# E. IMRE: Macro test for the testing of bonds

(Some special features of the multistage oedometric relaxation test in case of a servo control system)

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*Abstract. Some measured multistage oedometric relaxation test data of soils are discussed. This test reflect the energy storage capacity of the soil determined by the contact bonding behaviour of the particles. The results indicate that this test can be a candidate test for a mean particle contact bond qualification (reflecting the energy storage capacity of the bonds as an average) and for the determination of the tensile strength of (quasi-)saturated soils.*

## INTRODUCTION

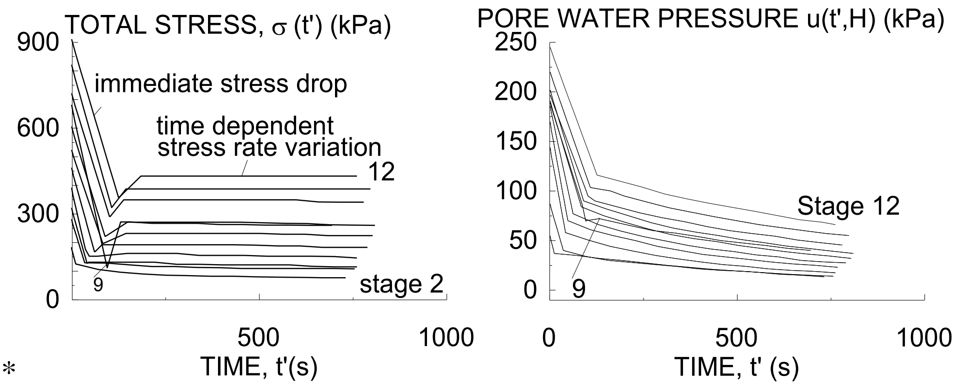
In the multistage oedometric relaxation test (MRT) the pore water pressure and the total stress are measured under constant displacement load. In its dual counterpart, the conventional multistage oedometric compression test (MCT), the pore water pressure and the displacement are measured under constant total stress load.

A model-pair consisting of a linear, coupled, consolidation part-model and an empirical relaxation/creep part-model was validated on identical sample-pairs tested by a short multistage relaxation test procedure and a conventional multistage compression test procedure (Imre, 1998; Imre et al., 2010, Imre et al., 2001), using identical samples.

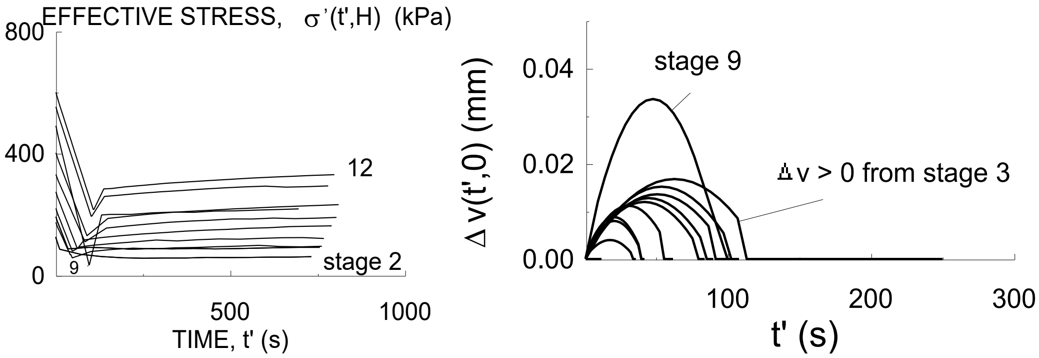
The aim of the paper is to discuss the compression curve results. As a by-product of this study, through the analysis of the coupled consolidation model and the measured data, the possibility for some special uses of the MRT emerge which are also presented in this paper.

## LABORATORY TESTS

In the short MRT procedure the load increment was uniform, 0.1 mm and the stages were 10 - 20 minutes long except the last one being longer than the $t_{99}$ dissipation time. The strain rate of the loading was varying between 0.002 and 0.08 %/s being too fast (Leroueil et al., 1985). Some features are shown in the Appendix.

