Investigation of development of the earth pressure coefficient at rest in clay during creep in the framework of hyper-viscoplasticity

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Abstract: The in-situ earth pressure coefficient at rest (K_0) for clay has been widely discussed in the literature. In engineering practice, empirical relationships between K_0, the overconsolidation ratio (OCR) and the normally consolidated value, K_0^{NC}, is often used. Where, K_0^{NC} is as a function of friction angle (φ). These relationships do not distinguish between an increase in OCR due to unloading or due to creep of the material. Although there is significant literature on measurements of the change in K_0 during unloading, there is a lack of data on the evolution of K_0 due to creep. The few existing in-situ measurements of K_0 are highly uncertain and difficult to be use for the purposes of investigating the time evolution of K_0. There is therefore no clear consensus on the time evolution of K_0 within the geotechnical community. During the last 20 years several creep models for clay have been developed within the framework of elasto-viscoplasticity. One common feature in many of these models is that they only predict a minor change in K_0 with time, as K_0 is given by one unique position on the potential surface. This contrasts with the unproven opinion of many practitioners who think that K_0 increases with time (even towards unity). In order to broaden the perspective of the discussion, this paper addresses the time evolution of K_0 in the framework of hyper-viscoplasticity. This framework offers a possibility for an increase in K_0 (even towards unity under certain conditions).

KEYWORDS: Earth pressure; time dependence; creep; clays; constitutive relations; plasticity

BACKGROUND AND INTRODUCTION

Schmertmann (1983) summarized the results of a survey on how different researchers considered the likely time evolution of K_0 during 1D creep (increase, decrease, constant). There was no clear consensus in the answers. However, the majority favored an increase. Almost forty years later the objective answer to this question, in the opinion of the authors, is not yet available. For example Shin and Santamarina (2009) stated that “the evolution of K_0 during secondary compression under no lateral strain is controversial”. Some researchers for example Devapriya and Said (2000) claim to have answered the question by showing a slight decrease in K_0 during the first 100 hours or so for different kaolin-bentonite mixtures. They showed that both the time period of decrease and the amount of decrease seems to depend on the quantity of bentonite. However, their evidence is inconclusive. It is interesting to notice that in one of their tests, a sample of kaolin with 7.5% bentonite, had a creep stage that lasted 400 h. In this test a decrease in K_0 could be observed in the period from 0 h to 100 h followed by a slight increase in K_0 in the period from 100 h to 400 h. Finally, after 400 h the K_0 was back to the same value as it was at 0 h. It must be pointed out that a short-term decrease does not rule out a long-term increase, as this could be due to totally different mechanisms. For example cementation of the material could explain a decrease in K_0, while shear relaxation, i.e. an increase in K_0, could be expected when considering the viscous nature of the bound water separating the clay particles (Schmertmann, 1983). Actually the tests by Devapriya and Said (2000) support this cementation (or thixotropy) theory, as the higher the bentonite content the greater the decrease in K_0 observed during this first period. Den Haan (2002) pointed out that from a modeler’s perspective, both an increase and decrease in K_0 could be experienced during the first hours of creep. This is due to internal ‘relaxation’ of the elastic contribution to the initial value of K_0 after a stress increase (K_0^{NC}), towards the asymptotic value of K_0, under pure creep deformation (den Haan, 2001). This point, of a duration of hours, not years, of possible time period for a decrease, is important as here the focus is on the long-term creep effects on K_0 (i.e. for decades). Hence a possible short-term decrease is not of primary interest. It is possible that this decrease happens independently of compression (creep), i.e. due to thixotropy, (Schmertmann, 1991). Thixotropy must be considered as a different mechanism during ageing than the effect of creep, as thixotropy happens at a constant volume. Independent of the period of which thixotropy possibly takes place, it is not considered as part of this study, since the focus here is on the development during creep.

This article first discusses some other available data and current modelling practice, giving different perspective on the evolution of K_0 during creep. Thereafter it describes a framework, using hyper-viscoplasticity (see e.g. Houlsby and Puzrin (2006)), that gives a flexibility for K_0 to increase with time during creep.

Some preliminaries for the theoretical framework used: Additive decomposition of elastic and viscoplastic strains, i.e. small strain assumption. The formulations are done in triaxial stress (p-q) space. It uses normal geotechnical sign convention, i.e. compression positive and the stress considered is the effective stress.

