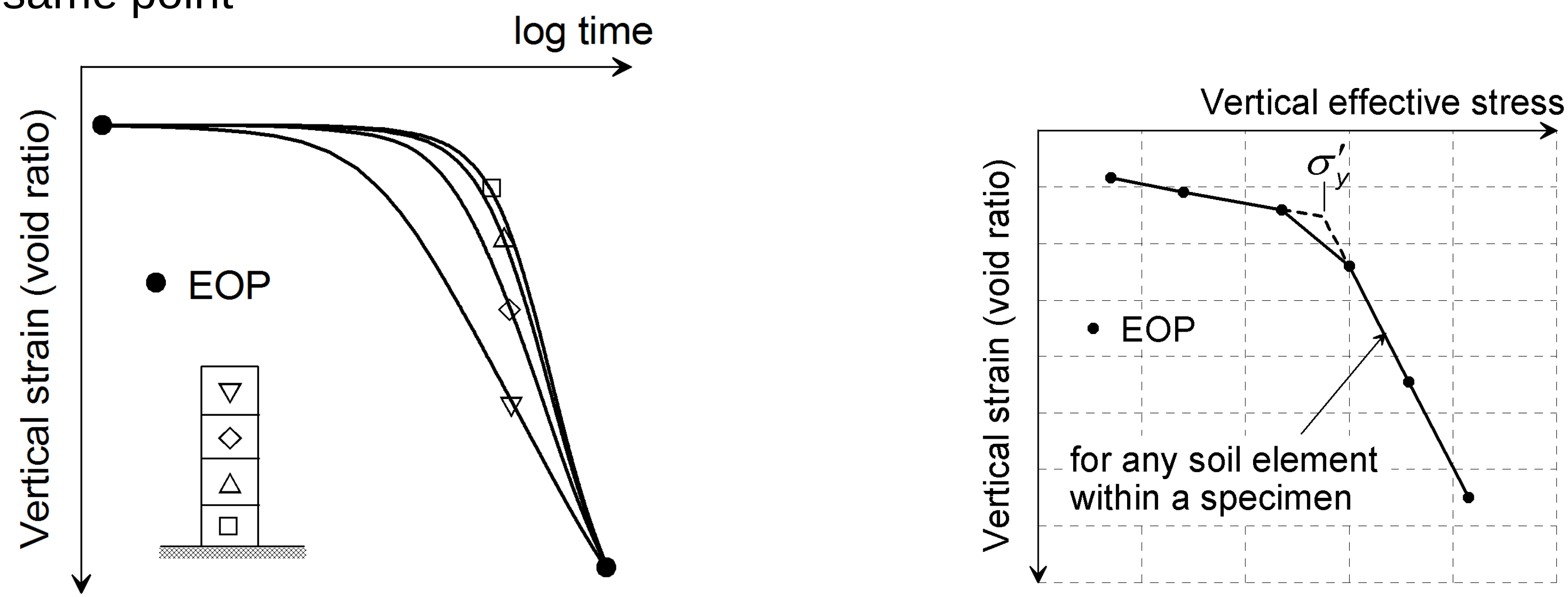
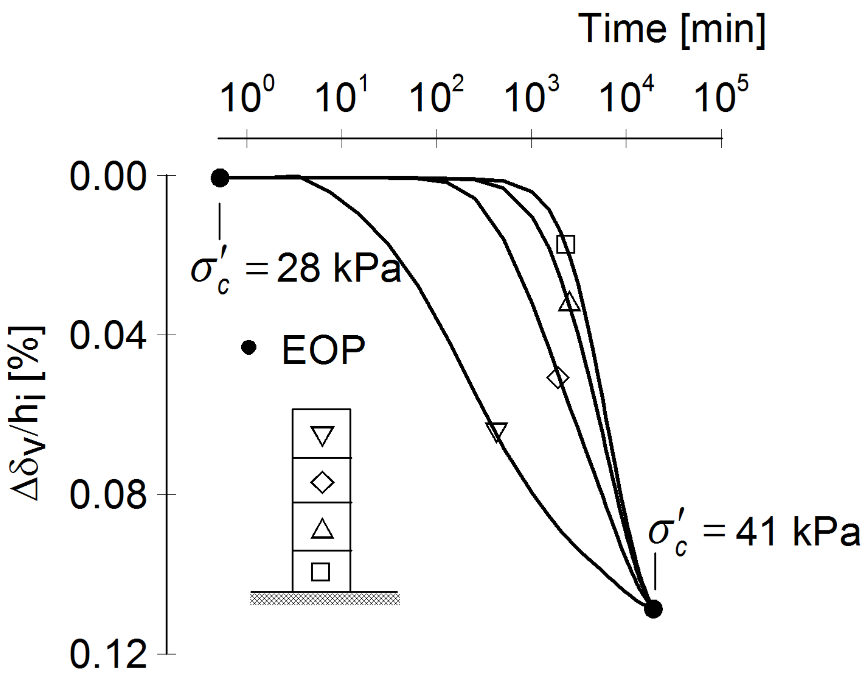


Fig.: Principle sketches of Strain-Time and Effective stress–Strain relationships according to hypothesis A

Hypothesis B



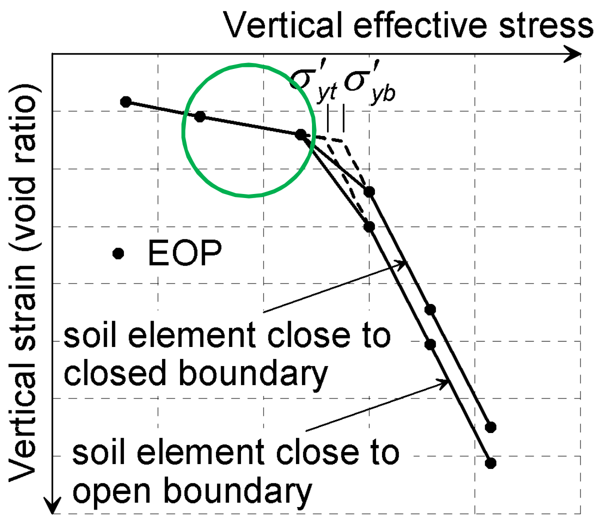
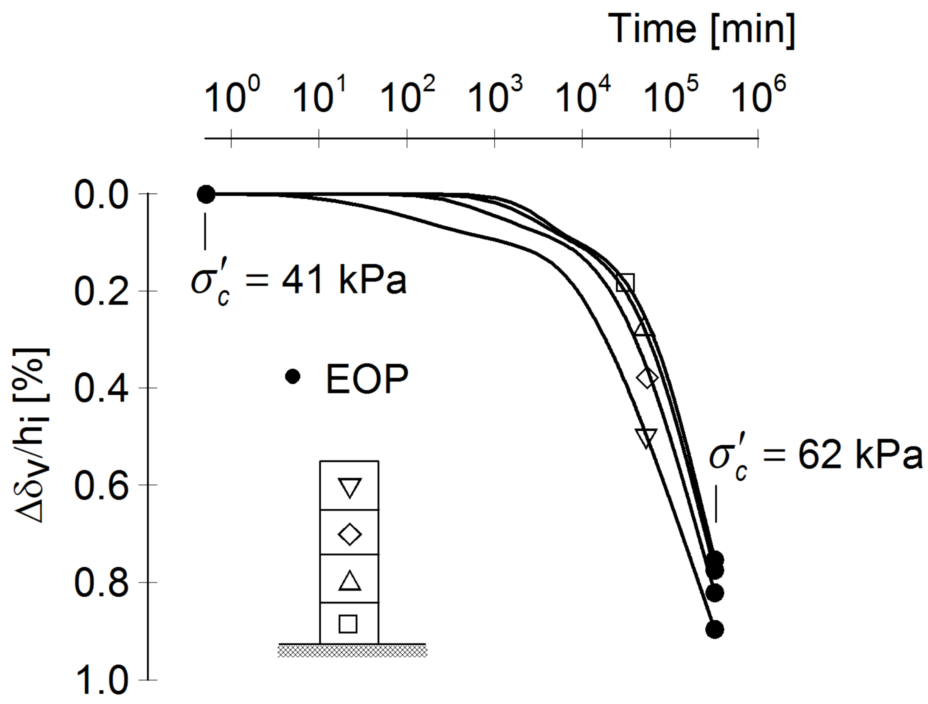