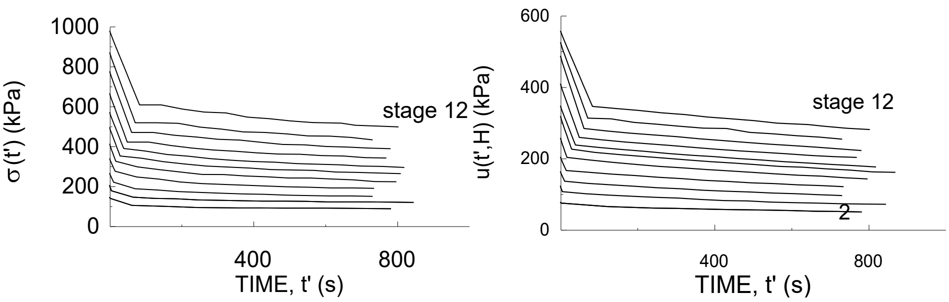



*(a) Total stress. (b) Pore water pressure.*

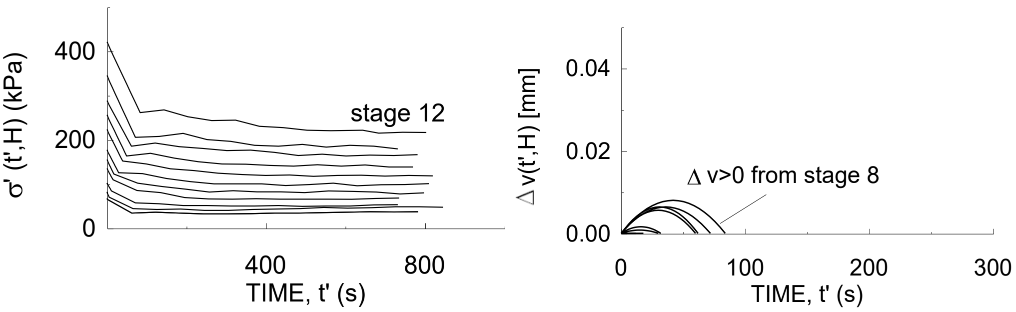



*(c) Effective stress. (d) Displacement overload.*

Fig. 1. *MRT, a typical data record, measured on soil 4. (Note the large, spontaneous partial unloading at the end of the load imposition of stage 9, probably due to the rearrangement of the grain structure).*




*(a) Total stress. (b) Pore water pressure.*




*(c) Effective stress. (d) Displacement overload.*

Fig. 2. *MRT, a typical data record, measured on soil 5.*

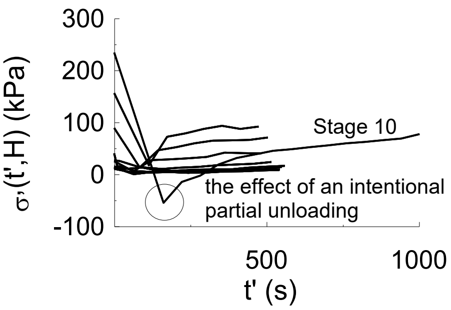



Fig. 3. MRT, detail of data record, effective stress – time, soil 5. (Note that at stage 10 a large partial unloading was intentionally caused inducing negative effective stress).

Table 1. *Basic properties of the tested plastic soils* (*saline)

| Soil | 1* | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Borehole#/depth[m] | 24/14 | 52/14 | 1/14 | 52/17 | 13/14 | ii |
| $I_p$ [%] | 10 | 16 | 17 | 22.8 | 31.7 | 41 |
| $w_L$ [%] | 32.4 | 37.2 | 41.7 | 57.9 | 56.1 | 72 |
| OCR | ~1, NC | ~1, NC | ~1, NC | ~1, NC | ~1, NC | ~NC |
| threshold load $v_t$ | 0.2 | 1.2 | 1.0 | 0.7 | 0.7 | NO |

A Geonor type swelling pressure apparatus h-200A was used (see eg., di Maio 2001). The microprocessor kept the displacement in the tolerance range through load reversal, resulting in quasi periodic side shear force variation in the sample with a saw-tooth-like the total stress response.

More than 30 quasi-saturated, natural soil sample-pairs were tested with the standard MCT (the stage loads are doubled) and short MRT procedures, only a few representative results are shown here in Tables 1, 2 and Figures 1 to 3.

