IAEA-SM-362/42

Use of special oedometer tests for the remediation of large uranium mill tailings impoundments at Wismut, Germany

U. Barnekow[1], **M. Paul**
WISMUT GmbH, Department of Engineering,
Chemnitz, Saxony, Germany

Abstract. The paper presents the use of recently developed special oedometer tests for designing the remediation of large uranium tailings ponds at WISMUT, Germany. Uranium ore mining and milling in eastern Germany by the former Soviet-German WISMUT company lasted from 1946 to 1990. Wastes from the hydrometallurgical uranium extraction processes were discharged into large tailings impoundments covering a total area of 5.5 km^2 and containing about 150 × 10^6·m^3 of uranium mill tailings. Tailings pond remediation is ongoing by in-place decommissioning with dewatering by technical means. Geotechnical properties and the most suitable so-called non-linear finite strain consolidation behaviour of fine uranium mill tailings are described. Decommissioning techniques comprise, among others, interim covering of under consolidated fine tailings, contouring of tailings surfaces and final covering. Contouring, in particular, has a huge potential for optimization in terms of cost reduction. For contouring total settlement portions, the spatial distribution of differential settlement portions and the time-dependent settlement rates, especially of the cohesive fine uranium mill tailings are of critical importance. A new special oedometer KD 314 S has been developed to generate all the input data needed to derive the fundamental geotechnical relationships of void ratio vs. effective stress and of permeability coefficient vs. void ratio for consolidation calculations. Since December 1999 the new special oedometer KD 314 S has been working successfully on fine uranium mill tailings from both acid and from soda alkaline milling. Results coincide with non-linear finite strain consolidation theory. The geotechnical functions derived were used as input parameters for consolidation modelling. An example of the consolidation modelling on Helmsdorf tailings pond is presented.

1. INTRODUCTION

A new special oedometer test apparatus, called KD 314 S, has recently been developed at WISMUT for special consolidation testing on weak or pulpy uranium mill tailings. Results from these special oedometer testings are needed to reliably characterize the time-dependent consolidation behaviour of fine uranium mill tailings, which is of fundamental importance for the remediation of the large uranium tailings ponds at WISMUT.

The automatic special oedometer test apparatus KD 314 S was jointly developed by WISMUT and WILLE Geotechnik, Göttingen in 1998/99 (Fig. 1; Fig. 2). Technical optimization of the apparatus for conducting consolidation tests on fine uranium mill tailings was carried out in a diploma thesis [1] developed at WISMUT with the support of the Technical University of Zwickau (FH), Germany in 1999. In addition, the testing procedure has been adopted by WISMUT for generating all geotechnical input data needed for consolidation modeling on fine uranium mill tailings.

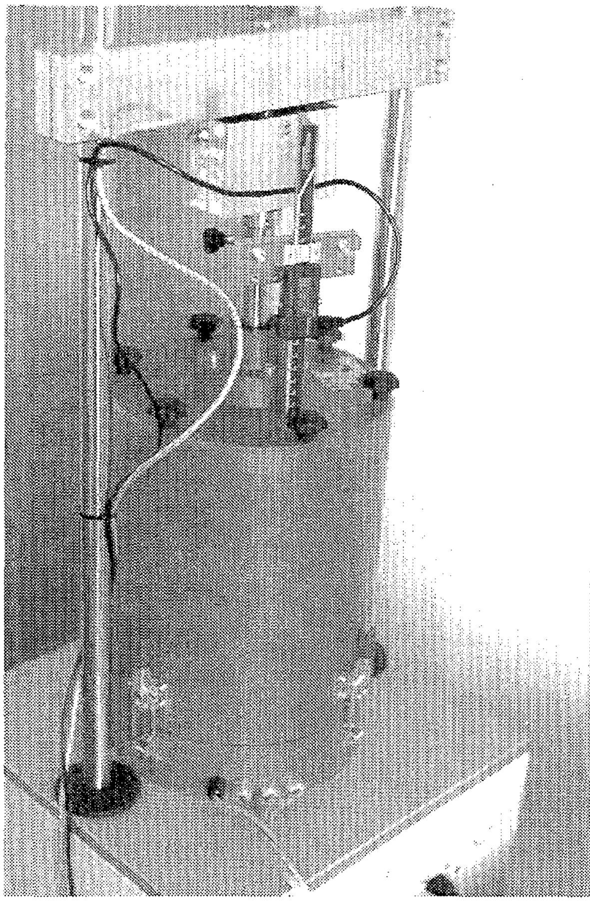
Since December 1999, several special oedometer testing campaigns have been carried out on uranium mill slime tailings from different tailings ponds at WISMUT. Some of the results are presented below.

