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Real-time interpretation of soil behavior

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ABSTRACT: Field behavior of clays in response to construction activities deviate considerably from the findings of the laboratory tests. These differences also affect the success of modeling techniques. To improve the ability of constructing safely and economically, the application of field monitoring techniques carries distinctive advantages provided that the readings could be interpreted in the scope of constitutive laws, without leaving a time gap between the measurement and parameter revision. This paper discusses the interpretations obtained through the application of such a methodology which was developed for the subject of embankments on soft clays. The implications of micro behaviour could also be detected through the application of the methodology and discussions regarding micro behaviour have been provided.

1 INTRODUCTION

Assessing and modelling the mechanical behavior of in-situ soils in response to construction activities have always been the major challenge of geotechnical engineering research. The problem mainly arises from the difficulties of matching the demands of a specific construction activity with what the soil could supply to absorb these destructions. This is a broad definition covering both the properties of stress application processes (loading patterns, rates, directions and quantities) and the numerous interactive factors that are effective on the soil response.

This lecture will try to link up the on-time measurements captured by field instrumentation to real soil behavior. The problem will be dealt with in the scope of embankment construction on soft clays. The end purpose is to find the implications of micro- structural changes in the macro-response of the foundation soils and be able to demonstrate these within a formal constitutive framework.

For this purpose, field deformation and stress measurements recorded in the foundation soils during embankment construction and afterwards, were transformed into their stress and strain equivalents, (q-p’-ν) at any point within the foundation soils. Facilitating this process, on time measurements were inserted into the constitutive framework of the Critical State Theory to draw stress paths in the q-p’-ν stress-strain space of the Critical State Soil Mechanics (CSSM) Theory. This process can be envisaged as an on-time process to demonstrate the changing soil behavior at any time during or after construction.

Embankments are massive structures covering large areas. Therefore the stresses exerted are high enough to act over the ranges from "below" to "after yielding" which may extend even to failure states if load control and contingency measures have not properly been applied. Embankments cover large areas, so stress axis rotation is an inherent part of the problem. Usually shear strength properties of soft clays are not sufficient and stage construction technique is preferred. Stage construction is associated with a greater variety of soil states and therefore serves better to the aim of interpreting the soil behavior through measurements taken by the field instrumentation. As a result, the problem of embankment construction on soft clays comprises almost all of the problems that are generally encountered in any geotechnical engineering project.

Considering the behavior of foundation soils, the mechanical response is also inherently variable due to the nature and evolution of clay properties. Clays in nature are of varying composition, state and structure formed during their depositional history, where complicated influences of all loading and chemo-physical processes are brought into action (Liu & Carter, 1999; Mitchell, 2005; Leroueil & Vaughan, 1990; Cotecchia et.al, 2011). From these; the effects of composition on the response of clays can be left outside, because differences of composition have no effects on the patterns of macro behavior; rather they only affect the values of the mechanical parameters (Burland, 1990; Cotecchia et al., 2011). However, state and structure are essentially sensitive to the current loading processes. This fact is well recognized by the past research that disturbances such as weathering or sampling or loading generally modify the original structure of the soil (Liu & Carter, 1999).

It is impossible to analyze the mechanical response of soft clays without considering time dependency. Soft clays exhibit time dependent stress-strain behavior (Bjerrum, 1967; Graham et al., 1983; Yin et al., 2002). Originally, viscoplastic behavior was observed by one-dimensional compression tests. However, the implications of this behavior are also observed in the field especially for the specific case of embankments on soft clays. Time dependency causes real field behavior to considerably deviate from the predictions due to the differences in strain rates between laboratory and field conditions which results in changes in preconsolidation pressures and consolidation processes.

Although, Critical State Soil Mechanics Theory was mainly developed to model macro-mechanical response of saturated clay, some aspects of CSSM have the capacity to model and observe the implications of micro-mechanical behavior. For example; specific volume can be recognized as fundamental soil variable controlling strain hardening behavior following the onset of the first yielding. The preconsolidation state is acknowledged as a yield state threshold of major changes in the clay at the micro-scale (Cotecchia & Chandler, 1998).

The definition of state boundary surface in relation to the flow rule also implies the evolution of the energy absorption capacity of the soil which is necessarily controlled by the micromechanical processes. Moreover, for soils exhibiting time dependent behavior the evolution of yield loci shows an erratic character; expanding and contracting, which is a direct indication of micro-structural responses.

According to CSSM the behavior of clay is considered as basically frictional defined by the critical stress ratio, M, being the parameter representing friction at the macro scale. Briefly, the capacity of CSSM to define macro-mechanical response of clays depends on three conceptual properties; i) the role of critical state as final constant volume state during shearing (Rowe, 1962), ii) the applicability of the dilation theory (Taylor, 1948), iii) allowance made to identify a linear flow rule. All of these properties carry the implications of the micro-mechanical response or defining in another way take their values according to the micro-structural changes that occur as a result of applied geotechnical processes. Therefore, CSSM provides a comprehensive framework to accommodate and to interpret the implications of micro-mechanical behavior.

