# DEVELOPMENT OF A CONCEPTUAL MATERIAL MODEL FOR STRUCTURED MATERIALS – S_BRICK

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### Abstract

*Materials known in literature as Soft Rocks& Hard Soils such as claystones, siltstones, flysh, hard soils, marls, etc. received a lot of attention in research community in recent years. It was demonstrated that some of these materials can be described through general theoretical framework (Cotecchia & Chandler [1]), which takes into account the structure as an intrinsic material property that is present in all natural geological materials. The influence of the structure is manifested as an increase in strength and stiffness in a material. Based on a laboratory results and existent theoretical frameworks, a further step was taken with the development of a conceptual constitutive model for structured materials. A model formulated in strain space named BRICK (Simpson [2]) was chosen as a base model and was further developed with the inclusion of structure and destructuring. The new model was named S_BRICK and was tested on a conceptual level where the results of numerical tests on structured and structure less (reconstituted) materials at different stress paths were compared. The results showed that S_BRICK was able to capture stress-strain behavior typical for structured material and could be potentially used for the modeling of Soft Rocks and Hard Soils.*

### Keywords

structure, destructuring, constitutive material models, Soft Rocks&Hard Soils, BRICK, numerical modeling

## 1 INTRODUCTION

The article focuses on the development of a constitutive model for an important group of natural geological materials like, claystones, siltstones, flysh, hard soils, marls, and others similar natural rocks and soils, whose strength properties place them in-between rocks and soils. They are known in literature as »Soft Rocks and Hard Soils« and have received increasing attention in research community in recent years. With the increasing amount of laboratory tests carried out on variety of different materials new theoretical frameworks have been developed, through which constitutive models which describe the stress-strain behavior of natural geological materials more accurately have been proposed.

First, a theoretical background is presented and concepts of structure and destructuring and its influence on the stress-strain behavior of natural geological materials are explained. It has been showed that in addition to important features like nonlinearity, state and stress history, a constitutive model has to include effects of structure and destructuring in order to describe the behavior of natural geological materials. The proposed model was developed by using some of the aspects of the theoretical concepts of elasto-plasticity and Critical State Soil Mechanics (Schofield&Wroth, [3]). The further step in the model development was taken using theoretical framework for structured soils developed by Cotecchia & Chandler [1]. This framework will be briefly presented here.

In order to select the appropriate numerical framework model for further development, a review of the latest constitutive models that take, into account the structure was carried out. A model formulated in strain space and named BRICK (Simpson, [2]) was chosen as a base model. This model as formulated already includes many of the important soil behaviors such as nonlinearity, stress path dependency, and state. The model was further developed with the inclusion of structure yet the influences of structure where decoupled and destructuring was modeled separately for compression, shearing and swelling. Appropriately, the new model was named

S_BRICK, which is a combination of the model's original name BRICK and the letter S which stands for structure.

Finally, the results of S_BRICK predictions at different stress-strain paths are presented. The results are presented by comparing two conceptual materials, one of a higher degree of structure and another one of a lower degree of structure. The results showed that S_BRICK was able to capture the stress-strain behavior typical for structured material and could be potentially used for the modeling of Soft Rocks and Hard Soils. The article concludes with a set of conclusions and a discussion.

## 2 THEORETICAL BACKGROUND

### 2.1 STRUCTURED MATERIALS

First, the basic definitions of structure and destructuring and their influence on stress-strain behavior in natural geological materials are presented. Further on, a theoretical framework for structured soils, within which the model was developed is explained, and finally the existent constitutive models for structured materials are briefly discussed.

The origins of structure in natural materials are complex and can be attributed to different processes and physical and chemical conditions during and after sedimentation. There are different classifications and definitions that take into account different aspects of structure. For the development of a model the definition by Lambe & Whitman [4] was chosen. The authors stated that structure is a combination of *fabric* and *bonding* where *fabric* represents the arrangement of the soil particles and *bonding* represents chemical, physical or any other types of bonds between particles. Bonding has predominant effects in rocks, while in soils the influence of fabric is more important. It is obvious that according to this classification, structure is present in both natural and reconstituted geological materials, because no matter how much material is remolded or destrucured it still have some type of fabric. But from the mechanical aspect the influence of structure in reconstituted materials represents the reference state beyond which the strength and the stiffness of a natural materials cannot fall.

The stability of structure also plays an important role in stress-strain behavior of natural materials. If the structure does not change with deformations, the material has stable structure. On the other hand, when destructuring completely destroys the structure, the structure is unstable. The materials that show some destructuring but stop short of complete destructuring have meta-stable structure. According to Baudet [6] a stable structure is predominantly governed by fabric and unstable structure by bonding. In meta-stable structure both elements of structure, i.e. fabric and bonding, are present.

Leroueil&Vaugan [5] have shown that in spite of the difference in origin, type and strength of structure a similar influence on stress-strain behavior can be observed in different materials ranging from soils to rocks. The influence of structure can be best observed when the behavior of structured material is compared to the behavior of reconstituted material. Structure is responsible for the increase of stiffness and strength in comparison with the reconstituted material but the influence of structure is most clearly manifested in a larger state boundary surface of structured material. Leroueil&Vaugan [5] introduced the concept of structure permitted space which is shown in *v*-*p* space in Fig. 1, where *v* represents the specific volume and *p* represents the mean effective stress.

