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Design, construction and monitoring of the final cover on Wismut´s Truenzig tailings facility

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Abstract

In East Germany, uranium mining and milling by the Soviet-German Wismut company lasted from 1946 to 1990. Since 1991 the Wismut GmbH has been remediating the legacies from uranium production. The Trünzig tailings facility near Seelingstaedt (Thuringia) covers 117 ha and contains 19 million m^3 of uranium mill tailings from the former Seelingstaedt uranium milling and processing plant. The remediation of Wismut´s tailings facilities constitutes one of the greatest challenges to the remediation effort in engineering as well as ecological and financial terms.

The Truenzig tailings facility is being remediated dry in situ and involves the following remediation steps: removal of pond water, catchment of contaminated seepage and surface runoff, interim covering of tailings surfaces, recontouring of dams and pond areas and placement of a final cover, including revegetation. Speeding up the consolidation of soft fine tailings during remediation is of crucial importance to ensure work safety during remediation and long-term stability of the soil cover. The final cover is to prevent access to radioactive tailings and dusting, control the percolation rate, limit oxygen intrusion and radon exhalation and provide long-term geotechnical and erosional stability with respect to time-settlements of the underlying tailings.

This paper presents a case study of the final covering, including preparative measures along with planned runoff diversion trenches intended to enhance consolidation of soft fine tailings. For this purpose, vertical wick drains were installed down to a depth of up to 27 m, and embankments were placed for surcharge loading. The design of the final cover was derived with respect to its functional performance criteria in terms of water balance, geotechnical and erosional stability. The design follows the principle of a store-and-release cover. On sandy tailings beaches, it consists of a 2 m thick moisture storage layer of mixed-grained soil (waste rock from overburden dump) underlain by a 1 m thick interim cover layer made of the same soil but compacted to a hydraulic conductivity k_f of $\leq 5*10^{-9}$ m/s. On soft fine tailings areas, the final cover has a minimum thickness of at least 2.5 m of mixed-grained soil (waste rock from overburden dump). Completion of the final covering is scheduled for 2013. Runoff diversion from the last remaining section of the tailings facility to the receiving stream is envisaged to be realised in 2014. The paper details the technical design, preparative measures and the final cover, the monitoring systems installed, monitoring results with respect to the final cover´s functional performance and experiences from 2005 to 2012.

1 Introduction

Under the control of and in cooperation with the Soviet Union, East Germany was among the world's largest uranium producers from 1945 through 1990. The Soviet-German (SDAG) Wismut company operated numerous uranium mines and two large mills in Saxony and Thuringia. Uranium ore was milled and processed to uranium concentrate (yellow cake) at two hydrometallurgical processing plants located near Seelingstaedt (Thuringia) and Crossen (Saxony) (Figure 1).

Mill tailings from the Seelingstaedt mill were deposited into the Truenzig and Culmitzsch tailings facilities (Table 1). Each tailings facility consists of two ponds for the separate disposal of tailings from either acid or alkaline processing. Mill tailings from soda-alkaline processing at Crossen mill were deposited in the tailings facilities Daenkritz 1 and 2 and later into the large Helmsdorf tailings facility.

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Table 1 Parameters of Wismut tailings facilities

Parameter		Culmitzsch	Truenzig	Helmsdorf/Daenkritz I
Tailings volume	Million m³	85	19	50
Tailings solids	Million t	91	19	56
Maximum tailings thickness	m	72	30	55
Tailings surface	ha	250	117	220

All tailings facilities contain a deposit of the residuals from the hydro-metallurgical processing of uranium ores mined in Saxony and Thuringia. While uranium was nearly completely removed during processing, the tailings still contain the ingredients of all mined ores, together with the residual processing chemicals, and have currently a high amount of chemical and radiological contaminants (Table 2).