Fine grained, cohesive uranium tailings of weak or pulpy consistency covers a huge area on the WISMUT tailings ponds. Fig. 3 presents a 3D-model of Helmsdorf Tailings Pond (area: 2.05 km^2, tailings volume 45 × 10^6·m^3). Cohesive fine tailings in the pond area are characterized by an undrained

[1] Present address: WISMUT GmbH, Abt. T 1.2, BT Paitzdorf, SB Ronneburg, 07580 Ronneburg.

shear strength values below 5 kPa near the surface. Such tailings cover about 0.70 km^2 of the Helmsdorf tailings pond. The entire Helmsdorf tailings pond is to be covered during remediation. High absolute settlement segments and local differential settlement segments must be taken into account due to covering requirements. To significantly reduce remediation costs it is of critical importance to know exactly the geotechnical consolidation characteristics of these fine uranium mill tailings.

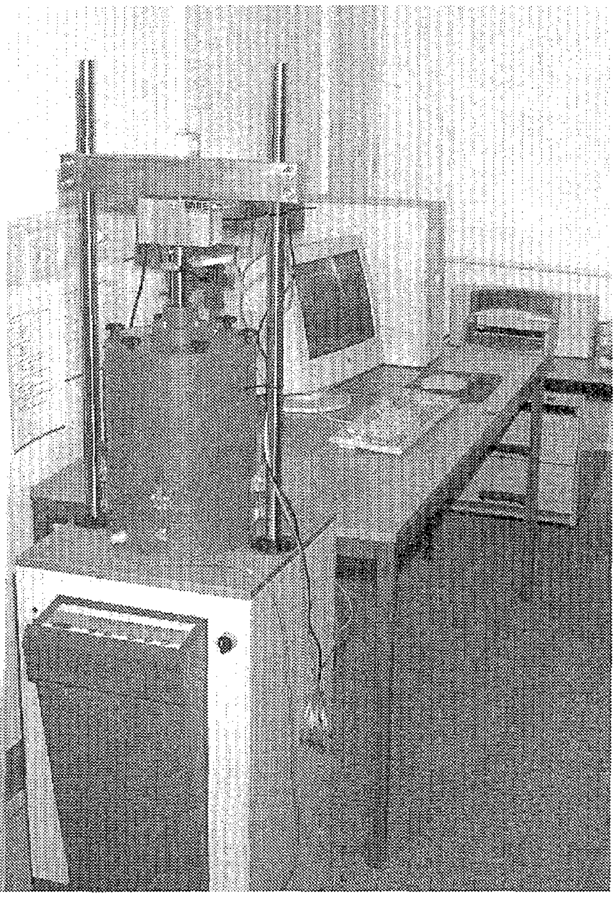
Conventional oedometer test procedures were found unsuitable for accurately determining the consolidation characteristics of such fine tailings materials. In the past, it was impossible to fill the oedometer cell with tailings pulp and run a conventional oedometer test successfully. The new special oedometer test KD 314 S was developed to address this problem.



in the foreground: electromechanically driven automatic press with oedometer cell (red tube)

in the background: oedometer testing controled by steering computer

FIG. 1. Special oedometer test apparatus KD 314 S.



oedometer cell (internal diameter: 200 mm, max. samples height: 190 mm) measured test parameters:

at the bottom:

base loading force (0...15 kN, three sensors à 0...5 kN) pore pressure (0...300 kN/m^2, accuracy 0.6 kN/m^2)

on top: surcharge loading force (0...10 kN) and settlement (mm)

FIG. 2. KD 314 S Oedometer cell.