Fig.: Strain-Time and Effective stress–Strain relationships according to hypothesis B

Hypothesis B



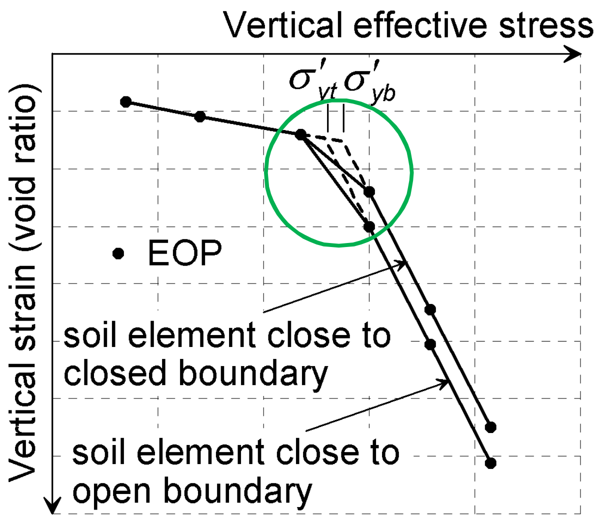
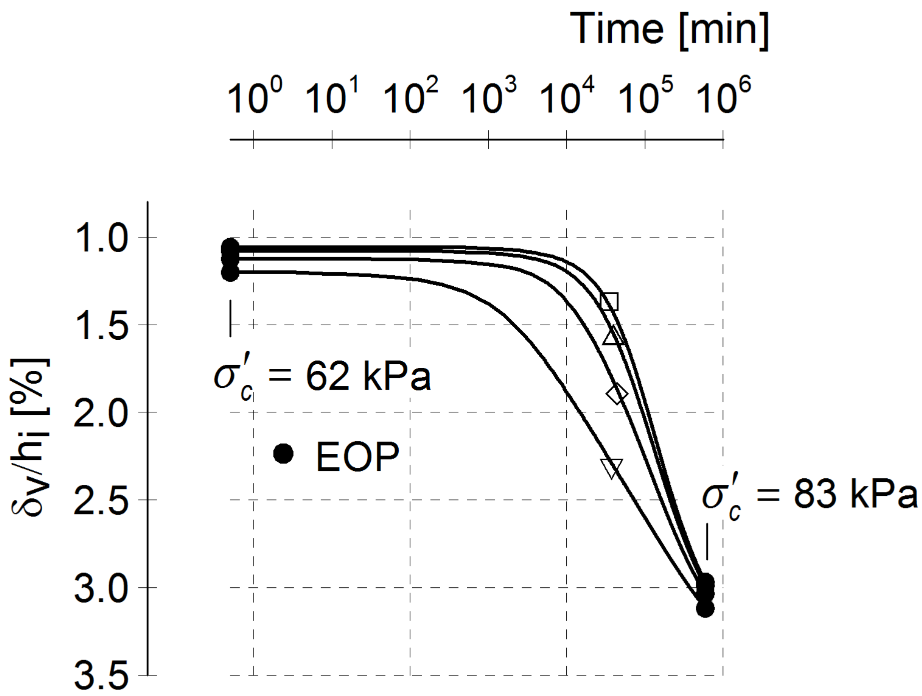


Fig.: Strain-Time and Effective stress–Strain relationships according to hypothesis B

Hypothesis B



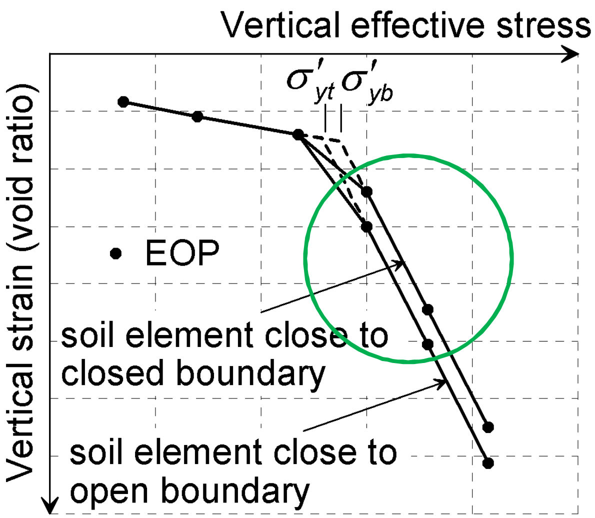


Figure : Strain-Time and Effective stress–Strain relationships according to hypothesis B

Strain-time relationships: laboratory test results

- Hypothesis B

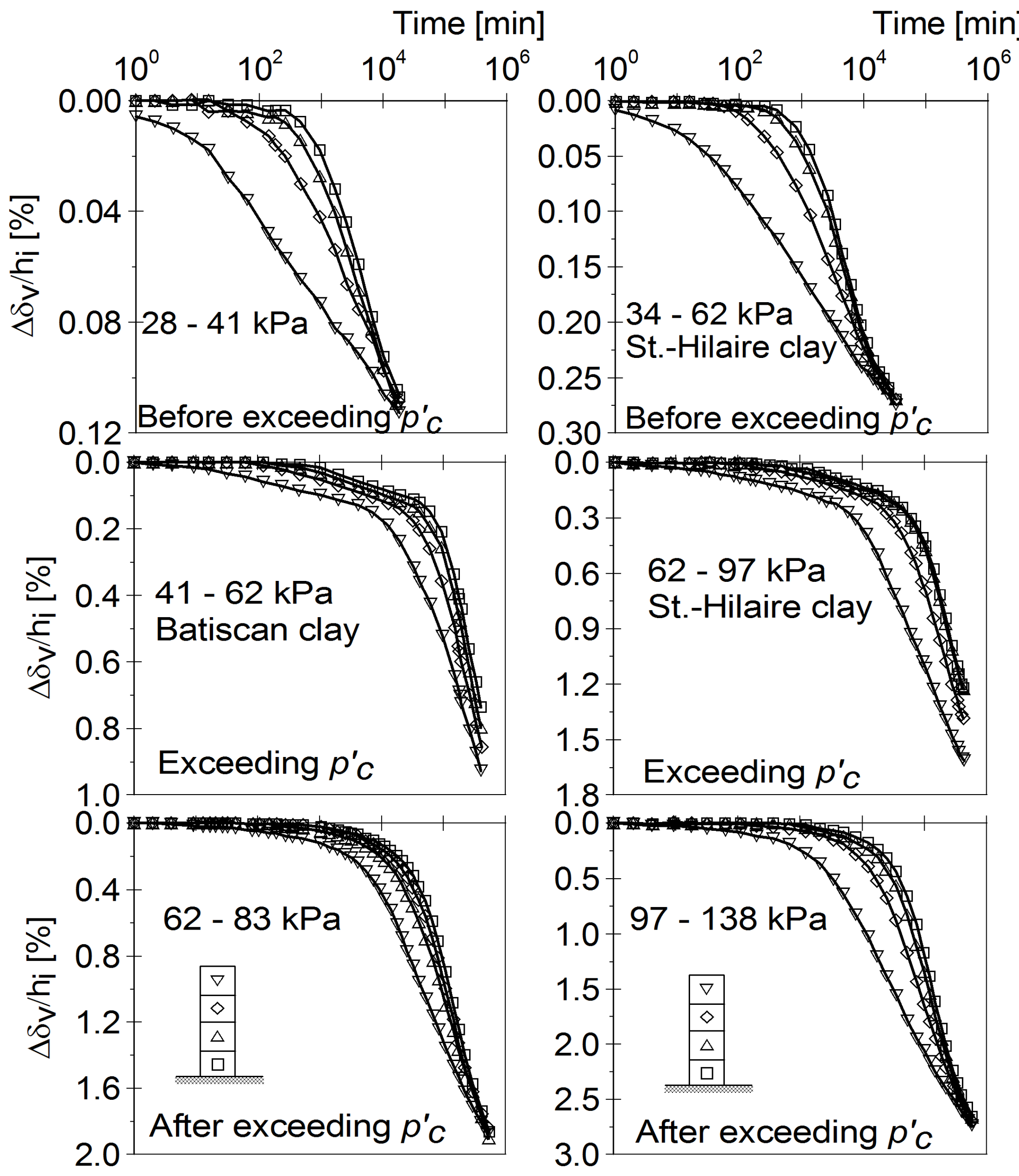


Fig: Experimental results on Batiscan and St. Hilaire clay (Feng, 1991)

