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# Shear banding and time effects in granular materials


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## Project background

The large international construction projects such as the Great Belt Link, Øresund and Fehmer Belt Link have clearly demonstrated the problems facing the designers when soil modeling are to be applied in practice. In short, only relatively simple isotropic elasto-plastic constitutive models are available in commercial Finite Element codes. While these models may capture the principal behavior they will only in special cases provide quantitatively correct answers. Leaving out a number of the most important characteristics such as

- **The influence of time on the strength and deformation behavior**. It is known that time dependent effects in soils, such as creep, relaxation and strain rate effects influence the strength and deformation behavior of soils. However, the governing mechanisms of time dependent behavior of soils are still to be understood in details, especially with respect to the time dependency of granular materials such as sand and silty sand.
- **The occurrence of shear bands and the effects of stress rotation on the stress-strain response**. This is important because shear banding is strongly connected to failure of soil when structures such as footings, retaining walls and slopes are loaded. That is, shear bands are an important phenomenon when modeling failure mechanisms and deformation behavior in the vicinity of failure. Furthermore, it is not investigated how stress rotation influences the occurrence of shear banding. In fact, the effects of stress rotation on the stress-strain behavior are in general not investigated in details but the phenomenon is also important because large stress rotations occur during almost all procedures for construction of geotechnical structures whether they include excavation for foundations or construction of embankments. Furthermore, repeated stress rotation occurs in pavement and road bases acted upon by traveling wheel loads. In summary, stress rotation is an important part of loading and unloading conditions.

## Research program

The research program is divided into two parts and addresses the questions of 1) The influence of time on the strength and deformation behavior, and 2) The occurrence of shear bands and the effects of stress rotation on the stress-strain response.

**Part I. Abstract:**


Time effects in soils, such as creep, stress relaxation and strain rate effects have a known influence on the strength and deformation behavior of soils. Review of the observed time dependent behavior reveal an essential characteristic situation for soils. That is whether the time dependent behavior can be characterized as isotach or non-isotach. The term "isotach behavior" has the same meaning as rate dependent behavior. That is, the stress-strain relation is unique for a given strain rate.

It seems reasonable that the isotach behavior is adequate for describing the time effects in clays in most situations. However there are exceptions, such as the time dependent behavior at very low strain rates, where the effects of structuration play a role. The structuration effects cannot be explained by isotach behavior. The isotach behavior is not valid for sands. The disagreement with the isotach behavior becomes evident in several situations. The rate dependency in sand appears to be small and follows different patterns of behavior than clays. However, when step change is made in the constant strain rate in tests on sand, the stress-strain state deviates temporarily from the unique strain rate-independent reference stress-strain relationship. This behavior is the so-called over- and undershooting. It appears that rate dependency in sand is of some temporary nature, which does not fit into the framework of isotach behavior. This leads to the fact that the phenomena of creep and relaxation cannot be related directly and predicted based on results obtained by constant rate of strain loading tests with respect to sand.

Whether or not the time dependent behavior of granular materials can be characterized as isotach or non-isotach is to be clarified in details. The reason for the importance of determining whether the behavior of the soil is isotach or not is related to capabilities (or framework) of the existing constitutive models for soils. Further theoretical studies may include investigations of the phenomenon of structuration and investigations of time dependent relations at the micro-mechanical level.

The reported experimental investigations of time dependent behavior for granular materials are few. In order to study the complex phenomena new fundamental experimental research is required. The experimental testing program contains three types of experiments with the purpose of investigating the non-isotach behavior of granular materials. All the tests are performed by means of an existing triaxial apparatus. The specimens are 250 mm in height and 250 mm in diameter. The soil type is silty sand.

The objective of the first Ph.D.-project is to elucidate the above-mentioned problems and take part in a comprehensive investigation of the general time dependent behavior of soils. An outline is as follows: 1) Achievement of fundamental theoretical understanding of the influence of time on the strength and deformation behavior of soils. 2) Experimental investigations of the time dependent phenomena. The investigations are performed by means of triaxial testing apparatus. 3) Investigate the possibilities of implementing time dependent behavior in constitutive modeling. This investigation is based on the achieved theoretical and experimental experiences.

**Part II. Abstract:**

Shear banding is associated with failure of soil. One failure mechanism is a so-called "peak failure", in which the soil continues to behave as a continuum with uniform strains and in which peak failure is followed by strain softening. Another mechanism consists of shear banding whose occurrence in the plastic regime limits the strength of the soil. Most constitutive models have been developed for soils based on elasto-plasticity and they may incorporate strain softening because this type of behavior corresponds to uniform strains. These continuum models have been included in a variety of numerical programs and procedures. The occurrence of shear banding is a discrete event that at first sight cannot be incorporated in continuum models. However, attempts can be found in the literature in which models may predict the occurrence of shear bands by means of continuum mechanics and bifurcation theory. From the literature it appears that fundamental and reliable experimental evidence from which to study the basic behavior has not been pursued to any great extent. That is, questions such as "What are the directions and when do shear bands occur?" are still not answered. Furthermore, the effect of principal stress rotation on the occurrence of shear banding is still not fully covered. In summary, experimental evidence is required to develop new theoretical techniques and/or to compare the predictions from theoretical and numerical techniques in the literature.

Advanced elasto-plastic models developed for modeling the behavior of engineering materials most often involves yield surfaces formulated in terms of stress invariants. That is, these models are basically developed for materials that are assumed isotropic. A consequence of this fact is that constitutive models do not predict any strains during large stress rotation while the principal stresses are held constant. In contrast, the few experimental investigations presented in the literature indicate that strains occur when the directions of the principal stresses change and their magnitudes are held constant. Therefore, a number of questions emerge from the realization that strains occur during stress rotation: What are the location, direction and the shape of the yield and plastic potential surface after a given amount of stress rotation? How can the plastic strains be predicted? The above-mentioned questions are not widely treated in the literature and in order to answer the questions appropriate experiments must be performed by means of a suitable testing device.

In summary, some experiments have to be performed in order to investigate the occurrence of shear bands and the effects of stress rotation on the stress-strain response. The testing device that is suitable in connection with running the appropriate tests is a torsion shear apparatus. The apparatus is at the moment not ready for testing. Hence, a great part of the experimental study deals with getting the device up and running. If the tests turn out "in the right way", the results may lead to a modification of the existing theory of elasto-plasticity.

The objective of the second Ph.D.-project is to elucidate the above-mentioned problems and take part in a comprehensive investigation of shear bands and stress rotations in soils. An outline is as follows: 1) Achievement of fundamental theoretical understanding of shear bands and the influence of stress rotation on the stress-strain behavior. 2) Experimental investigations performed by means of a torsion shear apparatus. 3) Investigate the possibilities of extending the Single Hardening Model in such way that it is capable of modeling shear bands and the effects of stress rotation.