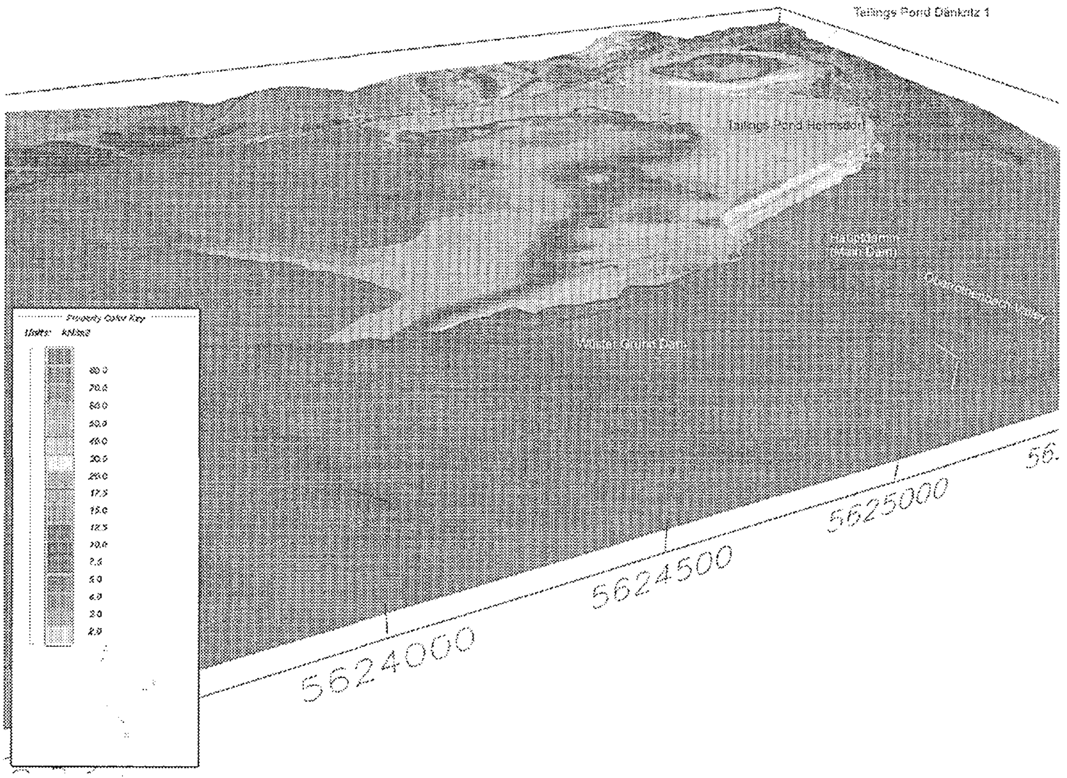


FIG. 3. Model of 3D-distribution of undrained shear strength (in kPa) in Helmsdorf (205 ha) and Dänkritz 1 (27 ha) tailings ponds (3D-model covered with airborne photograph in the background; software: EarthVision).

2. BACKGROUND OF URANIUM MINING AND MILLING HISTORY AT WISMUT

In eastern Germany, uranium ore mining and milling by the former Soviet-German WISMUT company lasted from 1946 to 1990. Wastes from the hydrometallurgical uranium extraction processes were discharged into large tailings impoundments covering a total area of about 5.5 km^2 and containing about $150 \times 10^6 \cdot m^3$ of uranium mill tailings.

Uranium ores were milled by acid leaching or soda alkaline leaching. Acid milling pulps were neutralized before discharge into the tailings ponds. In addition some of WISMUT's tailings ponds were used as water storage basins. Currently only residues from water treatment are still being discharged into two of WISMUT's tailings ponds.

Near Seelingstädt/Thuringia two old open pits were covered by waste dumps and dams before tailings deposition started. Trünzig A and Trünzig B tailings ponds were filled in the 1960s. Culmitzsch A and B tailings ponds were filled from 1967 until 1991. The tailings ponds near Seelingstädt cover a total area of nearly 3.5 km^2.

Near Crossen/Saxony, the Helmsdorf tailings pond was constructed and filled during the period from 1957 until 1990 in a valley. Two smaller tailings ponds Dänkritz No. 1 and No. 2 were constructed and filled earlier in the 1950s within old open gravel pits.

Controled by the milling/discharge history and the discharge pattern, different tailings materials with spatially varying geotechnical properties were deposited in each tailings pond. Because the historic discharge patterns varied, beach zones of sandy tailings, transition zones with interlayering of coarse and fine tailings and fine tailings zones containing thick homogenous fine tailings developed in each tailings pond. As shown in Fig. 3, beach zones in the Helmsdorf and Dänkritz-1 tailings ponds are characterized by undrained shear strengths above 15 kPa. So-called transition zones are characterized by shear strength variations between 5 and 15 kPa. Fine tailings zones show shear strength values that are usually below 5 kPa in the upper most tailings near the surface.

The total amount of uranium in the solids deposited in the WISMUT tailings ponds is 15.3×10^6 kg. The total amount of radium in the solids is 1.5×10^{15} Bq and the average Radium concentration of solids is 9 Bq/g. The Helmsdorf tailings pond also contains 7.6×10^6 kg of arsenic in the solids.

3. REMEDIATION OF WISMUT's LARGE URANIUM MILL TAILINGS PONDS

Remediation measures started in 1990 with defence measures against acute risks, together with complex environmental investigations and preparation of the first site-specific remediation concepts. Currently, none of the tailings ponds present any acute danger to human health or the environment. Based on extended investigation programmes, WISMUT has decided to start preparations for using the remediation option of in place dry decommissioning with partial dewatering by technical means.

Decommissioning techniques for the dry option comprise, at least the following activities: (1) initial defence measures against acute dangers, (2) removal and treatment of pond water, (3) interim covering including technical dewatering of (unconsolidated) fine tailings, (4) reshaping of tailings dams and contouring of interim covered tailings surfaces and (5) final covering and landscaping including revegetation.