A typical stage record for the total stress in the NC range showed a short pause before the total stress started to drop in accordance with the earlier experiences (see e.g. Mitchell, 1976), then the total stress drop consisted of two parts, an immediate, fast, constant stress rate stress drop (indicating the limitations of the control system) and a subsequent, slower, time dependent stress rate stress drop.

During the immediate stress drop, after a given threshold stage load $v_t$ depending on the sample, a slight partial unloading in terms of the displacement occurred. The size of the displacement overload monotonically increased with the stage load except for some stages where it was too large (see e.g. sample 2), which occurred in the case of some intact clays with $I_p$ between 20% and 25%.

It can be noted that during the immediate relaxation – due to the regulation of the displacement – the oedometer side shear force changes in terms of sign three times (i.e., reaching the stage load, the maximum overload and the stage load again the end of the stress drop) which may have a dynamic effect and can be important for frictionally bonded soils.

Some additional tests were made to test the soil response upon intentional partial unloading. An intentional, large partial unloading was caused in the case of the last stage for the intact clay sample 4 entailing temporarily negative effective stresses at the sample bottom. For the saturated sand sample intentional, large partial unloadings and very short stages were applied to test how the partial unloading and the dynamic effect of the side force variation may influence the compression curve. .

## EVALUATION

### Consolidation model

The consolidation model has some special features, which can be summarized as follows (Imre et al., 2010). Being the volume constant during a stage, the mean effective stress ($\sigma'_{mean}$) is equal to the final total stress ($\sigma_\infty$). It follows that the realization of the MRT compression curve point is 'instantanous' at the end of the loading period.

The constant volume condition is realized in such a way that the transient component of the total stress is equal to the mean water pressure:

$$\sigma^t(t) = u_{mean}(t) \qquad (1)$$

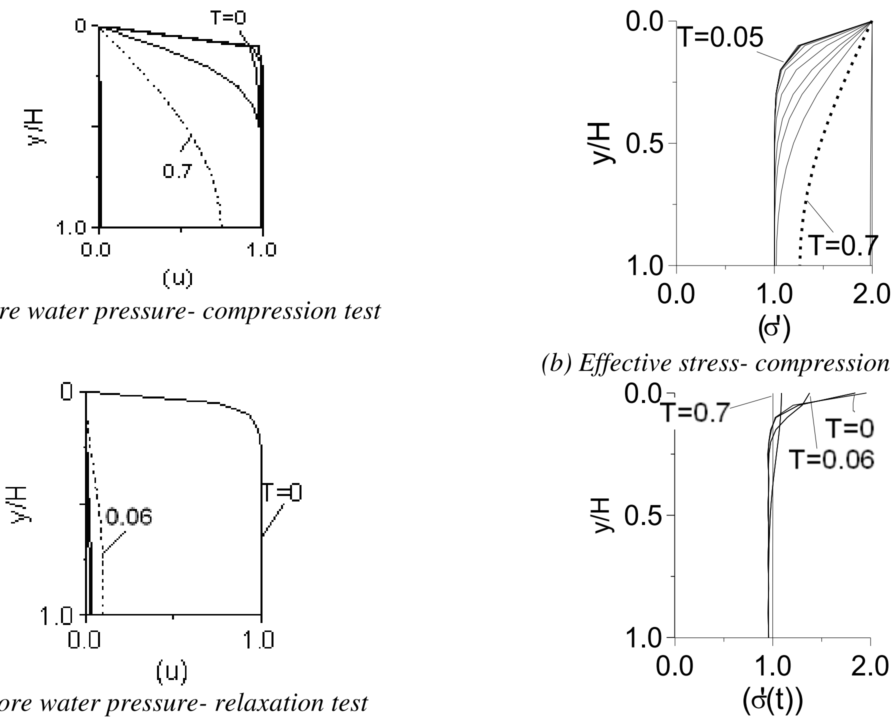
and the transient part of the effective stress:

$$\sigma'^t(t) = u_{mean}(t) - u(t,y) \qquad (2)$$

is partly positive and decreases with time to zero (i.e. at the sample top, in the vicinity of $y$=0) and partly negative and increases with time to zero (i.e. at the bottom of the single-drained sample which is the impermeable boundary). Assuming that $u$ is maximal at the sample bottom ($y$=H), the effective stress has its minimum there throughout the test (Fig. 4).