Table 2 Radiological characterisation of Wismut tailings facilities

Parameter		Culmitzsch	Truenzig	Helmsdorf/Daenkritz I
U_{nat} in solids	t	7,000	2,200	6,000
U_{nat} in pore water	mg/l	max. 16.5	max. 20.0	max. 85.0
Ra-226 in solids	E14 Bq	10.3	1.8	5.9
Ra-226 in pore water	mBq/l	max. 5,000	max. 630	max. 2,000

In 1991, the German Federal Ministry of Economics put the newly founded Wismut GmbH in charge of the remediation of sites and objects used by the former SDAG Wismut for uranium mining and processing operations. Securing and long-term stabilisation of the tailings facilities of the former ore processing plants constitute the greatest challenge to the Wismut remediation effort in engineering as well as ecological and financial terms.

Figure 1 Wismut remediation sites

This paper provides a brief explanation of the principles underlying rehabilitation of tailings facilities and an outline of the case study of design, construction and monitoring of the final cover on the Truenzig tailings facility.

In the 1990s, extensive technical and economic analyses were performed in preparation of the complete remediation of Wismut´s legacies. Following these analyses of environmental benefit and costs, Wismut worked out a remedial concept that calls for dry in situ rehabilitation involving partial dewatering by technical means as the most appropriate option for remediation. This option was chosen because environmental impacts from the operations can be kept under control, the post-remediation risk is low and the operation can be implemented at comparatively lower costs over a well-defined period of time. The prospective remedial work was divided into the following main sequences:

- Collection of seepage and supernatant water, water treatment and discharge.
- Interim covering.
- Contouring.
- Final covering.
- Landscaping, including vegetation.
- Post-remedial monitoring and maintenance.

The first main steps of the dry in-situ remediation option are the collection of contaminated surface runoff and seepage and the complete removal of pond water. Collected waters are treated before being discharged into the receiving streams. Water treatment plants (WTP) with specific working parameters were erected at both former processing sites. The water treatment unit that operated since 1991 at the Seelingstaedt processing site was replaced 10 years ago by a new plant with a capacity of 300 m^3/h. Technical dewatering is also defined as the removal of pore water by technical drainage measures in order to ensure work safety during remediation operations and long-term stability of embankments and surface covers.

The placement of an interim cover layer is the second remedial step that is to inhibit dusting from dried tailings beaches. The interim cover also provides a platform for investigation and stabilisation measures. As one of its most important functions, the load of the interim cover accelerates consolidation processes within the tailings and reduces the period needed for remediation to be completed.

After interim covering of exposed tailings, the tailings ponds are to be contoured in order to construct a surface profile that incorporates aspects of long-term stability. The contoured surface is to be capped by the final cover to reduce water infiltration and to create a basis for landscaping with vegetation as protection against erosion. All sequences are accompanied by extensive monitoring that continues during the entire remediation phase and extends into the post-remedial phase.

2 Site history and current state of the Truenzig tailings facility

From 1949 to 1957, uranium ore was exploited from the open cast mine Truenzig-Katzendorf. The construction of the Truenzig tailings management facility began soon after the end of mining. In 1958, starter dams were built around the mined-out area that was to be used for the disposal of uranium mill tailings. The Truenzig tailings facility consists of two ponds for the separate deposition of tailings from either the sulphuric-acid or the soda-alkaline processing. Since the beginning of discharge operations in 1960, the Truenzig tailings facility has been surrounded by embankments, including the West dam, the North dam, the East dam and the Karbonathauptdamm, as well as by mine dumps and natural slopes in the west and south.

During the operating life of the facility, approximately 19 million m^3 of mill tailings were deposited into the Truenzig tailings facility: 13 million m^3 of silicate mill tailings were disposed of in pond A and 6 million m^3 of carbonate mill tailings in pond B. Discharge in pond A started from the crest of starter dams only. Over the years, the discharge area was extended in pond A, as the dam was constructed at the entire northern front between the East dam and the West dam. During the operation of pond B, the tailings were discharged from a discharge point located at the crest of Karbonathauptdamm only. This explains the irregular vertical and horizontal layering of the tailings in the Truenzig tailings facility. In the north of the facility, a relatively flatly sloped tailings deposit consisting of sandy beach areas and some transition zones overlays the foundation. Tailings in the adjacent transition zone extending to the south are characterised by steeper slopes towards the basin centre. Tailings thickness increases towards the pond centre to a maximum of 30 m in pond A and 20 m in pond B. After the end of the operations in 1967, the exposed sandy tailings beaches in pond A were covered with mixed-grained soil from nearby mine dumps, consisting of overburden rock, while the central fine tailings remained covered with pond water. Up until 1990, pond B continued to be used as waste water storage for the uranium extraction processes.