The mechanical behavior of clays at their static equilibrium states (or at a constant strain rate) can be described by the original Critical State Energy Theory, but the rate effect should be incorporated with the strain hardening parameter to enhance the capacity of CSSM to highlight the main effects of micro features on macro behavior. The framework for constitutive models considering rate sensitivity was set up by Perzyna, 1963; Olszak & Perzyna, 1970; Chen, 1982. Following the elastic-viscoplastic model of Adachi & Oka (1982) attempted to combine the viscoplastic theory of Perzyna and Cambridge Critical State Energy Theory to derive a three dimensional constitutive equation. They considered the action of rate sensitivity by a dynamic yield function which incorporates the rate effect with the strain hardening parameter. Wood, 1990 described the way to extend the existing elastic-plastic models to accommodate rate sensitivity and creep effects as to assume an expanding and contracting yield locus depending on the strain rate.

Extensive research has been carried out to describe the effects of rate dependency since the originating concept of Šuklje (1969). As a result, constitutive models (Kim & Leroueil, 2001; Yin & Graham, 1994; and others) which incorporate the time dependent behavior of soils can be applied to increase the degree of accuracy in the estimation of consolidation behavior. In almost all of the cases at the present state, the estimation is based on the results of the laboratory tests. However the stress paths that are actually followed by soil elements in certain typical geotechnical structures may considerably deviate from the possibilities of laboratory apparatuses. Therefore, despite the evident superiority of improved constitutive models over the conventional elastoplastic analyses to describe soil behavior, deviations inevitably occur between the predicted behavior and actual field behavior. In addition to the typical causes of deviation such as nonhomogeneity and anisotropy of the foundation soils, the field strain rate which is actually occurring at any point and at any time may quite easily change the direction and quantity of the viscoplastic mechanism that was predicted. Also, constitutive relations are strictly limited to certain boundary and loading conditions which may not hold true for the considered real situation. Therefore, real time methods are needed to detect any deviations from the expected behavior and to modify the design according to the newly arising situations (Oztoprak & Cinicioglu, 2005).

Field monitoring which records responses of soils in terms of deformations and excess pore water pressures give invaluable information to interpret mechanical response of soils provided that they can be used to investigate the interaction of fields of stresses and strains via the materials constitutive laws. The methodology described in Cinicioglu & Oztoprak (2003); Oztoprak & Cinicioglu (2005, 2006) fulfills the objective of interpreting soil behavior at the real time in the scope of the constitutive framework without allowing any time lag between measurements and interpretation and without applying any back-analysis technique.

Oztoprak -Cinicioglu methodology will be dealt with in this paper. Authors believe that the strongest property of the Oztoprak -Cinicioglu methodology is its ability to interpret time dependency and this aspect will be discussed in relation to structuration-destructuration phenomenon at the micro-scale. Preliminary results of a continuing research work (Yigit & Cinicioglu) will be discussed to assess the structural response of clay during consolidation at the micro-scale.

2 REAL-TIME FIELD INTERPRETATION METHODOLOGY

The real-time field interpretation technique was developed by Oztoprak & Cinicioglu for the specific case of embankment construction on soft clays and presented in Oztoprak (2002); Cinicioglu & Oztoprak (2003); Oztoprak & Cinicioglu (2005). The method interprets field behavior within the framework of elastic-viscoplastic constitutive behavior. The input to the application of the method is field measurements. For this purpose volumetric expression of measured deformations were transformed into q-p'-ν stress space of the Critical State Theory. The real-time method was tested by Oztoprak (2002) by using the well documented field data for Cubzac-les-Ponts test embankment B (Magnan et al., 1983). The initial form of the mesh used for the application of the method is presented in Fig. 1. The applied loading program is seen in Fig. 2.

The method is basically a stress path method which follows and interprets the stress-strain behavior of foundation soils continuously during and after embankment construction an earlier crude approach of which was given by Cinicioglu & Togrol (1995). This property of the method comes from its ability to define the changes in stresses in relation to the changes in strains and specific volumes calculated from measured deformations.