- **Strain-time relationships: numerical study**
  - Simulation using hypothesis B (SSC) model
  - FE-code PLAXIS

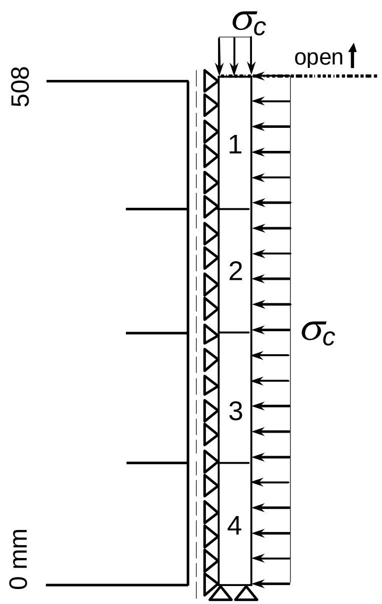


Fig.: Geometry adopted in FE simulation

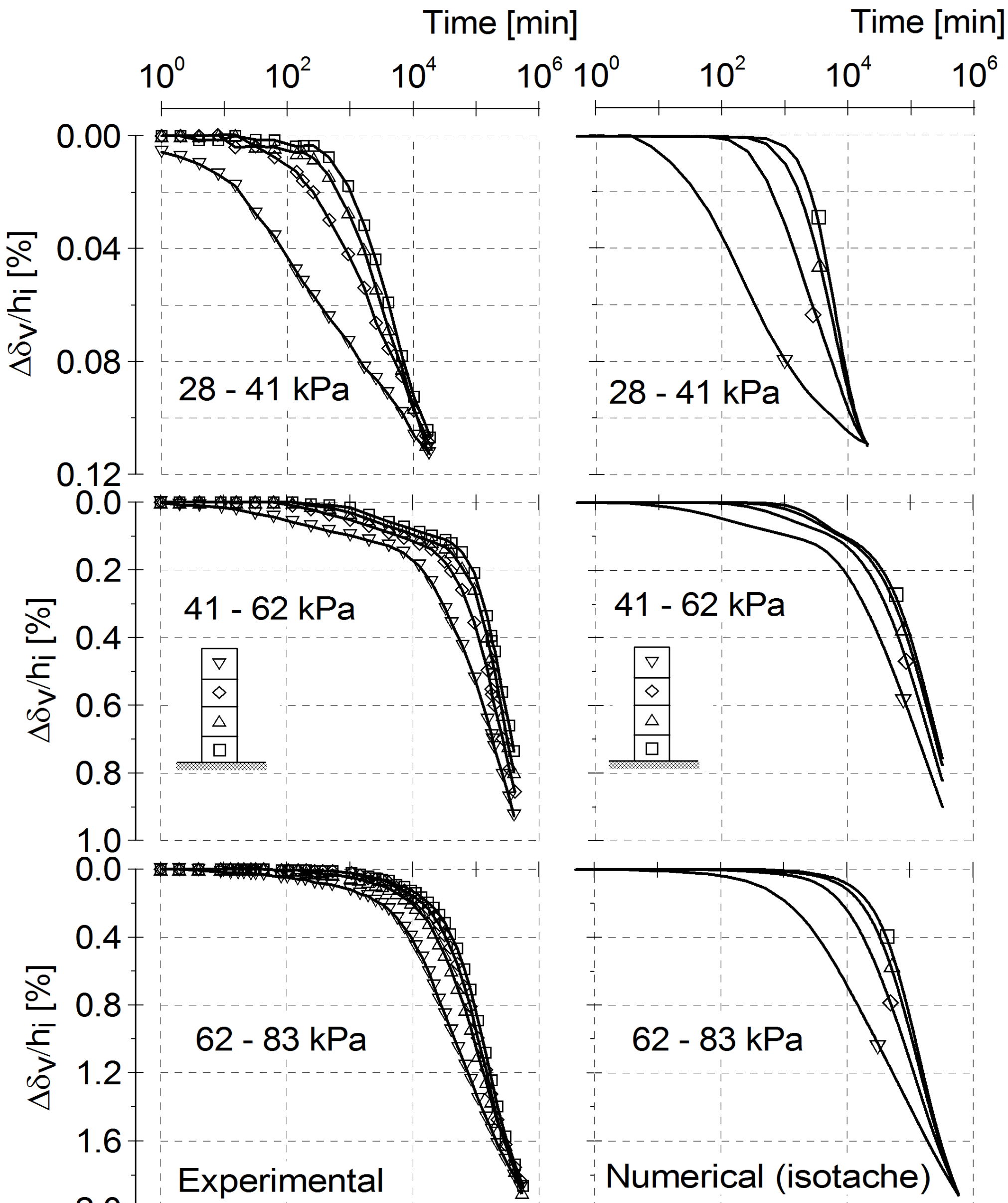


Fig.: Experimental measurements (Feng, 1991) Vs Simulation results of Batiscan clay

Tests conducted during this study

(@Chalmers University of Technology)

Hypothesis A :-

- The sub-layer at the drainage face does not experience any secondary consolidation until EOP state of the bottom sub-layer

  (Mesri & Vardhanabhuti, 2006).

Motivation

- Will a soil element at the drainage face really 'wait' for the EOP state of the bottom sub-layer to start its secondary consolidation?
  (Jostad, 2006 @CREBS I)

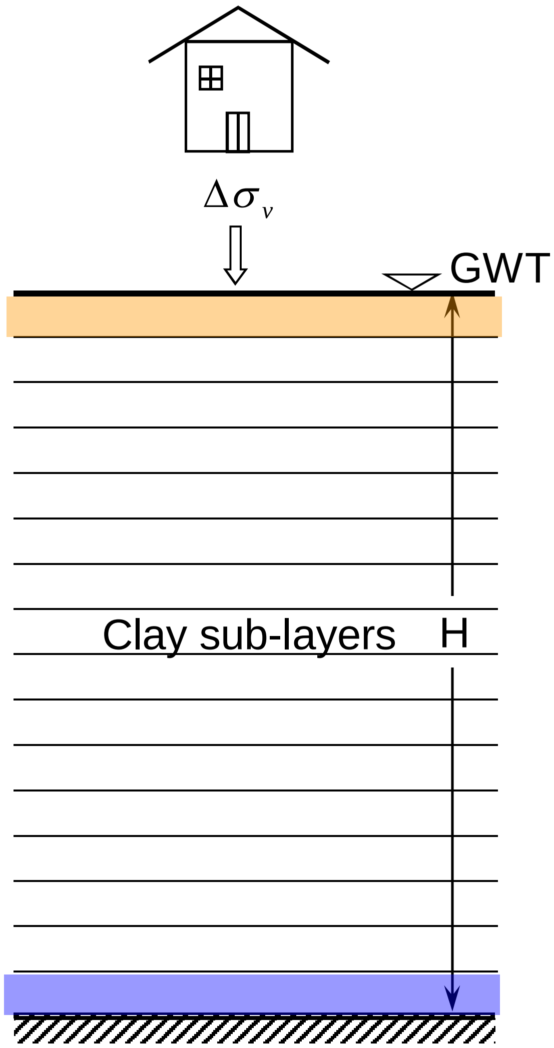


Fig.: A soil layer consisting of several soil sub-layers

An idealized case

- A clay layer placed on top of similar clay as compared to a clay layer placed on top of a soil material with different coefficient of consolidation.

