A case study on self-weight consolidation of uranium tailings

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ABSTRACT

The consolidation characteristics of fine tailings (slimes) in a large uranium tailings impoundment (158 ha) were studied to assist in the design of soil cover placement for final reclamation. The tailings impoundment is located in Eastern Thuringia, Germany. Between 1967 and 1991, a total of approximately $61*10^6$ m³ of tailings ($\sim 64*10^6$ t of solids) were discharged into a former open pit to a maximum depth of 72m. Frequent changes in the historic discharge pattern have resulted in a complex spatial distribution and thickness of the fine tailings. The process of filling and self-weight consolidation of the tailings was simulated for representative zones using the non-linear finite-strain consolidation model FSCONSOL. The consolidation model was calibrated with observed (current) profiles of void ratio and pore water pressure and observed rates of settlement (1994-97). The modeling analysis suggests that the current degree of consolidation is sensitive to the thickness of the slimes zone (not total tailings thickness). The greatest excess pore pressures are modeled for the central slimes zone with 50-60m of uniformly fine tailings. These modeling results are consistent with field measurements of in-situ pore pressures using CPTU tests and dedicated pore pressure gauges. The calibrated consolidation properties for the slimes also agreed well with those determined in the laboratory using a slurry consolidometer.

INTRODUCTION

The tailings impoundment Culmitzsch is a large uranium tailings impoundment (tailings area 234 ha) located east of the village of Seelingstädt in Eastern Thuringia, Germany. The impoundment Culmitzsch represents a former open pit complex, which was divided into two sub-basins and received uranium tailings from 1967 to 1991. Tailings from the acid leach were deposited in Basin Culmitzsch A covering a tailings area of 158 ha whereas tailings from the alkaline leach were deposited in Basin Culmitzsch B covering a tailings area of 76 ha.

Decommissioning of WISMUT's tailings impoundments is divided up into three fundamental work steps. These are
1. interim covering, to build up a stable working platform for further activities;
2. contouring to achieve a stable landform and long-term gravity drainage; and
3. final covering to control infiltration and seepage of contaminated pore water.

The interim cover will be placed by advancing from the coarser beach zones along the perimeter towards the central slimes, as the pond water is drawn down and the slimes become accessible. In order to place the interim cover (and subsequent layers for contouring) safely and economically, the consolidation behavior of the fine tailings has to be understood. This paper presents findings of a detailed study aimed at characterizing the consolidation properties of the fine tailings in the impoundment Culmitzsch A. The study consisted of field characterization, lab testing and in-situ monitoring. Independent estimates of the consolidation properties were obtained by simulating the filling and associated self-weight consolidation using finite-strain theory.

HISTORY OF TAILINGS DISCHARGE

Between 1967 and 1991 a total of approximately $64*10^6$ metric tons of tailings solids or approx. $61*10^6$ m³ of slurry were discharged into the impoundment Culmitzsch A. For the first 15 years of operation the tailings were discharged at a fairly constant slurry rate of about $5*10^6$ m^3/a (~$3*10^6$ t solids per year). After 1982 the discharge of tailings gradually declined until discharge ceased in 1991. The impoundment was also used in the past (and still is today) as a storage basin. Historic air photos were used to delineate regions with exposed beaches (sandy tailings) and ponded zones (slimes deposition) through time thus aiding in identifying zones of different geotechnical properties in this tailings impoundment.

The history of tailings discharge can be subdivided into three phases. In Phase 1 (late 1967 to 1972) tailings were discharged only into the deep portion of the open pit ("2nd Ore Horizon" at an elevation of about 270 m asl). Figure 1 illustrates the location of these early discharge points. In Phase 2 (1973 to 1978) the discharge points along the

southwestern perimeter of the deep basin were abandoned and tailings were discharged into the shallow basin ("1st Ore Horizon" at an elevation >310m m asl) by moving the discharge lines southward to the toe of the Southwestern Dump (SW-Halde) (Figure 1). The discharge points at the northeast corner and upstream of the South Dam and Southeast Dam were periodically raised during this phase to allow continued tailings discharge into the deep basin. In Phase 3 (1979 to 1991) the full perimeter of the tailings impoundment was used for tailings discharge. The frequent changes in the historic discharge pattern have resulted in a complex spatial distribution and thickness of the fine tailings.
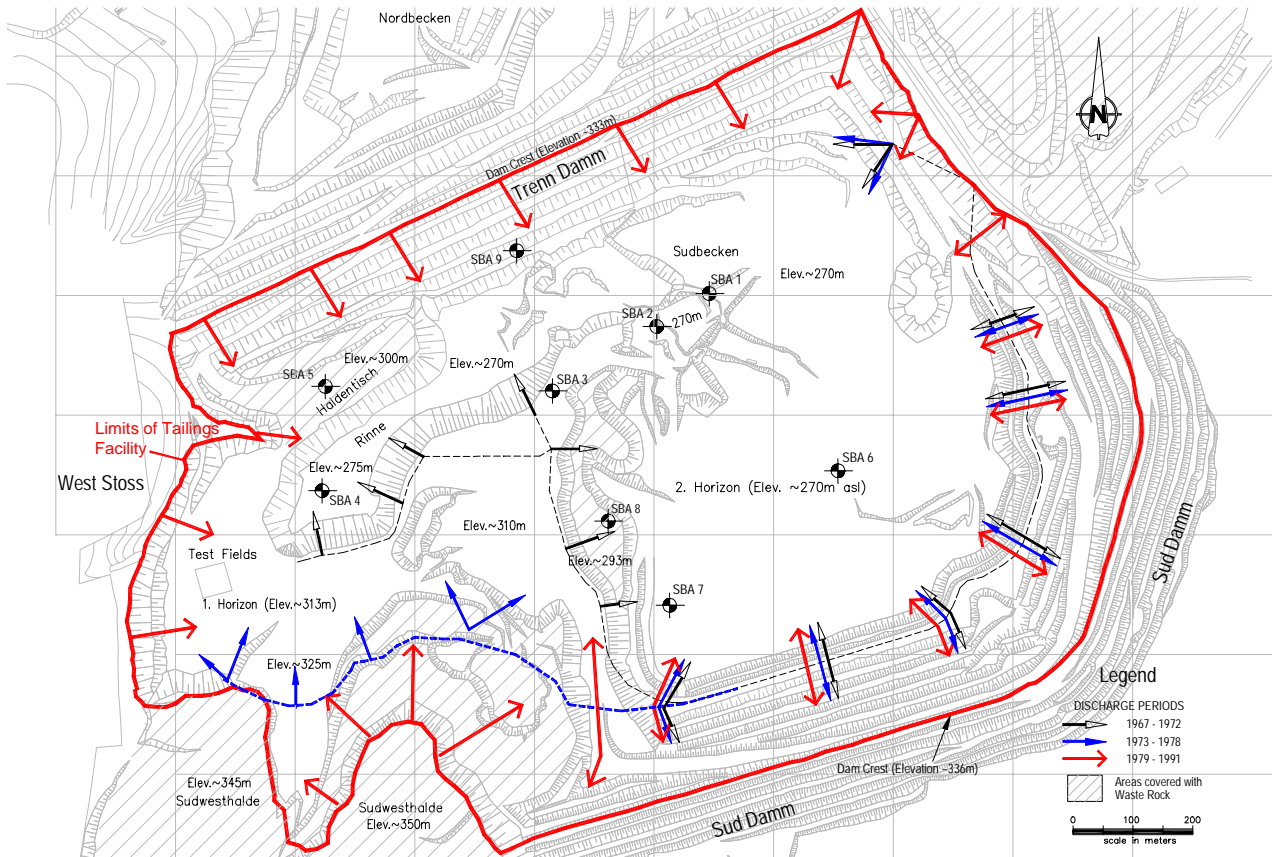

