

Geomechanical Fine Tailings Characterization and 1-D-Consolidation Modeling of Slime Zones at WISMUT Tailings Impoundments

Dipl.-Geol. Ulf Barnekow; *WISMUT GmbH, Chemnitz, Germany*

Dipl.-Phys. Dr. Matthias Haase, *WISMUT GmbH, Chemnitz, Germany*

M.Sc. Geol. Christoph Wels, Ph.D; *Robertson GeoConsultants, Vancouver, Canada*

Contents

1 Introduction.....	2
2 Aims of Consolidation Analysis.....	3
3 Consolidation Analysis on Fine Slime Zones of TP Culmitzsch A.....	4
3.1 Research of Site Specific Conditions: Construction, Milling and Discharge History....	4
3.2 Field Investigations on the Fine Slime Zone	4
3.3 Soil Physical Tailings Properties and Tailings Mineralogical Content.....	4
3.4 Lab Investigations on Consolidation Behaviour of Fine Tailings.....	5
3.5 Zoning of TP Culmitzsch A.....	6
3.6 Consolidation Modeling using FS-CONSOL (1D)	7
3.7 Conclusions	9

Abstract

In the context of decommissioning the Culmitzsch tailings impoundment the consolidation behaviour of the transition and fine tailings zones of the basin Culmitzsch A has to be evaluated. This paper presents consolidation analyses on this tailings pond (Basin A). It focuses on the one-dimensional consolidation analysis of fine tailings in the slime zone based on a detailed evaluation of the filling history and the geomechanical characterization of the fine slime zone. The self-weight-consolidation during and after filling has been modeled using the one-dimensional nonlinear finite strain code FS-CONSOL. The consolidation modeling of time-dependent future settlement due to capping and contouring is currently in progress. Based on the geotechnical evaluation of the tailings properties the consolidation modeling was done.

The modeling results allow the characterization of in situ tailings properties and in situ consolidation behaviour of the fine slimes. The current consolidation state of the fine slime zone are successfully characterized. A second CPT-campaign with dissipation testing is already under way to check and improve modeling results as well as to enhance knowledge about the in situ consolidation state of the fine slime tailings. Based on this the modeling provides a basis for reliably predicting future settlement due to capping and contouring. The FS-Consol code was quite stable running and had a simple handling. The code is a feasible tool to successfully characterize the consolidation process of fine tailings.

1 Introduction

This report presents an example of the geotechnical characterization and modeling work on consolidation problems of fine slime zones at the WISMUT tailings impoundments. In the context of decommissioning the tailings impoundments the consolidation behaviour of the fine tailings (slime) zones has to be evaluated. The uranium tailings impoundments at Wismut typically comprise fine tailings (slimes) zones of significant thickness. In those areas with homogeneous fines of great thickness large rates of settlement are being observed. Depending on the rate of filling and the drainage conditions large amounts of primary self-weight consolidation may already take place during the filling period, especially within fine tailings near to transition zones or beach zones.

In practice contouring the differential settlement of neighbouring tailings zones bearing different tailings materials with regard to surface runoff is the main problem of designing the final shape of the tailings impoundment. This is of critical importance in designing a stable final surface contour of the covered and decommissioned tailings impoundment, to minimize the over-all costs of remediation and to guarantee sufficient stability of the whole impoundment in the long-term. Here we present consolidation analyses on the tailings pond (TP) Culmitsch, Basin A. This paper focuses on the one-dimensional consolidation analysis of fine tailings in the slime zone based on a detailed evaluation of the filling history and the geomechanical characterization of the fine slime zone. The self-weight-consolidation during and after filling has been modeled using the one-dimensional nonlinear finite strain code FS-CONSOL. The consolidation modeling of time-dependent future settlement due to capping and contouring is currently in progress. Similar consolidation analyses have also been done for TP Helmsdorf in the past using the nonlinear finite strain code ACCUMV.