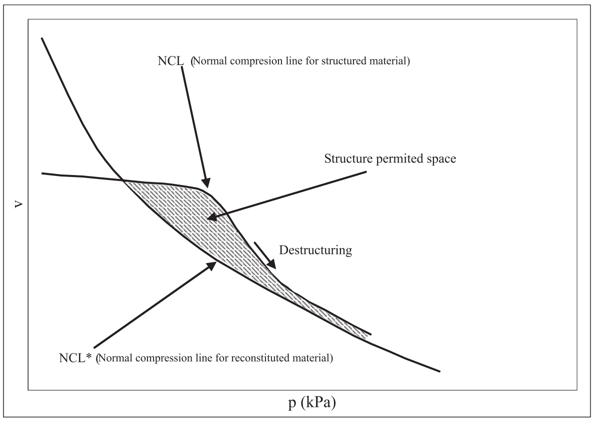


**Figure 1.** Structure permitted space by Leroueil&Vaugan [5].

We can see from Fig.1 that structured material can exist in space which cannot be attained by reconstituted material. Furthermore, a convergence tendency of normal compression line of structured material which implies destructuring towards the normal compression line of reconstituted material can be observed. Destructuring is responsible for decreasing state boundary surface, strength and stiffness with plastic strain. Leroueil&Vaugan [5] have distinguished different yielding modes in natural materials. According to these authors yielding, can occur in shearing, compression and swelling as shown in Fig.2. Similarly, destructuring can also be decoupled in shearing, compression and swelling.

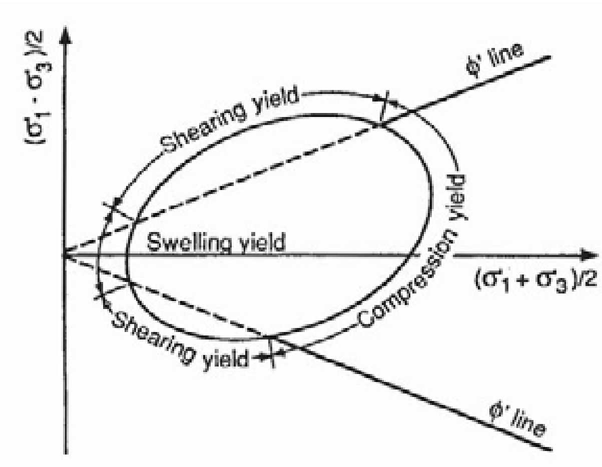


**Figure 2**. Different modes of yielding and destructuring by Leroueil&Vaugan [5].

The destructuring in isotropic compression and swelling is governed purely by volumetric component of plastic strain. In case of normal compression stress path, the role of deviatoric component on destructuring is still not fully understood. It is reasonable to suspect that because the deviatoric component shows no tendency towards state boundary surface the influence of deviatoric plastic strain is neglectable. In shearing the destructuring is governed by both volumetric and deviatoric components of plastic strain. It is also important to note that in swelling stress paths destructuring can occur inside state boundary surface, which was also shown by Leroueil&Vaugan [5].

## 2.2 THEORETICAL FRAMEWORKS

In addition to the well known concept of elasto-plasticity and Critical State Soil Mechanics by Schofield&Wroth [3], a theoretical framework for structured soils developed by Cotecchia & Chandler [1] was adopted. The authors demonstrated that in addition to the effects of nonlinearity, stress-path dependency, and the influence of the state, the effects of structure on mechanical behavior have to be accounted for. The main idea behind the framework is that the influence of structure ($S$) can be quantified by the difference in size of the state boundary surface for structured and reconstituted material if the geometric similarity between state boundary surfaces is assumed. The framework is conceptually presented in Fig.3 in the $q$-$p$-$v$ space where $q$ represents the deviatoric (triaxial) stress, $p$ represents the mean effective stress and $v$ represents the specific volume. Two idealized boundary surfaces for reconstituted and structured materials are plotted in Fig. 3.

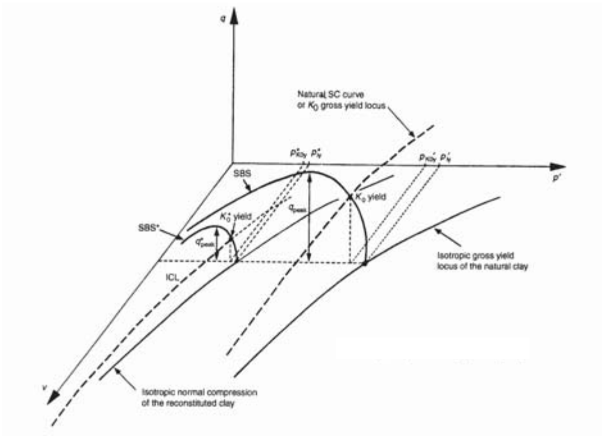


**Figure 3**. Theoretical framework for structured and reconstituted material in the $q$-$p$-$v$ space by Cotecchia & Chandler [1].

The authors have stated that the shear sensitivity $St$, which defines the ratio between peak shear strengths of natural or structured ($q_{peak}$) and reconstituted material ($q^*_{peak}$), is equal to the stress sensitivity $S_t$ which represents the distance between isotropic compression ($p_{iy}/p^*_{iy}$) or normal compression lines ($p_{K0y}/p^*_{K0y}$) of structured and reconstituted materials in the $v$-$p$ plane for a constant value of the specific volume ($v$). The relation is given by the following expression:

$$S = S_t = q_{peak} / q^*_{peak} = p'_{iy} / p'^*_{iy} = p'_{Koy} / p'^*_{K0y} = S_\sigma \qquad (1)$$

The value, of the parameter $S$ for reconstituted material is equal to 1, so when the state boundary surfaces of reconstituted and structured materials are plotted together in the normalized space $q/(S\, M^{crit}\, p^*)$-$p/(S\, p^*)$, which takes into account structure ($S$) and composition ($M^{crit} = q^{crit}/p$), they should coincide.