Figure 1 – Plan view of tailings impoundment Culmitzsch A. Historic changes in slurry discharge pattern were estimated from air photos.

GEOTECHNICAL CHARACTERIZATION OF SLIMES ZONE

Field Characterization Program

In 1996, a total of nine boreholes were drilled in the ponded zone of the IAA Culmitzsch A by Baugrund Dresden (1) using a floating platform (see Figure 1 for location). Undisturbed tailings samples were retrieved using liners, in 1m long core sections and submitted to the laboratory for further testing.

Figure 2 shows the void ratio profiles at the various borehole locations determined from the undisturbed samples. The three boreholes located in the center of the impoundment (SBA1, 2 & 3) show a general decrease of void ratio with depth as expected for a consolidating slimes column (Figure 2a). The void ratios in the middle portion of SBA6 and in particular in SBA5 tend to fall near or below the lower envelope curve of the slimes (Figure 2b). These boreholes are located more towards the edge of the central slimes zone and therefore have a more heterogeneous composition.

The void ratios in SBA4, 7, 8 and 9 are strongly influenced by changes in the historic tailings discharge pattern (Figure 2c). The deep portions of SBA4, 7 and 8 (below elevation ~307m NN) show low void ratios indicative of sandy tailings which were placed proximal to the discharge points during the first phase of discharge (see Figure 1). The high void ratios in the upper profile of SBA4 and SBA8 represent fine slimes settled in the water covered pond area distant from the discharge points.

In the fall/winter of 1996 pore pressure gauges were installed in the boreholes SBA2, 3, 4, 8 and 9 at several depths to monitor daily pore pressures (measurements still on-going). In 1999, three new pore pressure gauges were installed in vicinity of SBA2 to replace older gauges, which had been damaged as a result of ice movement during winter. In addition, CPTU measurements were carried out in 1999 at several transects across the pond zone. Pore pressure measurements show excess pore pressures in the deep fine slimes and lower boundary hydrostatic conditions. The upper approx. 15 m of these fine slimes show excess pore pressures of up to 50% of the consolidated self-weight under buoyancy at a given depth. Below 15 m depth, excess pore pressures of up to 25% of self-weight under buoyancy are observed. In shallow fine slimes zones underlain by permeable layers the hydraulic head (total pore pressure) typically decreases with depth by several meters suggesting downward movement of pore water (underdrainage). No significant excess pore pressures were measured in the intermediate zones (interlayered slimes and sands) suggesting good lateral drainage in this area.

Repeated (annual) surveys of the tailings surface elevation indicate that the fine tailings in the deep basin settle at a rate of about 0.2-0.5m per year whereas the fine tailings in the shallow basin settle at a rate of typically less than 0.2m/a. These results are consistent with the pore pressure measurements suggesting that the fine tailings are not yet fully consolidated.

In-situ shear vane testing results also corroborate with the other geotechnical findings. Within the deep fine slimes a depth-dependent undrained shear strength gain of <1.0 kPa/m was found in the upper part of the profile. In marginal fine slimes and transition zones and some shallow fine slime zones the undrained shear strength gain was typically > 1.7 kPa/m corresponding to lateral drainage/underdrainage conditions in these zones.
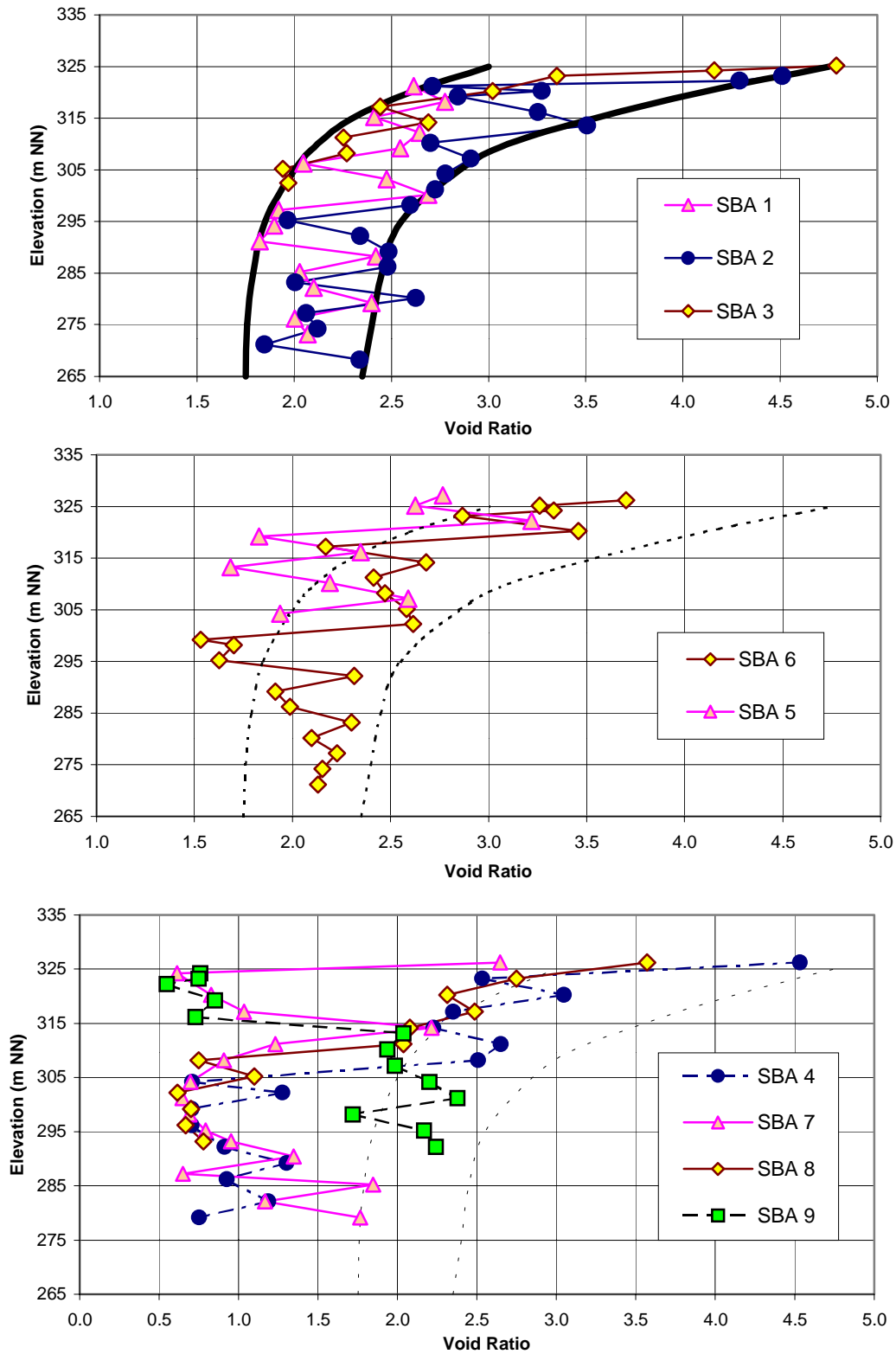
Figure 2 - Observed void ratio profiles at various boreholes.

