Displacement behavior of shallow foundations under cyclic loading

Simon Meißner, Prof. Hubert Quick
Prof. Dipl.-Ing. H. Quick · Ingenieure und Geologen GmbH, Darmstadt, Germany

Univ.-Prof. Dr. Ulvi Arslan, Christina Zimmer
Technische Universität Darmstadt, Institut für Werkstoffe und Mechanik im Bauwesen, Darmstadt, Germany

ABSTRACT: The publication presents typical phenomena which can occur due to cyclic loading. Numerical analysis with different material laws show the challenges to simulate the ground behavior realistically. First result of numerical calculations by means of the Finite-Element-Method are presented and the limitation of material laws discussed.

1 INDTRODUCTION

Besides the known static loadings conditions cyclic loadings are a major impact in the ground. These loadings for example due to high-speed railway lines or magnetic levitation train lines are transferred by foundation elements into the ground. The ground reacts with complex stress-strain behavior. Each loading step produces deformations which are partly not reversible after the unloading process. This may lead to an accumulation of strain increments. To describe this behavior realistically an appropriate material law must be used. In the following the results of different well known material laws and their limitations will be shown. Furthermore a rather new approach to simulate this behavior by using an hypoplastic material law with intergranular strain is presented.

2 CYLIC IMPACT

Due to the impact of magnetic levitation trains and the transfer of load by foundation elements into the ground, the ground reacts partially elastoplastic. The cyclic loading leads to an accumulation of strain increments. The following phenomena have been observed when cyclic loading occurs:

- Compaction
- Cyclic softening / cyclic hardening
- Liquefaction
- Grain damage and abrasion
- Cyclic shakedown
- Granulare ratcheting

In the following these phenomena are explained shortly.

2.1 *Compaction*

The ground is being compacted and reacts without any decrease of stiffness due to cyclic loading. The density of sand is targeting a limiting value (lower bound) (fig. 1). This limiting value is reached more quickly in case of a larger shear amplitude. The phenomena is known for dry and wet sand.

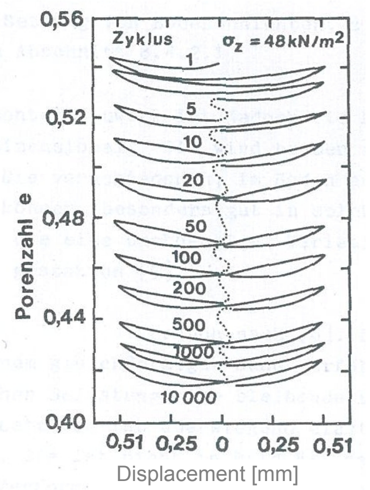


Figure 1: Compaction of granular soil due to cyclic loading

2.2 *Cyclic softening / cyclic hardening*

In case of saturated sand the stiffness may decrease or increase due to cyclic loading. The ground reacts with softening or hardening, if the cyclic shear loading exceeds the linear-elastic shear strain range.

2.3 *Liquefaction*

In some granular soil an adequate intense cyclic loading leads to an increase of pore water pressure. In this case the effective stress will decrease and therefore also the stiffness. In detail the phenomena can be decribed as follows:

Without any cyclic loading the pore water pressure corresponds to the groundwater level. The residual loads are carried by the grain skeleton. The cyclic loading will then bring the sand into a denser state. The pore volume decreases, the pore water pressure increases and therefore the effective stresses will decrease.

2.4 *Grain damage and abrasion*

Grain damage is defined as the breakdown of grains into pieces of approximately the same size, whereas abrasion means the removal of very small pieces of the grain surface. This phenomena can take place in granular soil.

2.5 *Shakedown*

The original definition of shakedown defines the behavior, that no more displacements take place after a certain amount of cycles. Practically it is defined as the phenomena, that no unsuitable displacements after a certain amount of cycles occur (fig. 2). However, after a shakedown it is still possible that further plastic displacements take place.