PREVIOUS EXPERIMENTAL STUDIES

Long before the work of Devapriya and Said (2000) there was others who tried to answer this fundamental question on K_0, both by laboratory and field testing. The 1983 note by Schmertmann was quickly followed by the work of Kavazanjian and Mitchell (1984) who presented interesting results on San Francisco Bay Mud. They showed a minor increase in K_0 over a period of 10,000 minutes, from 0.53 to 0.58. They also argued that K_0 should asymptotically approach unity given infinite time. Their reasoning was that this would represent a minimum energy state. If this were true, it would then be natural to assume that in-situ investigations on natural material that have been subjected to creep for a long time would give measurements of K_0 approaching unity. As an example Nash et al. (1992) made an attempt to measure K_0 in Bothkennar clay in-situ and although the measurements were highly uncertain, values significantly below 1.0 were measured (ranging from 0.6 to 0.9). The measured normal consolidation value of the earth pressure coefficient, K_0^{NC}, is close to 0.5 for Bothkennar clay, as found in an oedo-triaxial test by Watabe et al. (2003). It is not clear whether the field value increased due to creep or due to a stress history involving unloading (a reduction in the effective stress level). Mesri and Castro (1987) showed results of oedo-triaxial creep tests on clays from Saint Alban, Batiscan, Broadback and Atchafalaya. All the tests on these materials showed a small tendency for increase in K_0 with time. However, the scatter was generally large due to the difficulties in radial strain control in the tests. The reported increase in K_0 for e.g. the Saint Alban clay was from 0.49 to 0.52 over a period of 70 days. Similarly, the K_0 for Broadback clay increased from 0.51 to 0.56 over the same period. In contrast, Sletten (2015) and Gjengstø (2016) performed tests using the split-ring oedometer (Senneset, 1989) on both natural and reconstituted Tiller clay. Their results are presented in Figure 1. In a period of more than one week, no clear conclusion about a possible increase could be drawn. No trend was found, and larger variations were observed due to temperature variations alone (the data presented here are without temperature correction, hence the huge fluctuations). Despite the problem of temperature variations, the findings were generally more in line with that of Holtz et al. (1986), who showed a constant value, of about 0.55, for undisturbed Montalto di Castro clay over a creep period of four weeks. There is, however, one general difficulty in that all the laboratory data are from a limited time period of measurement (weeks), while the material in-situ has been left to creep for thousands of years. Therefore, a natural question to ask is that if it is fair to extrapolate conclusions on time evolution of K_0 from laboratory tests, that last a period of weeks, to the behavior in-situ, i.e. over a period of years in a manner to that done successfully for creep itself, e.g. Degago et al. (2011). Interestingly some attempts have also been made for measuring K_0 in-situ also for Tiller clay. Extensive efforts were made by NGI and NTNU (Ofstad and Lindgård, 2017) to measure in situ horizontal stress at the well characterized NGTS site at Tiller / Flotten using Glötzl push in pressure cells (L'Heureux et al., 2019). As L'Heureux et al. (2019) presented, this work resulted in some scatter in the data, which was thought to be due to installation effects. But overall the results showed an average K_0 of 0.8 and a with measured minimum value around the short-term normal consolidation value. Nevertheless, the average of the measurements suggests an increase, from the values reported in lab by Sletten and Gjengstø, also for this material when it is subjected to thousands of years of creep.

CURRENT PRACTICE

From a different practical perspective, geotechnical engineers are used to empirical relationships between K_0 and overconsolidation ratio (OCR). As pointed out by e.g. Ladd et al. (1977) these relationships are often based on oedo-triaxial tests during unloading and are therefore only valid for that case of simple unloading. The K_0-OCR (unloading) relationship is based on a large database of tests and is well documented. In contrast, since the OCR also increases with time, due to creep, the wrong estimation of K_0 can easily be made in practice. i.e. when this relationship is used in a case where the stress history of the material is more complicated than a simple case of unloading. Nonetheless, as Schmertmann (1983) pointed out, the opinion of many geotechnical engineers is that there is a similarity between unloading and creep, with respect to change in K_0.