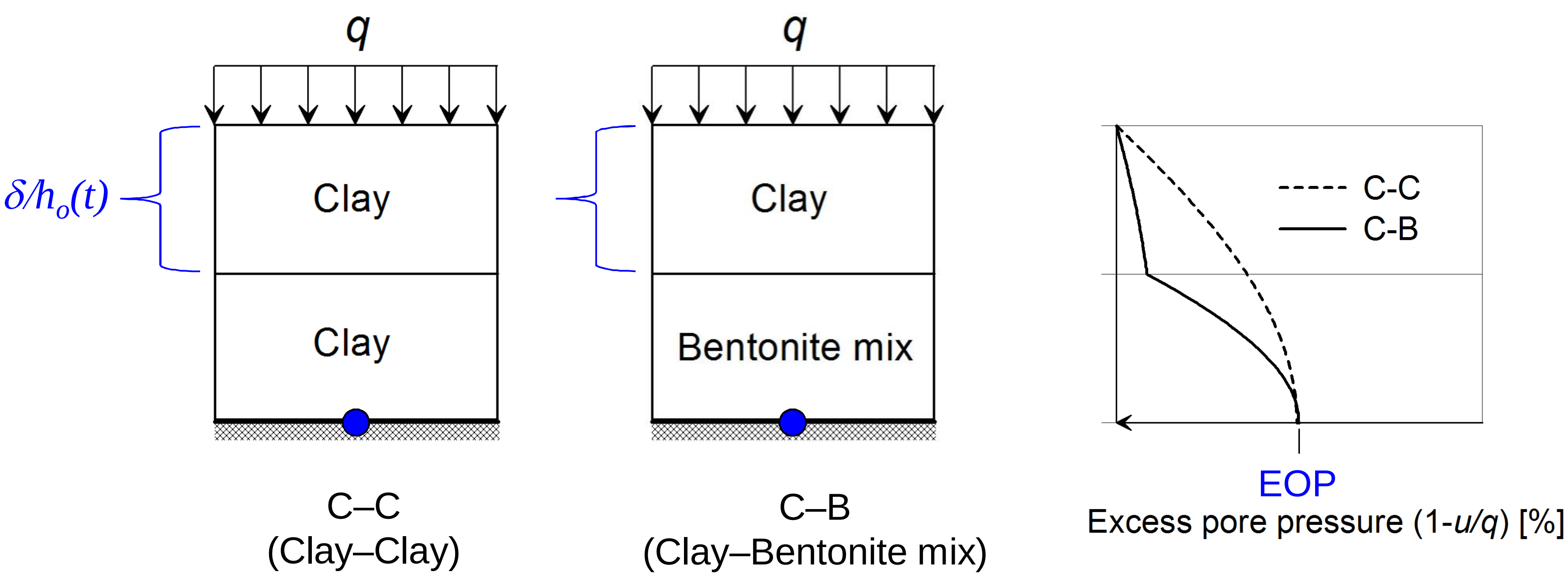


Fig.: Idealized cases

Expected strain-time relationship of the top clay: the creep hypotheses

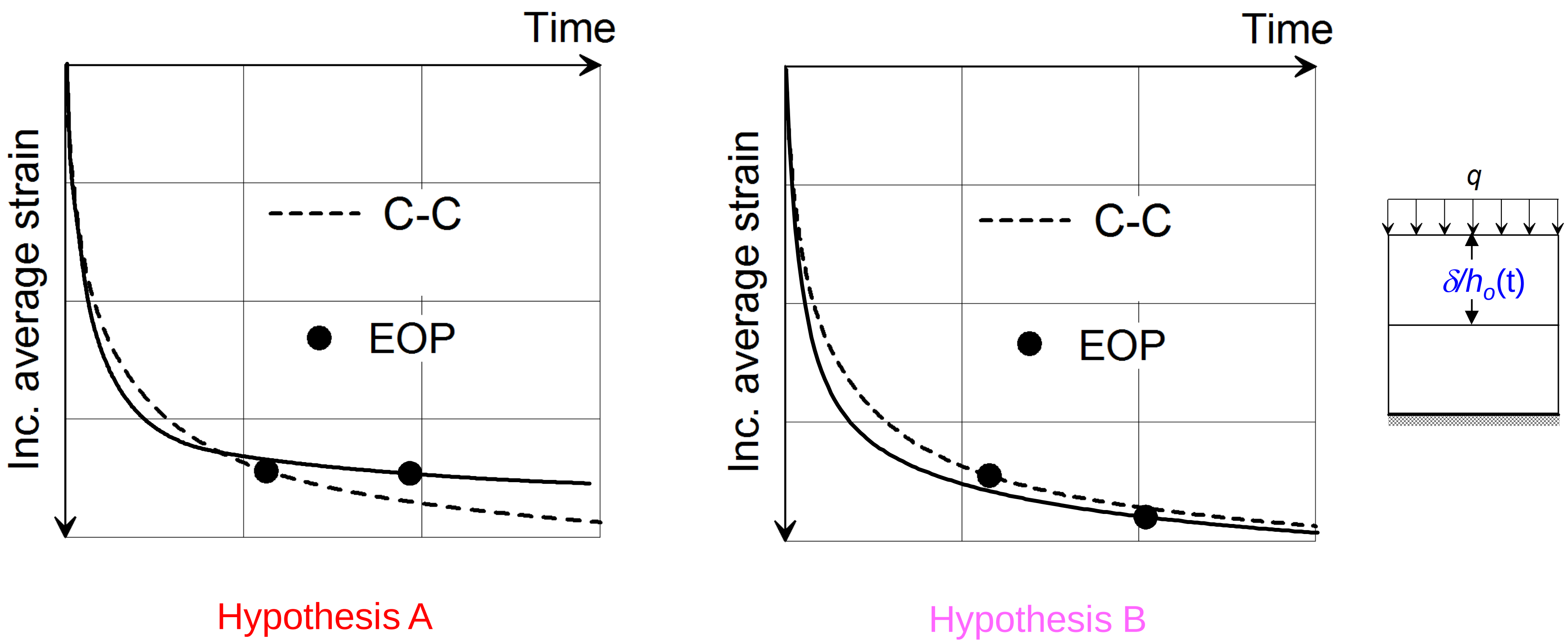


Fig.: Predicted incremental nominal strain-time relationship of the top clay

Test set up and measurements

- Conducted at Chalmers University of Technology
- Incremental load sequence of 10, 20, 30 and 80 kPa (EOP = 95 % EPP dissp.)
- Two sets of tests