The framework was validated by Cotecchia & Chandler [1] for Sibari, Bothkennar and Pappadai clays. The theoretical framework was also subsequently validated by other authors [6] for different materials ranging from soft to hard clays. Even though the data on soft rocks in literature are not so extensive as those on soft and hard clays, there is enough evidence that suggests that the basic concepts of the theoretical framework can be also applied to soft rocks ([5], [6] ,[7] [8], [12], [14]).

## 2.3 OVERVIEW OF EXISTING CONSTITUTIVE MATERIAL MODELS FOR STRUCTURED MATERIALS

Basic concepts for numerical modeling of structure and destructuring were given by Gens & Nova [7]. They introduced the increase and decrease of the state boundary surface with structure and destructuring and defined the size of the state boundary surface of reconstituted material as a limit state beyond which material cannot be destructured. Furthermore, they introduced the exponential law of destructuring which is dependent on volumetric and deviatoric plastic deformations. Their model however, did not include concepts of nonlinearity, state and stress-path dependency. Their ideas were subsequently used in other models which are mainly variations of multi surface models with elliptically shaped boundary surfaces originating from modified Cam-Clay model [3] and formulated in stress space. The models developed by Baudet [6], Kavvadas & Amorosi [8], Rouainia & Wood [9], and Gajo & Wood [10] included concepts of structure and destructuring. These models were reasonably successful, but due to mathematically demanding formulations and numerous parameters they are often too complex and numerically demanding, to be widely used in solving real geotechnical boundary value problems.

In order to overcome this, an alternative approach for development was chosen. A model formulated in strain space named BRICK and developed by Simpson [2] was chosen as a base model. Due to formulation of the model in strain space there is no need for elasto-plastic constitutive matrix in the form that is needed for models formulated in stress space. This makes BRICK model more stable numerically. The basic idea behind the model will be presented in the next chapter while more detailed background and formulation of the model are given by Simpson [2], [11].

## 2.4 BASIC CONCEPTS OF THE BRICK MODEL

The model is formulated in strain space defined with six dependent strain invariants $\varepsilon_i$ (i=1-6) in which the first one represents the volumetric component and other five represent the deviatoric components of strain as explained by Simpson [11]. The main idea is explained by the analogy of bricks and strings in which the shear stiffness decay with shear strain is represented by a normalized *S-shaped curve*. In Fig.4 we can see the discretization of the *S-shaped curve* with strings (*SL* – string lengths that define the *S-shape* curve) in a stepwise fashion, where the height of each step indicates the proportion of the material being represented by a single brick.

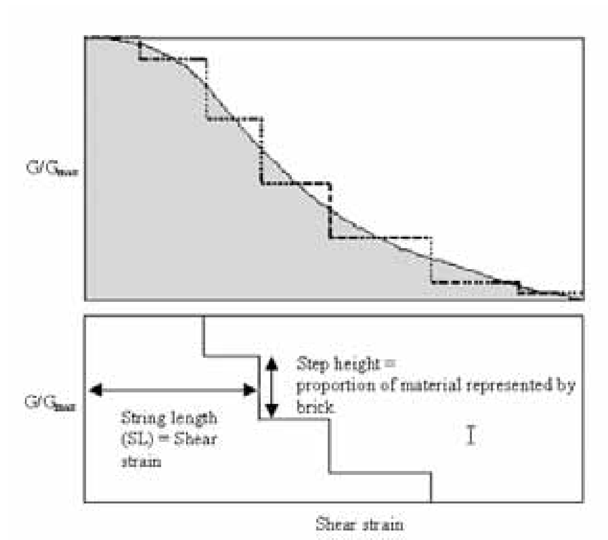


**Figure 4**. Discretization of the *S-shaped* curve by Simpson [2].

At very small strains the material is completely elastic, all strings are slack and the bricks do not move. As straining proceeds, the first brick starts to move, plastic strain begins and there is a drop in the stiffness of the material. With continuous straining more and more bricks are being pulled, there is more plasticity and there is a further drop in stiffness until the material is fully plastified. With shearing the stiffness limits towards zero. When the stress path is changed initially, all strings are slack so that immediate response is elastic. With strings and bricks analogy, concepts of non-linearity and stress history (kinematic hardening) are being accounted for.

Simpson [2] also demonstrated that the area behind the normalized *S-shaped* curve determines the critical state angle and therefore describes the strength response of a model. The stiffness response of a model in elastic range is accounted for with the parameter $\iota$ that represents the correlation of shear elastic modulus with mean effective stress. The parameter is derived from the measurement of a small strain shear stiffness at different levels of mean effective stress [12]. The *S-shaped* curve and the elastic parameter $\iota$ are additionally modified by the state parameter so the current state is accounted for with the increase or decrease of stiffness and strength. The state parameter is given by the following expression:

$$State = \varepsilon_v - \varepsilon_{v0} - \lambda \ln(p / p_0) \qquad (2)$$

The expression represents the distance of the current state given by $p$ (mean effective stress) and $\varepsilon_v$ (volumetric strain) from the reference state represented by the normal compression line of reconstituted material given by $p_0$, $\lambda$ and $\varepsilon_{v0}$. As the reconstituted material has not undergone any straining $\varepsilon_{v0}$ is equal to zero and

$p_0$ is taken at the arbitrary (non zero but small) value of 2 kPa. The parameter $\lambda$ represents the gradient of the normal compression line in the *v-logp* space. The concept of the state parameter is presented in Fig. 5.

