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Analysis of soil-structure interaction of large tailings heaps

Analyse de l´interaction sol-structure de larges terrils salés

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ABSTRACT: For potassium fertiliser production intact salt material is mined in underground mines and converted in factories. During the converting processes occurs residual material which is stored on large tailings heaps. The residual material has a strongly viscoplastic material behaviour. For the analysis of the soil-structure interaction of the large tailings heaps and of constructions in the area around these heaps numerical simulations are necessary. These numerical simulations have to consider the strongly time variant deformation behaviour and the strongly velocity dependent strength behaviour of the residual material. In addition the material behaviour of granular rock salt is influenced by the stress level, the temperature and the compaction state. To consider the full material behaviour of the residual material a new viscoplastic constitutive law called VISCOSALT 2017 was developed and implemented into a new Finite-Element-(FE-)Programme. The paper explains the necessity of extensive numerical simulations for the analysis of the soil-structure interaction of large tailings heaps and the application in engineering practice.

RÉSUMÉ: Dans le cadre de la production de fertilisants potassiques, le sel brut est extrait de mines souterraines et transformé en usine. Les résidus provenant de la transformation du sel sont stockés dans de larges terrils. Le comportement de ces résidus est fortement viscoplastique. Des simulations numériques sont nécessaires pour analyser l'interaction sol-structure de ces terrils et des constructions environnantes. Ces simulations numériques doivent prendre en considération le fait que le comportement en déformation varie fortement dans le temps et que la résistance du matériau dépend de la vitesse de déformation. Le comportement de ces sels de roche granulaires dépend également du niveau de contraintes, de la température et de l'état de compaction. Afin de prendre en compte le comportement du matériau dans son ensemble, une nouvelle loi constitutive viscoplastique intitulée VISCOSALT 2017 a été développée et implémentée dans un programme aux éléments finis. Cet article explique la nécessité d'études numériques approfondies pour l'analyse de l'interaction sol-structure des terrils et pour l'utilisation en pratique de la loi de comportement.

Keywords: rock salt; viscoplasticity; tailings heap; Finite-Element-Method; VISCOSALT 2017

1 INTRODUCTION

For the production of fertilizer and special products for the chemical industry pottassium salt is mined in underground mines. During the production processes granular residual material occurs. This granular residual material consists mainly of rock salt which is stored on large tailings heaps. The granular rock salt has a strong

time dependent stress-deformation behaviour. Figure 1 shows the fill up of a tailings heap in Germany. In the back ground there is another heap (left) and the production facilities (centre).

Figure 1. Tailings heaps

The dimensions of these tailings heaps can be enormous. The ground view can be bigger than 1 km^2 and the height can be more than 200 m above the surface (Katzenbach et al. 2010b). Because of the dimensions, the complex stress-deformation behaviour and the distinctive interaction between tailings heap, subsoil and infrastructure construction (streets, railway tracks, bridges etc.) and technical systems (sealing systems, dewatering elements etc.) in the area around these heaps have to defined as structures belonging to the Geotechnical Category GC 3 according to current technical regulations Eurocode EC 7 (CEN 2008). The Geotechnical Category GC 3 is the category for constructions with the highest complexity factor.

The time variant stress-deformation behaviour is based on the viscoplastic characteristic of the granular rock salt. Due to this behaviour the stress distribuation in the tailings heaps and in the subsoil changes continuously. The resulting soil-structure interaction between the heaps, the subsoil and infrastructure construction and technical systems around these heaps is stress and time dependent (Katzenbach et al. 2009, Leppla 2013). Using the Finite-Element-Method (FEM) the stability and the serviceability of the tailings heaps and the infrastructure constructions and technical systems around these heaps are analized. For the subsoil elastoplastic constitutive laws are used. For the granular rock salt a viscoplastic constitutive law is used, which has been developed at the Institute and Laboratory of Geotechnics of the Technische Universität Darmstadt, Germany (Leppla 2017).

The paper explains the necessity of extensive numerical simulations for the analysis of the soil-structure interaction of large tailings heaps and the application in engineering practice.