Laboratory Testing

The undisturbed tailings samples retrieved from the drilling program were tested in the laboratory for various geotechnical properties, Baugrund Dresden (1). As a first approximation the tailings are classified into coarser tailings ("sandy variety") and finer, clay-rich tailings ("clayey variety"). The tailings from the clayey variety are classified as clays (DIN 4022) with about 50-60% clay-sized particles (Ø < 0.006mm). The tailings from the sandy variety are classified as silty sands (DIN 4022) with typically less than 20% silt-sized particles (Ø < 0.06mm). Table 1 shows average values and the observed ranges for several relevant geotechnical parameters for these two classes of tailings (after Baugrund Dresden (1)).

Table 1: Summary of geotechnical properties of Culmitzsch tailings (after Baugrund Dresden (1)).

Samples	Tailings Type	Description	G_s [-]	Bulk Density ρ [g/cm³]	Dry Density ρ_d [g/cm³]	Water Content w [1] [-]	Void Ratio e [-]	Atterberg Limits w_P [-]	w_L [-]	Plasticity Index I_P [-]	Total Shear Strength (Lab Torvane) τ_f [kN/m²]
SBA1 - SBA 9	clayey variety	Average	2.805	1.532	0.845	0.851	2.437	0.258	0.657	0.399	12
		Minimum	2.670	1.180	0.496	0.366	1.034	0.178	0.366	0.182	0
		Maximum	2.909	1.812	1.323	1.627	4.788	0.293	0.846	0.553	42
		N	113	111	111	111	111	107	103	103	307
	sandy variety	Average	2.693	1.899	1.527	0.248	0.774	0.181	0.354	0.167	20
		Minimum	2.554	1.778	1.265	0.176	0.549	0.169	0.316	0.138	8
		Maximum	2.766	2.097	1.774	0.405	1.186	0.196	0.391	0.195	35
		N	27	27	27	27	27	4	2	2	82

Samples	Tailings Type	Description	Compression Index[2] C_c [-]	Coefficient of Consolidation c_v [m²/s] σ=47kPa	σ=174kPa	Hydraulic Conductivity[3] K_f [m/s] i=0.5	i=5	Friction Angle ϕ' [degrees]	Cohesion c' [kN/m²]
SBA1 - SBA 9	clayey variety	Range	0.6..0.8	$2..7*10^{-7}$	$1..9*10^{-7}$	$2*10^{-9}..2*10^{-6}$	$8*10^{-9}..6*10^{-6}$	29..33	2
		Void Ratio	1.2..3.2	1.4..2.9	1.3..2.1	0.9..3.0	0.9..3.0	2.6..2.8	
		N	N/A	36	36	10	20	2	2
	sandy variety	Range	0.02..0.08	$3*10^{-7}..1*10^{-6}$	$3*10^{-7}..1*10^{-6}$	$9*10^{-7}..2*10^{-5}$	$1*10^{-5}..3*10^{-5}$	38..41	13..24
		Void Ratio	0.7..0.9	0.5..0.9	0.5..0.9	0.6..1.2	0.6..1.2	0.6..0.8	
		N	N/A	17	17	10	12	3	3

Notes:
1. Backcalculated from density measurement
2. Data analysis by Wismut
3. Based on standard permeameter tests

The summary table illustrates the large difference in material properties between the fine and coarse tailings. The clayey ("fine") tailings are highly plastic clays with very little shear strength. These tailings are highly compressible with in-situ void ratios ranging from about 1.5 to 4.8 in the uppermost part of the profile. The sandy ("coarse") tailings have a low, if any, plasticity and relatively high shear strengths. These tailings are much less compressible than the fine tailings with in-situ void ratios ranging from 0.5 to 1.1.

The hydraulic conductivity of the coarser tailings ("sandy variety") is in the order of $k_f = 10^{-5}$ to 10^{-6} m/s. The hydraulic conductivity of the fine tailings determined by Baugrund Dresden with a standard permeameter were considered unreliable (Table 1).

Table 2: Preliminary estimates of k_f-e-relationship based on measured special oedometer testing data on fine slimes.