As a first defence measure, interim covering started in 1990 on sub-aerial sandy tailings surfaces of the so-called beach zones to guarantee dust control and to significantly reduce radon exhalation from the tailings surface.

Removal and treatment of pond water has lowered the water level progressively in the past. More and more fine tailings surfaces lost their water cover. Currently, all of the pond water has been removed from several tailings ponds at WISMUT.

From a geotechnical perspective, interim covering of poorly consolidated fine tailings is the next and most decisive step of the overall decommissioning technology. Various interim covering methods were tested successfully at WISMUT in the past. By 1995 the entire Trünzig A tailings pond (total area 0.67 km^2) had received an interim cover. WISMUT is currently placing interim covers on the transition zones and fine tailings zones of all other tailings ponds. Currently there is no acute danger from dust pollution, and the radon exhalation rate on sub-aerial cohesive fine tailings surfaces is limited. Because of these effects, interim covering of the fine tailings surfaces is not primarily an acute defence measure but works as a first stable platform for further remedial measures.

Prior to interim covering of the fine tailings area, the drying-out of sub-aerial fine tailings surface has been used primarily to improve trafficability. Interim covering measures on fine tailings surfaces start with the placement of (1) geotextile, (2) geogrid and/or (3) combined geomaterials like drainmats on the dried "tailings crust". Technical dewatering is enhanced by stitching vertical wick drains into the tailings. Loading of the tailings surface is carried out by progressively placing (thin) earthen layers using common earthwork machines like small dozers or hydraulic excavators.

The next remediation step is contouring. Reshaping the dams is done to guarantee long term stability and long term erosion control of the dams and their final cover. Contouring the pond area prepare for later final covering. Contouring creates a long term stable surface contour to ensure future surface runoff from the final cover. At the Trünzig A tailings pond, WISMUT will start reshaping the first tailings dam this year. It is anticipated that contouring the pond area of the Trünzig A and B tailings ponds will begin in 2001.

The contouring step, in particular, has a huge potential for optimization of cost reduction. Cost-optimization of contouring means minimization of the cut and fill materials that are needed to reach remediation objectives. To design for contour after total settlement, spatial distribution of differential settlement characteristics and time-dependent settlement rates, especially of the cohesive fine uranium mill tailings, are of critical importance. The Helmsdorf tailings pond encloses an area of about 2.05 km^2. Its fine tailings area covers about 0.70 km^2.

Reducing the average thickness of earthen cover layers required for contouring by only 1 m of thickness on an area of 0.5 km^2 means a reduction of approximately 3.3 million EUR. Therefore, the needed thickness of contouring should be minimized locally on each part of the tailings pond. The requirements are based on sophisticated calculations of time-dependent settlement rates and spatial differences of absolute settlement in each segment of the pond area. This is of critical importance for cost-optimization. This cost-optimization can only be carried out correctly if the consolidation behaviour of the fine tailings can be predicted exactly.

The KD 314 S special oedometer test was developed to accurately measure the consolidation behaviour of fine uranium mill tailings. From the test results, all input parameters for consolidation and settlement calculations on fine uranium mill tailings can be derived. Tailings consolidation properties are presented below.

Final covering is the last remediation step. The final cover must ensure long term stability of the reshaped dams and contoured tailings. It must control infiltration, and prevent erosion in the long term. The cover should also guarantee stable revegetation. At WISMUT's tailings ponds, final covering of contoured tailings ponds and dams will be completed within a few years.

4. GEOTECHNICAL CHARACTERIZATION OF FINE URANIUM MILL TAILINGS

Uranium tailings were generated by acid or alkaline leaching. Huge settlement variations and considerable spatial differential settlement can be expected in tailings pond areas where thickened fine tailings were deposited under the water table. Since deposition, these areas have never been influenced by air drying or any surcharge loading. Therefore interim covering refers to the initial loading of these slimes.

Typical physical properties of fine tailings are presented below for the alkaline slime tailings of the Helmsdorf tailings pond Helmsdorf:

- grain size: 60 ... 80% silt fraction (0.002...0.063 mm)
  20 ... 40% clay fraction (<0.002 mm), nearly no sand fraction
- water content: w = 70 ... 140 weight % of solids mass
- void ratio: e = 2 ... 4
- liquid limit: LL = 45 ... 70 weight%
- plasticity index: I_P = 22...40 weight%
- Consistency index: I_C = – 4 ... – 0.1 (liquid consistency acc. to Casagrande liquid limit test)
- Undrained shear strength near surface 0 ... 5 kN/m^2

Cohesive fine uranium mill tailings are typically silts or clays of high plasticity. Consistency under field conditions is often weak or pulpy. The typical mineralogical composition of the Helmsdorf fine tailings is 40 ... 50% muscovite-illite, 20% quartz, 15% chlorite, 7% feldspar, 5% dolomite, 3% calcite, some kaolinite.