In 1991, remediation activities started with the elimination of immediate hazards, like fencing to prevent public access to the facility and intensive monitoring to establish an inventory of the environmental and ecological state of the Truenzig tailings facility and its surrounding. The huge amount of data collected made efficient data management and stringent quality control indispensable. For better use, the monitoring data later were linked to a geographical information system.

Based on initial monitoring results, catchment systems were installed or refurbished to collect the entire seepage and runoff from the Truenzig tailings facility. Collected waters (seepage, surface runoff and supernatant) were treated in the Seelingstaedt WTP before being discharged into the receiving creek. In order to reduce radon exhalation and radiologically contaminated dusting from exposed tailings, the sandy beaches in pond B were covered with cohesive material from a nearby source.

In addition to environmental and ecological monitoring activities, geotechnical investigations were conducted to collect data on Truenzig dam stability. In this case, at first the short-term stability for the operational earthquake was investigated and the findings were confirmed by external experts.

The geotechnical investigations were performed in the geological underground, mine dumps, dam materials, tailings and soil materials at the site. The fine tailings, located in the centre of ponds A and B, were identified to be the most challenging materials. They could be described as clayey silts with water contents above liquid limit. The fine tailings are very compressible and have a low to very low hydraulic conductivity, depending on the void ratio. Their undrained shear strength varies from 0 to 3 kPa near the tailings surface.

Following analysis of the recorded environmental, radiological and geotechnical data, Wismut drafted an overall remediation concept for the Truenzig tailings facility that was approved by the regulator's consultant in 1996 as a policy decision.

The planned remediation activities were initiated in the early 1990s with further removal of pond water and placement of an interim cover of 1 m thickness. The planned interim covering started with a test loading in peripheral areas of pond A. As the test loading data were continually evaluated, the technology for interim covering could be adjusted accordingly. With the optimised application of geotextiles, geogrids and vertical wick drains, the interim covering of the centre of pond A was terminated in 1995. In pond B, the pond water removal and interim covering was finalised in 2002.

3 Design of the tailings remediation, including final covering

The conceptual design for Truenzig tailings facility started with the examination of various options for the contour design in pond A. The option chosen calls for a gentle valley with a substantially central east-to-west extending future main trench for runoff diversion. The surface runoff was to be diverted from pond A via an incision in the West dam. The preferred option was characterised by both a minimum incision into the West dam and a minimum amount of material needed for raising the surface along the main trench for runoff diversion.

Based on the results of extensive geotechnical investigations and laboratory testing, like laboratory oedometer tests, numerical analyses of the time-settlement process of the fine tailings were performed for pond A. The results showed that consolidation-accelerating measures would be required to create a stable surface on top of the fine tailings in the anticipated main trench area within the given time frame.

Therefore it was planned to accelerate the predicted settlements during the construction period. As best practice for raising the main trench area for runoff diversion, a surcharge loading of contouring material was planned. The surcharge loading was combined with the installation of deep vertical drains, a horizontal drainage layer and associated drainage wells in the respective pond area along the main trench. These measures were to ensure a continuous gradient of the main trench for runoff diversion at the end of the rehabilitation works.

Based on the experiences gained with the design for pond A, the same design principles were applied to pond B with regard to long-term stability. The predicted settlements were to be accelerated in the same way in pond B. When rehabilitation was complete, the surface water of pond B was to be removed via an incision into the underground rock barrier located in the southeast of pond B.