Void ratio (e)	Permeability coefficient k_f (m/s)
4.0	approx. $4...7 * 10^{-7}$
3.0	approx. $3...5 * 10^{-8}$
2.0	approx. $2...4 * 10^{-9}$
1.5	approx. $3...6 * 10^{-10}$

In a follow-up project the hydraulic conductivity of the fine tailings ("clayey variety") was determined by Wismut using a specially designed slurry consolidometer (the so-called special fine slime oedometer KD 314 S). This apparatus allows the measurement of the time-dependent consolidation behaviour of the soft slimes (including the hydraulic conductivity as a function of void ratio). Table 2 shows the hydraulic conductivity (k_f) as a function of void ratio for a sample from the deep fine slimes zone as determined from the dissipation of pore pressures in the test cell.

Spatial Classification and Zoning

The results of the geotechnical investigations were used to subdivide the IAA Culmitzsch A into different tailings zones. These zones differ significantly with respect to tailings properties and their potential for future settlement due to cover placement. The spatial classification scheme adopted here accounts for both the horizontal and vertical zoning of the tailings deposit. The tailings impoundment was first divided into three classes, i.e. beach, intermediate (=transition) and slimes zone, according to the tailings characteristics in the upper profile (~ top 30m). Each class was then subdivided further into subclasses according to the tailings characteristics in the deeper tailings profile (appr. >30m). Table 3 summarizes the classification scheme and Figure 3 shows the spatial extent of the different zones.

The **Beach Zone (Class I)** forms a band along the perimeter of the impoundment along the various more recent discharge points. This zone is subdivided into four subclasses (Table 3). In general, access for cover placement and potential for settlement are not a concern for the beach zones (in many areas an interim cover has been placed already).

The **Intermediate Zone (Class II)** represents the transition zone from the peripheral beach zones to the centrally located slimes zone. This zone typically shows a

wide range of tailings characteristics depending on the relative proportion of silts and clays and presence of sand lenses at a given location. The transition zone is typically consolidated due to significant lateral drainage through permeable layers. All intermediate zones have some potential for future settlement due to self-weight consolidation and in particular cover placement.

The **Slimes Zone (Class III)** is located in the center of the tailings impoundment (see shaded area in Figure 3). The slimes zone is subdivided into four subclasses, which differ in their tailings characteristics at greater depth (Table 3). The shallow fine slimes zones (Zone III_I and III_S) which are underlain by permeable tailings and/or aquifer layers exhibit underdrainage. This has accelerated the consolidation process in the past and has resulted in a higher degree of consolidation today. The deep fine slimes zone (Zone III_D) with > 50 m slimes is underconsolidated due to poor drainage (hydrostatic conditions prevail). This deep slimes zone has the highest potential for future settlement.

Figure 3 – Spatial classification of tailings according to geotechnical properties.

Table 3 – Classification of Tailings into different geotechnical zones, Culmitzsch A.

Class	Beach Zone (I)				Intermediate Zone (II)			Slimes Zone (III)			
Subclass	Shallow Beach (I_S)	Deep Beach (I_D)	Ponded Beach (I_{II})	Beach Material over Slimes (I_{III})	Shallow Intermediate (II_S)	Deep Intermediate (II_D)	Intermediate over Beach (II_I)	Shallow Slimes (III_S)	Deep Slimes (III_D)	Slimes over Beach (III_I)	Slimes over Intermediate (III_{II})
Tailings Profile	coarse tailings (5-30m)	coarse tailings (>30m)	coarse & intermediate tailings (20-30m)	~10-30m coarse tails over slimes	intermediate tailings (20-30m)	intermediate tailings (>30m)	~30m intermed. tails over beach material	fine tailings (20-30m)	fine tailings (>30m)	~30m fines over beach material	~30m fines over intermediate tailings
Geotechnical Characteristics[1]	high K and s_u; fully consolidated; very low potential for settlement		variable K and high s_u; fully consolidated; low potential for settlement	highly variable K; high s_u throughout profile; potentially underconsolidated at depth; some potential for settlement	highly variable K; low s_u near surface but increasing with depth; underconsolidated near surface but fully consolidated at depth; some potential for settlement			very low K in slimes; s_u very low in top 2-6m; highly underconsolidated in upper slimes profile; degree of consolidation at depths dependent on drainage conditions; high to very high potential for settlement			
Location[2]	western perimeter SW Halde; Trenndamm	northeast corner; Southwest & South Dams	Southwest & South Dams	south of Trenndamm (e.g. SBA 9)	western sections (e.g. SBA 5)	east & southeast sections	southwestern perimeter of 2nd Horizon (e.g. SBA7)	central portions of 1st Horizon (e.g. SBA 3)	central portions of 2nd Horizon (e.g. SBA 2)	western extent of 2nd Horizon (e.g. SBA4)	central portions of 2nd Horizon

Notes:

1. K = permeability and s_u = undrained shear strength

2. For location of different zones see Figure 3

CONSOLIDATION MODELING

Simulation of Filling and Selfweight Consolidation

The process of filling and self-weight consolidation was simulated for representative locations of the slimes zone using the non-linear finite strain consolidation model FSCONSOL (2). The purpose of this modeling work was (i) to determine representative material functions (e-σ' and e-k_f relationships) for a given tailings type and (ii) to estimate the current degree of consolidation (for 1996).

The consolidation model requires the input of filling rate, slurry density (initial void ratio) and consolidation properties of the tailings (i.e. e$\rightarrow$ σ' and $k_f \rightarrow$ e functions). The rate of filling and initial dry densities of the tailings were estimated from the historic discharge records. Initial guesses for the non-linear material functions (e$\rightarrow$ σ' and $k_f \rightarrow$ e) were taken from the laboratory analyses. The consolidation model was then calibrated against observed void ratio profiles, measured rates of settlement (after filling was completed) and observed pore pressures (where available) using a trial-and-error approach. Sensitivity analyses indicated that the degree of consolidation of the tailings profile is much more sensitive to the non-linear material functions (e$\rightarrow$ σ' and $k_f \rightarrow$ e) than to details in the rate of filling and/or the choice of the initial void ratio. Hence the trial-and-error procedure to calibrate the consolidation model for a given location focused on varying the nonlinear material functions. The influence of the bottom drainage condition was assessed by way of sensitivity analysis (see RGC-Wismut (3) for more details).

A total of seven scenarios were simulated using this approach. The modeling results are summarized in Table 4. In the following we discuss the results for a uniform slimes profile in the deep and in the shallow basin (SBA2 and SBA3, respectively) and for a profile with interlayered coarser and finer tailings (SBA6).