The permeability coefficient is low and depends on the in situ void ratio. It varies in the range of 5×10^{-8} to 5×10^{-10} m/s. Compression index C_C of fine tailings increases with increasing distance from the original discharge location. In the fine tailings zone, the compression index increases from $C_C = 0.30$ next to the beach zone up to $C_C = 0.55 ... 0.65$ in the distal tailings zone. The time-dependent consolidation behaviour of fine uranium mill tailings cannot be described exactly by conventional Terzaghi consolidation theory. A much more realistic determination of the time-dependent consolidation behaviour is given by the non-linear finite strain-consolidation theory as described by GIBSON et al. (1981) [2]. This geotechnical consolidation behaviour is of fundamental importance for remediation progress.

Conventional theory, which holds that deformation and pore pressure dissipation have a one-to-one coincidence is not valid! This can seriously effect laboratory determinations of strength parameters and stability calculations [3]. It should be noted that non-linear finite strain theory predicts a progress of settlement that is substantially faster than predicted by conventional Terzaghi theory. On the other hand, pore pressure decrease occurs substantially slower. In addition, fine tailings may be under consolidated. In this case self-weight consolidation and settlement under surcharge loading are additive, which increase this geotechnical problem. Fig. 4 presents an example from SCHIFFMAN et al. (1984) [3] of a consolidation calculation for loading a marine clay with 200 kPa. In Fig. 4 one observes that the degree of settlement is faster than the degree of pore pressure decrease, as was stated above. Such consolidation behaviour is typical for mine waste (mill) tailings and natural cohesive marine sediments being deposited under water [3].

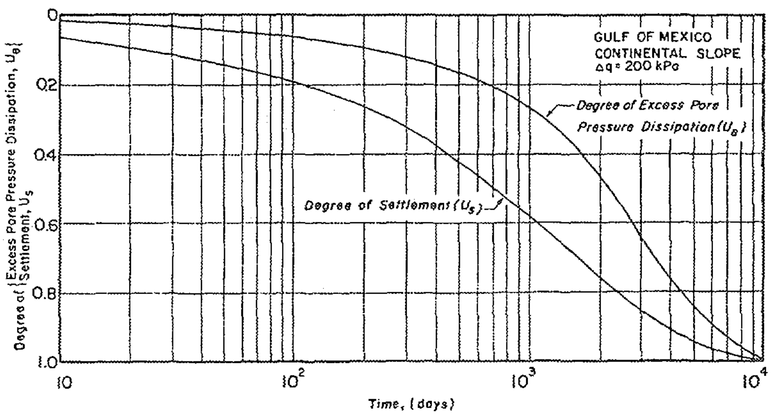


FIG. 4. Diagram of degree of time-dependent settlement and degree of pore pressure decay acc. to non-linear consolidation behaviour of a marine clay form the continental slope of the Gulf of Mexico [3].

5. RECENTLY DEVELOPED SPECIAL OEDOMETER TEST APPARATUS KD 314 S

Standard lab compression tests, such as the DIN 18137, were found to be unsuitable for investigating pulpy cohesive soils for a number of reasons. These tests cannot measure pore pressure during testing. Samples must have a flat shape with a height vs. diameter ratio of less than 1 to 5. Otherwise the geometry of a "high" sample would effect the measurement of loading pressure on the sample. In international geotechnical investigation campaigns on tailings ponds, these effects have often not been taken into account properly.

The task to be solved was to design and construct an improved compression test apparatus and to develop a methodology for deriving all the input data needed for non-linear finite strain consolidation calculation and modelling on fine uranium mill tailings. Geotechnical input functions, which should be derived from the special oedometer test results, are the relationship of void ratio to effective stress and also the permeability coefficient to void ratio.

The automatic oedometer test apparatus KD 314 S was jointly developed by WISMUT and WILLE Geotechnik, Göttingen in 1998/99 (see Fig. 1 and Fig. 2). The lab test was optimized for pulpy fine uranium tailings in a diploma thesis developed at WISMUT with the support of the Technical University of Zwickau (FH), Germany in 1999 [1]. The apparatus consists of an oedometer cell, a consolidation press with an electromechanical driving mechanism and a PC for test steering (see Fig. 1). The KD 314 S oedometer cell is based on a similar oedometer cell, that had been developed earlier to carry out consolidation tests on fine soft harbour slimes by the Bundesanstalt für Wasserbau (Federal Bureau on Hydraulics Construction, Hamburg, Germany). Only oedometer cell dimensions and measurement principles were adopted from the aforementioned apparatus. The new special oedometer KD 314 S test works automatically. It allows software-controlled testing and continuous measurement of all parameters of interest that are related to the material behaviour of consolidating fine-grained uranium mill tailings. Usually, samples with a 200 mm diameter (314 cm^2) and about 150 mm in height are tested.