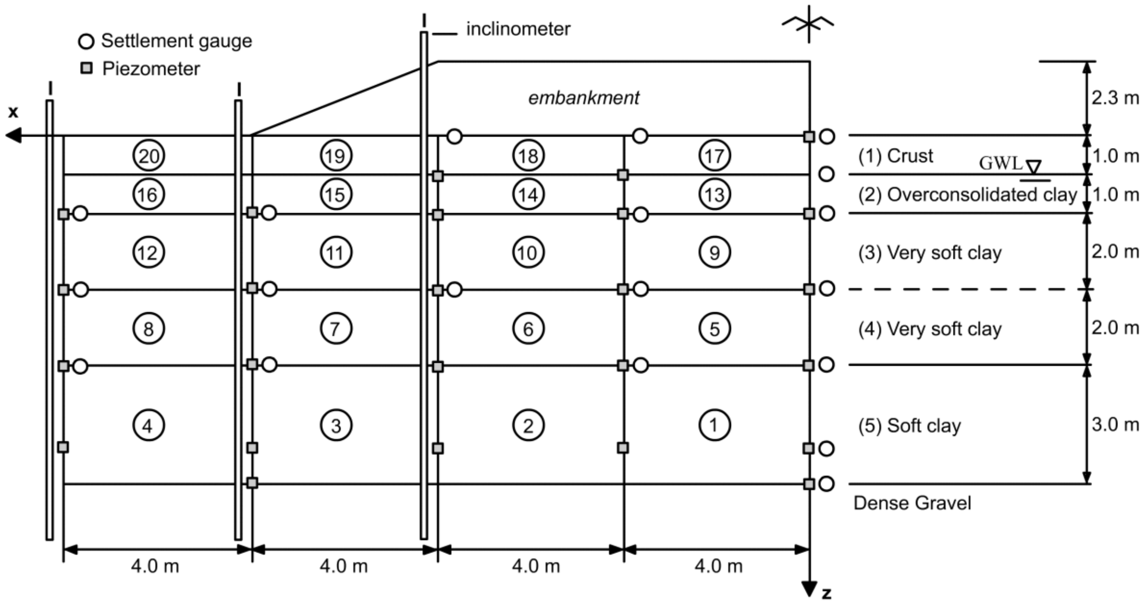

Figure 1. Soil conditions at Cubzac-les-Ponts and the initial form of the mesh used for the method.

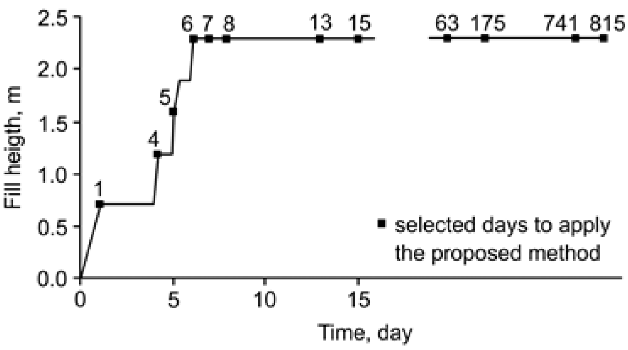

Figure 2. Loading program of embankment B with time at Cubzac-les-Ponts (After Magnan et al. 1983).

An important consideration is to accommodate the initial and succeeding stress states at the correct positions in the stress-strain framework provided by the adopted Constitutive Theory. The place of current stress state is also an indication of the current mechanism controlling the behavior. It is therefore necessary to adopt a parameter which can reflect the structural changes occurring in the soil body during the processes of loading and consolidation. Coefficient of lateral earth pressure, K_o for the initial at rest condition depends on the anisotropy and consolidation state gained by geological and other processes. Therefore K_o is an indication of structural properties of the at rest state. Experimental evidence suggests that structural changes in a soil are reflected in the values of lateral pressure, K (Feda et al. 1995) as stress states divert from the initial at rest state. Thus, $K=\sigma'_h/\sigma'_v$ represents the stress ratio for any lateral deformation. It follows from the above definition that K is the parameter that reflects the type of shearing action caused by the current state of deformation as well as the degree of inter-particle sliding resistance mobilized in the soil. Strong dependence of earth pressure coefficient on strain increment ratio was revealed based on triaxial loading tests along different constant strain paths. From this finding Zhang et al. (1998) developed a methodology for solving earth pressure problems under any boundary strain constraint covering all the small strain cases which range between the active and passive stress states. Considering the length of the paper, the application of the method is presented as a flow chart accompanying the schematic representation in Fig. 3 in which the procedure to calculate K values is also demonstrated.