This report presents the characterization and design work progressing on a logical path from geomechanical data evaluation to consolidation analysis. The steps of this logical path are (in sequence):

1. Research of construction, milling and discharge history incl. site specific conditions (geology, hydrogeology, hydrology, geomorphology of the TP and the surrounding area)
2. Field investigations: measurements, tests, drilling and sampling
3. Lab investigations on soil physical properties incl. mineralogy/geochemistry
4. Lab investigations on consolidation behaviour (if possible also field trials)
5. Zoning of the tailings pond based on the results of steps 1. to 4. due to consolidation modeling
6. Consolidation modeling for each of the identified distinct slime zone areas applying the local geotechnical conditions.

Fig.1 shows the Culmitsch A tailings impoundment site in 1991. See the free tailings surfaces of the sandy beach zones located in the proximal area next to the former discharge points. There was also discharge against the South Dam and South East Dam as shown on fig. 1 (see next page).

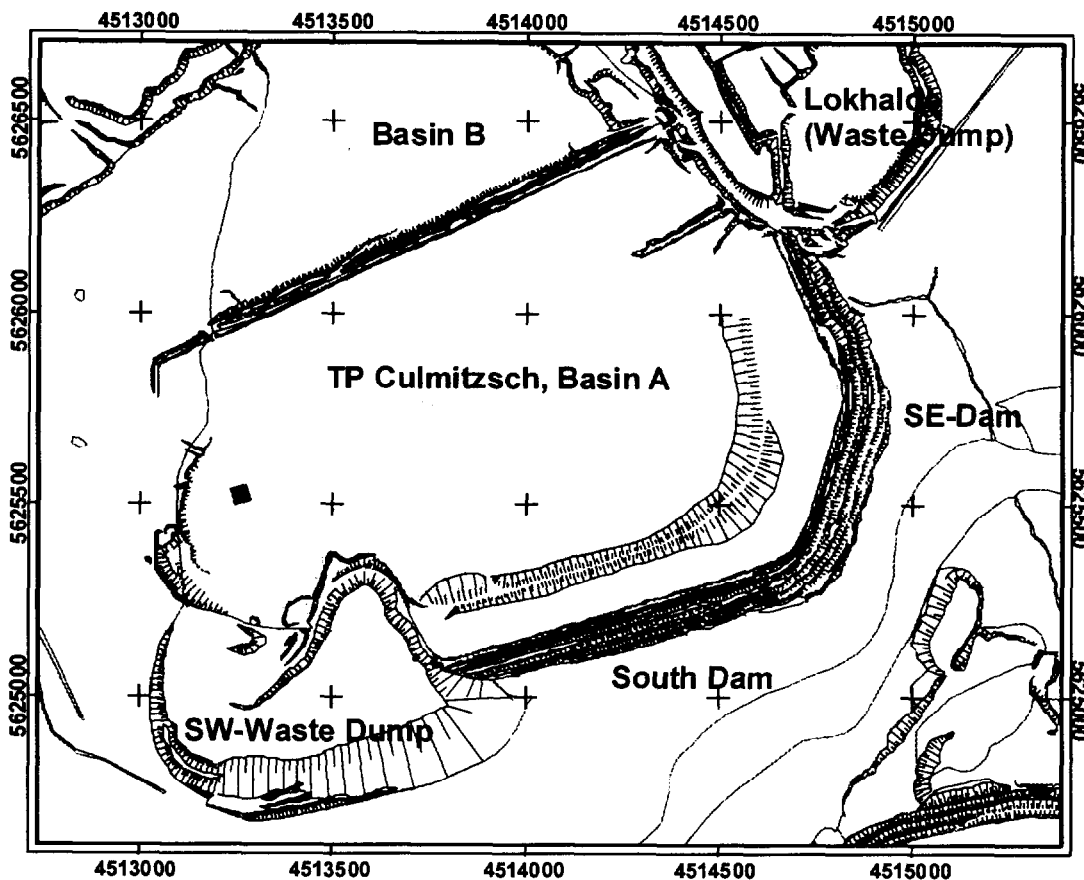
2 Aims of Consolidation Analysis

The consolidation analysis aims at determining the consolidation process in the slime zone during the remediation phase and the spatial distribution of settlement in the slimes zone of the TP in the long-term.