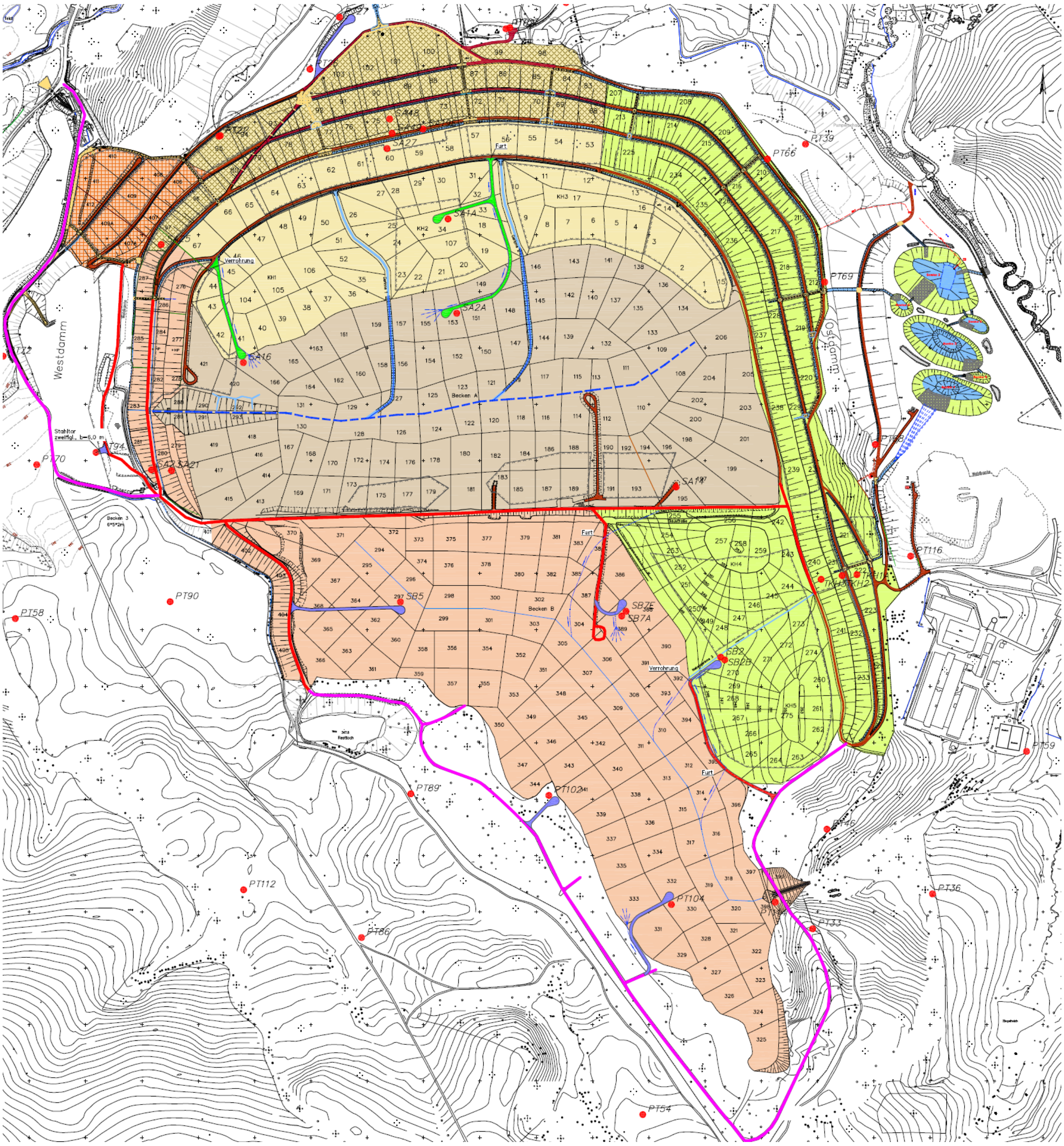


Figure 2 Draft of general design of Truenzig tailings facility

The final covering of Truenzig tailings facility, including construction of runoff ditches, maintenance roads and vegetation, will complete the remediation activities on the tailings facility (Figure 2). The final cover has to avert access to radioactive tailings and prevent dusting, control percolation rate, limit oxygen intrusion and radon exhalation, and provide geotechnical and erosional stability with respect to time-settlements of the underlying tailings. In order to achieve long-term stability and a design life of 200–1,000 years, construction materials, technical design criteria and types of vegetation have to be carefully selected with due regard to their environmental impacts.

