# Large tailings heaps and the influence on infrastructures due to the resulting soil deformation

## Les grands terrils miniers et leur influence sur les infrastructures voisines à travers la déformation des sols


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ABSTRACT: In the context of potassium fertilizer production the residua, mostly consisting of granular rock salt, is stored on large tailings heaps. The salt residue has a strongly visco-plastic material behaviour with a rate-dependant strength. The heaps have a base area up to a square kilometre and heights up to 120 m. Using the Finite-Element-Method (FEM) and a numerical constitutive law for the salt residue, developed at the Technische Universität Darmstadt (TU Darmstadt), the influence of the heaps on infrastructures like buildings, streets, railway tracks and pipelines can be estimated. In the context of the approval procedures of the extension of existing heaps comprehensive numerical investigations regarding stresses and deformations are necessary to guarantee the stability and the serviceability of the heaps and influenced infrastructures. For verification of the numerical investigations according to the observational method monitoring programs have to be installed.

RÉSUMÉ : Dans le contexte actuel de production d'engrais riches en potassium, les résidus, principalement constitués de sel gemme granulaire, sont stockés sous forme de larges terrils. Les résidus salins présentent un important comportement visco-plastique, et une résistance à la rupture fortement dépendante du temps. La surface occupée par ces terrils peut atteindre un kilomètre carré et une hauteur de 120m. L'influence de ces terrils sur les infrastructures du type bâtiments, routes, rails et pipelines peut être estimée en combinant la Méthode des Eléments Finis (MEF) et l'utilisation d'une loi constitutive numérique pour le matériau salin, développée à la TechnicheUniversität Darmstadt (TU Darmstadt). Dans le contexte actuel qui encourage l'extension des terrils existants, il devient nécessaire de mener des études numériques poussées évaluant les contraintes et déformations, afin de garantir la stabilité et le bon fonctionnement des terrils et des infrastructures avoisinantes. Des programmes de contrôle doivent être mis en place afin d'effectuer la vérification des études numériques, obtenues grâce aux méthodes observationnelles.



KEYWORDS: Tailings heap, visco-plastic material behaviour, observational method.

MOTS-CLES : Terrils miniers, comportement visco-plastique, méthode observationnelle


## 1 INTRODUCTION

During the production of potash and the converting into fertilizer for agriculture and into specialty products for the chemical industry a large amount of residua, mostly consisting of granular rock salt, is deposited on large heaps. The resulting tailings heaps with a ground view up to 1 km² and a height up to 120 m cause normal stresses of 2,200 kN/m² and shear stresses of 550 kN/m² on the contact surface. An impression of the dimensions of such tailings heaps is given in Figure 1.

Figure 1. Rock salt heaps.

For analyses of the load and deformation behaviour of the heaps the Finite-Element-Method (FEM) in combination with elastoplastic constitutive laws for the soil and a viscoplastic constitutive law for the granular rock salt, developed at the Institute and Laboratory of Geotechnics of the TU Darmstadt, are used.

The verification of the developed constitutive law for the granular rock salt was done by back-analyses of laboratory tests and the monitoring data of specific projects. The paper focuses on the challenges of an extension of a tailings heap and the influence on a railway track as only 1 example from engineering practice (Katzenbach et al. 2004, Katzenbach et al. 2006).

## 2 PROJECT DESCRIPTION

In order to ensure the further production an existing 120 m high tailings heap needs to be extended (Figure 2).

The planned extension of the tailings heap approaches the railway track to the south. The existing heap was stored in blocks with a lower and an upper layer (Figures 3 and 4). The slope ratio is up to 40°. Since 2008 the extension is stored with layers on the slope (Figure 5).

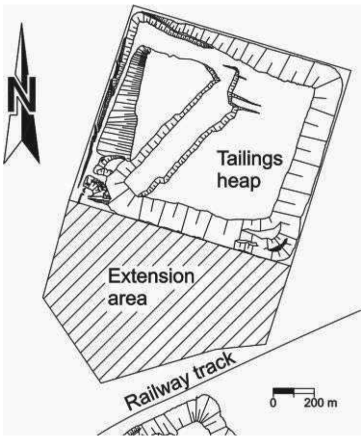


Figure 2. Site plan of the project.

Figure 3. Spreader on a heap.