The results of the consolidation and settlement analyses are used to evaluate the stability of fine tailings surface contour, i.e. to ensure that continuous free surface runoff on the contoured shape is provided during and post remediation. Settlement rates of the fine tailings have to be distinguished between primary and secondary (long-term) consolidation portions. Essential criteria for both stabilisation of tailings due to covering and ensuring long-term stability due to decommissioning are:

1. absolute magnitude of settlement in order to design a final surface contour plan
2. time dependent consolidation rates to ensure a successful stabilisation progress
3. magnitude of secondary settlement to ensure long-term stability of the shape and of the final cover.

Fig. 1: Culmitzsch tailings impoundment site



3 Consolidation Analysis on Fine Slime Zones of TP Culmitsch A

3.1 *Research of Site Specific Conditions: Construction, Milling and Discharge History*

The uranium tailings of the tailings pond were discharged into the former open pit Culmitsch from 1967 until 1991. The over-all Culmitsch tailings impoundment (total impoundment area: 234 ha) was divided up into two basins due to the separated discharge of acid and alkaline mill tailings. The Culmitsch A basin contains 62.5 million m³ tailings from the acid milling process. The total area of basin A is 158 ha; maximum tailings thickness is 72 m. The main part of the total tailings volume had been discharged from discharge points in a certain distance from the crest of the south dam using the centreline method. This created proximal to the south dam a wide sandy beach zone and a fine slime zone of round about 60 ha in the distal area. During filling of the former open pit the self-weight-consolidation and dewatering of the tailings were progressively controlled by the open pit surface contour and the drainage conditions within the underlying and surrounding rock. According to two different mined ore horizons the pit is filled with up to 57 m of homogeneous fine slimes in the eastern fine slime zone and 25 to 30 m of fine slimes in the western pit area. The slime zone is still nearly covered by pond water. The beach zones and some transition zone areas are already interim covered with earthen waste rock material. With respect to consolidation analysis lateral drainage of tailings pore water is of critical importance in the beach zones, transition zones and some parts of the marginal fine slime zone. In the western area drainage is dominated by sandy tailings at greater depth and the permeable Culmitsch sandstone aquifer underlying fine tailings. Since the end of discharge in 1991 the beach zone has been progressively dewatered.

3.2 *Field Investigations on the Fine Slime Zone*

The fine slime is nearly fully covered by pond water. Therefore in situ investigations and measurements had to be carried out from the water table using a pontoon or a boat. The data of field and laboratory investigations were used as input data for geotechnical calculations on consolidation problems. The following investigations were carried out:

- Drillings with liner sampling through the whole tailings thickness into the foundation
- slime sampling using special slime corer
- cone penetrometer testing with dynamic pore pressure measurements
- in situ torvane testing
- geophysical borehole logging and geophysical surveys
- installation of in situ pore pressure gauges

3.3 *Soil Physical Tailings Properties and Tailings Mineralogical Content*

The WISMUT fine tailings can usually be handled like natural soils applying conventional soil mechanics and foundation engineering. Hence conventional soil physical properties are used to describe soil physical tailings properties.

Lab investigations on soil physical properties of fine slime tailings led to the following results: The fine slimes of the inner pond are clayey silts of high plasticity. Some soil samples of higher clay content can be described as clays of high plasticity. The clay fraction ($< 2 \mu\text{m}$) varies from 7 weight% up to 25 weight%. In-situ void ratio ranges from $e = 2$ in deeper tailings layers up to $e \geq 4.5$ near the tailings surface. Consistency measured according to CASAGRANDE's definitions is always liquid. Nevertheless the observed consistency in the field often seems to be quite higher. In-situ water content ranges from $w = 50$ weight% up to 160 weight% while the liquid limit is typically ranges from $LL = 60\%$ to 70% .