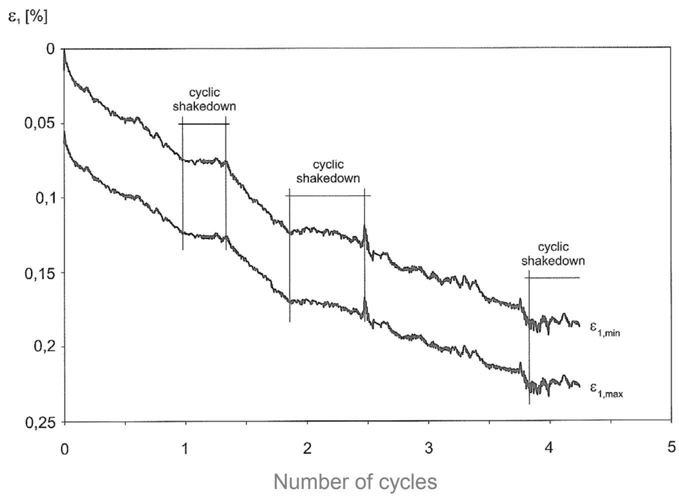


Figure 2: Cyclic shakedown

2.6 *Granular ratcheting*

In case of granular ratcheting it has been discovered that a sand sample deforms step by step due to cyclic loading although no dilatancy and contractancy occurs and the sample is not loaded up to failure. The sample deforms by grain moving over each other. In very small steps the grain skeleton can experience a quite large amount of displacement, which can be seen in figure 3.

3 MATERIAL LAWS

Simulations with the Finite-Element-Method are always based on material laws. A material law can be depicted as the mathematical relation between stress and strain. However, even the latest results of research do not comprise all cyclic phenomena depicted in chapter 2. A short overview of common material laws follows.

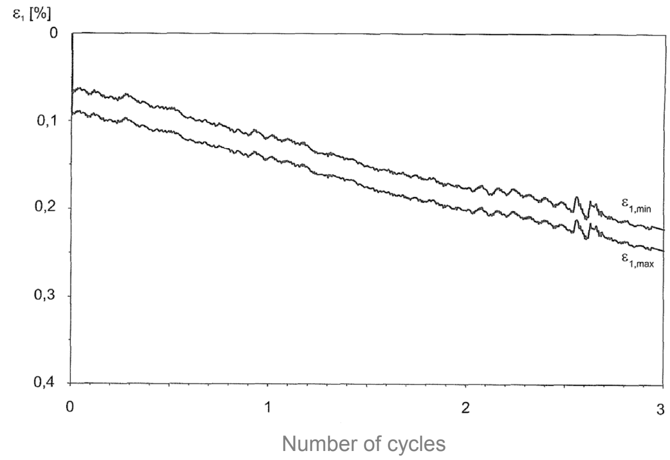
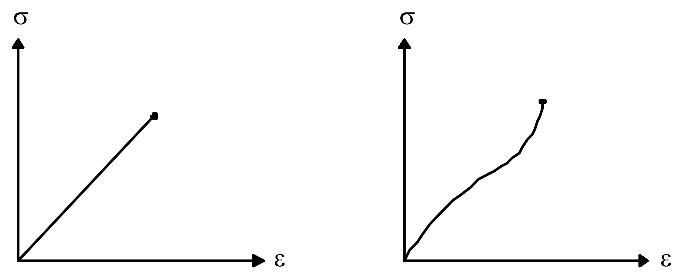


Figure 3: Granular ratcheting due to cyclic loading

3.1 *Elastic behavior*

The elastic material behavior is a very simple material law. The stress component can be assigned directly to the strain component. All strains are reversible, that means all strains / deformations will return to zero by a load removal. The elastic material behavior can be distinguished into a linear and nonlinear behavior (fig. 4). The elastic behavior is in most cases not appropriate to simulate the stress-strain behavior of soil.



linear behavior non-linear behavior

Figure 4: linear and non-linear elastic behavior

3.2 *Elastoplastic behavior*

A more realistic behavior for the simulation of ground shows an elastic-plastic material law. Besides the elastic (reversible) component, irreversible strain (plastic behavior) is taken into account. Manifold material laws which are based on elastoplastic behavior are in use for different soil mechanical problems. In order to evaluate whether or not plasticity occurs in a calculation, a yield function is needed as a function of stress and strain. A yield function is often presented as a surface in principal stress space (fig. 6).