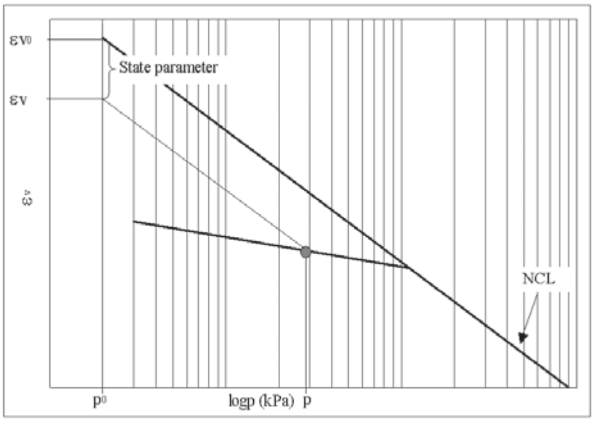


**Figure 5.** The concept of the state parameter as modeled in BRICK.

Simpson [11] has subsequently introduced the influence of state on stiffness and strength with two new parameters $\beta_G$ and $\beta_\varphi$ so that the influece of state is given by the following two expressions:

$$SL = SL_{current}\frac{(1+\beta_{\varphi}State)}{(1+\beta_{G}State)} \qquad (3)$$

$$\iota \;=\; \iota_{current}(1+\beta_{G}State) \qquad (4)$$

It is clear from Eq.3 that string lengths (*SL*) are influenced by the state parameter ratio that takes into account the influence of state on stiffness and strength so that their influence is not fully decoupled. The BRICK model requires in total, the basic model ten parameters from which four can be determined with laboratory results, two are constants and four can be determined through a trial and error process. The values of most of the parameters fall into relatively narrow intervals so the values given by Simpson [2], [11] can be used as suitable starting values. More detailed information about the model and necessary parameters are given by Simpson [2], [11].

# 3 DEVELOPMENT OF THE S_BRICK MODEL

In this chapter the formulation of the S_BRICK model is given. The model is implemented as a stand alone single element integrator routine developed in C++, so it can be relatively easily incorporated into a finite element or some other numerical program (Vukadin, [13]). First, the formulation of structure is given, followed by the presentation of the destructuring formulation. The chapter is concluded with a brief discussion on necessary parameters.

## 3.1 FORMULATION OF A MODEL FOR STRUCTURE

The influence of structure is accounted for with the introduction of two new parameters $\alpha$ and $\omega$. The first parameter $\alpha$ is used to increases or decreases the size of the area beneath the *S-shaped* curve and has a direct influence on the value of the critical state angle and hence strength response of the model. The *S-shaped* curve for London clay published by Simpson [2] was taken as a reference shape. The parameter $\alpha$ is implemented by modifying Eq.3 with the following expression:

$$State = \varepsilon_v - \varepsilon_{v0} - \lambda \ln(p/p_0) + \omega \qquad (5)$$

The influence of the parameter $\alpha$ is graphically presented in Fig. 6.

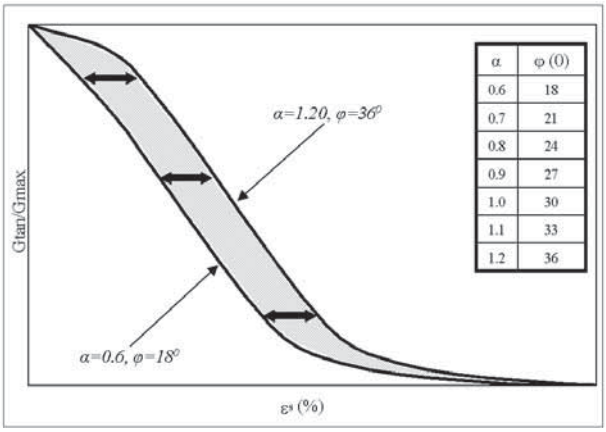


**Figure 6.** The influence of the parameter $\alpha$.

The lower and upper range for the parameter is defined so that the critical state angle can range from $18^0$ ($\alpha$=0.6) to $36^0$ ($\alpha$=1.2). The rest of the values for the parameter $\alpha$ are presented in the Fig. 6.

The second parameter $\omega$ represents the state parameter for structured materials and is best understood as the increase of the distance between the normal compression line and the critical state line in structured material in comparison with reconstituted material. The results published by Cotecchia & Chandler [1] on hard Pappadai clay show that this is a reasonable assumption for Soft Rocks and Hard Soils. The parameter $\omega$ is responsible for the increase of the state parameter which influences both string lengths *SL* and parameter $\iota$. The definition of the parameter $\omega$ is graphically presented on Fig. 7.

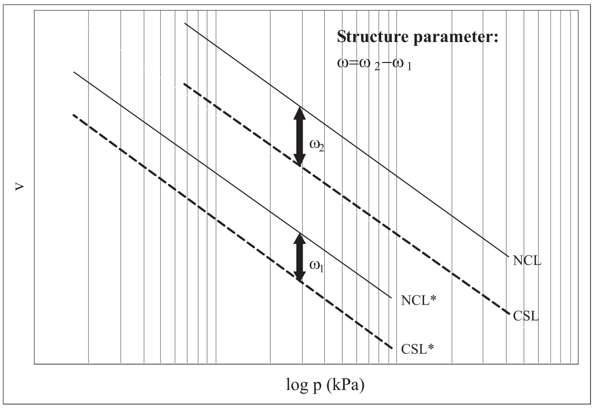


**Figure 7.** Definition of parameter $\omega$.

The parameter $\omega$ is implemented by modifying Eq.2 with the following expression:

$$State = \varepsilon_v - \varepsilon_{v0} - \lambda \ln(p/p_0) + \omega \qquad (6)$$

The state parameter influences both the $\iota$ and *S-shaped* curve so there is obviously some overlapping of the influences of the parameters $\alpha$ and $\omega$ on model behavior. However, the influence of the parameter $\omega$ on $\iota$ and hence the stiffness is bigger than the influence on the *S-shaped* curve because the *S-shaped* curve is modified by the state parameter ratio (Eq.3). The parameter $\omega$ therefore represents the key parameter for modeling the stiffness increase and the parameter $\alpha$ for the strength increase due to structure [13].