In contrast, to this expectation of increased K_0 with time, the most popular creep models for clay predict a constant value for K_0 during creep. This is a consequence of model restrictions, as the K_0 condition is uniquely related to a single stress state on the potential surface where the volumetric strain increment equals the vertical strain increment. Examples of such models, predicting constant K_0, are found in e.g. Stolle et al. (1999) and Grimstad et al. (2010). In such models, the slight change in K_0 from K_0^{NC} (both increase or decrease possible) is only due to the contribution from the elastic strains to the K_0^{NC} value (den Haan, 2001), which generally can be considered to be small.

HYPER CREEP MODEL FORMULATION

In hyper-viscoplasticity, in order to ensure fulfillment of the basic laws of thermodynamic, the material response is derived from a force potential and a free energy function. The free energy function provides the basis for reversible response of the material, while the force potential is responsible for the irreversible response. The notation used here follows closely the book of Houlsby and Puzrin (2006) with some minor exceptions. Grimstad et al. (2020) used the force potential, z, given in Equation (1), to show that the conventional creep model based on the Modified Cam-Clay Model (Roscoe and Burland, 1968) can be derived within the hyper-viscoplastic formalism. They assumed that the free energy is only a function of elastic strains. This basically means, in their model, the dissipative generalized stress and the true stress are identical. Note that the generalized dissipative stresses are the work conjugated stresses to the viscoplastic strains, just as the true stress (p and q) are conjugated to the total strains. For convenience the same assumption will be made here. This means that the focus is primarily directed towards the force potential. The contribution from elastic deformation is also assumed to be small, such that it only will play a minor role on the K_0 value during 1D creep.

$$z = \frac{p_0}{2^n} \cdot \frac{r^{1-n}}{n} \cdot \left(\sqrt{\left(\dot{\varepsilon}_v^{vp}\right)^2 + M^2 \cdot \left(\dot{\varepsilon}_q^{vp}\right)^2} + \dot{\varepsilon}_v^{vp} \right)^n \tag{1}$$

Where p_0 is a state variable equivalent to the isotropic "pre-consolidation" stress, r is a reference rate, n represents the rate dependency ($n = 1$ means rate independent, while $n = 2$ gives linear increase with strain rate, for clays, n would be slightly larger than 1 typically around 1.04 (Grimstad et al., 2020)), $\dot{\varepsilon}_v^{vp}$ is the volumetric viscoplastic strain rate and $\dot{\varepsilon}_q^{vp}$ is the deviatoric viscoplastic strain rate, and M is the critical state stress ratio.

Consider the following force potential adapted from the dissipation function proposed by Collins and Kelly (2002)

$$z = \frac{p_0}{2^n} \cdot \frac{r^{1-n}}{n} \cdot \left(\sqrt{\left(\dot{\varepsilon}_v^{vp}\right)^2 + M^2 \cdot \left(\gamma + (1-\gamma) \cdot \frac{2 \cdot p}{p_0} \right)^2 \cdot \left(\dot{\varepsilon}_q^{vp}\right)^2} + \dot{\varepsilon}_v^{vp} \right)^n \tag{2}$$

where p is the mean effective stress and γ is a number between 1.0 and 0.0. For $\gamma = 1$ the Modified Cam Clay surface (elliptical in p-q space) is retrieved, and for reduced values of γ, the surfaces will be more and more "skewed" in shape. The argument to modify the force potential of MCCM, eq. (1), in this way is to better model the "dry" side of the critical state line, i.e. for over-consolidated clays. This is a similar to the argument made by e.g. Houlsby et al. (1984). Note that eq. (2) is not the only way to improve the prediction of the material response at higher *OCR*s, e.g. Collins (2003) gives also some other alternatives. It is demonstrated below that the modification used here will influence the time evolution of K_0 during creep. It can be shown that this also will be the case for other alternative force potentials that involves the normalization p/p_0.