3.2.1 Mohr-Coulomb model

The Mohr-Coulomb material law simulates the soil behavior as perfect-plastic. A perfect-plastic model is a material law with a fixed yield surface, i.e. a yield surface that is fully defined by model parameters and not affected by straining (fig. 5). For stress states the behavior is purely elastic and all strains are reversible.

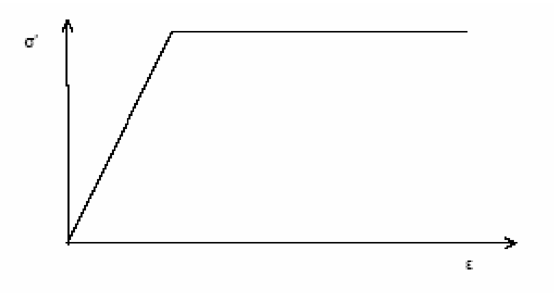


Figure 5: elastic – perfectly plastic behavior

The Mohr-Coulomb model involves five input parameters, i.e. E and ν for the soil elasticity; ϕ and c for the soil plasticity and ψ as an angle of dilatancy. The yield surface of the Mohr-Coulomb model is shown in figure 6.

3.2.2 Hardening Soil model

In contrast to the Mohr-Coulomb model, the yield surface of the Hardening Soil model is not fixed in the principal stress space. It can expand due to plastic straining.

Furthermore it distinguishes between different stiffness for loading, unloading and reloading. The material behavior can be simulated with an hyperbolic relationship between the vertical strain and the deviator stress.

To close the plastic region in the direction a cap is introduced.

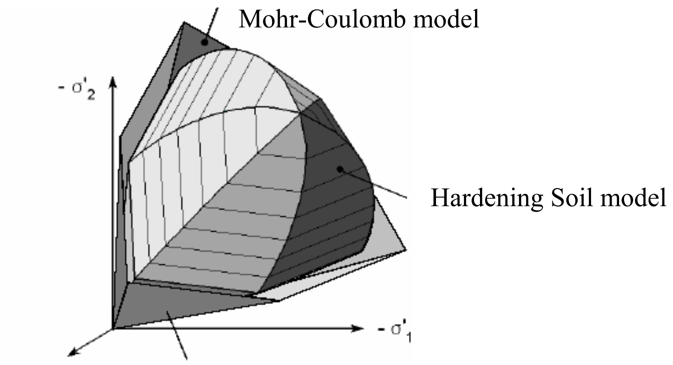


Figure 6: Mohr-Coulomb and Hardening Soil failure criterion in the principal stress space

Both the shear locus and the yield cap have the hexagonal shape of the classical Mohr-Coulomb failure surface (fig. 6). The cap yield locus expands as a function of the pre-consolidation stress. The Hardening soil model involves six main input parameters.

3.3 Hypoplasticity

The material law of Hypoplasticity was developed in the late seventies and has been improved since then. This material law has been especially developed for granular soil, such as sand and gravel. It does not take into account the principles of plasticity and therefore does not distinguish between elastic and plastic components. In order to eliminate the over prediction of strain under cyclic loading the intergranular strain was introduced in the last nineties (chap. 3.3.2).

3.3.1 Hypoplastic model

The Hypoplastic model is defined by the following properties:

- the state of a granular material is fully characterized by granular stress and by void ratio only
- grains are permanent
- deformation of the granular skeleton is due to grain rearrangements
- abrasion and crushing of grains are negligible
- surface affects are absent
- change of the limiting void ratio with the mean pressure is related to the granular hardness
- three pressure dependent limiting void ratios can be distinguished (fig. 7)
  - e_i represents the upper bound of the simple granular skeleton and corresponds to maximum void ratio during isotropic compression
  - e_c corresponds to the critical void ratio
  - e_d represents the lower bound of the simple granular skeleton and corresponds to the minimum void ratio after a cyclic shearing with a small amplitude