## 3.2 FORMULATION OF DESTRUCTURING

The destructuring is implemented for both structure parameters $\alpha$ and $\omega$. The rate of destructuring is made dependent on the sum of volumetric and shear components of plastic strains, and is of exponential type. The destructuring implemented in S_BRICK is given by the following two expressions:

$$\alpha_t^{c,sh,sw} = \alpha_k + \left(\alpha - \alpha_k\right)\exp\left[-\left(x_1^{c,sh,sw}\left(\varepsilon_v^{pl} + \delta\varepsilon_v^{pl}\right) + y_1^{c,sh,sw}\left(\varepsilon_s^{pl} + \delta\varepsilon_{s_i}^{pl}\right)\right)\right] \quad (7)$$

$$\omega_t^{c,sh,sw} = \omega_k + \left(\omega - \omega_k\right)\exp\left[-\left(x_2^{c,sh,sw}\left(\varepsilon_v^{pl} + \delta\varepsilon_v^{pl}\right) + y_2^{c,sh,sw}\left(\varepsilon_s^{pl} + \delta\varepsilon_{s_i}^{pl}\right)\right)\right] \quad (8)$$

In which the symbols represent the following:

| | |
|---|---|
| $\alpha, \ \omega$ | inital values of structure parameters |
| $\alpha_k, \ \omega_k$ | final values of structure parameters |
| $\alpha_t^{c,sh,sw}, \omega_t^{c,sh,sw}$ | current values of structure parameters in compression (c), shear (sh) and swelling (sw) |
| $\varepsilon_v^{pl}, \ \varepsilon_s^{pl}$ | volumetric and shear component of plastic strain (i=2-6) |
| $\delta\varepsilon_v^{pl}, \ \delta\varepsilon_{s_i}^{pl}$ | increment of volumetric and shear component of plastic strain (i=2-6) |
| $x_1^{c,sh,sw}, y_1^{c,sh,sw}$ | parameters that quantify influence of volumetric and deviatoric plastic strain of destructuring of parameter α |
| $x_2^{c,sh,sw}, y_2^{c,sh,sw}$ | parameters that quantify influence of volumetric and deviatoric plastic strain of destructuring of parameter ω |

Destructuring is in S_BRICK implemented separately by introducing different parameters $x_i$ and $y_i$ for shearing, compression and swelling. The decoupling of influence of plastic strain on volumetric and shear components and the introduction of the parameters *x* and *y* which quantify the rate of destructuring gives to the model an additional flexibility [13].

## 3.3 PARAMETER DETERMINATION FOR STRUCTURE AND DESTRUCTURING

The full implementation of structure and destructuring as implemented requires the determination of additional 16 parameters in total. Four of them ($\alpha$, $\alpha_k$, $\omega$ and $\omega_k$) represent the structure and twelve $(x_i, y_i)^{c,sh,sw}$ represent the destructuring of structure in compression, swelling and shearing. A volumetric component of destructuring is present in all drained stress paths, while shear components are present in all but isotropic compression and swelling stress paths.

The volumetric deformations and hence destructuring due to volumetric deformation is prevented in undrained stress paths, which is useful for separating the relative influence of volumetric and deviatoric plastic strain on destructuring. It is still not clear whether or not shear components of plastic strain have noticeable influence for stress paths with no characteristic change in a deviatoric component, for example in normal compression and recompression stress paths. Some authors [12] argue that for those stress paths only isotropic hardening and destructuring due to volumetric plastic strain have a noticeable effect. According to this the number of necessary parameters is reduced to twelve.

It is reasonable to expect that not all types of destructuring are present, for a dominant stress path, so it is very likely that the necessary number of total additional can be as low as four. Accordingly, the destructuring is implemented in a way that model parameters that are not necessary or are not available can be omitted without hindering the model behavior.

Only a basic guideline for parameter determination is given. For full parameter determination a set of different laboratory stress path tests taken on both natural and reconstituted materials are necessary. A more detailed parameter determination procedure together with model validation needs to be adopted to the real geological materials its structure and dominant types of destructuring. This procedure is subject of the continuation of the research.

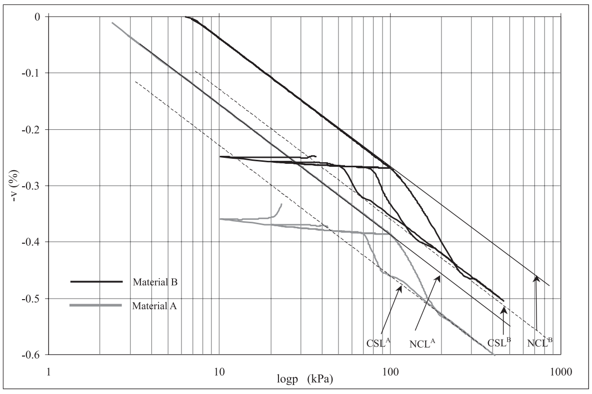


**Figure 8.** S_BRICK predictions of normal compression and swelling with drained triaxial shearing taken at different states for the materials A and B.

# 4 PRESENTATION OF S_BRICK BEHAVIOR ON CONCEPTUAL LEVEL

Stress-strain predictions of S_BRICK of two conceptual materials with different amount of structure and destructuring are presented here. Numerical results from different stress-strain paths taken at different states will demonstrate that the model successfully captured the main features of the behavior of a structured material as proposed by theoretical framework of Cotecchia & Chandler [1].