Shallow Uniform Slimes Profile

SBA3 is located in Zone III$_S$ in the central (but shallow) slimes zone of the impoundment (Figure 3). The tailings at this location consist of slimes of the clayey variety only. The observed void ratio profile could be reproduced very well by assuming a compressibility typical of very fine slimes (Figure 4). The calibrated permeability function agreed well with laboratory estimates using the slurry consolidometer. The consolidation model suggests that this borehole is underconsolidated with excess pore pressures up to 32 kPa and an annual rate of settlement of about 0.3m per year.

Pore pressure data measured in the field (see above) indicate that the tailings are in hydraulic contact with the underlying sandstone aquifer. For modeling purposes it was assumed that the base of the impoundment is free-draining. In reality, the boundary condition at the base may have changed during filling. Hence a direct comparison of the

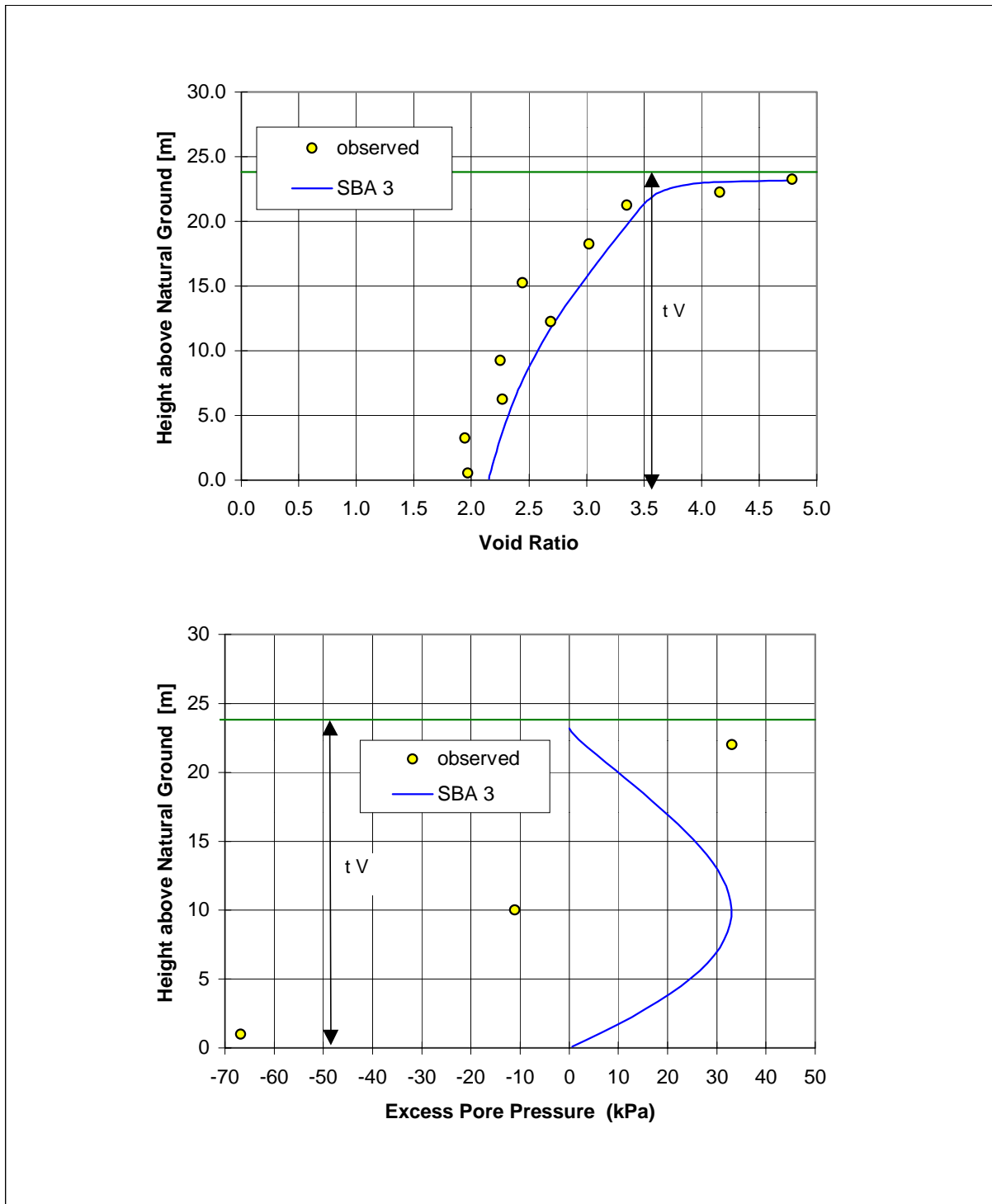simulated excess pore pressures with the observed total pore pressures was not possible at this location.

Figure 3 – Simulated void ratios and excess pore pressures for SBA-3.

Table 4 – Summary of Consolidation Modeling Results, Culmitzsch A.

| Tailingszone | Zone | Borehole | Tailingsthickness (m) (Dec 1996) | | annual rate of settlement[1] (1994-1997) | | maximum excess pore pressure simulated w/ FSCONSOL | |
			measured	simulated	measured	simulated	absolute (in kPa)	normalized[2]
Beach Material over Slimes	I_{III}	SBA 9 (Case A)	36	37.1	-0.13	-0.07	178	69%
		SBA 9 (Case B)		35.92		-0.09	83	40%
Intermediate over Beach	II_I	SBA 7	51	50.2	-0.08	-0.09	114	67%
Transition from shallow Intermediate to Slimes	II_S/III_S	SBA 5	28.4	28.92	0.25	-0.29	21	46%
Transition from deep Intermediate to Slimes	III_D/II_D	SBA 6	57	54.26	-0.45	-0.45	73	52%
Deep Slimes Zone	III_D	SBA 2 (Case A)	56	53.6	-0.23	-0.55	102	64%
		SBA 2 (Case B)		53.9		-0.35	61	31%
Shallow Slimes Zone	III_S	SBA 3	23.8	23.2	-0.09	-0.28	33	83%
Slimes over Beach Material	III_I	SBA 4 (Case A)	52.4 (total)	50	-0.22	-0.13	7	5%
		SBA 4 (Case B)	25.4 (slimes only)	21.2		-0.09	0	-111%

Note:
1. Negative values indicatesettlement; positive values indicate rise in tailings surface
2. Relative to hydrostatic pressure

Deep Uniform Slimes Profile

SBA2 is located in Zone III_D in the center of the slimes zone of the impoundment (Figure 3). This borehole was simulated assuming a uniform column of slimes of the clayey variety. This deep slimes profile was modeled with two different sets of material functions for the clayey variety (Cases A & B) to illustrate the sensitivity of the modeling results to the choice of material input functions.