2 DESIGN AND SAFETY CONCEPT

2.1 Basics

Due to the categorisation of tailings heaps into the Geotechnical Category GC 3 high requirements on the analysis of the stability and the serviceability including the safety concept are given. For the necessary analysis FE-Programmes and special constitutive laws can be used. These constitutive laws have to consider the time variant stress-deformation behaviour of granular rock salt. The subroutine ViscoSalt 2017 developed especially for the numerical analysis of tailings heaps consisting of granular rock salt (Leppla 2017).

The fill prozesses of a tailings heap has to be simulated step-by-step. The numerical model consisting of the tailings heap with defined fill sections and the subsoil is called a system with changing arrangement. After the activation of a fill section the corresponding creep phase is simulated.

For verification of the numerical model and the material parameters used a calibration is necessary. E.g. a back-analysis of measured displacments and displacement rates are useful.

2.2 Analysis of stability

For the analysis of the stability (Ultimate Limit State, ULS) the current technical regulations have to be considered. According to these regulations the analysis are carried out with reduced shear parameters of the subsoil and the granular rock salt. The shear parameters are the

angle of friction φ' and the cohesion c'. The analysis has to be carried out for the permanent design situation BS-P. The safety factors are $\gamma_{\varphi'} = 1{,}25$ for the angle of friction and $\gamma_{c'} = 1{,}25$ for the cohesion.

Due to the time variant stress-deformation behaviour a sufficient investigation time frame is necessary to detect a stable, stationary state. The investigation time frame includes the filling phase of a tailings heap and the time after the end of the filling for observation. The time for observation after the end of the filling normally lasts over several decades.

Using numerical simulations the stability is given if the system consisting of the tailings heap and the subsoil is in equilibrium. The system is in equlibrium

- if the FE-simulation converges at every moment, which means that the calculations go until the planned end, and
- the displacement rates are constant or decrease after the simulated end of the filling.

The FE-simulations have time increments Δt_i until the end of the investigation time frame. The proof of the stability is given with a safety factor of $\gamma = 1{,}25$ for the reduced shear parameters when an equilibrium is reached for every time increment. If only one time increment has no equilibrium the FE-Programme stops the calculation. In this case the stability is only give until the time increment Δt_{i-1} before. For the whole investigation time frame the stability is not given for the safety factor of $\gamma = 1{,}25$.

The analysis of the stability are carried out with reduced shear parameters. Because of this the calculated displacements and displacement rates are overestimated. To check if the displacement rates have a constant or decreasing trend the displacement rate v_i at the time t_i is scaled by the maximum displacement rate v_{max} (Eq. 1).

$$\frac{v_i}{v_{max}} \tag{1}$$

For the proof of the stability often the horizontal displacement rate $v_{h,i}$ resp. $v_{h,max}$ at the toe of the final slope are used. When the filling of a heap gets closer to the toe of the final slope the horizontale displacement rate increases. The horizontal displacement rate is getting a maximum when the filling of a heap reaches the toe of the final slope. The stability is given if the horizontal displacement rate has a constant or decreasing trend for the rest of the investigation time frame. The proof is given when the trend of the scaled horizontal displacement rates is like shown in Figure 2.

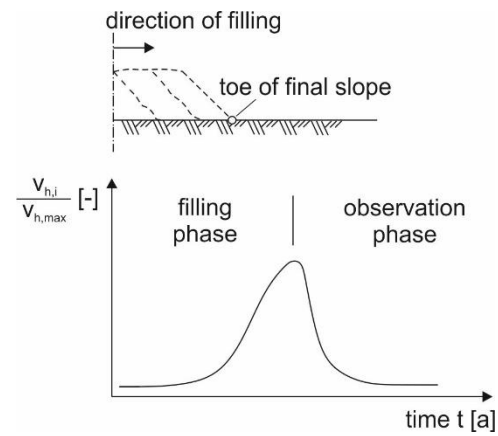

Figure 2. Horizontal displacement rate for the toe of the final slope

2.3 Analysis of the serviceability

The analysis of the serviceability is carried out with characteristic shear parameters which are not reduced. This analysis is for the evaluation of the estimated displacements of the tailings heap, the subsoil and of infrastructure construction (streets, railway tracks, bridges etc.) and technical systems (sealing systems, dewatering elements etc.) in the area around the heaps. The numerical simulations deliver stresses, displacements, displacement rates and strains, which are time variant and change according to

the filling process. These values are the input parameters for the analysis and the design of structures and technical systems. The results of the numerical simulations are normally given as contour plots and diagrams.