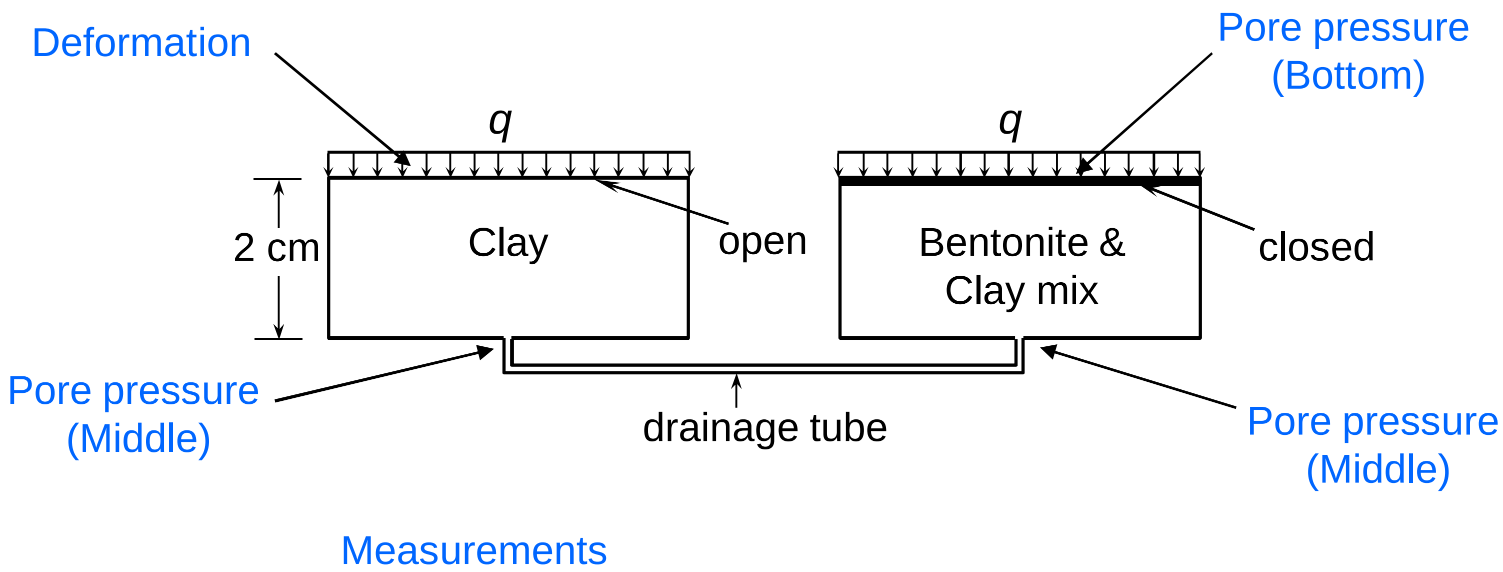


Fig.: Test set up and measurements

Fig.: Running the interconnected tests at Chalmers GeoEngineering laboratory

- Experimental results

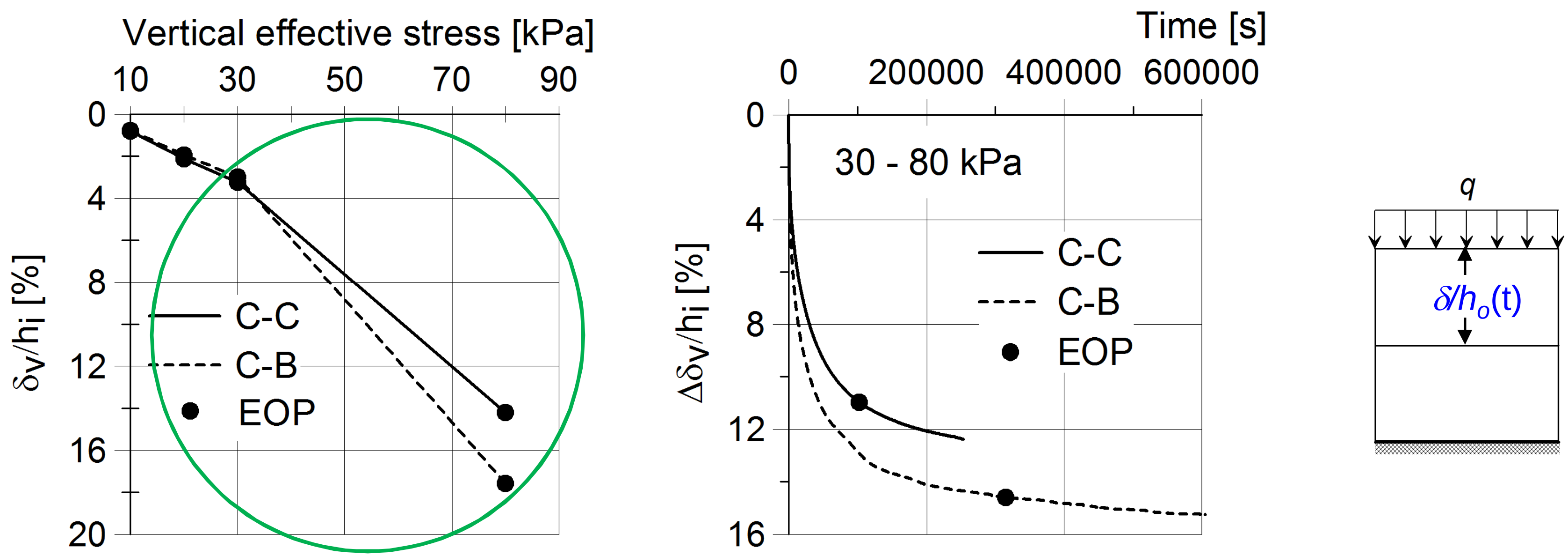


Fig.: Test measurements

- EOP is slightly more than expected for hypothesis B
- EOP strain not unique !

Numerical study

- Simulation using hypothesis B (SSC) model
- FE-code PLAXIS

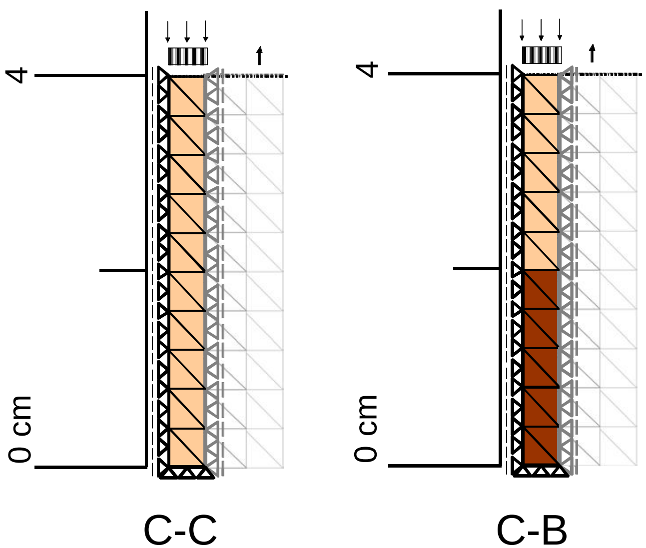
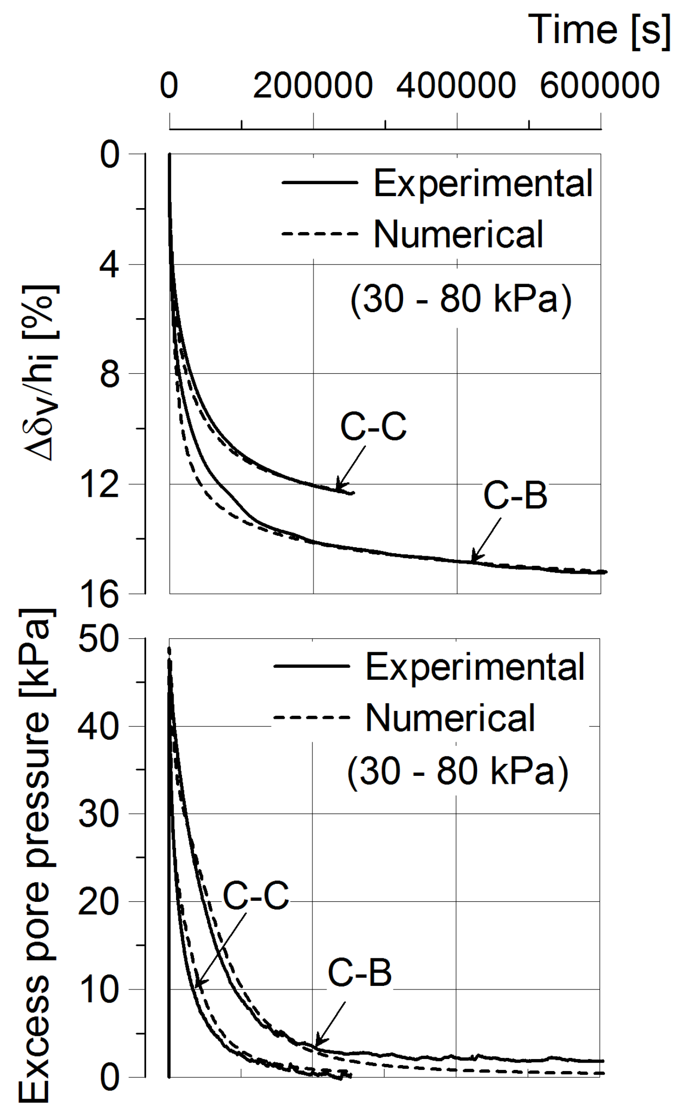


Fig.: Geometry adopted in FE simulation



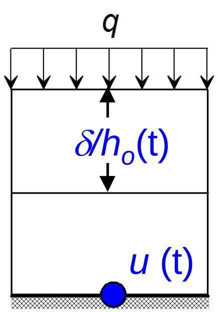


Fig.: Measurements vs. simulation (30-80 kPa)

Laboratory studies II: Creep hypotheses for soil element compressibility

Final remarks

- ✓ Laboratory studies on soil element compressibility imply hypothesis B.
  - Local compressibility of a soil element is governed by its prevailing effective stress-strain-strain rate on that particular soil element rather than what is happening elsewhere in the soil layer.
  - This means that a soil element creeps during primary consolidation and starts its secondary consolidation phase right after its primary consolidation phase rather than 'wait' until the completion of the primary consolidation of all the other soil elements
- ✓ Numerical simulation results using hypothesis B model can explain experimental measurements.

Field studies

- The two hypotheses could give significant practical differences when predicting settlements of in-situ soil layers
- However, on several occasions, the advocates of the two hypotheses have *independently* presented acceptable predictions of in-situ settlements to support the hypotheses.
- In this study, the *constitutive models* for the two hypotheses are evaluated based on the performance of a *common* and well-documented test fill.
- This is mainly motivated by the analogy to the hypothetical case exercises given to CREBS II participants in 2007 (Pisa) by Hans Petter Jostad.
- Constitutive models for hypothesis A (ILLICON), hypothesis B (SSC) and elasto-plastic model (SS) are considered.