The ratio of height to diameter of the sample varies during testing from 1:1.33 up to 1:5. This must be taken into account for evaluation of the test results. Parameters measured during testing include settlement value, surcharge pressure (load) on top, base pressure at the bottom of the sample as well as pore pressure. Based on these parameters it is possible to eliminate the effect of the test sample geometry.

Tailings samples can be loaded gradually in response to the gently with respect to non-linear consolidation behaviour of the fine slime tailings. Usually one starts with 1 kPa surcharge pressure. Subsequently, surcharge loading is applied to conform with the consolidation behaviour of fine tailings and according to the requirement of suitable covering technology. Typically loading is done in steps of 4, 8, 12, 20, 50, 100, 200, 300 kPa of surcharge load.

6. GEOTECHNICAL RESULTS OF SPECIAL OEDOMETER TESTS

Since December of 1999 the new special oedometer has been used regularly and many measurements have been made on the consolidation behaviour characteristics of fine uranium mill tailings at WISMUT. Results have confirmed the applicability of the KD 314 S oedometer test for fine-grained, especially weak or pulpy, uranium mill tailings. Tailings samples were loaded gradually to conform to the non-linear consolidation behaviour of the slime tailings. All the data needed to determine input parameters for further calculations of time-dependent dewatering and consolidation of such fine tailings were measured directly and automatically.

Very high sample compaction was observed for pulpy fine tailings samples. A surcharge loading of only 10 kPa on pulpy fine tailings samples often produces a 25% reduction in samples height. A final loading of 250 kPa often reduces the sample height up to 50% and more. This leads to a varying sample geometry. To determine the effective consolidating stress in the sample, one has to eliminate the effect of the sample's geometry. Therefore, base pressure is measured time dependently.

The diagram of Fig. 5 presents measurement data for the time-dependent settlement of fine uranium mill tailings when using a 25 kPa surcharge loading. The plot illustrates that the degree of settlement is faster than the degree of pore pressure decrease. This is typical for non-linear finite strain consolidation behaviour. It is the same consolidation behaviour as presented on Fig. 4 and described by SCHIFFMAN et al. (1984) [3] as typical for mine waste (mill) tailings and natural cohesive marine sediments.

Based on the measurement results, one can determine the compression curve (void ratio vs. effective stress) and the permeability coefficient vs. void ratio relationship of fine tailings. Typical testing results are presented in Figures 6 and 7. Fig. 6 shows a typical curve of void-ratio vs. effective stress (load: 5 ... 250 kPa) Fig. 7 shows the permeability coefficient vs. void ratio relationship derived from the time-settlement curves of each loading step.

This function can be used to predict settlement rates using conventional consolidation calculations. In fact, this function does not represent the true permeability coefficient because pore pressure decay is slower than that of the settlement rate. Because of this, one determines a filter velocity.

For non-linear finite strain consolidation calculations, true permeability coefficient data are needed. For this permeability coefficient, each loading step must be determined from time-dependent pore pressure decay or by correcting the time-settlement data in accordance with the observed delay of pore pressure decay (see Fig. 5).

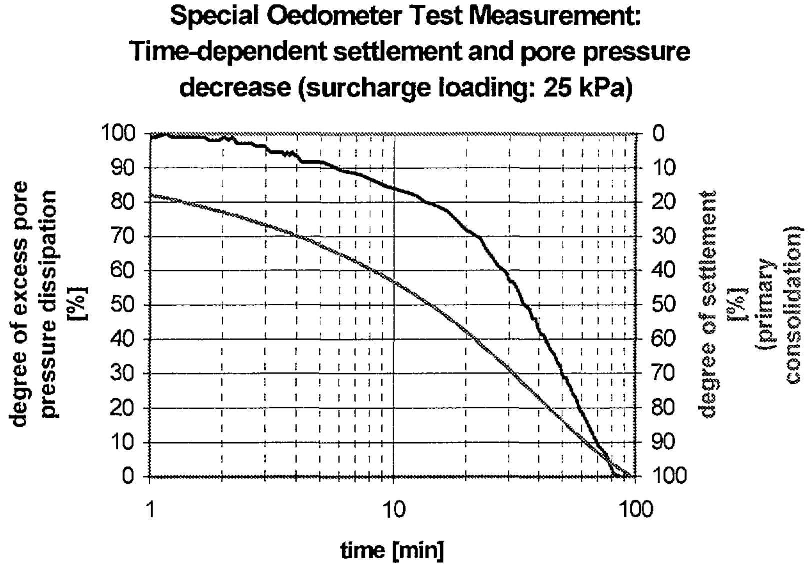


FIG. 5. Diagram: Example of measured time-settlement data on fine uranium mill tailings (WISMUT; Dep. of Eng.; geotechnical lab).