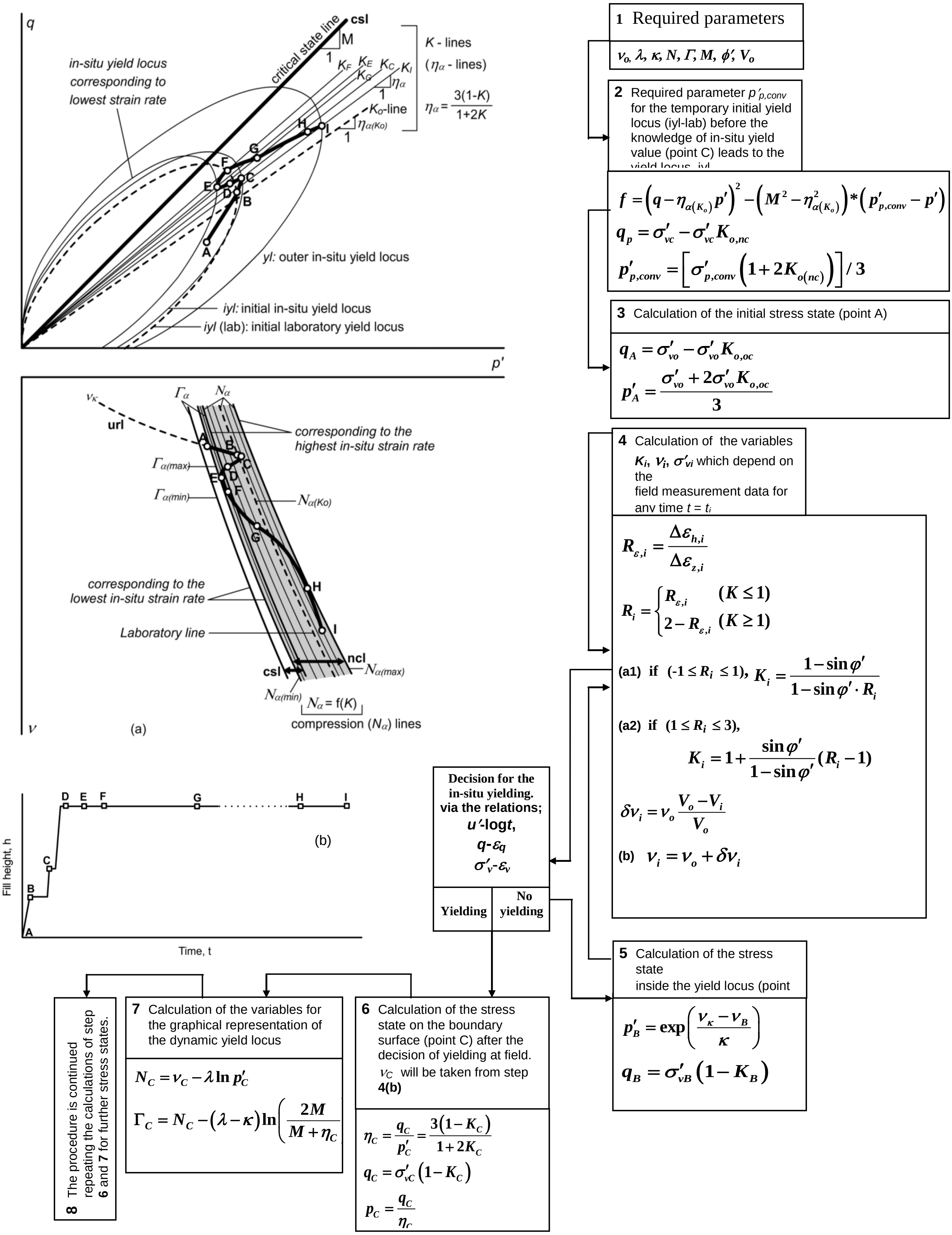

Figure 3. Schematic representation and flow chart of the proposed method (a) stress paths on q-p′ and ν-p′ planes, (b) construction program of the embankment. (K relations in step 4 are from Zhang et al., 1998)

3 TIME-DEPENDENCY

Originating from Šukjle (1957) recent research (Graham et al., 1983; Leroueil et al., 1985; Mesri & Choi, 1985; Leroueil & Marques, 1996; Kim & Leroueil, 2001 and Yin et al., 2002) provided significant scientific evidence on the time dependent behavior of soft clays during primary consolidation. Basic implications of the behavior can be summarized as; (i) Stress-strain curves of a soft soil take their shapes in accordance with the variation in strain rate. (ii) In accordance with the variation of stress-strain curves, preconsolidation pressures also vary. (iii) With the passage of preconsolidation pressure, unanticipated increases in pore water pressures are experienced. This behavior was evidenced both in laboratory relaxation tests and in the field. (iv) Following a progressive reduction in effective stress with time, the strain rate decreases and strain develops. This behavior described by Kim & Leroueil (2001) can be observed in Fig. 4 along the effective stress-strain curves drawn for different sublayers within a thick soil element representing a consolidating soil layer.

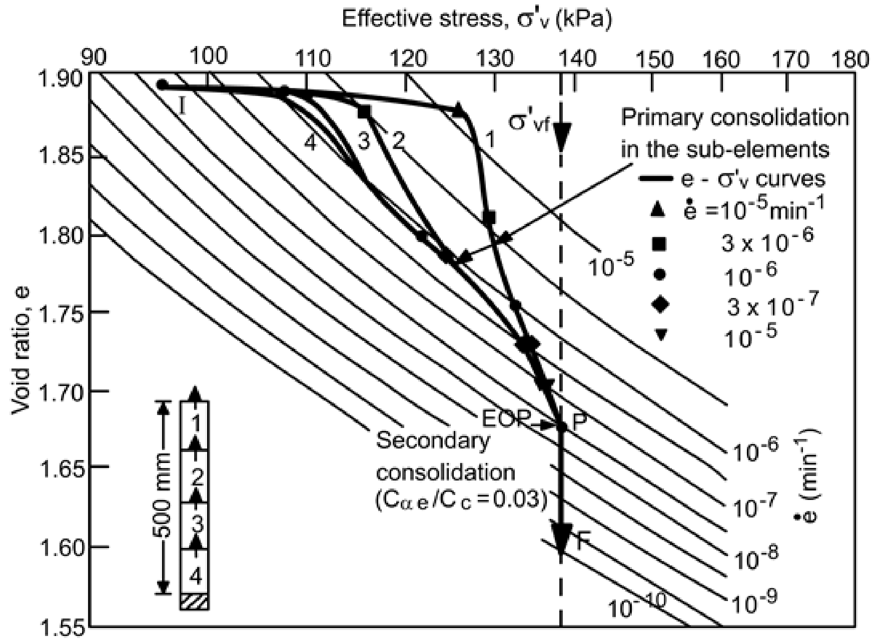

Figure 4. Consolidation of soft clay under varying strain rates (After Kim & Leroueil 2000)