Following from the constant volume condition, the uniform pore water pressure distribution is the initial condition of a non-trivial zero solution, an immediate dissipation resulted there. (Because of this, the load imposition during the test cannot be instantaneous like for the MCT).

Being the volume constant during a stage, the loading is drained with respect to the mean effective stress. If there is a slight overload and unload at the end of the loading in terms of displacement then the mean effective stress level moves along the unload-reload line while the pore water pressure- depending on the volume – does not change . Since the mean effective stress drops, the effective stress level at the sample bottom may be very low (even negative).




*(a) Pore water pressure- compression test*

*(b) Effective stress- compression test*

*(c) Pore water pressure- relaxation test*

*(d) Effective stress- relaxation test*

Fig. 4. Comparing the staged tests. (a) to (d) Modelled stage behaviour for the same initial condition.

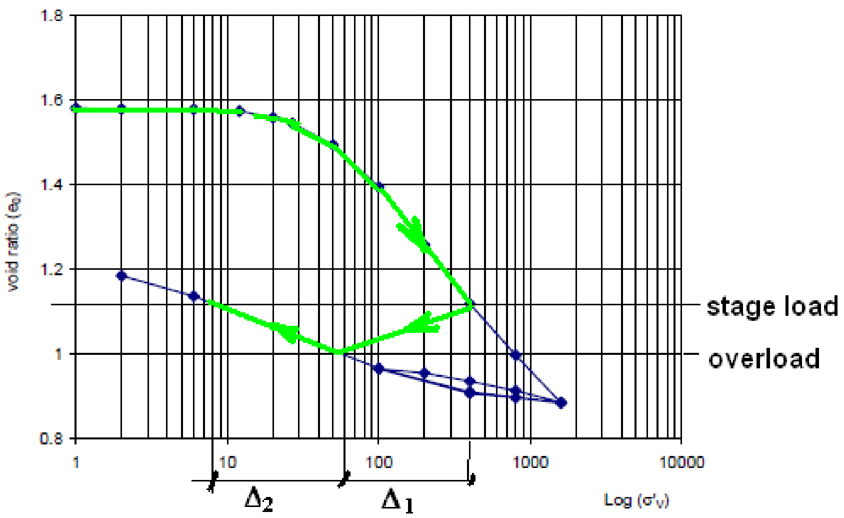



Fig. 5. The tentative explanation in terms of compression curves (blue: a theoretical MCT, green: the actual MRT). The first stress drop (∟1) happens due to the difference of the elastic response of the sample and the effective stress at the end of the loading period. Since this stress drop is realized slower than needed due to the limitation of the equipment, an overload happens in terms of the displacement. The second stress drop (i.e. partial unloading, ∟2) is caused by the of the control system. The compression curve point ends in the OC range.

## The identified compression curve

The final total stress ($\sigma_\infty$) was identified by the consolidation model for each stage. Since the parameter error was extremely small, the MRT compression curve could be compared with the MCT compression curve. The results showed two basic patterns, one for intact (non-fissured) clays with $I_p$>20%, one for the remainder soils.

For intact (non-fissured) clays with $I_p$>20%, the identified MRT compression curve basically coincided with the usual MCT compression curve, the slight difference can be attributed to the different test duration (Fig. 6). In case of "large" partial unloading (e.g. for samples 2 and 4) the compression curve became non-monotonic due to a local drift.

For clays with plasticity index below $I_p$=20%, the MRT compression curve was increasingly drifted away from the usual MCT compression curve, starting generally from the beginning of the test. For the low plasticity silts with $I_p$ =10%, the drift was so huge that the final total stress became zero. A similar breakdown did not occur for soils with $I_p$ being less than 6% or for saturated, uniformly distributed sands.

## DISCUSSION

### The immediate stress drop

The immediate stress drop in relaxation tests with quick loading is mentioned with no explanation in several works [see e.g. Whitman (1957, Kondner & Stallknecht (1961); Topolnicki (1987)] and it is encountered if cone penetration stops, also (Imre et al., 2010).

It can be attributed to various reasons. If the initial pore water pressure distribution has a uniform component then it dissipates instantaneously, being the consolidation model solution the zero function. Another reason is the change of the loading rate at the end of the load imposition (such that the time dependent constitutive law may change as well).