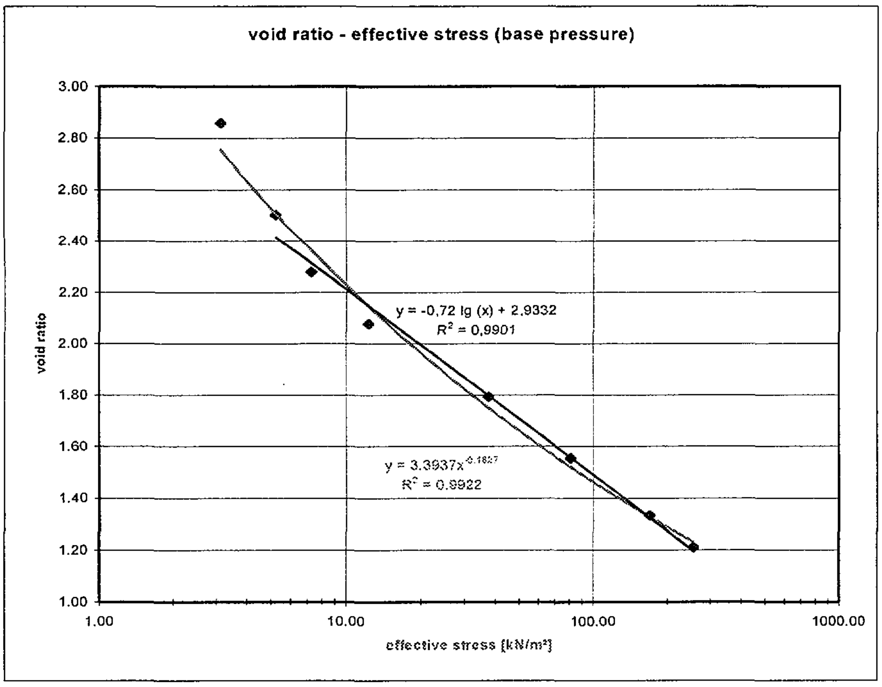


FIG. 6. Diagram: void ratio - effective stress relationship derived from load – settlement analysis.

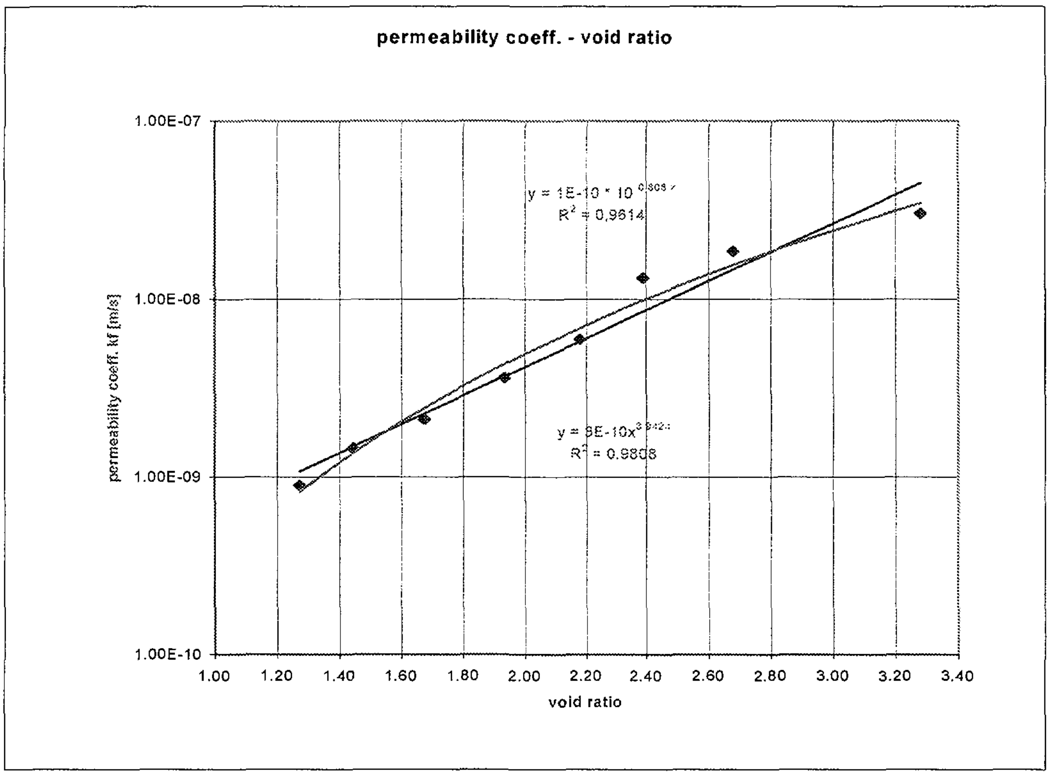


FIG. 7. Permeability coefficient – void ratio relationship derived from time-dependent settlement analysis.