The calculation results of the numerical simulations are the basis for the monitoring programme which is necessary to guarantee an adequate level of safety.

2.4 Monitoring

Due to the complex soil-structure interaction of the tailings heaps, the subsoil and infrastructure constructions in the area around the heaps a geodetic and geotechnical monitoring programme has to be installed. This monitoring programme is for checking the calculation results and gives the possibility for an early detection of unplanned and/or critical states (Katzenbach et al. 2010a). The monitoring programme is based on the calculation results of the numerical simulations carried out with characteristic shear parameters.

To give an impression about the area that can be influenced the monitoring programme and the measurement data of a tailings heap in Germany are shown in the following. At this mining site the subsoil consists of different layers of sand and gravel and clay until a big depth. At the mining site exist two tailings heaps with a railway track between them (Fig. 3). At the moment the northern heap is extended to the south. This heap is about 120 m high. To detect the range of influence and for security aspects of the railway track a geodetic and geotechnical monitoring programme was installed. It consists of measurement points and inclinometers (Katzenbach et al. 2013). The filling of the extension area began in 2008 and is shown in Figure 4.

The measured horizontal displacements orthogonal to the toe of the slope on four different locations A to D are shown in Figure 5. At the beginning of the filling of the extension area the measurement points are at the toe of the original slope (A) resp. 150 m (B), 250 m (C) and 400 m (D) away. Until the measurement points are covered with granular rock salt horizontal displacement of up to 0.7 m are measured. The measurement data shows, that the range of influence is 200 m to 300 m.