Model comparisons – Strain formulations

- ILLICON strain decomposition

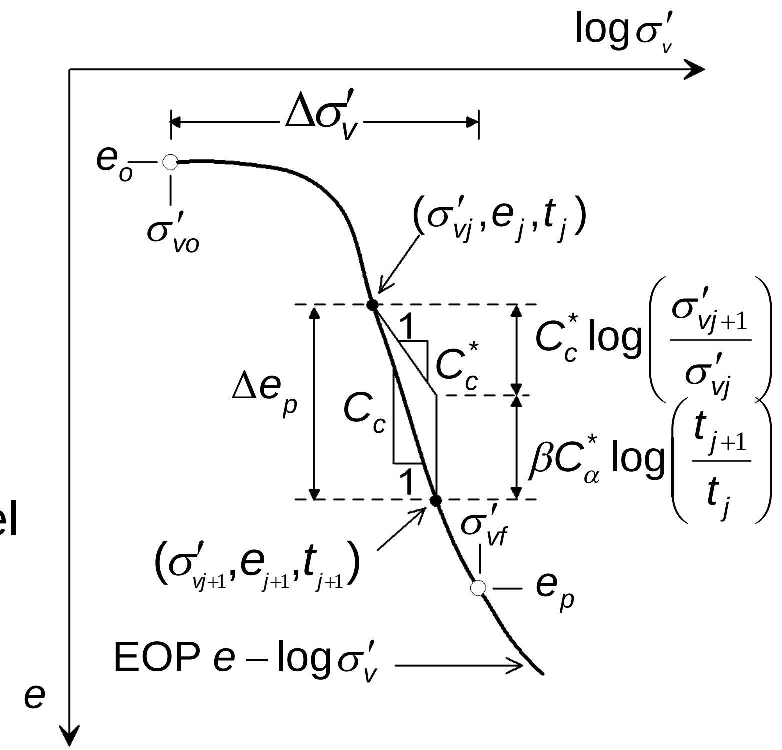
$$\Delta e_p = C_c^* \Delta \log \sigma_v' + \beta C_\alpha^* \Delta \log t$$

where C_α^* merely decomposes the input and out put Δe_p into two 'arbitrary' parts.

- SS is a rate-independent elasto-plastic model
- SSC is a rate-dependent elasto-viscoplastic model

- ILLICON is equivalent to SS model.

- The SSC would give larger EOP strain than both ILLICON and SS models.



$$C_\alpha^* / C_c^* = C_\alpha / C_c$$

Fig.: ILLICON strain formulations (after Choi, 1982)

Model comparisons – Excess pore pressure formulations

- Continuity equation as used in ILLICON assumes that the excess pore pressure dissipation is only affected by the so-called stress-compressibility.

$$\frac{(1+e_o)^2}{\gamma_w}\frac{\partial}{\partial z}\left(\frac{k_v}{1+e}\frac{\partial u}{\partial z}\right)=\frac{de_\sigma}{dt}\neq\frac{de}{dt}\left(=\frac{de_\sigma}{dt}+\frac{de_t}{dt}\right)$$

- In SSC and SS model the continuity equation is controlled by total strain rate.

- ILLICON would give faster EPP dissipation than SS model.

- SSC would give significantly slower EPP dissipation than both ILLICON and SS model.

Comparison of the models based on analysis of Väsby test fill

- ILLICON vs. SS
- SSC vs. SS

- ILLICON, SSC and SS models are indirectly compared based on analysis of the test fills.
- For a given set of soil data, the SS model is used in order to provide reference predictions with respect to disregarding the effect of creep.

Analyses results ILLICON & SS – Väsby test fill

- “ILLICON-Equivalent” parameters were adopted for SS model.

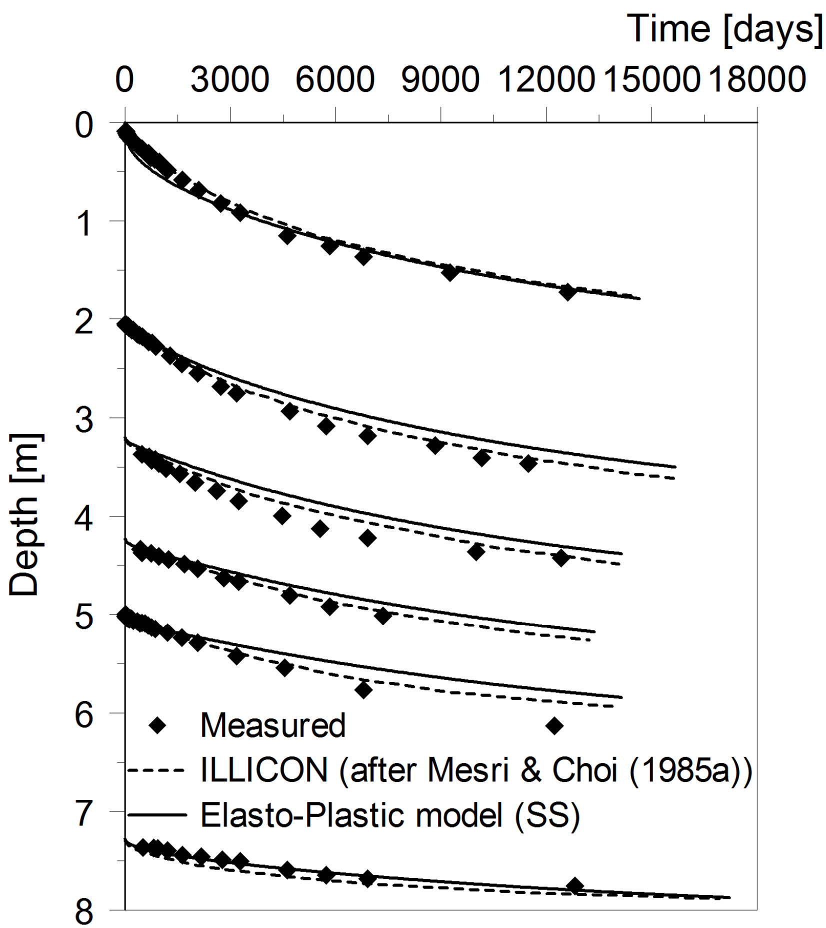


Fig.: Settlement history predictions (ILLICON vs. SS)

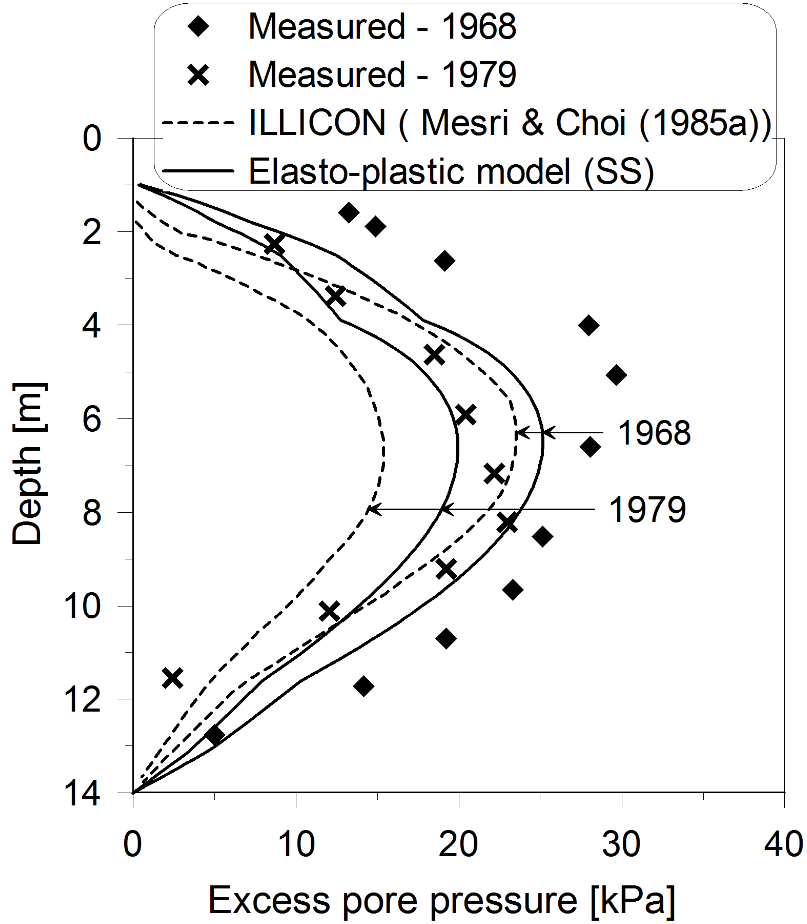


Fig.: Excess pore pressure profile predictions (ILLICON vs. SS)

ILLICON and SS model predictions vs. Measurements

- While disregarding creep, both ILLICON and SS model gave an overall acceptable predictions.
- This should not imply that the soft clays considered do not undergo creep deformation.
- The acceptable predictions were mainly due to two factors, i.e. use of soil data from disturbed samples and disregarding effect of large deformations.