7. USE OF SPECIAL OEDOMETER TEST RESULTS

The results obtained have already been used successfully as input data for consolidation modelling on the Helmsdorf tailings pond. Non-linear finite strain theory was applied in one-dimensional computer code. Spatial distribution of the total settlement values were illustrated using the software Earth Vision (see Fig. 8). The figure shows the areas, which have a total settlement of greater than 2 m beneath a final cover that would produce a loading of 100 kPa. Total settlement as well as time- dependent development of settlement must be taken into account when designing and planning the surface contour of the final cover for optimum remediation. The final cover must guarantee a stable surface runoff over the long-term. Based on these settlement calculation results, contouring will be optimized and the volume of cut and fill materials removed will be minimized. Therefore, results from the recently developed new Special Oedometer Test Apparatus KD 314 S will distinctly minimize remediation costs.

Special Oedometer Test KD 314 S can be used to measure the geotechnical compression or consolidation behaviour for all sorts of cohesive soils or tailings. In addition, the permeability of pulps and pulpy slimes can be measured reliably as a function of the void ratio of the "soil" or as a function of the solids content of the "pulp". This testing method is able to work at the boundary between soil and pulp material. The Special Oedometer Test KD 314 S is a very helpful tool for readily determining the geotechnical tailings properties required for designing, planning and operational control of recent and future mill tailings impoundments.

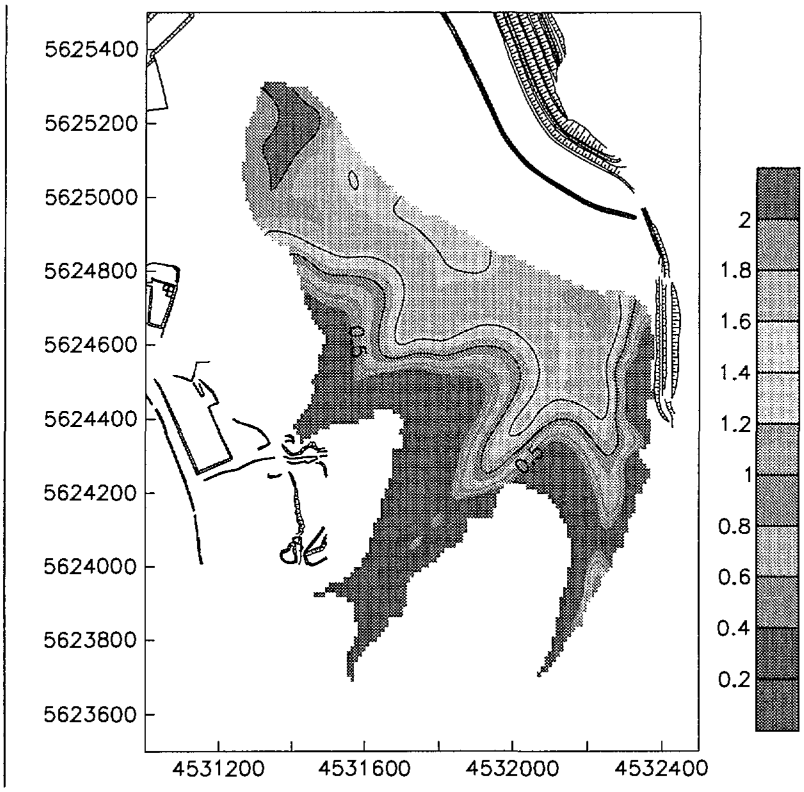


FIG. 8. Tailings Pond Helmsdorf: Spatial distribution of settlement portions under a cover load of 100 kPa in the fine tailings zone as derived from non-linear finite strain consolidation modeling.

REFERENCES

[1] MEHLHORN, T., Optimierung eines Großödometers, Westsächsische Hochschule Zwickau (FH), FB Maschinenbau und Fahrzeugtechnik (1999).

[2] GIBSON, R.E., SCHIFFMAN, R.L., CARGILL, K.W, The theory of one-dimensional consolidation of saturated clays, II. Finite non-linear consolidation of thick homogeneous layers, Canadian Geotechnical Journal, 18, (1981).

[3] SCHIFFMAN, R.L., PANE, V., GIBSON, R. E., The theory of one-dimensional consolidation of saturated clays, IV. An overview of non-linear finite strain sedimentation and consolidation, in YONG, R.N. & TOWNSEND, F.C. (editors): Sedimentation Consolidation Models – Prediction and Validation, American Society of Civil Engineers, New York (1984).