This force potential, eq. (2), results in the following flow potential (i.e. plastic potential in the generalized dissipative stress space):

$$w = z - d = p_0 \cdot r \cdot \frac{n-1}{n} \cdot \left(\frac{p_{eq}}{p_0} \right)^{\frac{n}{n-1}} \tag{3}$$

where the equivalent stress measure, p_{eq}, is:

$$p_{eq} = \chi_p + \frac{1}{M^2} \cdot \frac{1}{\left(\gamma + (1-\gamma) \cdot \frac{2 \cdot p}{p_0} \right)^2} \cdot \frac{\chi_q^{\,2}}{\chi_p} \tag{4}$$

And, where χ_p is dissipative generalized mean effective stress and χ_q is dissipative generalized deviatoric stress. d is the dissipation function, i.e. the differential of z, Equation (5).

$$d = \frac{\partial z}{\partial \dot{\varepsilon}_v^{vp}} \cdot \dot{\varepsilon}_v^{vp} + \frac{\partial z}{\partial \dot{\varepsilon}_q^{vp}} \cdot \dot{\varepsilon}_q^{vp} \tag{5}$$

It is worth noticing that Equation (3) for infinite time under constant volume will predict a relaxation to zero stress condition. And for a constant effective stress it will result in infinite volumetric strain for infinite time. However, this has limited practical meaning under any practical time span. Even for several hundred thousand years the strains can still be considered as small and the *OCR* typically still stays far below a ratio of 3. As an example den Haan (2001) associated the creep behavior of a clay with *OCR* of 4 with longer timespan than the postulated age of the universe. Nevertheless, this “limitation” can be addressed by adding a simple linear term, with the same mathematical structure as the present term, with $n = 1$, to the force potential. The consequence, of such a term, is a “static” surface describing an elastic region. However, this needs pre-knowledge of such a final asymptotic state. In order to more easily understand why this is not important in this study, it can be seen that

Equation (3) gives a linear relation for log(p_{eq}/p_0) vs log($\partial w/\partial p_{eq}$). Also for a reasonable time interval (i.e. an interval of the ratio p_0/p_{eq}) the modified form, with the static surface, could also be practically linear in log(p_0/p_{eq}) vs log($\partial w/\partial p_{eq}$), see also e.g. Grimstad et al. (2017). As an example, Equation (8) gives a resulting flow potential, w', where a linear term of a quarter of the exponential term is added to the force potential z', Equation (6). Note that the quarter is just an arbitrary choice, as no laboratory test would last long enough or have sufficient measurement accuracy to justify any particular value.

$$z' = \frac{p_0}{2^{n'}} \cdot \frac{(r')^{1-n'}}{n'} \cdot X^{n'} + \frac{p_0}{8} \cdot X \tag{6}$$

where:

$$X = \sqrt{\left(\dot{\varepsilon}_v^{vp}\right)^2 + M^2 \cdot \left(\gamma + (1-\gamma) \cdot \frac{2 \cdot p}{p_0}\right)^2 \cdot \left(\dot{\varepsilon}_q^{vp}\right)^2} + \dot{\varepsilon}_v^{vp} \tag{7}$$

$$w' = p_0 \cdot \frac{n'-1}{n'} \cdot r' \cdot \left\langle \frac{p_{eq}}{p_0} - \frac{1}{4} \right\rangle^{\frac{n'}{n'-1}} \tag{8}$$

where <> are the Macaulay brackets. Note that n' and r' would take different numerical values than n and r to make a good fit in the interval of, for example, a ratio of p_0/p_{eq} from 0.8 to 2.0. In addition, the derivations that follow in the rest of the paper, for the evolution of K_0, is actually independent of the choice between Equation (3) and Equation (8). This is because the expression for p_{eq} and hence the flow direction is actually unaffected by this choice, as long as the ratio of p_0/p_{eq} is below the arbitrary 4.0, for the case of Equation (8).

Regardless of using Equation (3) or Equation (8) in 1D creep (assuming negligible elastic contribution) the following condition must hold:

$$\frac{3}{2} = \frac{\dot{\varepsilon}_v^{vp}}{\dot{\varepsilon}_q^{vp}} = \frac{\partial w}{\partial \chi_p} \Bigg/ \frac{\partial w}{\partial \chi_q} = \frac{\partial p_{eq}}{\partial \chi_p} \Bigg/ \frac{\partial p_{eq}}{\partial \chi_q} \tag{9}$$