The soil response is dependent on the energy storage capacity of the bonds. It should be uniform due to the equilibrium condition of the consolidation model. Since the minimum value of the past preconsolidation pressure of the sample is smaller than the mean effective stress of the sample during loadig, a stress drop may occur.

If the control system is not fast enough to realize this stress drop, a temporary overload may occur which is followed by an additional stress drop along a rebound line afterwards (Fig. 5).

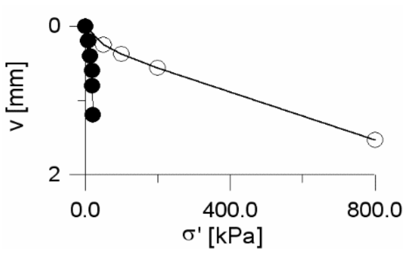
Finally, it can be mentioned that the initial fast stress drop is missing in case when the load is controlled by a rigid spring in series instead of a servosystem, since the dynamic component of the force immediately dissipates in this case by the small displacement of the spring at stress release.

### The compression curve – effect of the partial unloading

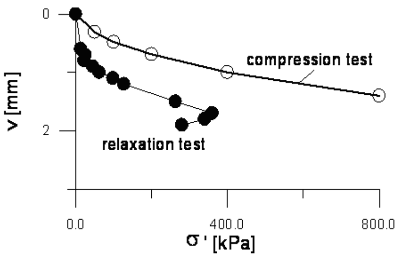
For intact (non-fissured) clays with $I_p$ >20%, unexpectedly, the MRT compression curve did not drift away from the usual MCT compression curve, only a “large” partial unloading could have had such an effect (see Fig. 6, samples 4 to 6). This can be explained by a recent micromechanical contact force model for cohesive particles (Luding, 2008) indicating that due to a tiny partial unloading the stiffness does not change (i.e., the path is fully reversible), and the stiffness changes only at a non-slight partial unloading.

Moreover, for intact clays with $I_p$ 20% to 25%, the compression curve was not monotonic. This can be explained by the force chain rearrangement (see e.g. the numerical experiments of Bojtár and Bagi, 1993). The conventional MCT compression curve with the usual doubled load increment does skip these changes since the load steps are generally too large.

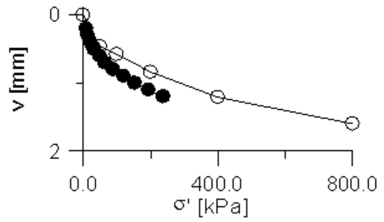
Finally a note can be made. Surprisingly, the evaluation of not only the MRT but also the MCT yielded some micromechanical results as well. The identified initial compression parameter - reflecting the compressibility of the grains and pore fluid – was negligible for silts but was extremely high for clays (Figs 7-8). Further research is suggested on this.



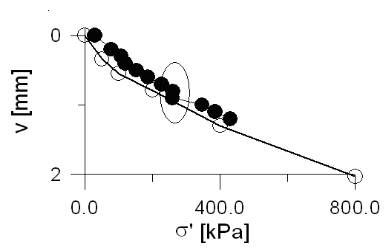

*(a)~NC sample 1 Ip =10% (vt=0,2 mm, MRT: full circle, MCT: open circle)*



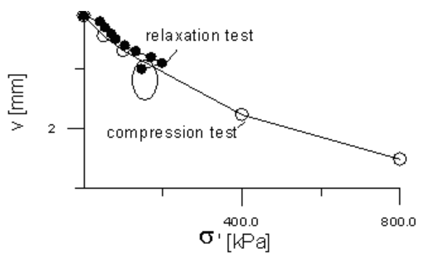

*(b)~NC sample 2 Ip =16% (vt=0,2 mm, MRT: full circle, MCT: open circle)*



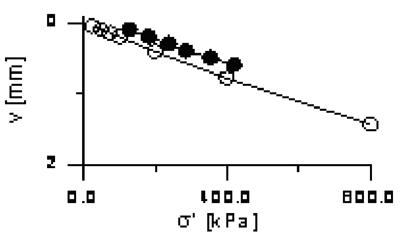

*(c) ~NC sample 3 Ip =17%(vt=1 mm, MRT: full circle, MCT: open circle)*




*(d) ~NC sample 4 Ip =23% (vt=0,7 mm, MRT: full circle, MCT: open circle, marked spontaneous partial unloading)*




*(e) OC sample 5 Ip =37% (vt=0,8 mm, MRT: full circle, MCT: open circle, marked intentional partial unloading)*




*(f) ~NC sample 6 Ip =41% (monotonic loading for MRT, MRT: full circle, MCT: open circle)*

Fig. 6. Compression curves of the samples with increasing plasticity and OCR from (a) to (g) (notation: vt is the measured limit for monotonic loading).