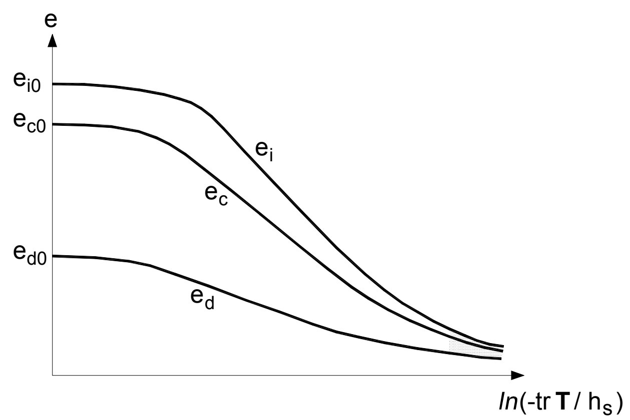


Figure 7: Pressure dependent void ratios

The Hypoplastic model does not comprises realistically the ground behavior for cyclic loading. The accumulation of strains are overestimated with this model (see chap. 4).

3.3.2 Hypoplastic model with intergranular strain

The original model of Hypoplasticity has a shortcoming in the region of small stress cycles. An excessive accumulation of deformations occurs and therefore the displacements are over predicted (ratcheting). This ratcheting effect is reduced by means of the intergranular strain. It can be described as a mind effect. With the implementation of the intergranular strain the small-strain stiffness and the recent loading history is taken into account. The concept of the intergranular strain introduces an interface between the grains. This interface is able to simulate deformations of the grain in conjunction with varying stiffness, the intergranular strain (fig.8).

The maximum value that can be reached is R. Stiffness at the same time varies. For a reversal of strain (180°) a maximum stiffness is used, which decreases step by step until it reaches the stiffness for the monotonic path. In case of a reversal of strain the material behave purely elastic in a very small range.

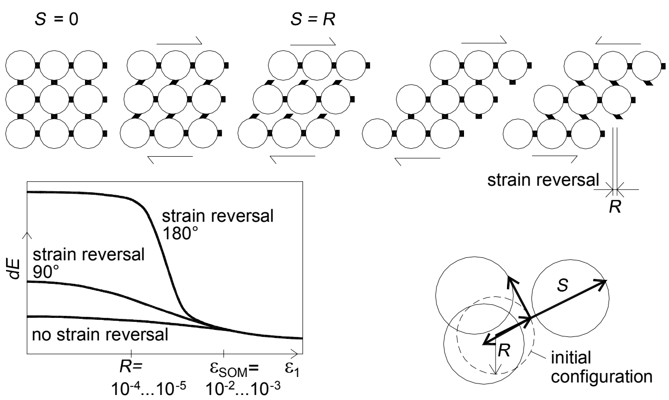


Figure 8: Intergranular strain

4 CALCULATIONS

4.1 Oedometer test (Compression test)

An oedometer test with granular soil was simulated by means of the Finite-Element Method to test and verify different material laws. In the calculation the sample was loaded as follows:

From 0 to 1000 kN/m² (loading)
From 1000 to 50 kN/m² (unloading)
From 50 to 1000 kN/m² (re-loading)
From 1000 kN/m² to 2000 kN/m² (loading)
From 2000 kN/m² to 50 kN/m² (unloading)
From 50 kN/m² to 2000 kN/m² (reloading)
Loop between 2000 and 1000 kN/m² (cyclic loading)

As expected the results show a linear behavior when using an elastic material law or the Mohr-Coulomb model (fig. 9). Both curves (marked by squares) follow the same path.

The Hardening Soil curve is marked with a triangle (fig. 9). Due to the different stiffness for loading and unloading, the Hardening Soil model shows rather good correspondence with in-situ tests. However, in case of cyclic loading, there is no accumulation of deformations due to the same stiffness of unloading and re-loading (fig. 9). The results show that these common used material laws are not appropriate for the simulation of cyclic loading.

The Hypoplastic model shows in the beginning similar behavior as the Hardening Soil model (fig. 10). However, the simulation of a cyclic behavior leads as expected to an excessive accumulation of deformations.

When using the Hypoplastic model with intergranular strain (fig. 11) the accumulation of strain due to cyclic loading is much smaller and resembles more the reality.