By defining, *OCR*, as in Equation (10) (note that this is not the same as the vertical stress based definition used in the empirical relationships), it is possible to solve for the evolution of K_0 as function of *OCR*, M and γ, i.e. solution of Eq. (11). M and γ are the only two input parameters controlling the evolution. The evolution of *OCR* with time depends on the value of r, n (or r', n') and the plastic compressibility of the material or a reference time (i.e. the choice of the numerical value of three independent parameters). Hence, for different clays the actual time evolution of K_0 could be different even though they could share the same M and γ. However, an *OCR* of more than 2.0 is typically not expected for a time period of any practical concern. An *OCR* greater than 1.83 would typically require about 10^4 years of creep deformations , with n = 1.04 and a reference time of 1 day. (Grimstad et al., 2016). This corresponds roughly to a strain rate of $1.3\cdot10^{-8}$ yr^{-1} (Watabe and Leroueil, 2015) (with the linear fit, i.e. Equation (3) and n = 1.04).

$$OCR = \frac{p_0}{p_{eq}} \tag{10}$$

$$\left(\sqrt{\frac{3}{M}\cdot\frac{\eta}{M}+\left(\frac{\eta}{M}\right)^2}-\gamma\right)\cdot\left(\frac{3}{M}\cdot\frac{\eta}{M}+2\cdot\left(\frac{\eta}{M}\right)^2\right)-\frac{2\cdot(1-\gamma)}{OCR}\cdot\left(\frac{3}{M}\cdot\frac{\eta}{M}+\left(\frac{\eta}{M}\right)^2\right)=0 \tag{11}$$

where K_0 is found from:

$$K_0 = \frac{3-\eta}{2\eta+3} \tag{12}$$

RESULTS AND DISCUSSION

Figure 2 shows the results, for two values of M (1.0 and 1.5), having numerically solved Equation (11) for η and inserting it into Equation (12). A M value between 1.0 and 1.5 will represent the actual range for many typical soft clays (Ouyang and Mayne, 2017). As seen in the figure for a value of γ, other than 1.0, the modified force potential predicts an increase in K_0 with increasing *OCR*. It is also worth noticing that in the modified model the reference time (or rate) is no longer an independent choice but is uniquely connected to K_0. This might pose an unnecessary complication, if no real data supports a K_0 increase for the clay in question. The other consequence, observed with the modified force potential, is that the value of the critical state line, *M*, now also only corresponds to the reference rate. For more details, see the change in stress ratio, for the stress state at the two different surfaces, where there is a vertical arrow in Figure 3. This means that if a unique Critical State Line is sought, then $\gamma = 1.0$ must be used. This again implies a constant K_0 under 1D creep deformation.

On the other hand, empirical relationships are of the form of Equation (13). The parameter *m* is a function of type of clay (i.e. plasticity index etc.) and *m* is typically in the order of 0.4 to 0.5. Figure 4 shows the empirical relationship in graphical form. For a coefficient *m* in the range 0.4 to 0.5, this equation clearly over-predicts the development of K_0, when compared to predictions for values of $\gamma > 0.5$ from the hyper-viscoplastic model in Figure 2. This suggests that there is a limited correlation between the empirical $K_0 - OCR$ unloading relationship and the potential K_0 - *OCR* creep relationship.

$$K_0 = K_0^{NC} \cdot OCR^m \tag{13}$$

CONCLUSIONS

There has been a gap in reasoning and understanding between clay modelling researchers and the opinion of practicing geotechnical engineers with respect to evolution of K_0 under 1D creep deformations of clays. Popular constitutive models predict a constant K_0 during 1D creep, but many practitioners believe in an increase in K_0 with time. Despite this fundamental question raised many years ago, there has not yet been a consensus in the community. The modelers have opted for a constant value, perhaps mainly out of convenience, as that is what the available tools predict. However, within the framework of hyper-viscoplasticity, an increase in K_0 can be predicted. The expected increase, found possible within this framework, is significantly less than offered by empirical relationships. Hence these empirical equations should be used with care when a measured apparent *OCR* is due to creep/aging. The predicted increase is especially quite moderate when considering reasonable timespan, i.e. *OCR* increase from 1 towards 2. This clearly indicates a difference between the evolution of K_0 under creep and for unloading. For the actual measured time evolution, there is still not enough data to support one or other conclusion, unless a unique (rate independent) critical state line (in p-q) is required to describe the “true” clay behavior. This limitation suggests a constant K_0 value during 1D creep, which is in line with the experiments by Holtz et al. (1986). Other experimental data, however, showed that both increase and decrease has been measured for evolution of time. Here it is important to distinguish between a result of a creep process and that of thixotropy (cementation effect). When considering creep only, the framework can capture well the range of increase as measured in the work of Kavazanjian and Mitchell (1984) and Mesri and Castro (1987). The K_0 evolution measured in the field data of Nash et al. (1992) and of L'Heureux et al. (2019) also fits well within the predictions. However, in the opinion of the authors the fundamental question still cannot be answered in a satisfactory manner. More high-quality long-term tests and accurate in-situ measurements are necessary to finally conclude on the actual evolution of K_0 under 1D creep.