## CONCLUSIONS

The research was primarily undertaken for the validation of the joint model-pair of the staged tests and for the validation of a short multistage procedure.

The main results concerning the consolidation modelling of the oedometric relaxation test are as follows.

(i) In case of the generally assumed uniform initial pore water pressure distribution the dissipation is instantaneous for the relaxation test. Therefore, the load imposition can not be instantaneous and the initial condition has to be identified.

(ii) During a stage of the relaxation test the upper part of the single-drained sample swells, the lower part of the sample compresses. During compression - instead of increasing - the effective stress may decrease due to relaxation (i.e. due to the time dependent constitutive law).

(iii) Being the volume constant during a stage, the loading is drained with respect to the mean effective stress. If there is a slight overload and unload at the end of the loading in terms of displacement then the mean effective stress level moves along the unload-reload line while the pore water pressure- depending on the volume – does not change. Since the mean effective stress drops, the effective stress level at the sample bottom may be very low (even negative).

The immediate stress drop

- According to the laboratory test results, a total stress drop occurred at the start of the stages of the MRT, entailing a slight partial unloading when the load was larger than a soil-dependent threshold load at the start of the stages. The slight partial unloading monotonically increased with stage number which can tentatively be explained as follows.
- The MRT, applying constant strain rate during each load increase period, is basically a CRS test. However, the inclusion of the stages - where the response of the sample is measured under constant displacement load, depending on the energy storage capability of the bonds, being limited by the largest preconsolidation stress – may result in a stress drop.
- The stress drop can also be attributed to the change of the loading at the end of the load imposition from a basically dynamic to a basically static, from a “fast” to a

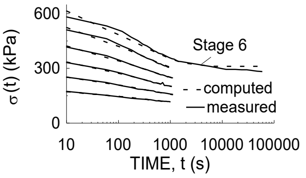
"normal" strain rate range (such that even the time dependent constitutive law may change as well). Moreover, if the initial pore water pressure distribution has a uniform component due to fast loading then it dissipates instantaneously.

The short multistage rexation tests data were evaluated with the consolidation model, and the so determined compression curve was compared with the conventional compression curve. According to the results, the difference of the MRT and the MCT compression curves after a slight partial unloading depended on soil type and texture as follows.

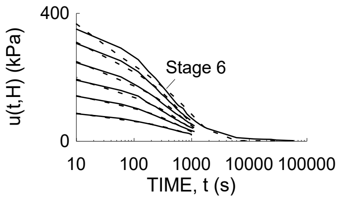
- The MRT compression curve point is instantaneous in the sense that the mean effective stress ($\sigma'_{mean}$) is constant during a stage, being equal to the final total stress ($\sigma_\infty$), which is an upper bound for the compression curve point.

- The stress drop may have caused some slight partial unloading due to the limitation of the testing system. . As a result, the compression curve point may have been drifted to the OC range. However, basically no deviation was observed for intact plastic clays (20% $< I_p$), the compression curve point is not drifted on the OC range after a slight partial unloading. This can tentatively be explained by a recent micromechanical contact force model for cohesive particles in case of small displacements. The large energy storage capacity of the bonds may be responsible, the precise explanation needs some further research.
- For clays with decreasing plasticity (20% $< I_p$) an increasing deviation between of the MRT and MCT compression curves was found. It was attributed both to the slight partial unloading and to the limited energy storage capacity of the increasingly frictional bonds.
- The saline silts showed a nearly zero MRT compression curve due to the zero storage capacity of the bonds. The reason for it was possibly the presence of no proper bonds.