(1) Sample disturbance

- Generally the OCR values used in ILLICON and SS analysis were low and are believed to be affected by sample disturbance.

- For instance,
  - Väsby test fill, EOP OCR = 1.31 or 1.82 ? (Leroueil and Kabbaj (1987))

  - In Skå-Edeby test fill, OCR = 1.0 ? (field tests by SGI)

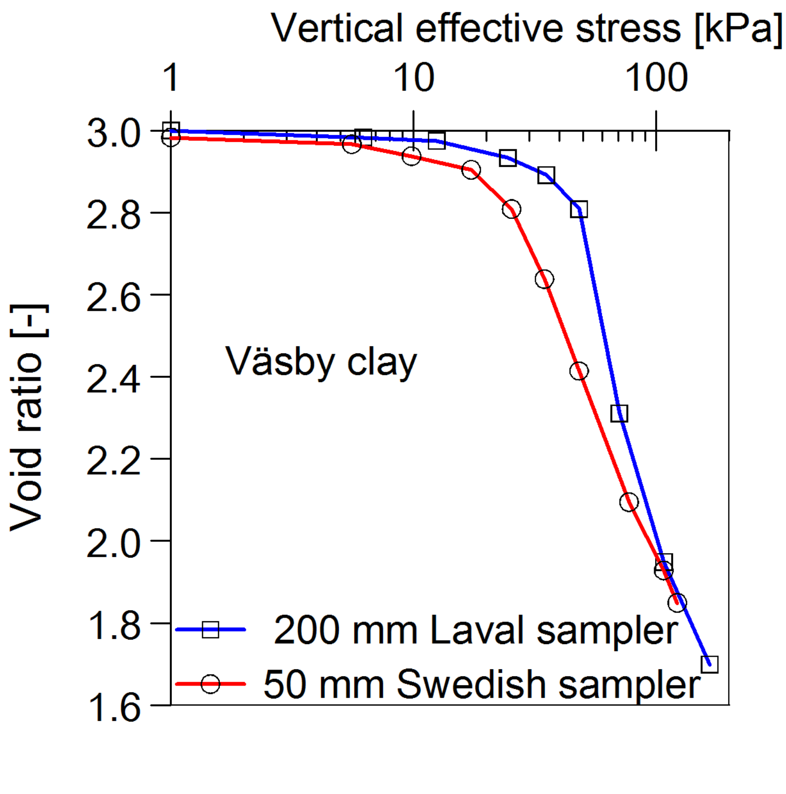


Fig. : Sample disturbance at Väsby test fill (after Leroueil & Kabbaj, 1987)

(2) Effect of large deformations (buoyancy)

- ILLICON and SS model analyses disregarded load reduction due to buoyancy forces.

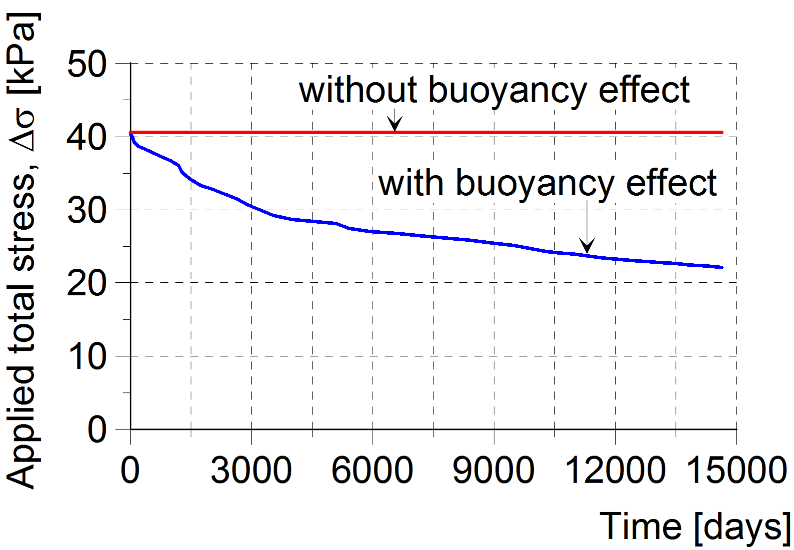


Fig. : Applied load with and without consideration of buoyancy effect (Väsby)

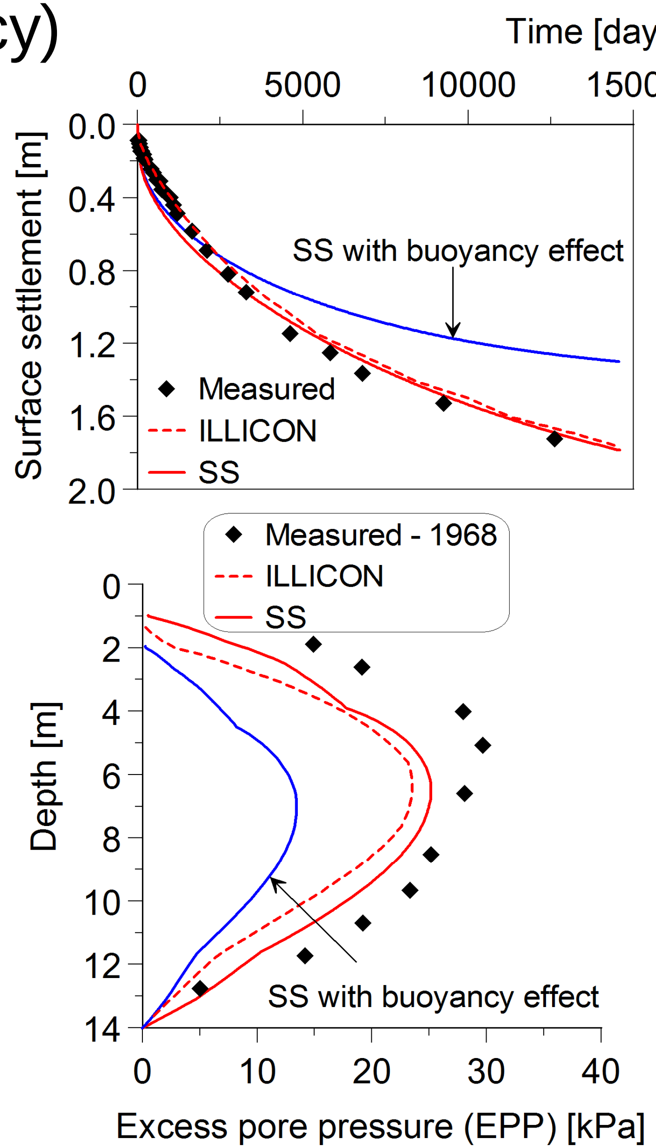


Fig.: Effect of buoyancy on predictions

Comparison of SSC vs. SS model

- ✓ Use of OCR values from high quality sample data or clay age considerations
- ✓ Effect of large deformation (buoyancy) taken into account