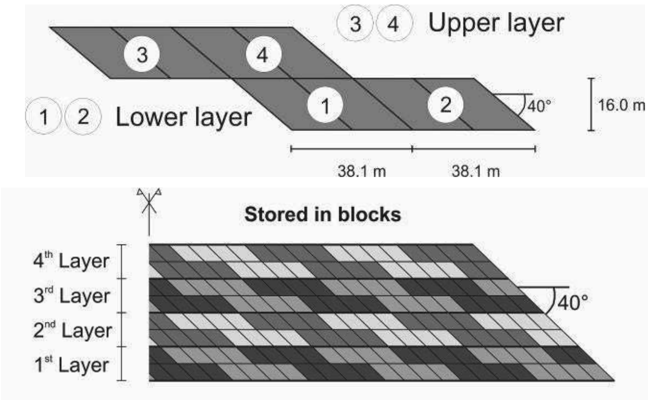


Figure 4. Schematic procedure of the block storing method.

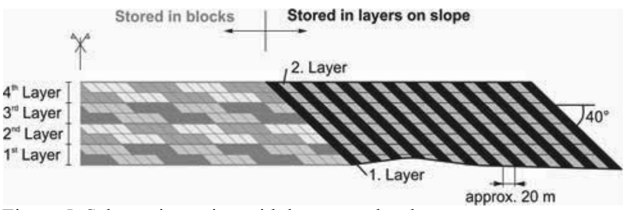


Figure 5. Schematic storing with layers on the slope.

The project area is situated in a glacial plain with a rather flat ground surface. The soil is horizontally stratified. At the surface a 5 m to 10 m thick layer of sand and marl glacial deposits was investigated. Below the sand and marl deposits a 50 m thick layer of quaternary sand with loose density was found, followed by a 130 m to 150 m thick layer of Rupel Clay and dense sand with varying layers of silt. At a depth of approximately 200 m below the surface the new red sandstone begins. The groundwater level is about 5 m below the surface.

## 3 MATERIAL BEHAVIOUR OF GRANULAR ROCK SALT

The material behaviour of granular rock salt is characterized by a distinctive time and stress dependence. Initially fresh granular rock salt has a non-cohesive texture. After a short period the loose, granular rock salt converts into a cohesive texture with a high strength (Ankes 1972). The salt material attains a shear strength with a friction angle of $\varphi' = 50°$ and a cohesion of $c' = 850$ kN/m², as well as a stiffness of $E_s = 2{,}500$ MN/m². The material behaviour of the granular rock salt is strongly dependent to the deformation rate. High, overcritical deformation rates lead to high strength and stiffness of the rock salt and to brittle fracture. Small, undercritical deformation rates lead to minor strength and stiffness and to a plastic creep without fracture.

Directly after storing the granular stockpiled material has a density of $\rho = 1.4$ to $1.5$ t/m³. Due to the atmosphere, chemical processes and the pressure because of the increasing covering the granular stockpiled material in the core of the heap transforms nearly into solid body.

Under constant deviatoric stress the stockpiled material presents a constant creep behaviour despite a huge strength. The material behaviour of stockpiled material is strongly dependent on the state of stress and of the deformation rate. Figure 6 shows the results of two strain controlled triaxial tests on specimen of stockpiled material, obtained from core drillings from the top of a heap. For both tests a cell pressure of $\sigma_3 = 0.5$ MN/m² was specified. Both deformation rates vary by the factor 1,000.

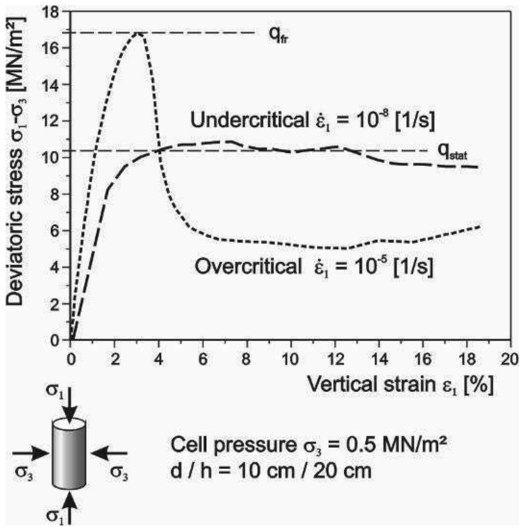


Figure 6. Typical results of strain controlled triaxial tests on stockpiled material samples.

The sample with the higher, overcritical deformation rate of $d\varepsilon/dt = 10^{-5}$ 1/s presents the usual material behaviour on high deformation rates. After the peak stress $q_{fr}$ follows a deep drop of the deviatoric stress (brittle fracture). The sample with the lower (undercritical) deformation rate of $d\varepsilon/dt = 10^{-8}$ 1/s does not collapse. The sample creeps under a constant deviatoric stress $q_{stat}$.

On the left in Figure 7 is shown the specimen after the test with undercritical deformation rate. On the right is shown the specimen after the test with overcritical deformation rate.