It is now well-accepted that compression is controlled by a unique effective stress (σ'_v) – viscous strain (ε_v) – viscous strain rate ($\acute{\varepsilon}_v$) relationship. The framework for constitutive modeling of the time-dependent stress-strain behavior of soils was set up by Perzyna (1963), Chen (1982). Adachi & Oka (1982) attempted to combine the viscoplastic theory of Perzyna and Cambridge Critical State Theory. Wood (1990) described the way to extend the existing elastic-plastic models to accommodate rate sensitivity and creep effects as to assume an expanding and contracting yield locus depending on the strain rate. Yin & Graham, 1988; Yin et al., 1994; Yin et al., 2002; made studies to incorporate the increased understanding about time and strain rate effects into constitutive models. Starting from a 1-D model for stepped loading they developed their model into a general constitutive equation for continuous loading. The main stream of these studies can be identified as the concept of "equivalent times" during time-dependent straining. In Zhou et al., 2005, the model of Yin et al. has been extended to a 3D anisotropic elastic viscoplastic model for the stress-strain behavior of K_0-consolidated clays (Fig. 5). As seen in Fig. 5, in their 2005 publication, the concept of equivalent times has been incorporated with the concept of evolution of yield loci.

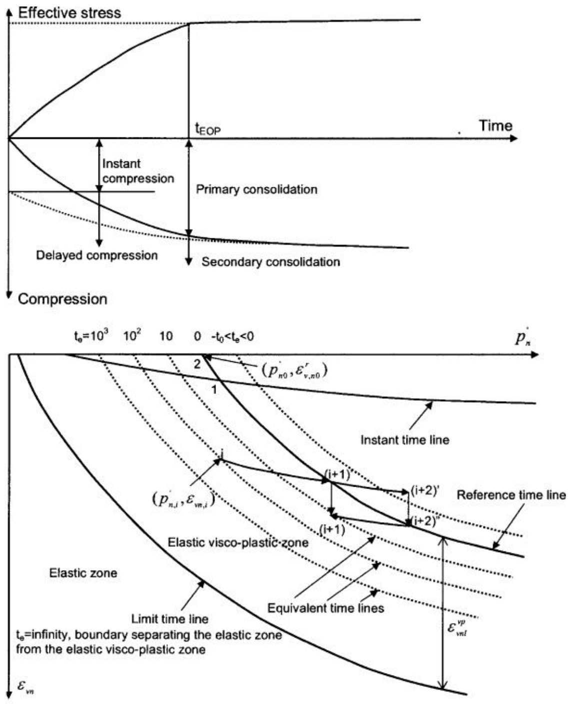

Figure 5. Strain-rate dependency described by the concept of "equivalent times" in 3D EVP Model (After Zhou et al. 2005)

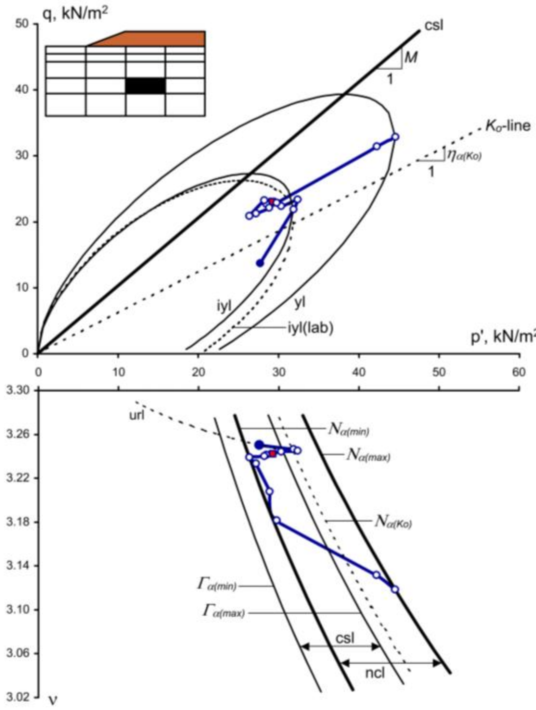

Figure 6. An example of stress paths obtained by Oztoprak-Cinicioglu method for Cubzac-les Ponts test embankment.