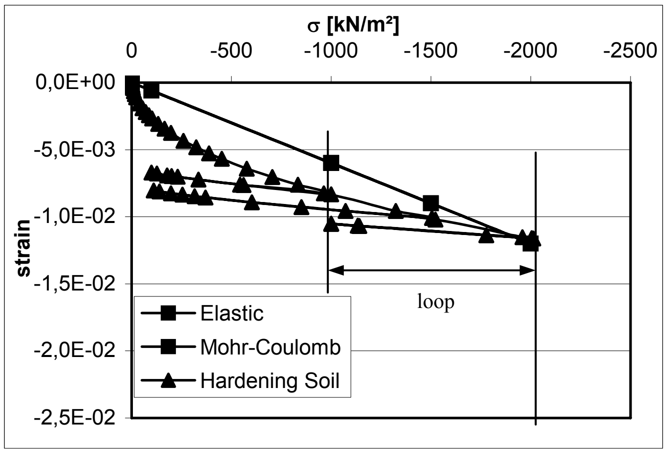


Figure 9: Numerical results of compression test

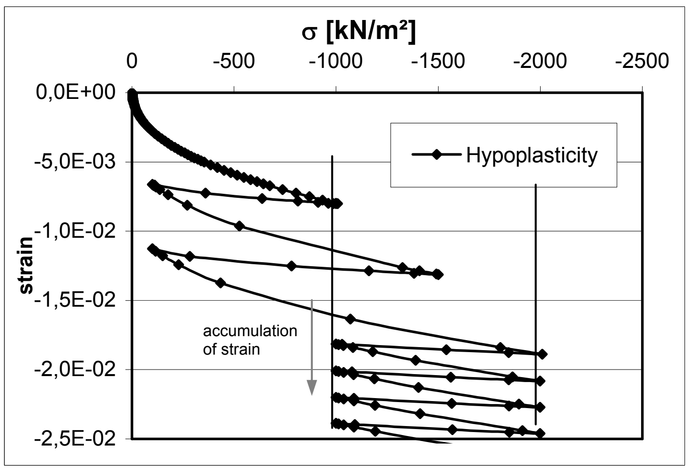


Figure 10: Numerical results of compression test

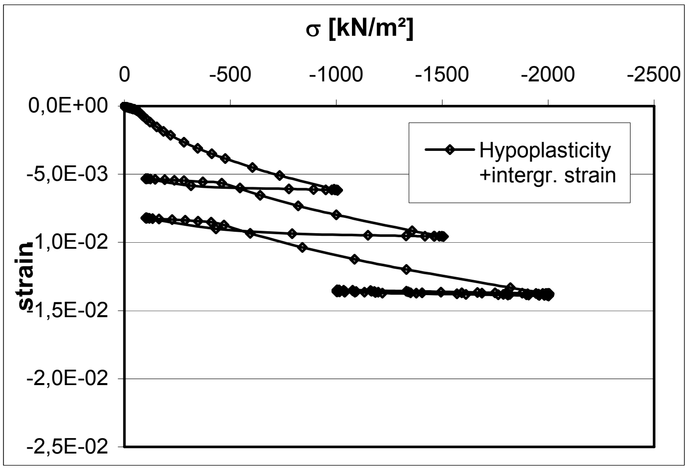


Figure 11: Numerical results of compression test

4.2 *Triaxial test*

The Hypoplastic model with intergranular strain was also used for a simulation of a triaxial test. The results in figure 12 show a good agreement to reality. The simulated cycles (loops) lead only to a small accumulation of strains.

The amount of accumulation is depending on the input value of the intergranular strain.