## 4.1 MODELING OF STRUCTURE

The influence of the structure parameters $\alpha$ and $\omega$ on the increase of strength, stiffness and state boundary surface (SBS) is presented by comparing two conceptual materials. Model parameters describing both materials are the same except for values for the parameters $\alpha$ and $\omega$. The input values for the material of lower structure (material A) are $\alpha_A=1.0$ and $\omega_A=0.0$, and for the material of higher structure (material B) $\alpha_B=1.2$ and $\omega_B=0.15$.

In Fig.8 S_BRICK predictions of a stress path that comprises of: normal compression, swelling, and drained triaxial shearing for both materials. The results presented in the *v-logp* are taken at different states (OCR from 1 to 10). In this figure normal compression lines (NCL) and critical state lines (CSL) are plotted for both materials. It is evident that the $CSL^B$ and $NCL^B$ lie to the right of the $CSL^A$ and $NCL^A$, which indicates that the material of higher structure has a larger state boundary surface. It is also clear that the distance between the $CLS^B$ and $NCL^B$ is greater that the distance between the $CSL^A$ and $NCL^A$, which is also expected for a material of higher structure.

Furthermore, it can be observed that S_BRICK has correctly predicted the position of CSL, regardless of the state at which numerical test were taken. The following two figures show results of drained shearing tests taken at different stress paths, three in compression, and three in extension planes in the *q-p* space. The results in Fig.9 are taken from normally consolidated material (OCR=1) and the results in Fig.10 are from heavily overconsolidated state (OCR=10).

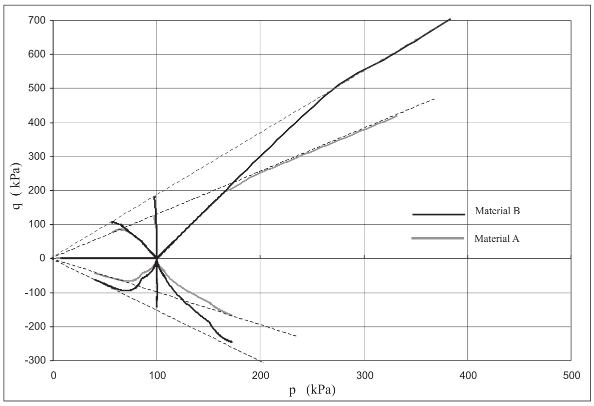


**Figure 9.** S_BRICK predictions of drained triaxial shearing taken at different directions at normally consolidated state for the materials A and B.

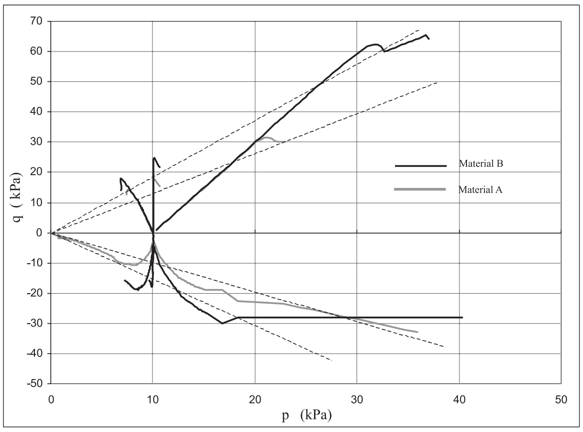


**Figure 10.** S_BRICK predictions of drained triaxial shearing taken at different directions at heavily overconsolidated state (OCR=10) for the materials A and B.

Both figures show that the material B reached higher peak deviatoric stresses than the material A regardless of the direction of the tests (compression, extension) and the state at which they were taken. Fig.9 and 10 shows that the test taken in compression plane directions reached higher values than the tests taken in extension plane directions, hence different slopes of the $M^{crit}$ lines are shown in figures. In Fig.10, the increase of peak deviatoric stress due to heavy overconsoldation and subsequent softening towards the $M^{crit}$ line are also evident.

In Fig.11 an increase in shear stiffness due to structure is presented in triaxial compression and extension shearing tests. The material B has higher stiffness from small to large strains in both compression and extension.

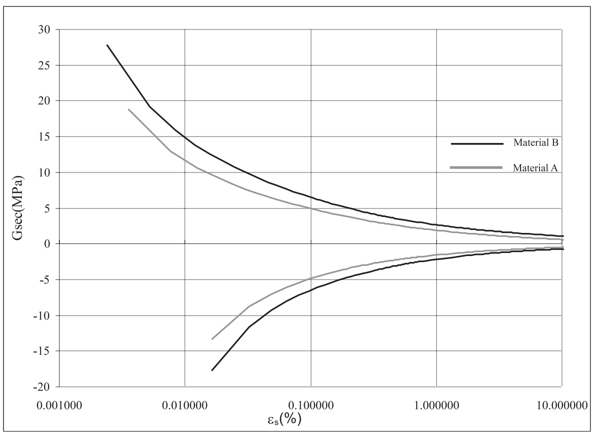


**Figure 11.** S_BRICK prediction of shear stiffness response in triaxial compression and extension shearing tests.

State boundary surfaces for both materials are plotted in Fig. 12 and Fig. 13. In these figures results from triaxial shearing in extension and compression plane at different levels of overconsolidation are presented. In Fig.12 results are presented as a normalized plot $q/p^A_e$-$p/p^A_e$ where $p^A_e$ represents the equivalent pressure taken on a normal compression line of the material A. It is evident that the material B has a much larger state boundary surface than the material A, which was expected for a material with a higher structure.