In Case A, the material functions determined from oedometer results were used to simulate the filling and selfweight consolidation. The simulated void ratio profile agrees fairly well with that observed in the field (Figure 5). This set of material functions results in a high degree of underconsolidation with excess pore pressures up to ~100 kPa and a simulated annual rate of settlement of about 0.55 m per year.

In Case B, a significantly higher compression curve (higher C_c and e(1kPa)) and an overall lower permeability was assumed for the slimes. The simulated void ratio profile for this case also fits the observed void ratio fairly well (Figure 4). However, the simulated tailings profile for this Case B is significantly more consolidated than Case A

with excess pore pressures only up to 60 kPa and an annual rate of settlement of only 0.35 m per year.
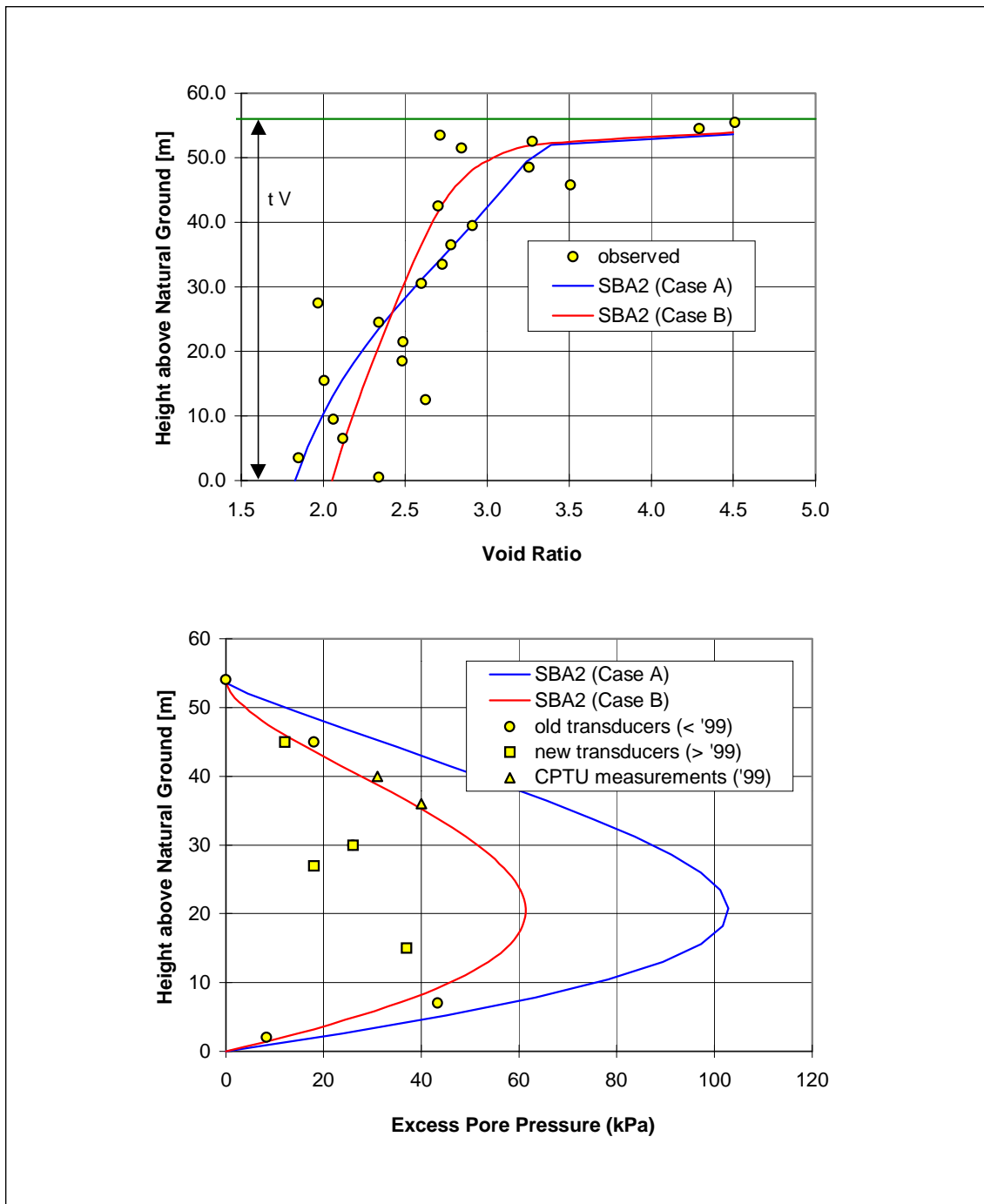

Figure 4 – Simulated void ratios and excess pore pressures for SBA-2.