In addition to criteria such as meeting remediation targets and achieving long-term stability, the design has to take the costs for the final cover into account. In this context, a distinction was made between construction costs, including vegetation, and long-term costs for maintenance and other long-term activities. Baseline meteorological data were provided by a series of meteorological daily means and daily sums recorded during the past 20 years by the nearby Gera-Leumnitz weather station. Data for global radiation, adjusted precipitation and wind speed converted to a 2 m reference elevation were derived from those baseline data for modelling input. Pertinent annual sums or annual means, respectively, are listed in Table 3 (Oswald et al., 2001).

Table 3 Baseline meteorological data

Parameter		
Precipitation	mm/a	673
Mean air temperature	°C	8.4
Mean relative air humidity	%	78.7
Sunshine duration	h/a	1,654
Global radiation	J/cm²	354,200
Average wind speed	m/s	2.7

For the final cover of Truenzig tailings facility, only natural mineral materials were chosen because the long-term stability of synthetic materials cannot be guaranteed for periods of up to 1,000 years. The selected materials must be sufficiently cheap and available in sufficient quantity not too distant from the site. Soil materials used for final covering must comply with the requirements set by the German Federal Soil Protection Ordinance. The required properties of the earthen materials were defined by the design requirements of the respective cover layer for the construction they will be used for – i.e., storage layer, sealing layer or drainage layer. The used earthen materials are cohesive waste rock from nearby mine dumps (usually mixed-grained soil from excavated overburden rock), till, loess loam, clay, crude sand, gravel-sand-mixtures or gravel from off-site sources.

The conceptual designing of the final cover included the evaluation of various cover options using day-to-day water balance modelling. Combinations of different cover layer systems, different material types, variations of layer thicknesses, different installation geometries and different vegetation types were evaluated. Based on the results of a sensitivity analysis (Neudert et al., 2000), the number of combinations was restricted to groups of three principal layer systems (Table 4).

Table 4 Principal examined layer systems

System	Layer (Type of Use)		
Single layer system	Storage layer		
Double layer system	Storage layer	Sealing layer	
Multilayer system	Storage layer	Drainage layer	Sealing layer

In this case, configuration of theoretically suitable layer systems for dam and plateau areas was based on the results of the sensitivity analysis (Figure 3). They varied significantly with respect to the full range of potential water balance parameters.