Time-dependent stress-strain behavior modeled in Fig 4 and 5 belong to odometer K_0-consolidated or isotropic stressing conditions. It can easily be observed that these figures and the underlying concepts are comparable to the real-time stress-strain behavior schematized in Fig 6, which is generated through the application of the Oztoprak-Cinicioglu methodology. The most straightforward advantage of the real-time interpretation methodology is its ability of reflecting and interpreting 3D real field behavior in the context of a constitutive framework. As known, despite the evident superiority of improved constitutive models over the conventional elastoplastic analysis to describe soil behavior, deviations inevitably occur between the predicted behavior and actual field behavior. Oztoprak-Cinicioglu method is applicable for any shearing or consolidation condition. The method is applied as a natural follow-up of the real behavior, keeping track of the changes that occur in the parameters due to the micro-structural changes.

In the application of the method, time-dependent behavior is followed through the variations in specific volume compared to the applied stress state, variations in coefficient of earth pressure values corresponding to any current strain ratio state, the evolution of yield loci and corresponding translocations of the compression lines on the v -p' plane. All these stated variations are also direct indications of the micro-structural changes. Therefore, the method has the capacity of reflecting the fundamentals of real soil behavior. The concept behind the consideration of the time-dependent behavior in the method is given in Fig. 7.

Any current stress state is characterized by its coordinates in terms of q, p' and v in the CSSM framework. Among the quantities to calculate these coordinates, only σ'_v, is a stress parameter and entails a calculation process, but the other components K and v are found by measured deformations. Moving from the deformation side (i.e. on the v - p' plane) v and p' represent a state on a compression line located by the parameter N_α corresponding to the current strain rate. Point Y is such a point and $N_{\alpha(Y)}$ is the parameter for ncl in Fig. 7. In the same way, the critical state line corresponding to this state is located by the $\Gamma_{\alpha(Y)}$ for the sample point. To comply with this state, the stress state (point Y′) on the q-p' plane should lie on the relevant K-line. If the strain rate could be kept at the current specific value, the stress state would be defined on the path '1YY′2' leading to the $q_{expected}$ in Figs. 7a and 7b. However, this condition is almost impossible to be met with rate dependent soils and strain rate is influenced by surcharge load applied at the considered lift. The in-situ load, $q_{in\text{-}situ}$, may either be greater (overstress) or lower (understress) than the expected load. If in-situ conditions are relevant to the overstress case, higher strain rates are encountered and the reverse is true for understress case. This requires an evolution of the considered yield curve (from $yl_{(Y)}$ to $yl_{(X)}$) and corresponding shifts in the compression lines (from $N_{\alpha(Y)}$ to $N_{\alpha(X)}$ and from $\Gamma_{\alpha(Y)}$ to $\Gamma_{\alpha(X)}$). In Figs. 7a and 7b the modified positions can be followed along the path '1XX′3'.