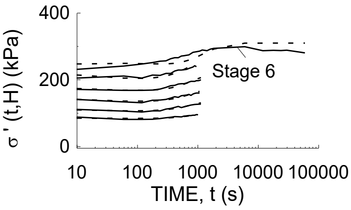
The results showed that the MRT can be a candidate test for the determination of the tensile strength of saturated, intact clays since negative effective stress can be caused at the sample bottom by a large enough partial unloading in the NC state.
It was found that – conversely - any non-monotonic step in the compression curve of plastic, intact clays may be realized by a large partial unloading as well.



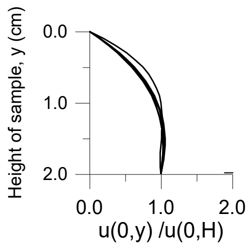

(a) Total stress.




(b) Pore water pressure.

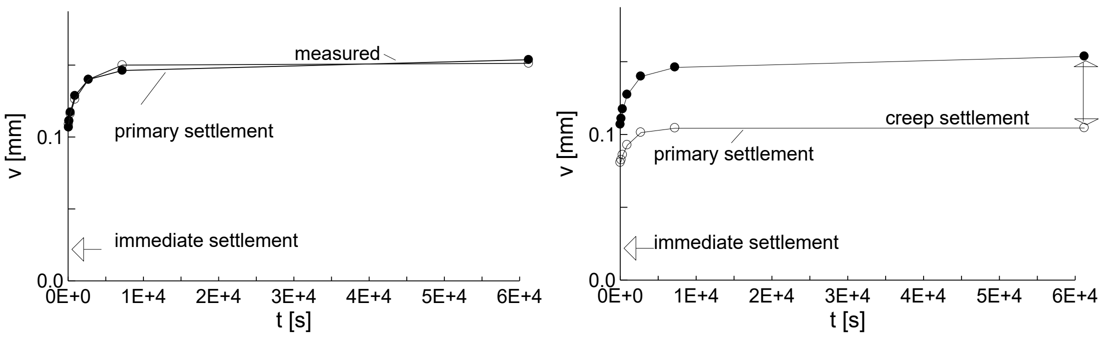



(c) Effective stress.




(d) Identified initial condition.

Fig. 7. MRT, simulated and measured stresses, sample 6.




(a) (b)

Fig. 8. MCT, simulated and measured stresses for a stage, sample 5.(a) Terzaghi's model completed by immediate settlement, (b) Bjerrum's model completed by immediate settlement.

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## Appendix : Equipment, phenomena during a stage