The measured rate of settlement from 1994 to 1997 would suggest that Case B better reflects the current degree of consolidation (Table 4). However, the accuracy of these field measurements of settlement is not known and may not be sufficient to distinguish between Case A and Case B.
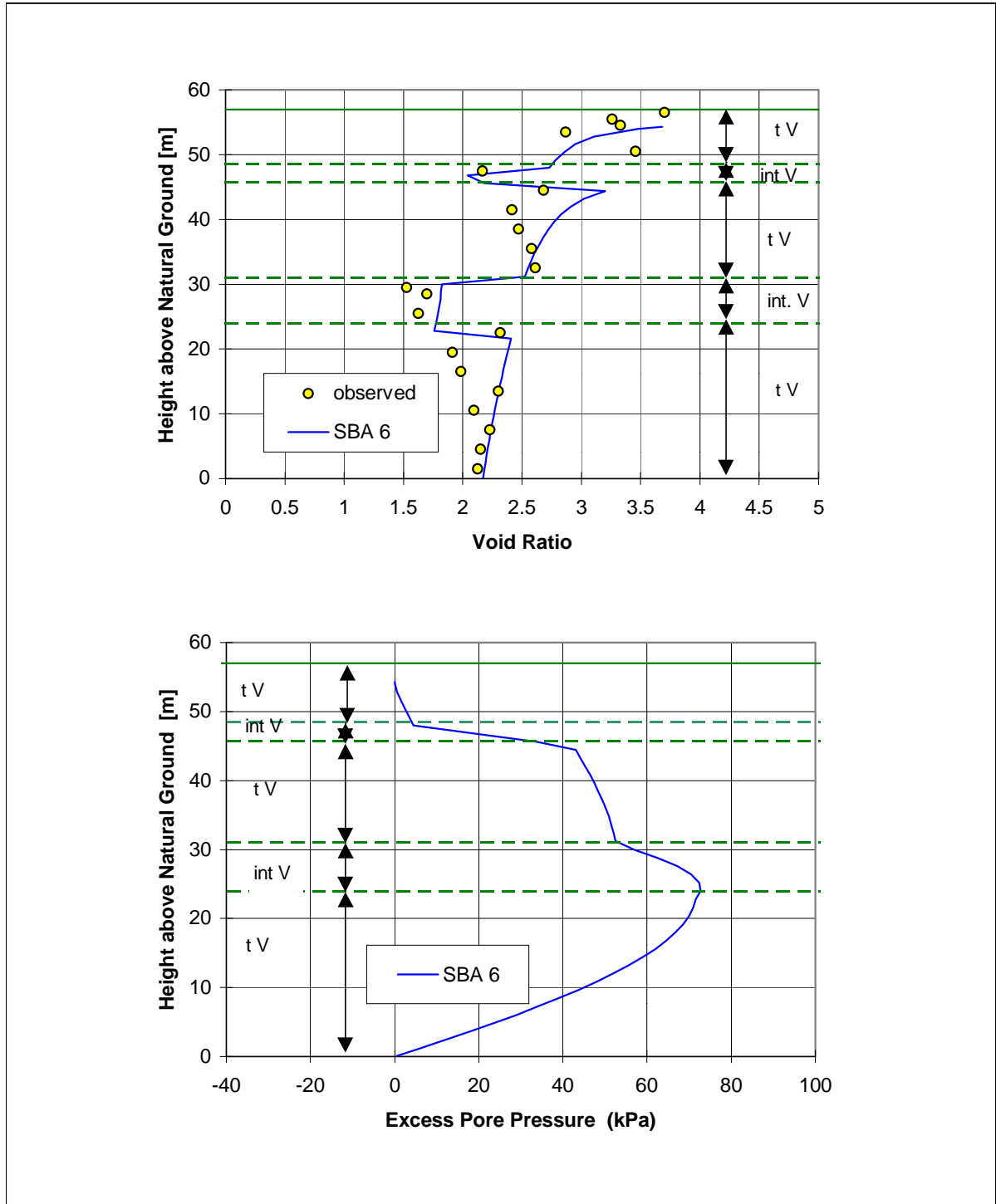

Figure 6 – Simulated void ratios and excess pore pressures for SBA-6.

At the time of modeling no sufficiently reliable pore pressure measurements had been available to determine whether Case A or Case B was more appropriate. However, more recent pore pressure measurements in vicinity of SBA2 (carried out in 1999) suggests that Case B is the more realistic scenario. This analysis demonstrates that the degree of consolidation can not be accurately determined without detailed measurements of in-situ excess pore pressures. Preliminary fine slime compression test results using the new special fine slime oedometer KD 314 S also support the Case B-assumption.

Deep Layered Profile of Finer & Coarser Slimes

SBA6 is located at the transition of Zone II_D and Zone III_D in the southeastern (deep) region of the impoundment (Figure 3). The observed void ratio profile indicates that the tailings in this borehole consist predominantly of slimes of the clayey variety with some interlayering of the intermediate variety (Figure 6). For modeling purposes the tailings deposit was subdivided into two layers of intermediate variety and three layers of clayey variety. The calibrated model fits the observed void ratio profile fairly well (Figure 6).

The calibrated model suggests that the tailings are significantly underconsolidated with excess pore pressures up to 73 kPa and a present rate of settlement of 0.45m per year (Table 4). There are no pore pressure measurements available to confirm these modeling results. However, the fact that observed rates of tailings settlement agree with those simulated suggests that the calibrated model predicts the excess pore pressures reasonably well.

Simulation of Test Fill

Wismut has performed field trials on two test fields in the shallow intermediate zone (Zone II_S) located in the western portion of the IAA Culmitzsch A (Figure 1) in order to evaluate the influence of vertical drains on tailings consolidation (Wismut GmbH (4,5)). These field trials were simulated to provide an independent calibration of the consolidation characteristics based on surcharge loading (rather than based on selfweight consolidation discussed in the previous section).

The field trials were designed to test the effect of different geometries of shallow vertical drains on tailings settlement and shear strength gain. In test field 1, vertical drains were placed at a horizontal spacing of 1.5m and to a depth of 5m. In test field 2, vertical drains were placed at a horizontal spacing of 1.1m to a depth of 2.5m. Both test fields (25mx25m) were then covered with a 1m thick interim cover consisting of waste rock The vertical drains result in horizontal (radial) drainage of pore water towards the drain in the those upper tailings layers penetrated by the drains. At greater depth the pore water movement is predominantly vertical.

The consolidation in the presence of vertical drains was modeled using CONSOL-2D, which was developed by Wismut GmbH to simulate three-dimensional

flow with radial symmetry and two-dimensional strain (deformation). The principles of the numerical algorithm and its capabilities are described in Reichel (6), Wismut (7) and Haase et al. (8), respectively. This model is suited to simulate the consolidation of one or several tailings layers with fully or partially penetrating vertical drains. The depth profile of the material properties is approximated by piecewise linear interpolation.