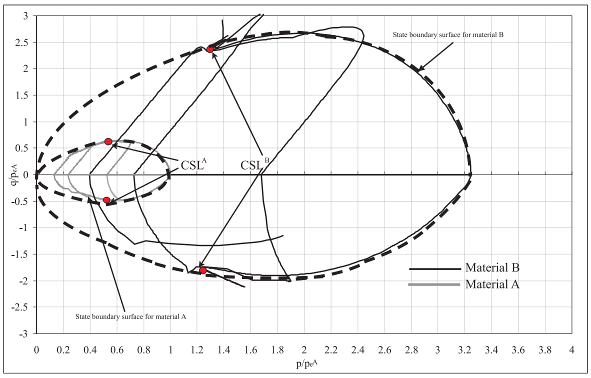


**Figure 12.** State boundary surfaces in the $q/p^A_e$-$p/p^A_e$ plot.

In Fig.13 results are further normalized with inclusion of composition ($M^{crit}$) and structure ($S$) in the $q/SM^{crit}p^A_e$ - $p/ S\,p^A_e$ plot. It can be seen that the state boundary surfaces of the materials A and B coincide as suggested by theoretical framework for structured materials [1].

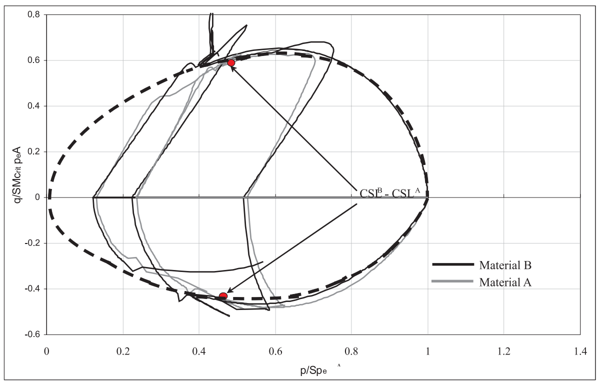


**Figure 13.** State boundary surface in the $q/SM^{crit}p^A_e$ - $p/ S\,p^A_e$ plot.

## 4.2 MODELING OF DESTRUCTURING

The results of destructuring of the structure parameters $\alpha$ and $\omega$ in compression, swelling and shearing by comparing two conceptual materials are presented in this chapter. Again, the parameters describing both materials are the same except for the values of the parameters $\alpha$ and $\omega$. This time the difference between them is made larger so that the effects of destructuring are more obvious. This time the material A has no structure at all, so the parameters $\alpha_A=0.6$ and $\omega_A=0.0$ are chosen. The material A represents the final state or reconstituted material beyond which the material B cannot be destructured. Parameters for the material B are the same as before ($\alpha_B=1.2$ and $\omega_B=0.15$). Additionally, the parameters $\alpha_k$ and $\omega_k$, which determine the level of destructuring. The parameters $x_i$ and $y_i$ (i=1,2), which desribe the rate of destructuring as given by Eq.7 and Eq.8, are introduced here and will be discussed subsequently.

Different rates of destructuring at normal compression are presented together with normal compression lines for the materials A and B in the *v-logp* plot in Fig.14. The parameters $x_i$, $y_i$ describing the rate of destructuring in normal compression are the same for a volumetric and deviatoric component. The values that were used are $x_i$, $y_i$=1000 for the fastest rate of destructuring $x_i$, $y_i$=500 for the intermediate rate and $x_i$, $y_i$=200 for the slowest rate of destructuring, which can be seen from Fig.14. The final values of destructuring in compression are $\alpha_k=0.6$ and $\omega_k=0.0$ hence implying total destructuring of the material B towards the material A. It is evident from Fig.14 that in all three tests, reach the normal compression line for the material A but at different rates.

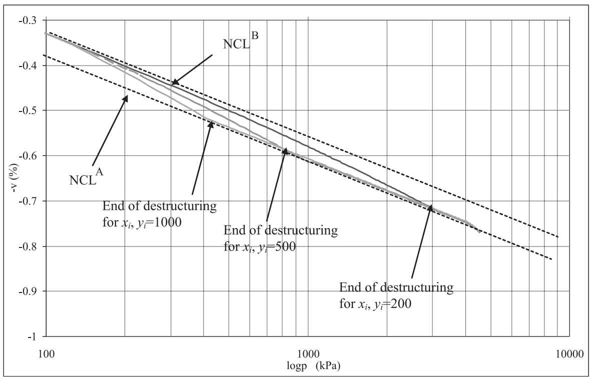


**Figure 14**. Different rates of destructuring at normal compression.

The modeling of destructuring in swelling is presented in Fig.15 in the *v-logp* plot. The final values of destructuring in swelling are $\alpha_k=0.9$ and $\omega_k=0.075$ implying a 50% destructuring of both parameters. The swelling line of destructured material is presented together with normal compression and swelling lines of the materials A and B in Fig.15. It can be seen that the slope of the swelling line of the destructured material lies in-between the swelling lines of the materials A and B, so that destructuring in swelling was reasonably modeled. It can be observed that after recompression the normal compression line of destructured material lies closer to the normal compression line of the material A. The reason for that is that a 50 % destructuring of the parameter $\omega$ has stronger effect to overall response of destructuring than a 50 % destructuring of the parameter $\alpha$. This confirms that the parameter $\omega$ has a predominant effect in the formulation of structure due to the overlapping effect of both parameters as described previously.