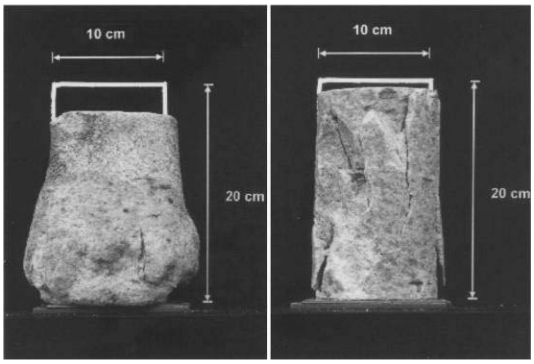


Figure 7. Specimens of triaxial tests with undercritical (left) and overcritical (right) deformation rates.

Due to deviatoric stress levels the stockpiled material creeps with high deformation rates at the beginning. The deformation rate decreases under constant deviatoric stress dependent on the time and approaches asymptotic the stationary creep rate (Figure 8).

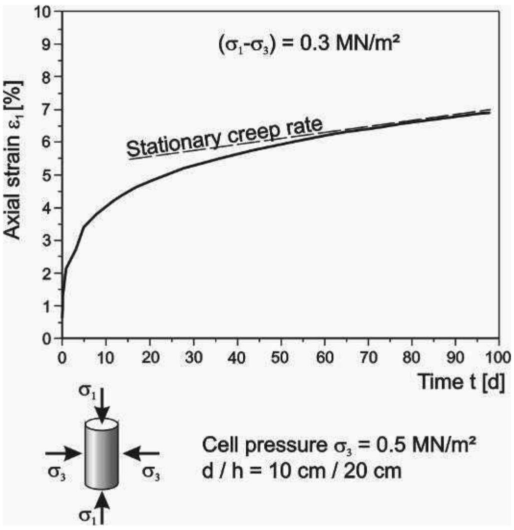


Figure 8. Typical creep curve of granular stockpiled material.

For further information of the material behaviour of granular rock salt see *Fordham 1988*, *Munsan and Wawersik 1991*, *Chumbe et al. 1996* and *Boley 1999*.

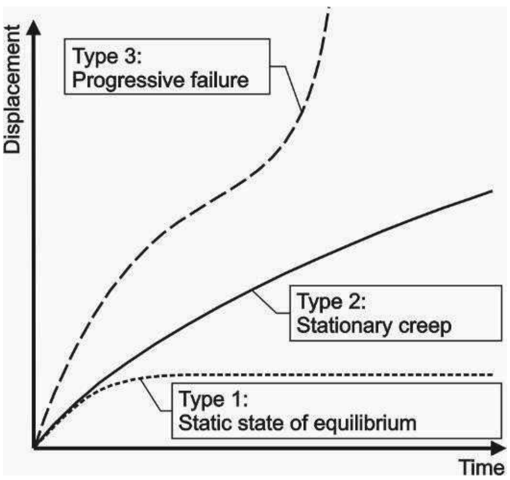


Figure 9. Deformation rate dependent system behaviour.

Although the heaps have a slow creep deformation and the soil has a continuously, slow changing load the heaps do not collapse due to the viscoplastic material behaviour of the granular rock salt as long as the deformation rate is undercritical. The collapse of the slope of a heap only results from a progressive failure (Figure 9) due to an increasing overcritical deformation rate. The system behaviour of a heap consisting of granular rock salt normally is like type 2 in Figure 9, if there is no weakening in the contact area.
On the basis of more than 150 triaxial tests a constitutive law for the material behaviour of granular stockpiled material was developed at the Institute and Laboratory of Geotechnics of TU Darmstadt (Boley 1999, Wachter 2009, Wachter and Katzenbach 2009). This constitutive law was implemented in a Finite-Element-Software for analyses of the ultimate limit state (ULS) and serviceability limit state (SLS) of granular rock salt heaps and infrastructures and buildings in the influenced area around the heaps.

## 4 ANALYSES OF THE EXTENSION OF THE HEAP

For analyses of the extension of a tailings heap and the influence on the railway track numerical simulations using the FEM were carried out. The model has a length of 1,800 m. The heap is 120 m high. Regarding the analyses of an extreme situation the groundwater level was set to the surface. The soil is modelled with an elastoplastic constitutive law based on a modified Drucker-Prager-Modell, the new red sandstone was modelled with an elastic constitutive law. The FE-Model is shown in Figure 10.