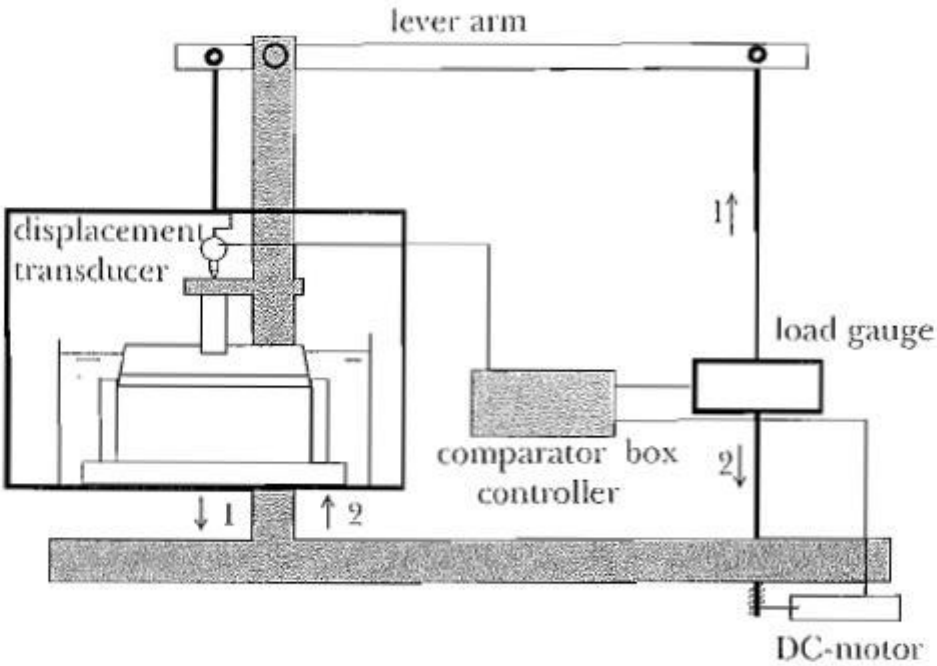
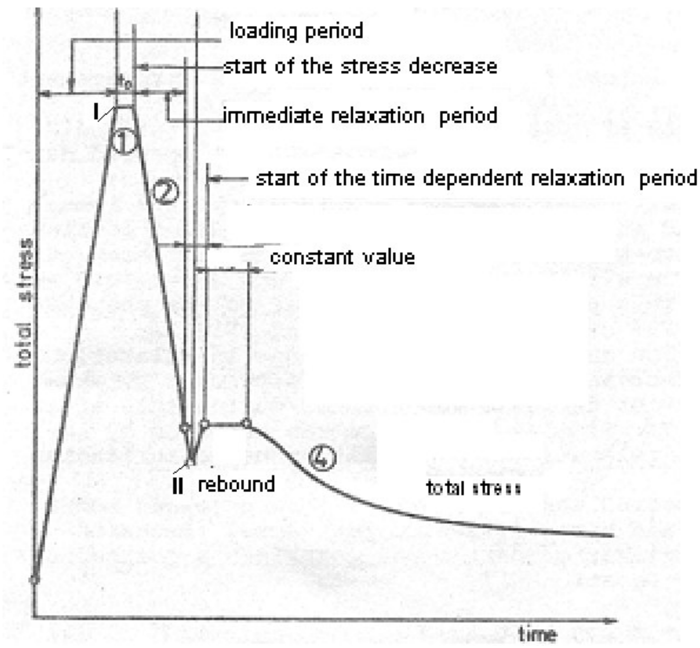
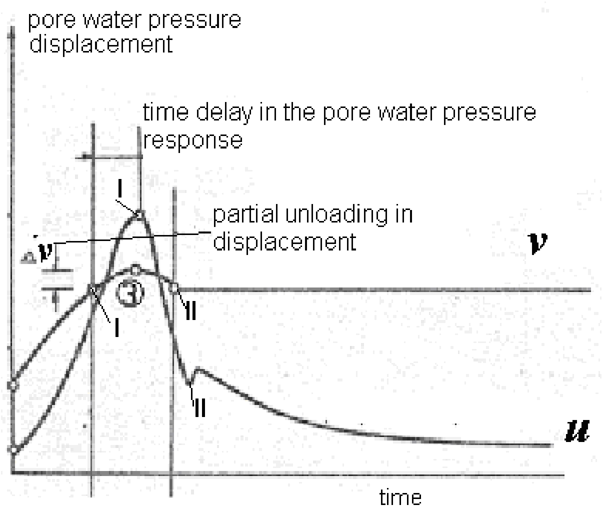



Figure A-1. Geonor type swelling pressure apparatus

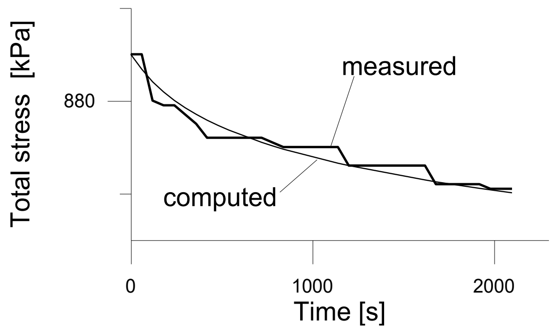


(a) The simplified total stress history (measured at $y$=0, sample top)




(b) The pore water pressure measured at $y$=H (impermeable boundary, sample bottom, note the time delay due to the compliance) and the displacement measured at $y$=0 (sample top).

Figure A-2. MRT, schematic stage record for pore water pressure and displacement. Notes: 1: delay time of relaxation, 2 or 4: immediate or time dependent relaxation, resp., 3: partial unloading in terms of displacement, the points denoted by I and II are conciding, I: end of load imposition, II: end of partial unloading.




The 'unsmoothened' total stress record, the effect of the side shear force for sands

Figure A-3. MRT, the time dependency of measured stresses, stage record. Notes: 1: delay time of relaxation, 2 or 4: immediate or time dependent relaxation, resp., 3: partial unloading in terms of displacement, I and II are conciding points, I: end of load imposition, II: end of partial unloading.