The main mineralogical components of the fine tailings are muscovite/illite and quartz with $\approx 33\%$ of the total each; further more dolomite ($\approx 9\%$), calcite ($\approx 7\%$), chlorite ($\approx 6\%$) and some gypsum, pyrite, caolinite and feldspar. With respect to geomechanical consolidation behaviour there are no relevant gas developing components within the fine tailings. Swelling clay minerals like i.e. mixed layer clays have not been found in significant amounts. Small amounts of brucite have only been found next to the discharge point of the water treatment plant which is still operating.

Based on all the soil physical property results and according to oedometer testing results presented below one can distinguish three fundamental tailings varieties within TP Culmitzsch A. These are sandy tailings, intermediate fine tailings and fine tailings. The sandy tailings belong to the beach zones. Some layers are observed within the transition zone. The intermediate fine tailings are located in the transition and the marginal fine slime zone. They possess low permeability but they are less compressible than the fine tailings of the inner fine slime zone. The fine tailings variety belongs to the inner fine slime zone and is also observed in the transition zone. Basic geotechnical parameters are presented in tab. 1 below:

Tab. 1: Soil physical properties of fine tailings

	TP Culmitzsch A			Intermediate Fine Tailings	Fine Slime Tailings
	Soil Physical Property	Parameter	Unit	typical value ranges	typical value ranges
Densities/Gravities	wet density	ρ_n	[g/cm ³]	1.50 ... 1.70	1.18 ... 1.70
	specific gravity	ρ_s	[g/cm ³]	2.81	2.81
Soil Classification	Grain Size Class	DIN 4022	-	Silt, clayey	Silt; clayey
	Soil Group (see fig. 1)	DIN 18 196	-	Silt or Clay, moderate or high plasticity	Silt soil or Clay soil of high plasticity
Water content, consistency	water content	w_n	%	55 ... 85	65 ... > 160 (dried crust: ≈ 50)
	liquid limit	w_L	%	50 ... 60	60 ... 70
	plasticity limit	w_p	%	22 ... 30	22 ... 30
	plasticity index	I_p	%	28 ... 35	35 ... 45
	consistency index (calculated value)	I_c	-	< 0	< 0
	void ratio	e	-	1.5 ... 2.4	2 ... 4.5
	compression index	C_c		0.40 ... 0.55	0.60 ... 0.87
	consolidation coeff.	C_v	m ² /s	5 [*] E-7 ... 2 [*] E-6	1 ... 9 [*] E-7
Permeability	(vertical) permeability	k_f	[m/s]	3 [*] E-8 ... 1 [*] E-9	1 [*] E-7 ... 1 [*] E-9

3.4 Lab Investigations on Consolidation Behaviour of Fine Tailings

The first fundamental geotechnical parameter relationship to describe the consolidation behaviour of a fine grained soil is the effective stress-void ratio relationship. It describes the compressibility of a soil. The amount of settlement of stiffer soils due to a certain load can quite simply be measured in an oedometer (compression test). Very compressible fine tailings of high void ratio should be investigated in special oedometers or using field tests. Such special oedometer testing is just being developed at Wismut. Prior to that a big number of standard compression testings were carried out on „undisturbed“ liner samples that had been obtained from the drilling project. The results of the compression curves gained from the oedometer testing for TP Culmitzsch A are considered to be of good accuracy. The oedometer results for the void ratio - effective stress relationship are presented in tab. 2 below. The few oedometer testings on samples of very high void ratio and compressibility led to inaccurate results. Therefore compression indices of $C_c > 0.82$ weren't determined in the lab but recalculated by the modeling of the filling history.

Tab. 2: oedometer testing data on compression behaviour of tailings

tailings variety	compression index C_c	void ratio $e(1kpa)$
fine tailings	0.60 - 0.82	3.0 - 4.2
intermediate fine tailings	0.40 - 0.55	2.4 - 2.9
(sandy tailings)*	(0.02 - 0.08)*	(0.6 - 1.2)*

**) sandy tailings data only used if sandy interlayering had to be mentioned*

The permeability-void ratio relationship determines the dewatering velocity under a given load and therefore the time dependent consolidation behaviour. It is the second fundamental geotechnical parameter relationship describing consolidation behaviour of fine tailings. From the deflection curve of the time-settlement function of the oedometer test one can only estimate the vertical permeability. In practice one has to mention the field conditions and the hydraulic regime of the tailings pond. Lateral drainage may prevail the dewatering regime in some areas of the fine slime zone. Because of these facts the permeability-void ratio relationship determined in the lab is considered to be of lower accuracy. It was used as a first roughly estimated input function for the first loop of the modeling with FS-Consol. The permeability - void ratio curve is further discussed in chpt. 3.6.