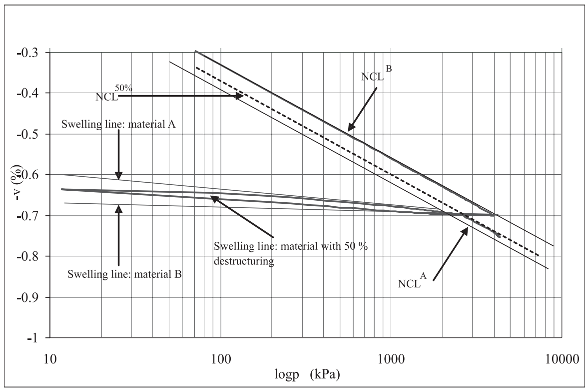


**Figure 15.** Destructuring in swelling.

The modeling of destructuring in shearing is presented in Fig.16 in the $q/p^a_e$-$p/p^a_e$ plot. The final values of destructuring in shearing are $\alpha_k=1.06$ and $\omega_k=0.12$ implying a 20% destructuring of both parameters. In Fig.16 the normalized results from triaxial tests taken at different states on the materials A and B and on the material that was allowed to destructure are presented. It can be seen that the state boundary surface of destructured material lies between the state boundary surface of the materials A and B thus implying that destructuring in shearing was successfully modeled.

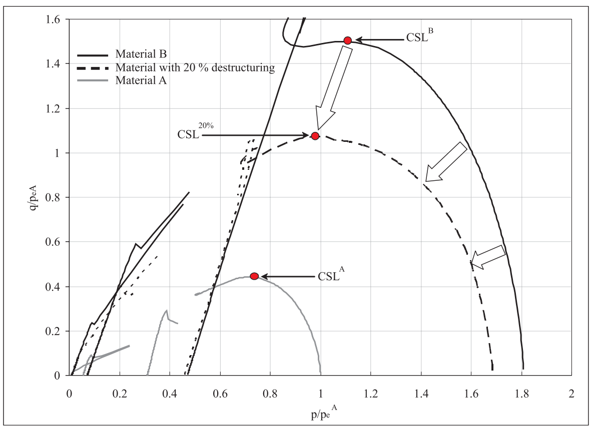


**Figure 16.** Destructuring in shearing in the $q/p^a_e$-$p/p^a_e$ plot.

# 5 CONCLUSIONS AND DISCUSSION

The results of S_BRICK predictions were presented in order to demonstrate the effectiveness of the proposed formulation. Numerical tests were carried out on conceptual materials at different stress paths in compression, recompression and shearing. Shearing tests were taken at different states from normally consolidated to heavily overconsolidated materials in different directions both in compression and extension plane. With the introduction of the parameters $\alpha$ and $\omega$, the increase in strength, stiffness and state boundary were successfully modeled and gave results that are fully in accordance with the theoretical framework for a structured material of Cotecchia & Chandler [1]. Additionally, the destructuring was also successfully modeled for different stress paths and states.

It was demonstrated that, S_BRICK was able to capture the stress-strain behavior typical for a structured material and could be potentially used for the modeling of Soft Rocks and Hard Soils. The capabilities of S_BRICK will have to be validated on the real behavior of different natural and reconstituted materials. This will potentially lead to a further improvement of the formulation of a model. In addition to validation, a detailed parameter determination procedure will have to be defined for all the model parameters defining structure and destructuring. Finally, in order to be used to solve geotechnical boundary problems the S_BRICK model will have to be incorporated into a finite element or finite difference program, that has a commercial and technical value.

## USED SYMBOLS

| | |
|---|---|
| $v$ | specific volume |
| $p$ | mean effective stress |
| $p_e$ | equivalent mean effective stress |
| $p_{iy}/p^*_{iy}$ | equivalent mean effective stress taken at the isotropic compression line of natural/reconsti tuted material |
| $p_{Koy}/p^*_{Koy}$ | equivalent mean effective stress taken at the normal compression line of natural/reconsti tuted material |
| $p_0$ | initial mean effective stress in BRICK at the begining of calculation |
| $q$ | deviatoric (triaxial) effective stress |
| $q^{crit}$ | deviatoric effective stress at the critical state |
| $q^{peak}$ | peak deviatoric effective stress |
| CSL | critical state line |
| CSL* | critical state line for reconstituted material |
| $G$ | shear stiffness modulus |
| $G_{max}$ | maximal shear stiffness modulus |
| $G_{sec}$ | secant shear stiffness modulus |
| $G_{tan}$ | tangential shear stiffness modulus |
| $M^{crit}$ | stress ratio at the critical state |
| NCL | normal compression line |
| NCL* | normal compression line for reconstituted material |
| OCR | overconsolidation ratio |
| S | structure parameter |
| SL | string length |
| St | shear sensitivity |
| State | state parameter |
| $S\sigma$ | stress sensitivity |
| SBS | state boundary surface |
| SBS* | state boundary surface for reconstituted material |
| S-curve | normalised curve showing the mobilization of shear stiffness ratio with shear strain |
| $\alpha$ | parameter describing structure in the S_BRICK model |
| $\beta_G,\beta_\varphi$ | parameters describing the infuence osstare on stiffness and strength in BRICK/S_BRICK model |
| $\varepsilon$ | strain |
| $\varepsilon_a$ | axial strain |
| $\varepsilon_i$ | deviatoric strain invariants used in BRICK/S_BRICK model (i=2 to 6) |
| $\varepsilon_s$ | shear strain |

$\varepsilon_v$ volumetric strain

$\varepsilon_{vo}$ initial volumetric strain in BRICK at the begin ing of calculation

$\iota$ elastic parameter representing the correlation of shear elastic modulus with mean effective stress

$\lambda$ gradient of normal compression line

$\sigma_a$ axial effective stress

$\sigma_r$ radial effective stress

$\sigma_i$ major stress components (i=1 to 3)

$\omega$ parameter describing structure in the S_BRICK model

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