Based on the vertical drain configurations, test fields 1 and 2 were simulated assuming an effective radius of 0.8m and 0.6m and a drain depth of 5m and 2.5m, respectively. The total tailings depth was assumed to be 22m and 24m, respectively, as inferred from the isopach map of the tailings. The material parameters for the simulation were determined by samples from some boreholes near the test field (DH1 and DH 2) and the void ratios were varied in several simulation runs to bracket the observed void ratios observed at some distance from the test field.
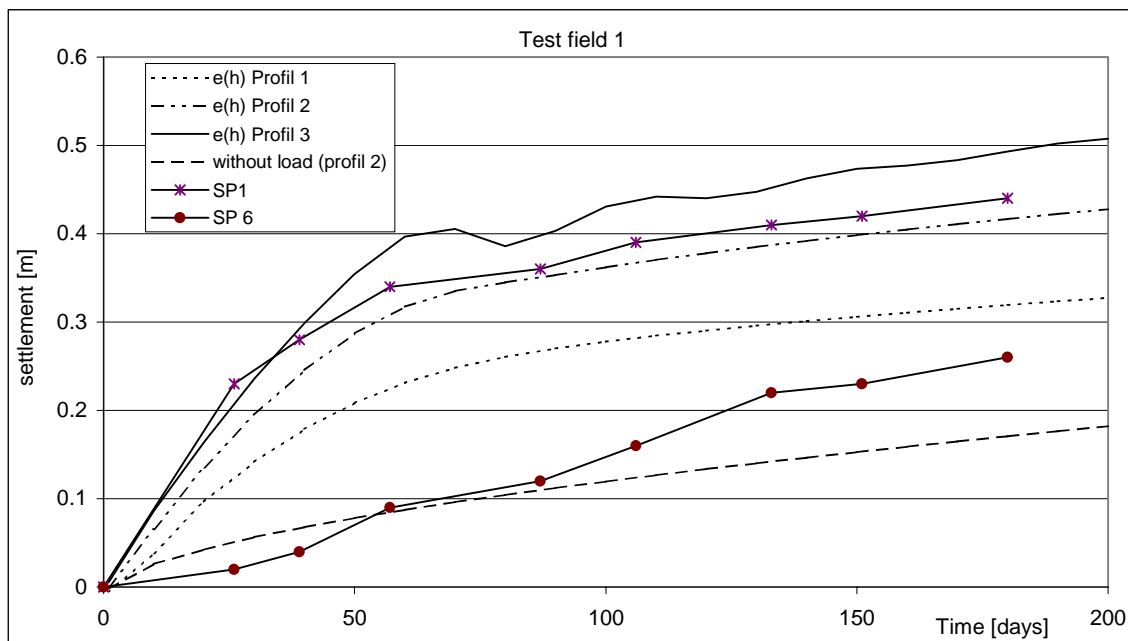

Figure 7 – Measured and simulated consolidation in test field 1 (SP 1 - measured settlement under load, SP 6 – measured settlements without load).

Figure 7 shows the results of three different simulation runs for the first 200 days compared with the measured data in test field 1. Using the two parameter sets from the bore holes DH 1 and DH 2 good agreement was obtained between measured and modeled settlement rates under load (SP 1) in test field 1. The modeled values for the settlement without load are also in good agreement with measured values (SP 6).The model simulations indicate that the early settlement (say initial 75 days) is largely due to settlement in the upper tailings layers where vertical drains are placed (top 5m). After this initial settlement period the two simulated settlement curves become nearly parallel suggesting that most of this on-going settlement is occurring within the deeper tailings

profile where no drains are present. The observed trends in settlement clearly confirm these simulated trends.

The measured settlement rates on test field 2 (under load) are similar to those observed in test field 1 (Figure 8) although the vertical drain geometry used in test field 2 (narrower spacing but shallower depth) should have resulted in significantly less settlement over the monitoring period then observed (see model prediction). At the same time, the settlement rate in those areas of the test field 2 which were not exposed to loading (i.e. at SP 7) are comparable to those in test field 1 and corroborate with the model predictions. Variability in the material properties across the test field may account for these discrepancies between theory and observation.
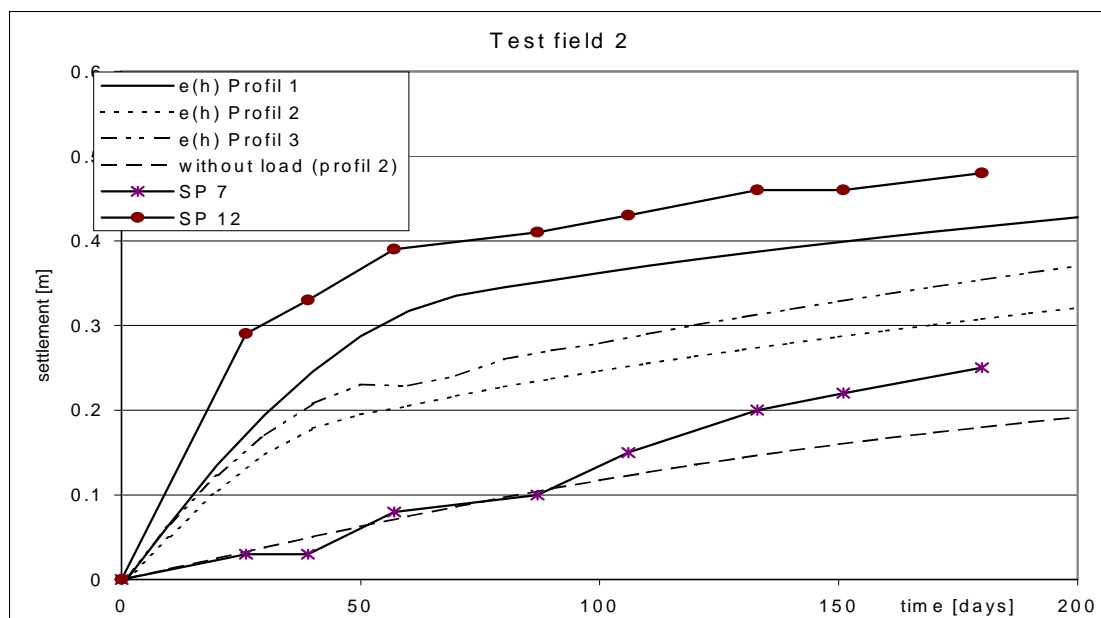

Figure 8 - Measured and simulated consolidation in test field 2 (SP 12 - measured settlement under load, SP 7 – measured settlement without load).

CONCLUSIONS

A detailed study consisting of field and laboratory measurements as well as consolidation modeling was carried out to characterize the consolidation properties of the fine tailings in the impoundment Culmitzsch A. The degree of consolidation in the impoundment was found to vary significantly as a result of segregation of the fine tailings as well as historic changes in the slurry discharge pattern. The greatest excess pore pressures are modeled for the central slimes zone with 50-60m of uniformly fine tailings. These modeling results are consistent with field measurements of in-situ pore pressures using CPT and dedicated pore pressure gauges. The calibrated consolidation properties for the slimes also agreed

well with those determined in the laboratory using a slurry consolidometer. It is planned to use the calibrated consolidation model to estimate the time rate of consolidation and total amount of settlement in response to placing an interim cover on various zones of the tailings impoundment.

ACKNOWLEDGEMENTS

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