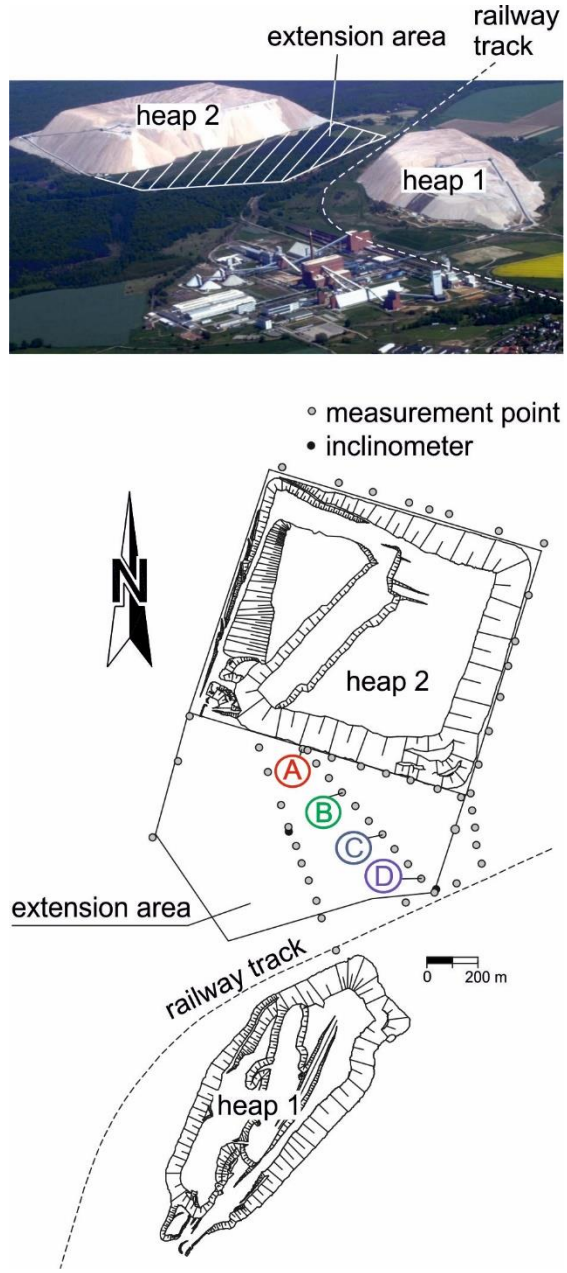

Figure 3. Mining site with tailings heaps

Figure 4. Extension of a existing heap

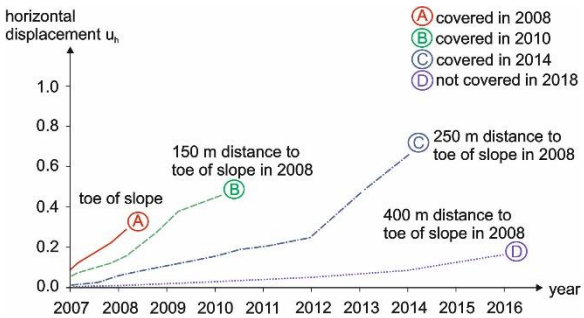

Figure 5. Measured horizontal displacements

3 ANALYSIS OF A TALININGS HEAP

In the following hte analysis of the stability and the serviceability of a tailings heap consisting of granular rock salt is explained by an example from engineering practice. The tailings heap is located in the centre of Germany and is filled since about 35 years. The mining site with the tailings heap is show in figure 6. The project area climbs form east-north-east to west-south-west.

The analysis are carried with a numerical simulation using the FEM. To consider the time variant and velocity variant material behaviour of the granular rock salt the developed subroutine VISCOSALT 2017 is used (Leppla 2017).

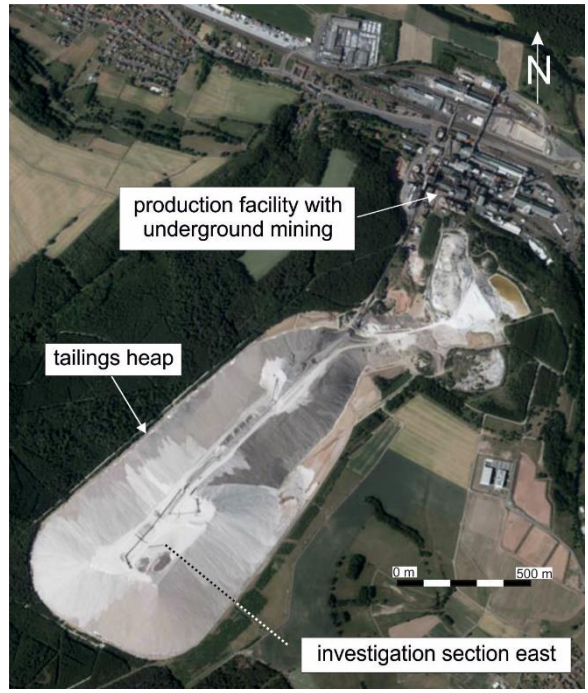

Figure 6. Mining site with tailings heap in 2016

3.1 Subsoil, geometry and history

The idealised subsoil model from the surface into the depth is as follows:

- granular soil material
- weathering zone of coloured sandstone
- intact coloured sandstone

The layer at the surface of granular soil material consists of sand, silt and clay. Below this granular soil material follows the coloured sandstone which consists of alternating layers of sandstone and silt-/ claystone. The silt-/claystone layers have a thickness of a few centimetres to a few decimetres. The coloured sandstone can be divided into the weathered coloured sandstone with a thickness of several decametres and the intact coloured sandstone which reaches into a great depth. The the coloured sandstone groundwater layers have been detected.

The silt-/claystone layers can be strongly weathered and can have comparatively small

shear parameters. These silt-/claystone layers with small shear parameters are named as weak zones which normally only can be detected by inclinometers. The idealised subsoil model including a weak zone which was detected by an inclinometer in a depth of 12 m below the surface is shown in figure 7. The soil mechanical parameters have been detected by laboratory tests on specimen of core drillings. The angle of friction δ_S of the weak zone is determined by numerical back-analysis of the inclinometer measurements. A cohesion is not detected in the weak zone.

The existing tailings heap has a length of about 1,500 m and the width of about 600 m. The height above the surface is up to 200 m. The inclination of the slope is between 36 ° and 38 °. The production facilities including the underground mining are in the north the heap. As an example the stability and the serviceability of the investigation section east are analised.