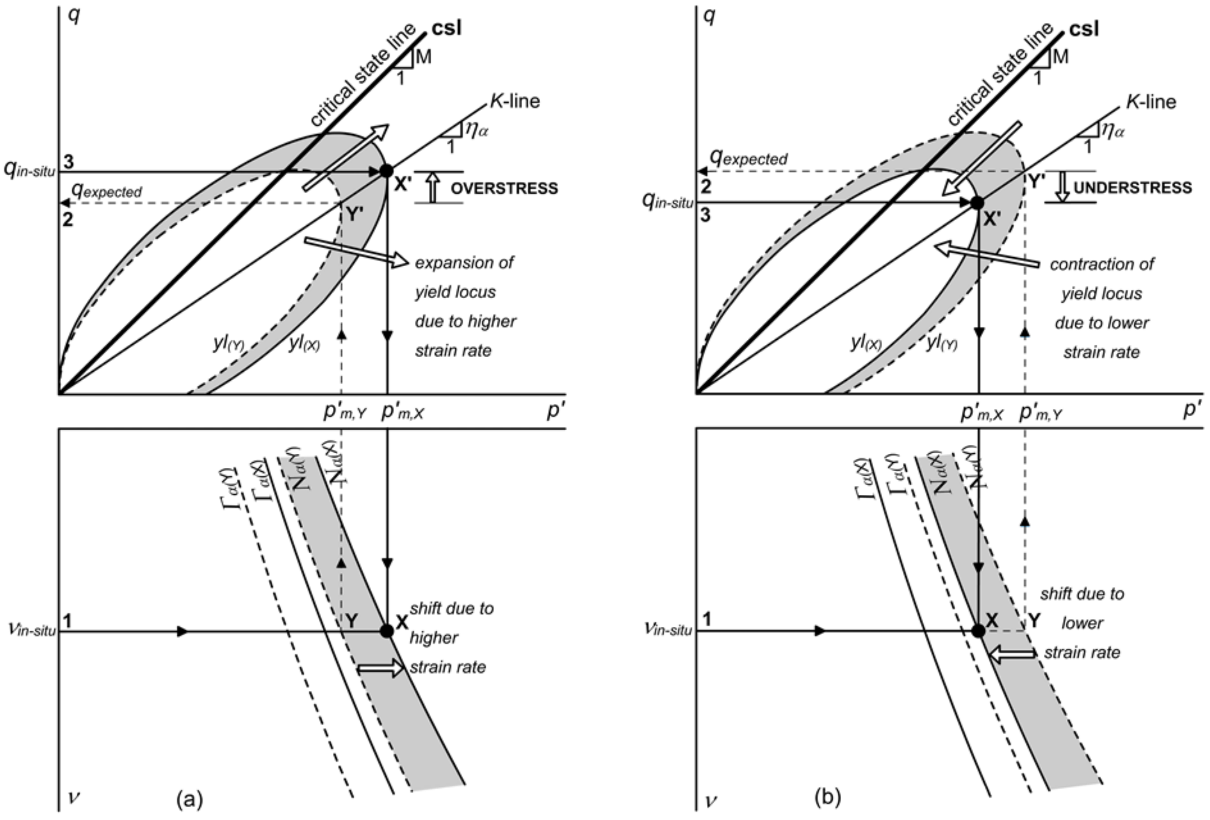

Figure 7. The concepts of (a) overstress and (b) understress.

While applying the procedure, as seen in Fig. 6, shift in the stress states band bordered by the ncl and the csl is caused within the q, p'-v framework. The values of N_α and Γ_α take appropriate values corresponding to the strain rate at any state. The extent of the movement of the stress state bands is dependent on the extent of variation of the strain rates. As a result, in contrast to the considerably smooth variations of the stress-strain curve (σ'_v-ε_v curve or v-p' curve) for elastoplastic soils, time dependent soils exhibit an erratic character on these curves. It should also be noted that the evolution of yield loci is controlled by the η_α lines which take their values in relation to the current strain rate applicable at the considered time. Therefore, the applicable flow rule can be defined as

$$\frac{d\varepsilon_s^p}{d\varepsilon_v^p} = \frac{2(\eta - \eta_\alpha)}{M^2 - \eta^2} \tag{1}$$

The symbol η_α was chosen as a composite variable to express the corporate effectiveness of both stress anisotropy and strain anisotropy. K values are found as a function of current strain ratio at any stress state as explained in the subsequent section. The definition of η_α in terms of K transforms measured strain ratios to stress ratios. In this way, the action of η_α is to feed the implications of the measured stress and strain states into the construction of the current yield envelope. As a composite variable, η_α is supposed to be effective both on the inclination and the shape of the yield curve. The approach of the method which defines inclination of yield curve by η_α = f(K) complies with the basic concept of a flow rule which is defined as a function of the relation between the stress state and ratio of plastic strain increments. Since η_α values are found as a function of the current strain ratio at any stress state, they comply with the concept of alteration of material anisotropy during deformation (Kavvadas 1991; Sivakumar et al. 2001). The suggestion of Kobayashi et al. (2003) who hypothesized the existence of a mutual relation between anisotropy and structure of clays and the experimental data given by Tavenas and Leroueil (1987), which indicated that anisotropy and structure of clays are inseparably related to each other can be quoted as examples of supportive arguments to the adoption of a single parameter, η_α.

4 MICRO-STRUCTURAL MECHANISMS

Above, the implications of micro-structural changes on the macro-behavior have been discussed. The next stage was to seek the effects of this behavior at the micro scale. There is burgeoning research interest in this area in the last decade, but the interpretation of the behavior lacks consistency. Considering the complexity of micro-mechanical clay behavior, the first attempt has been diverted to the analysis of one-dimensional consolidation behavior, because the related test method is simple and has the potential to model a behavior that is directly observable and measurable. Moreover, an oedometric consolidation test has comparable properties with the stage loading application carried out for embankment construction on soft clays. This is due to the nature of load application involving loading and consolidation stages. It was argued in relation with the method reported in this paper, that strain rates encountered are controlled by the interaction between the applied loading rate and the internal absorption capacity of the soil. The internal absorption capacity tries to enhance itself through the structuration and destructuration processes. This is a hypothesis that needs evidence to gain validity. To search the validity of this hypothesis and to highlight the aspects underlying micro-mechanical behavior of clays constitute the driving force behind the ongoing PhD work of İbrahim Yigit supervised by the author. The study will be developed towards observing the changes in the micro fabric and micro-structure during both consolidation and shearing using a specifically developed triaxial apparatus but as this part of the study hasn’t finished yet, the first findings obtained through oedometer consolidation tests will be given in the scope of this lecture.

As discussed in this paper, time dependent behavior shows itself in the strain rates and also in changed consolidation processes. Strain rates are high just after increasing the load but decreases with time and strain develops. This implies that as the rate changes fabric also shows variation. Image processing is the only available and approved technique to observe soil fabric and can be facilitated to reveal the microstructural changes during consolidation. If it is desired to see the effect of the changes of the strain rate on soil fabric, micrographs should be taken at various times under a specific load increment. In accordance with this, the method used in this paper was designed to understand the possible mechanisms involved at the microstructural level, during one-dimensional consolidation of kaolin clay. The method adopted is to analyze micrographs captured in ESEM (Environmental Scanning Electron Microscope) at various stages and times during consolidation.