3.5 Zoning of TP Culmitzsch A

The whole TP Culmitzsch A was divided up into geotechnical zones. At first the three main zones were identified. These are the beach zone with sandy tailings, the transition zone with interlayering of sandy and cohesive tailings and the fine slime zone, built up by thick fine slime tailings.

Afterwards these three zones were subdivided into several geotechnical homogeneous zones. These homogeneous zones are characterized by homogeneous geotechnical boundary conditions. The pond drilling project that had been carried out before was designed to cover most of these different geotechnical conditions that prevail the local consolidation behaviour. The most meaningful geotechnical conditions that determine the time-dependent consolidation process are the drainage conditions and the permeability of the different tailings layers.

The fine slime zone was divided up into seven local subzones that are determined by four different cases of drainage thus anticipated consolidation behaviour. Each of these four different cases was described separately by a typical borehole profile including all the geotechnical field and lab data for the different tailings layers in this borehole profile. Furthermore the discharge history of each of these cases was evaluated separately. This evaluation led to the following results:

The eastern fine slime zone consists of a wide area of about 56 m of homogeneous fine slime tailings without interlayering and without underdrainage conditions. The western fine slime area consists of 25 ... 30 m of fine slimes with a certain underdrainage into the underlying sandy tailings layers or into the Culmitsch sandstone by now. The consolidation process of the transition zone and the beach zone was dominated by lateral drainage through the permeable layers. These zones are likely fully consolidated by now. The fine slime zones, especially the eastern area of thick fine slimes may still be underconsolidated today. Annually measured settlements of the tailings surface show settlement rates from 0.2 to 0.5 m/year in the area of the deepest tailings surface in the eastern pond area still covered by water. In the western area the settlement rates vary from 0 to 0.2 m /year.