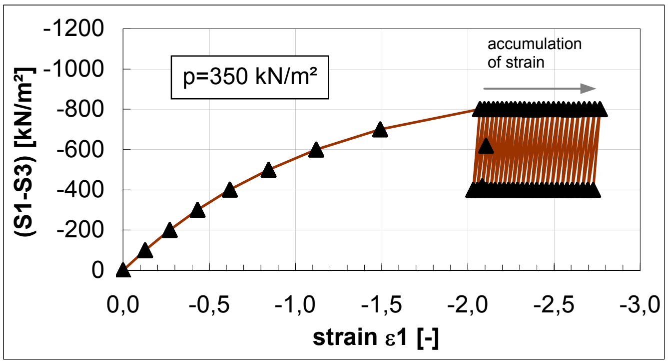


Figure 12: Numerical results of triaxial test

5 CONCLUSION

The paper presented possible cyclic impacts on granular soil. A short overview of material laws and their limitations concerning the simulation of cyclic behavior are discussed. To depict and verify these material laws laboratory tests were simulated numerically by means of the Finite-Element Method. The calculations show that a realistic simulation of cyclic behavior is partly possible by using appropriate material laws such as the hypoplastic material law. By means of this material law the sensible evaluation of the behavior of foundation elements such as shallow foundation of high speed railway lines or magnetic levitation train lines could be possible. However, further calculations and research have to be carried out to test, evaluate and verify this material law. Calculation including sensitive analysis to evaluate the influence of all decisive parameters as well as the settlement predictions for foundations elements under cyclic loading are in progress.

6 REFERENCES

Brinkgreve, Broere. 2004. Plaxis, 2D-Version 8.

Fellin. 2000. *Hypoplastizität für Einsteiger*. Bautechnik 77, Heft 1

Fellin. 2002. *Hypoplastizität für leicht Fortgeschrittene* . Bautechnik 79, Heft 12

Festag. 2003. *Experimentelle und numerische Untersuchungen zum Verhalten von granularen Materialien unter zyklischer Beanspruchung* . Technische Universität Darmstadt, Heft 66

Herle. 1997. *Hypoplastizität und Granulometrie einfacher Korngerüste*. Publ. Series of Institut für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe, No. 142, 1997

Niemunis. 1993. *Hypoplasticity vs. elastoplasticity, selected topics*. Modern Approaches to Plasticity , D. Kolymbas (ed.), 278-307, Elsevier, 1993

Niemunis, Herle. 1997. *Hypoplastic model for cohessionless soils with elastic strain range* . Mechanics of Cohesive-Frictional Materials , 2:279-299, 1997

Niemunis, Wichtmann, Triantafyllidis. 2005. *Long term deformations in soils due to cyclic loading*. Modern trends in geomechanics, International Workshop 2005, Vienna

Niemunis, Wichtmann, Triantafyllidis. 2005. *Explicit accumulation model for cyclic loading*. Cyclic Behaviour of Soils and Liquefaction Phenomena, Proc. of CBS04, Bochum, Balkema, pp. 65 - 76

Triantafyllidis, Wichtmann, Niemunis. 2004. *Kumulatives und dynamisches Verhalten von Böden*. Festschrift zum 60. Geburtstag von Prof. Savidis, TU Berlin

von Wolffersdorff. 1996. *hypoplastic relation for granular materials with a predefined limit state surface*. Mechanics of Cohesive-Frictional Materials , 1:251-271, 1996

von Wolffersdorff, Schwab. 2001. *Schleuse Uelzen I - Hypoplastische Finite-Elemente-Analyse von zyklischen Vorgängen*. Bautechnik 78, Heft 1

von Wolffersdorff. 2004. *Ausgewählte Probleme bei der Berechnung von Stützkonstruktionen mit der Methode der Finiten Elemente*. Geotechnical Innovation, Festschrift für Prof. Vermeer zum 60. Geburtstag

von Wolffersdorff. 2004. *Implementation of Hypoplasticity*. Plaxis User meeting (2004)

Wichtmann, Niemunis, Triantafyllidis. 2005. *FE-Prognose der Setzung von Flachgründungen auf Sand unter zyklischer Belastung* . Bautechnik 82, Heft 12

Wichtmann, Niemunis, Triantafyllidis. 2005. *Setzungsakkumulation in nichtbindigen Böden unter hochzyklischer Belasatung* . Bautechnik 82, Heft 1

Wu, Bauer, Kolymbas. 1996. *Hypoplastic constitutive model with critical state for granular material*. Mechanics of Materials , 23:45-69, 1996