DATA AVAILABILITY STATEMENT

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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NOTATION

The following symbols are used in this paper:

d = dissipation function;

K_0 = Earth Pressure Coefficient at rest;

K_0^{NC} = Earth Pressure Coefficient at rest, normally consolidation value;

m = power number;

n = creep power number;

OCR = over consolidation ratio;

p = mean effective stress;

p_0 = isotropic pre-consolidation stress;

p_{eq} = equivalent effective stress;

q = deviatoric stress;

r = reference rate;

w = flow potential function;

z = force potential function;

γ = parameter;

ε_v^{vp} = volumetric viscoplastic strain;

ε_q^{vp} = deviatoric viscoplastic strain;

η = stress ratio (q/p);

M = critical state line in p-q space;

χ_p dissipative generalized mean stress; and

χ_q dissipative generalized deviatoric stress.

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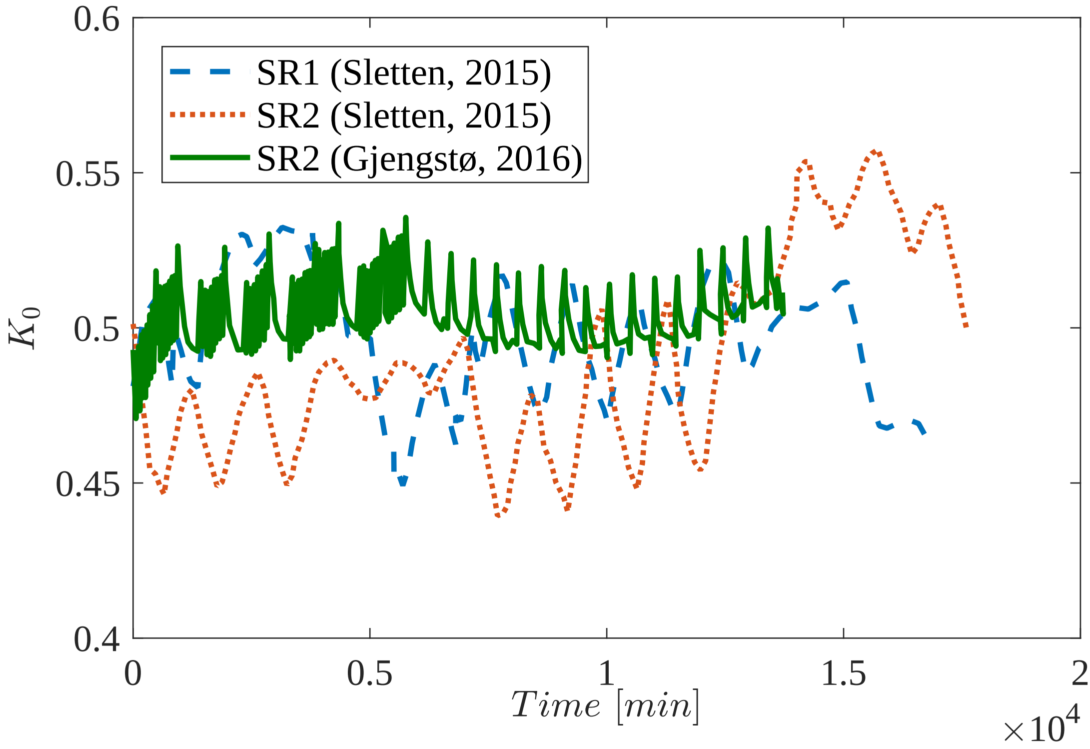
List of figures:

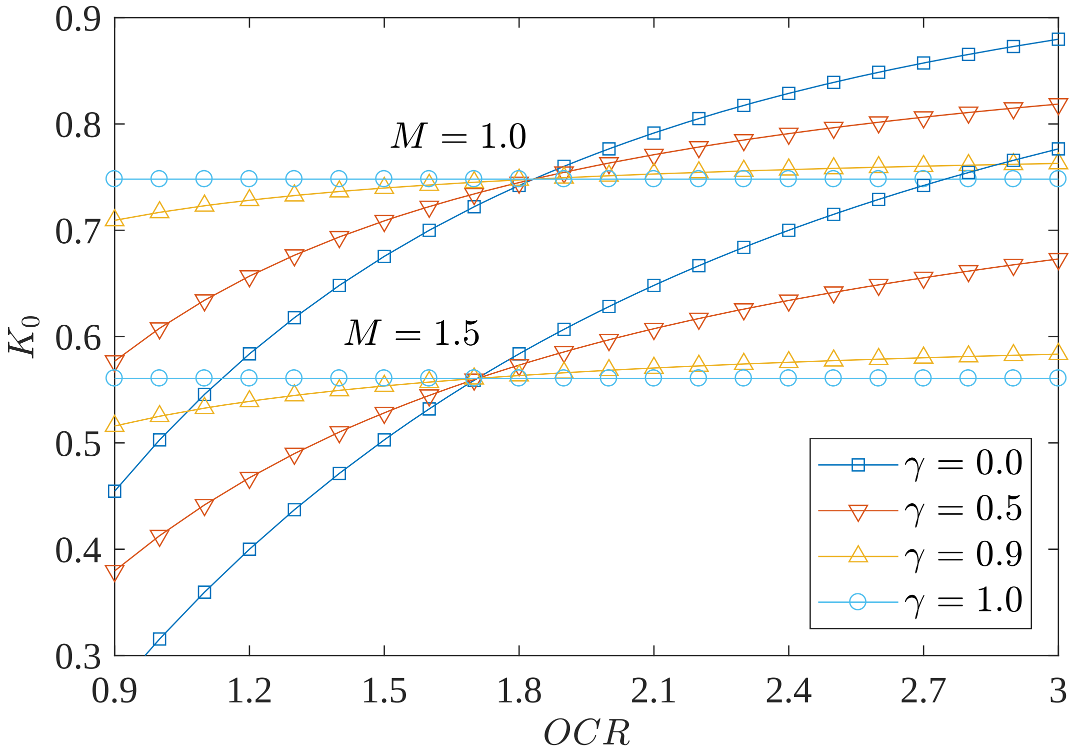
Figure 1 Measured K_0 *during creep of Tiller clay in split-ring oedometer tests, adapted from Sletten (2015) and Gjengstø (2016)*

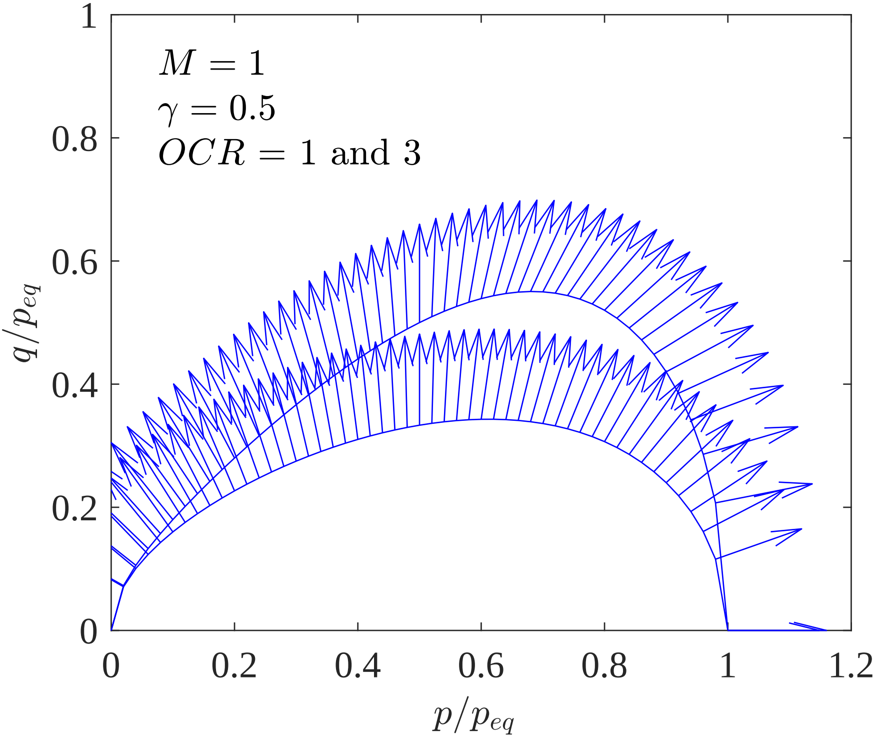
Figure 2 K_0 *as a function of OCR and* γ *for* $M = 1.0$ *and* $M = 1.5$.