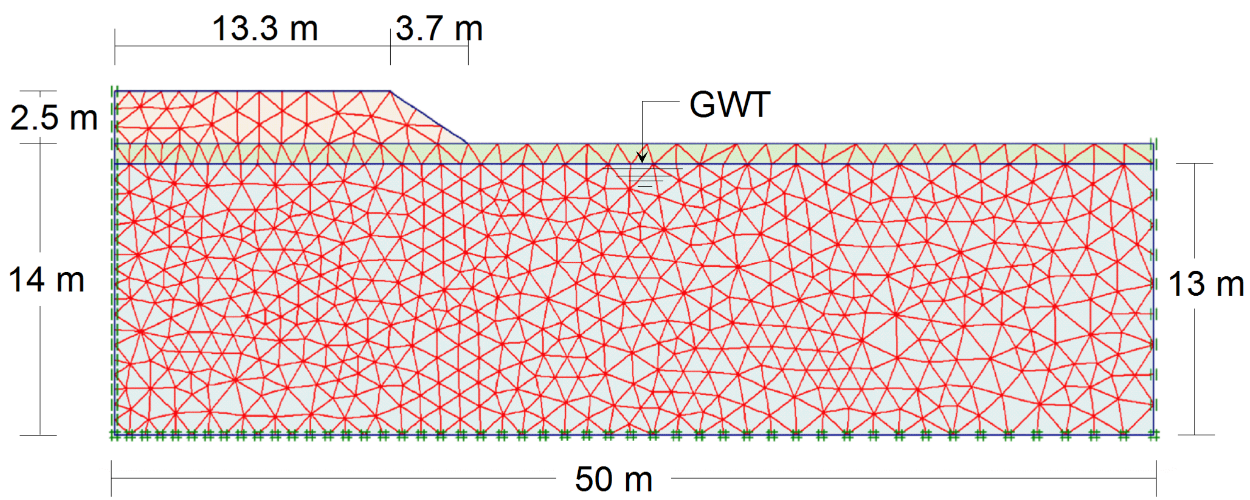


Fig.: Axisymmetric FE geometry adopted for Väsby test fill analysis

Analyses results SSC & SS – Väsby test fill

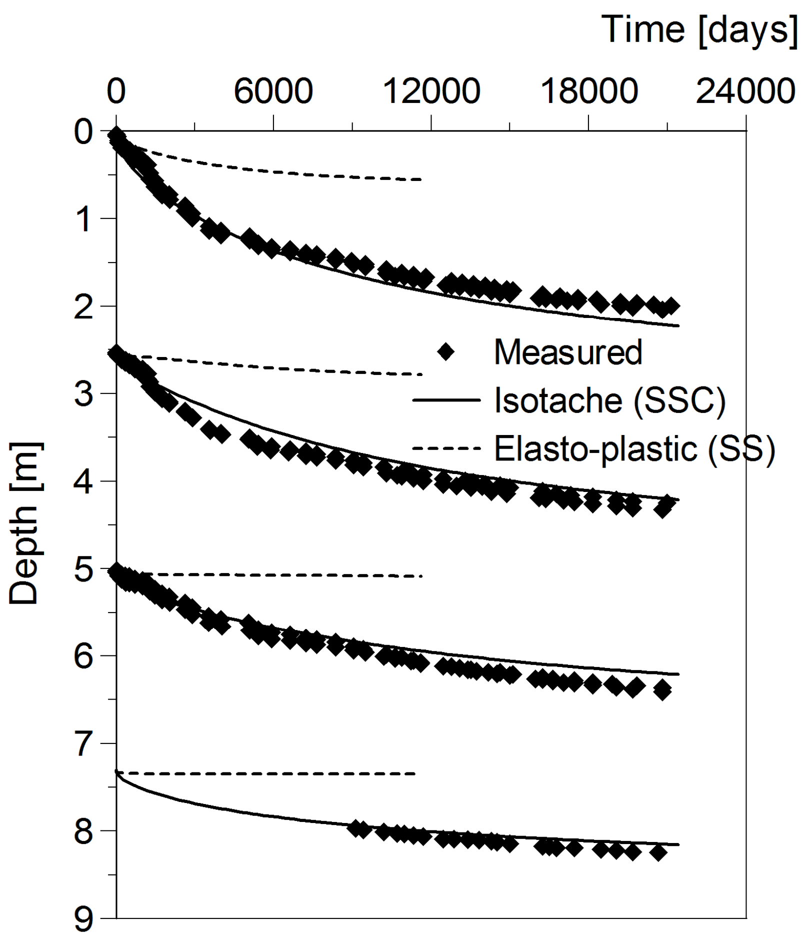


Fig.: Settlement history predictions (SSC vs. SS)

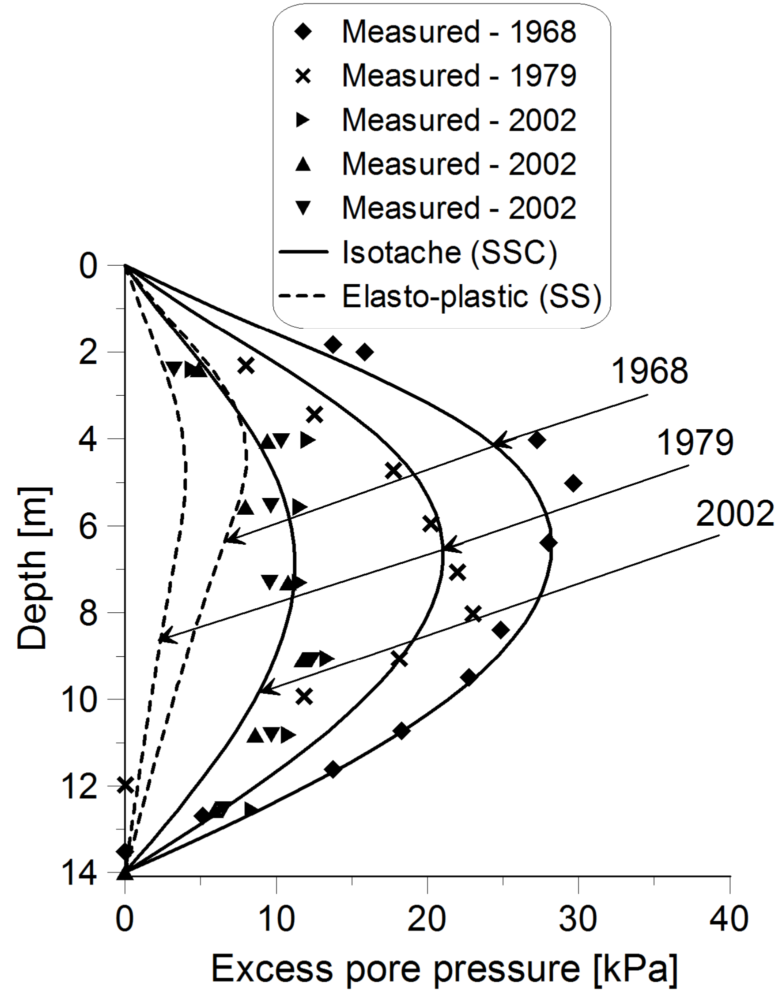


Fig.: Excess pore pressure profile predictions (SSC vs. SS)

Field studies

Final remarks (based on Väsby, Skå-Edeby & Ellingsrud test fills)

- ✓ When soil data are interpreted from tests on disturbed samples are used for settlement analysis then some effect of creep is already 'incorporated'.
  - A rate-independent elasto-plastic model, along with some simplifying assumption, could give acceptable settlement and reasonable but somehow low excess pore pressure responses.
  - An isotache model would significantly overestimate settlement and could give unrealistically large excess pore pressure responses.
- ✓ When soil data are interpreted from tests on high quality samples and used for settlement analysis,
  - A rate-independent elasto-plastic model significantly underestimates settlement and excess pore pressure responses
  - An isotache model would yield excellent prediction of settlements and excess pore pressure.

Conclusions

- In response to the important question raised by Ladd *et al*. in 1977, this study has shown that there exist definitive data to demonstrate that hypothesis B agrees very well with the measured behaviour of cohesive soils.

- Several EOP laboratory tests considered in this study demonstrated the validity of hypothesis B. In fact, this study disclosed that all the empirical data that were previously used to support substantiate hypothesis A actually imply hypothesis B.

- The experienced p'_c as well as EOP strain are rate dependent even for EOP loading conditions and this fact has been experimentally supported by several EOP tests and field observations.

- The isotache theory (hypothesis B (SSC)) can explain and convincingly capture important feature of various types of laboratory tests considered in this study.

Conclusions

- Great care needs to be exercised during interpretation and use of preconsolidation stress (p'_c) in settlement analyses. With this aspect, sample quality deserves extra attention.

- Awareness regarding the significance of p'_c (OCR due to creep) on settlement analysis needs to be stressed by the profession.

- The isotache models are well suited to predict settlements of water saturated soft clay deposits when the input data are deduced from laboratory tests of good quality soil samples.

- Future developments related to the compressibility of natural clays such as anisotropy and destructuration should be focused on enhancing models that are based on the isotache framework or similar.

Thank you for your attention !

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