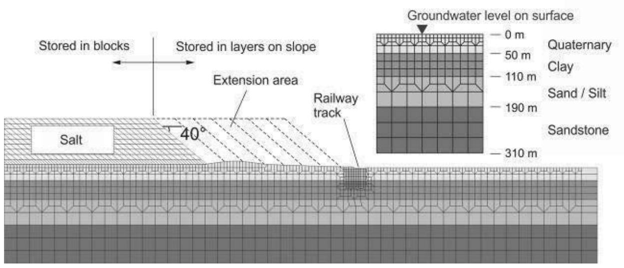


Figure 10. FE-Model of the soil and the heap before and after the extension.

The interaction between the tailings heap and the soil is modelled by a contact surface. The shear strength is defined by the friction law of *Coulomb*. The shear stress is proportional to the vertical stress. The time dependent material behaviour and the changing geometry of the heap are considered by a step-by-step analysis.
Figure 11 shows the analysed cross sections. The horizontal distance $s_i$ of the toe of the slope to the railway track is varying along the track.
The relative deformations and the deformation rates have been calculated. The deformation rates increase when the extension approaches the railway track and decrease to a low rate when the extension area is totally filled up.
Due to the complexity of the project and the interaction between soil, heap and the infrastructure an extensive monitoring program according to the observational method was installed. The main part of the monitoring program consists of geodetic and geotechnical measurements (Figure 12).
For example the measured, absolute, horizontal displacements orthogonal to the toe of the slope of 2 measurement points are presented. The measurement point MR 54 is at the toe of the slope before the extension started. The measurement point MR 51 had a distance of 150 m to the toe of the slope before the extension started.

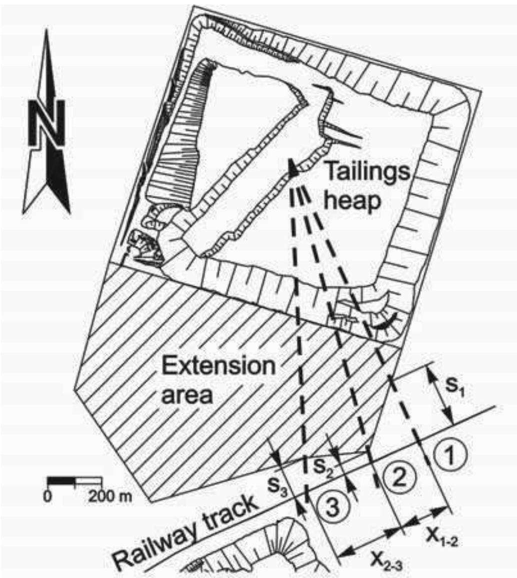


Figure 11. Cross sections for the analyses of the deformation of the railway track.

The measurement point MR 54 had a horizontal displacement of 0.30 m before it was covered with salt. After the covering no further measurement data for this point existed. The measurement point MR 51 had a horizontal displacement of 0.45 m before it was covered with salt.

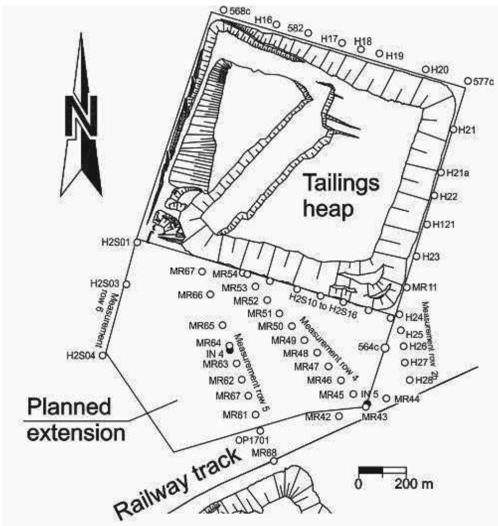


Figure 12. Geodetic and geotechnical monitoring program.

For calibration of the numerical simulations the calculated displacements are compared to the measurement data. In result numerical simulations supply horizontal displacements in a comparable range.

## 5 CONCLUSIONS

Due to the storing of granular residues of potash production on large tailings heaps enormous loads are transferred into the soil. In this context vertical and horizontal deformation occur even in a distance of hundreds of metres. For analyses of the ultimate limit state and the serviceability limit state of the heaps and infrastructures and buildings in the area of influence realistic simulations are necessary.

Using a complex constitutive law for the viscoplastic stockpiled material, developed at the Institute and the Laboratory of Geotechnics of TU Darmstadt, the numerical simulations of an extension of a heap and the influence on a railway track were investigated. The comparison of the results of the numerical simulations and the monitoring program shows a good accordance.

The developed constitutive law can be judged as a robust, efficient and purposeful material routine which offers an instrument for the simulation and investigation of complicated, time variant systems using numerical simulations.

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