3.6 Consolidation Modeling using FS-CONSOL (1D)

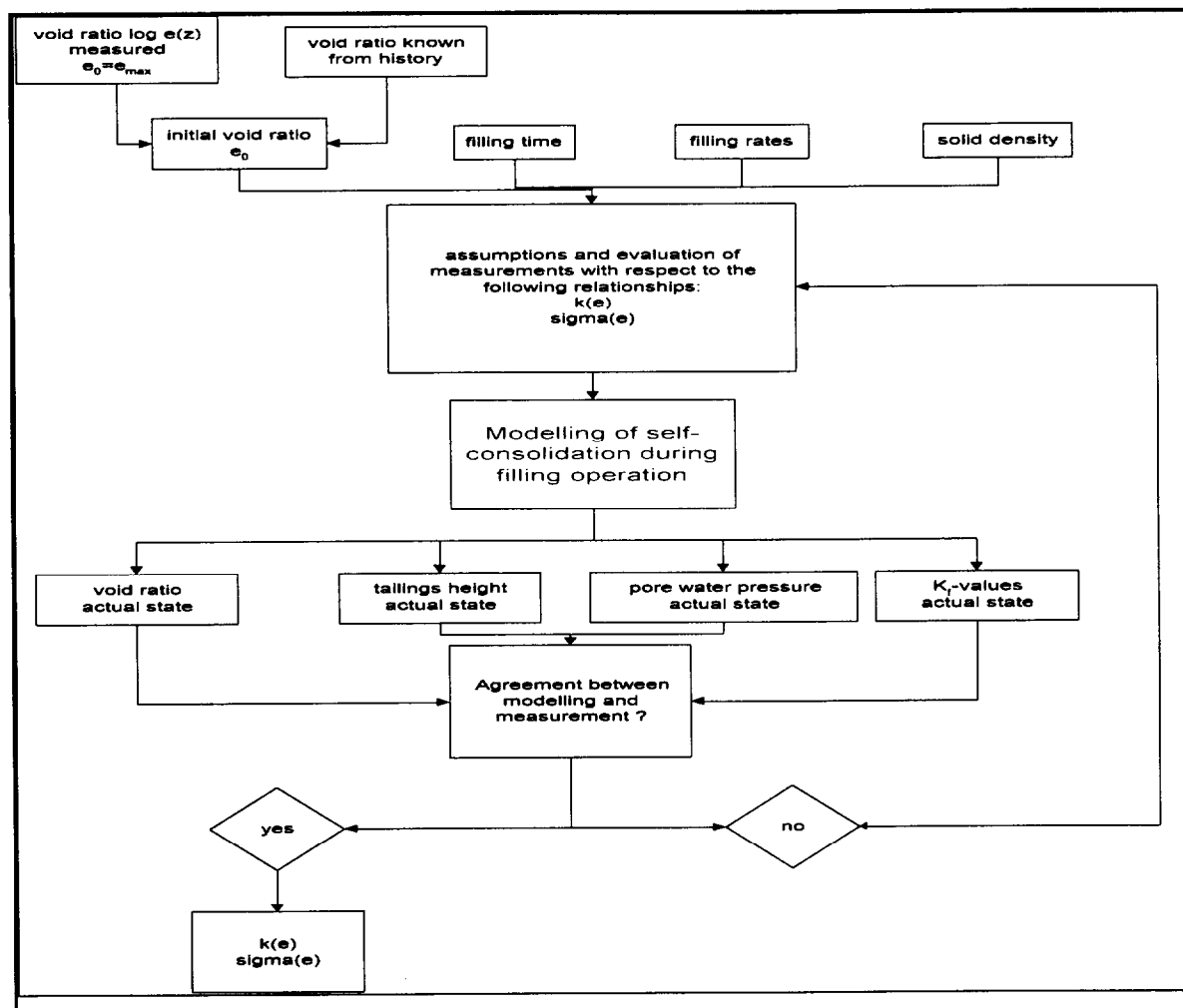
The first step of the consolidation modeling is the evaluation of the current consolidation state of the fine tailings within the tailings pond. These data are the input conditions for predictive modeling of the consolidation due to surcharge loading (i.e. cover placement). Modeling results show the necessity of accurate knowledge of the actual consolidation state to optimize future remediation progress. For example the design of the future final shape is fundamentally controlled by the need of fill materials.

Nonlinear finite large strain codes, like i.e. ACCUMV or FS-CONSOL have to be preferred to model accurately the time-dependent consolidation process, especially if the tailings body is built up by thick, homogeneous layers of highly compressible fine slime tailings. In addition the results of modeling provide estimates on the time dependent volumes of pore water being expelled out of the fine tailings during the various load placement stages. The commercially available consolidation code FS-Consol was chosen because of its ability to model layered tailings profiles with variable drainage conditions. The simulation of the filling period with the above mentioned geotechnical laboratory data gives a good indication for the in situ permeability conditions. The accuracy of these simulations of filling and self weight consolidation depends on the given geotechnical input data and the accuracy of the time-dependent filling progress.

Note that FSCONSOL is a one-dimensional model hence can simulate only vertical drainage. Vertical drainage is likely predominant in the deep central slimes zone. However, lateral drainage is likely important in the transition zone and the marginal areas of the fine slimes zone. Future modeling due to surcharge loading and covering will be done using a new 2D-nonlinear finite strain model to evaluate the effectiveness of vertical wick drains accurately.