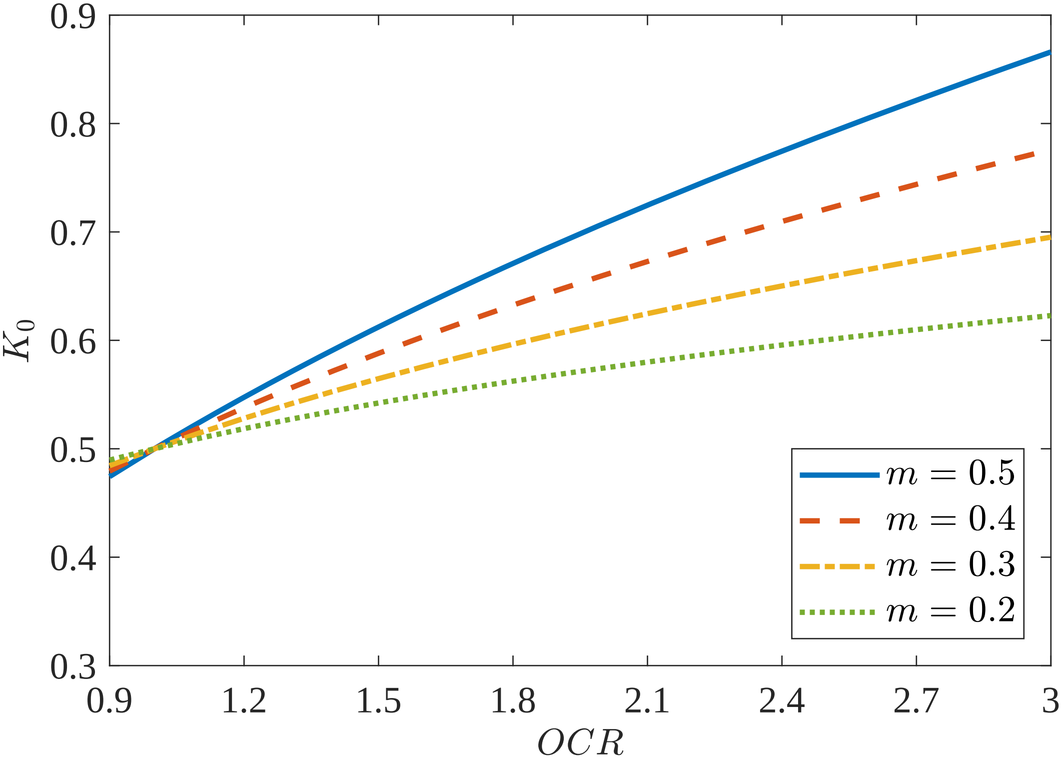
Figure 3 Shape for the equivalent surface with plastic flow directions (not actual size of $\boldsymbol{\varepsilon}^{vp}$*) for OCR = 1 and OCR = 3*

Figure 4 Empirical relationship for K_0 *as a function of OCR for different values of m,* $K_0^{NC} = 0.5$


SR1 (Sletten, 2015)
SR2 (Sletten, 2015)
SR2 (Gjengstø, 2016)
0.6
0.55
0.5
0.45
0.4
K_0
0
0.5
1
1.5
2
$Time\ [min]$
$\times 10^4$


K_0
OCR
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
$M = 1.0$
$M = 1.5$
$\gamma = 0.0$
$\gamma = 0.5$
$\gamma = 0.9$
$\gamma = 1.0$


$M = 1$
$\gamma = 0.5$
$OCR = 1$ and 3
q/p_{eq}
p/p_{eq}
0
0.2
0.4
0.6
0.8
1
0
0.2
0.4
0.6
0.8
1
1.2


K_0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
OCR
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
$m = 0.5$
$m = 0.4$
$m = 0.3$
$m = 0.2$