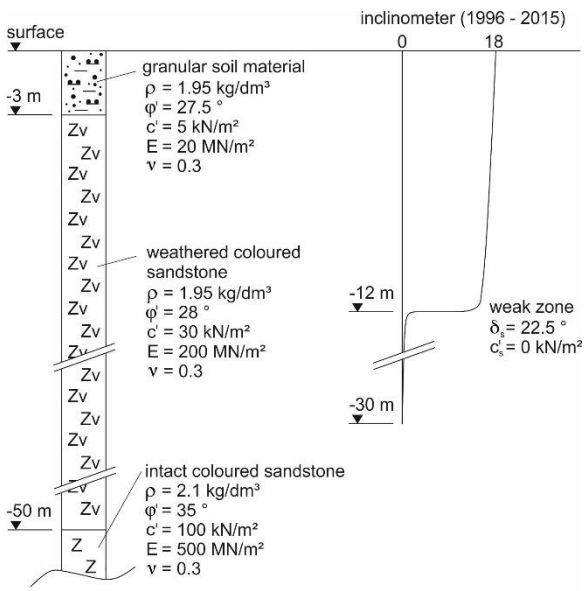

Figure 7. Subsoil conditions

3.2 Numerical model

Due to the filling processes and the viscoplastic material behaviour of the granular rock salt tailings heaps are systems with changing arrangement. The filling processes are simulated with alternating calculations step by step. In a time independent calculation step the FE-net is increased by an group of elements. Then follows a time dependent calculation step for the simulation of the viscoplastic deformations of the heap with the new geometry. The time frame for this calculation step is the filling time of the activated elements.

For the FE-simulations of the tailings heap threedimensional, isoparametric elements with eight nodes are used in the FE-Programme ABAQUS. The numerical model with the single filling sections is shown in figure 8. At the toe of the final slope the measurement points A and B are marked which exist in reality as well. The weak zone in a depth of 12 m below the surface is drawn as a dotted line.

The subsoil is modelled until a depth of 400 m below the surface. At the left edge a symmetry axis with a horizontal fixing is modelled. The right model edge is also fixed in the horizontal direction. The lower model edge is fixed in horizontal and vertical direction.

For the viscoplastic material behaviour of the granular rock salt the subroutine VISCOSALT 2017 is used (Leppla 2017). For the granular soil and the coloured sandstone an elastoplastic constitutive law with a hardening at the cap area is used.

Between the tailings heap and the subsoil and in the area of the weak zone a contact surfaces are implemented. The shear strength of theses contact surfaces is given by the friction law of COULOMB (Wriggers 2001). The possible shear stresses τ_{max} in the contact surface are proportional to the normal stress σ. The proportional factor is the tangens of the friction angle in the basis (tan δ_A) resp. the weak zone (tan δ_S). Relative displacements occur when the possible shear stress are passed. The friction angle in the basis is δ_A = 30 ° and in the weak zone tan δ_S = 22.5 °.

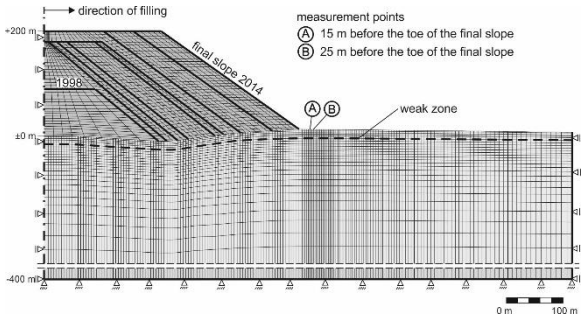

Figure 8. Numerical model of investigation section east

3.3 Calibration of the numerical model

According to the design and safety concept the numerical model has to be calibrated. For the investigation section east of the tailings heap the horizontal displacement rates and characteristic mechanical parameters have been used in a numerical back-analysis.

The geodetic measurement points A and B are 15 m resp. 25 m before the toe of the final slope. The inclinometer is at measurement point B and has a depth of about 30 m below the surface. As evaluation parameter the horizontal displacement rates v_h on the surface and in the depth are common.