Fig. 2 presents the scheme of modeling and calibration with geotechnical parameters:

Fig. 2: scheme of modeling progress and calibration with different parameters



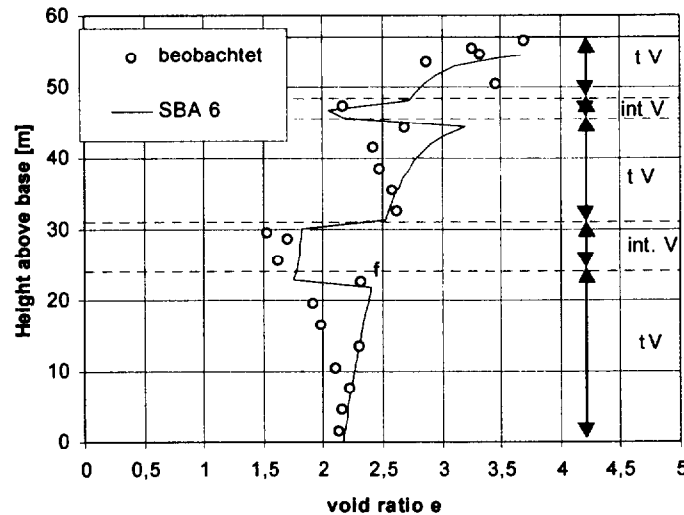
Input and calibration data for the consolidation model are:

- detailed data evaluation of annual discharge: filling time, filling rates, solid density and density of the discharged slurry
- initial void ratio estimated from slurry density and in situ void ratio observed near tailings surface
- in-situ borehole profile data for void ratio - depth (void ratio - effective stress and e_0)
- compression test data for void ratio-eff. stress and with less quality void ratio-permeability
- actual tailings height (thickness)
- annual settlement rates
- in-situ pore pressure measurements to get local drainage conditions or excess pore pressure data

Fig. 2 presents the iterative way of the model's calibration process. Geotechnical lab and field data of high quality are set fixed. Only data of lower quality, as for example the permeability-void ratio relationship were calibrated. Best calibration of the model is possible using in-situ pore pressure measurements. As an example for the above presented calibration functions fig. 3 presents the modeled and measured void ratio - depth correlation of such a layered tailings profile. Three layers of fine tailings variety are interlayered by intermediate fine tailings layers. The modeled borehole profile is located in the marginal fine slime zone next to the

transition zone. The actual tailings thickness is 57 m. The yellow points are in situ void ratio data measured on liner samples. The blue line is the modeled void ratio - depth function. The modeled system of only five layers gives a quite good correlation with in situ measured values.

Fig. 3: Comparison of in situ data and modeling results for layered fine slimes



The modeled and recalibrated geotechnical properties of the different modeled zones were reviewed with respect to their position to the former discharge points. The lab and field data as well as the remodeling of the discharge history show a quite good consistency of each modeled borehole profile and its distance to the former discharge points. The fine slime of the marginal fine slime zone proximal to the discharge point show measured and remodeled compression indices of $C_C \approx 0.60 \dots 0.67$ and $e_{(1kPa)} \approx 3.0 \dots 3.8$ while in the distal inner fine slime area $C_C \approx 0.78 \dots 0.87$ and $e_{(1kPa)} \approx 3.8 \dots 4.2$ were obtained. The modeling results suggest that the deep (56 m) fine tailings profile in the central fine slimes zone is still significantly underconsolidated. Owing to the more favourable drainage conditions the shallow western fine slime area should be nearly fully consolidated.

3.7 Conclusions

The one dimensional nonlinear finite strain code FS-Consol has successfully been applied to recalculate the filling period of TP Culmitzsch A and to characterize the current consolidation state of the fine slimes of the TP Culmitzsch A. The modeling results lead to the following conclusions:

- The characterization of in situ tailings properties and consolidation behaviour of the fine slimes has successfully been worked out.
- The characterization of the actual consolidation state for cohesive (layered) fine tailings based on given data has been successful. A second CPT-campaign with dissipation testing is already under way to check and improve modeling results as well as to enhance knowledge about the in situ consolidation state of the fine slime tailings.
- There is a good coincidence of observed and recalculated actual settlement rates of the tailings surface. Based on this the modeling provides a basis for reliably predicting future settlement due to capping and contouring.
- The FS-Consol code was quite stable running and had a simple handling. The code is a feasible tool to successfully characterize the consolidation process of fine tailings.