At the end of each consolidation stage, vertical pressure was increased to predetermined magnitudes. In order to determine the influence of consolidation level and thus time on the micromechanical behavior, consolidation was stopped at various times corresponding to different degrees of consolidation to extract undisturbed samples for ESEM analysis. In this way 60 photographs were taken to investigate the influence of load increments and consolidation degrees on clay fabric. The results imply the presence of a continuous interaction mechanism both among the solids and also between the solids and pore water, while soil fabric arranges itself to absorb the energy induced by applied loads (Yigit, 2010; Yigit and Cinicioglu, 2011). The micrographs were digitized using an image analysis technique and a new approach was used to interpret the micromechanical mechanisms involved. In the analysis of the micrographs the area covered by macro-voids against the total void area is estimated and the area of micro-voids could thus be found as the difference of these two. In the same way the variation in clump gradation at different stress levels and time was also analyzed. The gradation curves were found by applying a technique similar to that used in the presentation of sieve analyses results, but in this case the application was conducted on digitized micrographs. In this context, discrete clusters were detected and then grouped in the order of their areal sizes. The results of the observations implied that there is a continuous process consisting of accumulation and disintegration of clumps and aggregates. The findings are crude yet, but it seems that, they give some clues validating the hypothesis defined as internal absorption mechanism, The clues in relation to the hypothesis can be defined in terms of the observed micro-changes as; the reduction of void ratio, e due to the drainage is caused by the drainage from the macropores at the early times. Consistent with macropore reduction aggregates come closer and start to transfer shear stress to each other which is accompanied by clump disintegration as time passes. The succession of the events of aggregate accumulation and disintegration at other stress levels may not follow the same order as in 20 kPa or 400 kPa, but may change depending on the current stress state and degree of structuring. The observed behavior has been displayed in Fig. 8 (Yigit, 2012) together with "equivalent times" detected by applying the method of Yin and Graham,

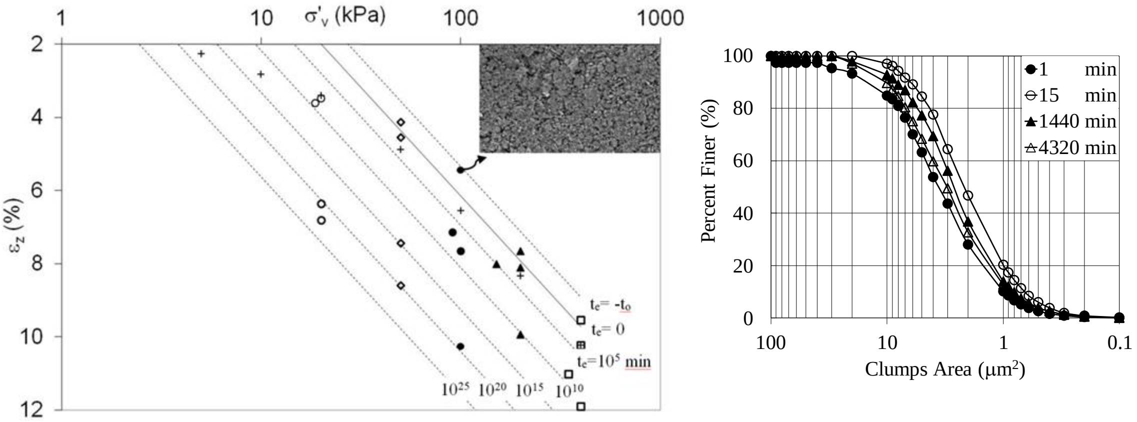

Figure 8. Consolidation plane with a micrograph taken at 100 kpa stress state and corresponding gradation curve (Yigit 2012)

5 CONCLUSIONS

The in-situ behavior of soils, deviate considerably from their predicted behavior. Strain rate effect, structure, anisotropy, stress axis rotation and many other properties cause changes in the behavior predicted by the parameters based on the laboratory tests. The loading patterns and conditions of the considered geotechnical construction activity affect these changes together with the internal properties of the soils affected by the construction activity. This paper tries to link up the on-time measurements captured by field instrumentation to real soil behavior. The problem was dealt with in the scope of embankment construction on soft clays. The methodology developed by Oztoprak & Cinicioglu (2005) has been referred by discussing the advantages of this methodology to find the implications of micro-structural changes in the macro-response of the foundation soils and demonstrating these within a formal constitutive framework. The results indicated that the methodology has a distinguished capacity to control the construction activities in the real time, in the scope of constitutive laws and in a way to disclose real field behavior. Through this approach, real field behavior could be demonstrated by defining all of the stress and strain variables as direct functions of the field measurements without applying any back-analysis procedure. Stress strain paths for any point within the foundation soils were constructed simultaneously as the measurements were recorded and they were located in the constitutive framework of CSSM. The evolution of yield loci was controlled by stress ratio lines which take their values according to the level of shear straining compared to the rate and intensity of load application. The compression lines were shifted on the compression plane in accordance with the changes noticed in the energy absorption capacity of the soil. This behavior has directly been attributed to the visco-plastic action which is controlled by the micro-structural changes. Realizing the need to understand the micro-mechanical behavior a new research program was planned by Yigit and Cinicioglu. Although, this research work is continuing now, some results from the preliminary attempts have been included in the paper.

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