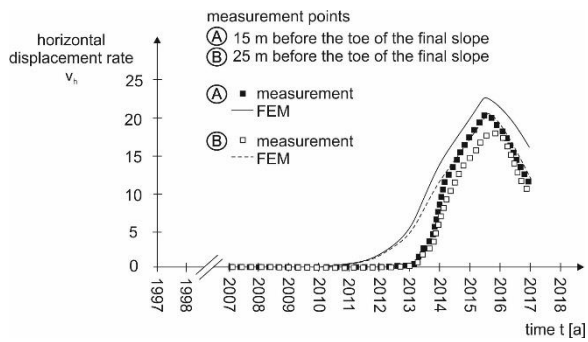

Figure 9. Horizontal displacement rates on surface

Figure 9 shows the measured and calculated horizontal displacement rates of the measurement points A and B on the surface. Figure 10 shows the distribution of the horizontal displacement rates over the depth of the inclinometer. The measurement data and the results of the numerical back-analysis show a good accordance. The small overestimation delivers calculation results on the safe side.

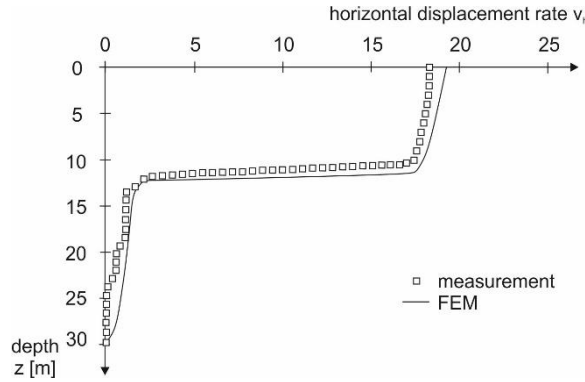

Figure 10. Horizontal displacement rates over depth

3.4 Proof of stability (ULS)

For the proof of stability the mechanical parameters are reduced by the factor of safety. The simulated filling phase is about 19 years and the simulated observation phase is about 40 years. For the visualisation of the calculation results the scaled horizontal displacement rate is used (Fig. 11).

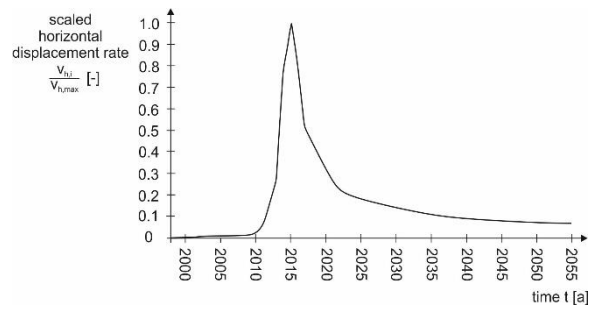

Figure 11. Scaled horizontal displacements for proof of stability

The maximum horizontal displacement rate occurs when the toe of the final slope is reached in 2014. The numerical simulation has converged until the end of the observation phase and the horizontal displacement rates have a decreasing

trend after the end of the filling phase. The system is in an equilibrium state and the stability is given at any time.

3.5 Proof of serviceability (SLS)

For the proof of serviceability the characteristic mechanical parameters are used. The resulting estimation of the time variant stresses, displacements, displacement rates and strains are the basis for the analysis of instrastructure constructions and technical systems in the area around the heap. As an example for the calculation results the horizontal and vertical displacements at the end of the observation phase are shown in figure 12. The differential displacements on the weak zone are visible. On the surface horizontal and vertical dispacements occur.

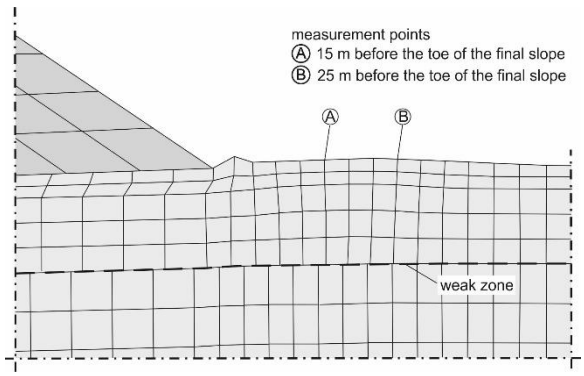

Figure 12. Deformed FE-net at the end of the observation time

4 CONCLUSIONS

For the analysis of stability and serviceability of tailings heaps consisting of granular rock salt the time variant material behaviour has to be considered. The developed subroutine VISCOSALT 2017 is a sufficient tool for numerical simulations of the filling phase and the time after the end of the filling. At the moment the explained principles of analysing these tailings heaps is used at several projects in engineering practice.

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