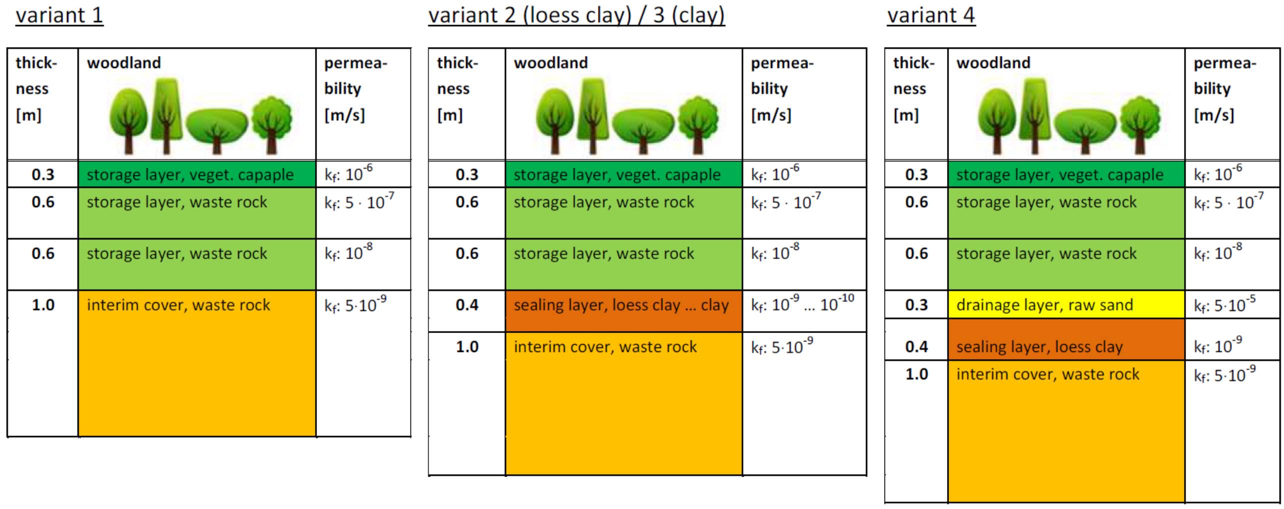


Figure 3 Investigated layer systems

Modelling of the day-to-day water balance of various final cover designs was based on test field result analyses of actual infiltration rates, with a view to providing water for plant growth and stability against cracking by soil suction. In the runup to water balance modelling, soil parameters of final cover materials excavated from the Lokhalde mine dump had been investigated both at the excavation site and under placement conditions. The soil texture was classified as medium silty sand to medium loamy sand. Parameters for the storage layer from statistical surveys are shown in Table 5 (Oswald et al., 2001).

Table 5 Soil parameters of storage layer material

Parameter		Mineral Storage Layer, Condition At Time Of Placement	Mineral Storage Layer, Long-Term Condition	Humus Storage Layer, Long-Term Condition
Saturated water content	Vol. %	32	37	39.5
Field capacity (at pF 2.5)	Vol. %	23	23	26
Permanent wilting point	Vol. %	14	14	16.5
Permeability (saturated)	m/s	1E-08	5E-07	1E-06

The water balance modelling was carried out with a compartment model of the whole site. The model incorporated the relevant water streams from across the entire site with the objective of deriving the requirements for water management and identifying acceptable flow rates as well as chemical components of the seepage from the tailings pond. Then modelling of the hydraulic flow and contaminant transport in the tailings and the surrounding catchment area was carried out in order to assess the efficiency of different layer systems and yield data for input in the site compartment model for optimisation calculations.

Relevant data for the cover performance assessment include the percolation ratio for the assessment of seepage water as well as the seepage line for dam areas. The water balances of different cover designs were calculated with HELP (Hydraulic Evaluation of Landfill Performance) and compared with measurement results from cover test fields operated over many years. The water balance effects of forest areas compared with grassland were estimated with analogy considerations. The results showed that the evaporation of forest areas was approximately 20%, or 100 mm/y higher than that of grassland.

The hydrologic modelling was carried out for surface runoff and dimensioning runoff diversion measures. Geotechnical stability calculations for the planned final cover were prepared regarding differential deformation with time, sliding on slopes and erosion/suffusion.

Carefully weighed, the evaluation and optimisation of the cover yielded the preferred cover design. A compact and stable layer system with a design life of up to 1,000 years is to ensure sustainable control or reduction of the environmental impacts to an acceptable level. As expected, minimisation of the infiltration rate was a matter of importance in the areas of sandy tailings beaches along the outer ring of pond A and in the eastern part of pond B. Vegetation established on the final cover had its positive effects on water balance only in these areas. In the central fine tailings areas of ponds A and B, low infiltration rates were found through the fine tailings layer caused by its low conductivity of $k_f = 10^{-9}$ m/s or less. That is why vegetation on the final cover was an important component of the accompanying landscape planning, including establishment of woodland vegetation in tailings beach areas and grassland in the central fine tailings areas (Figure 4).

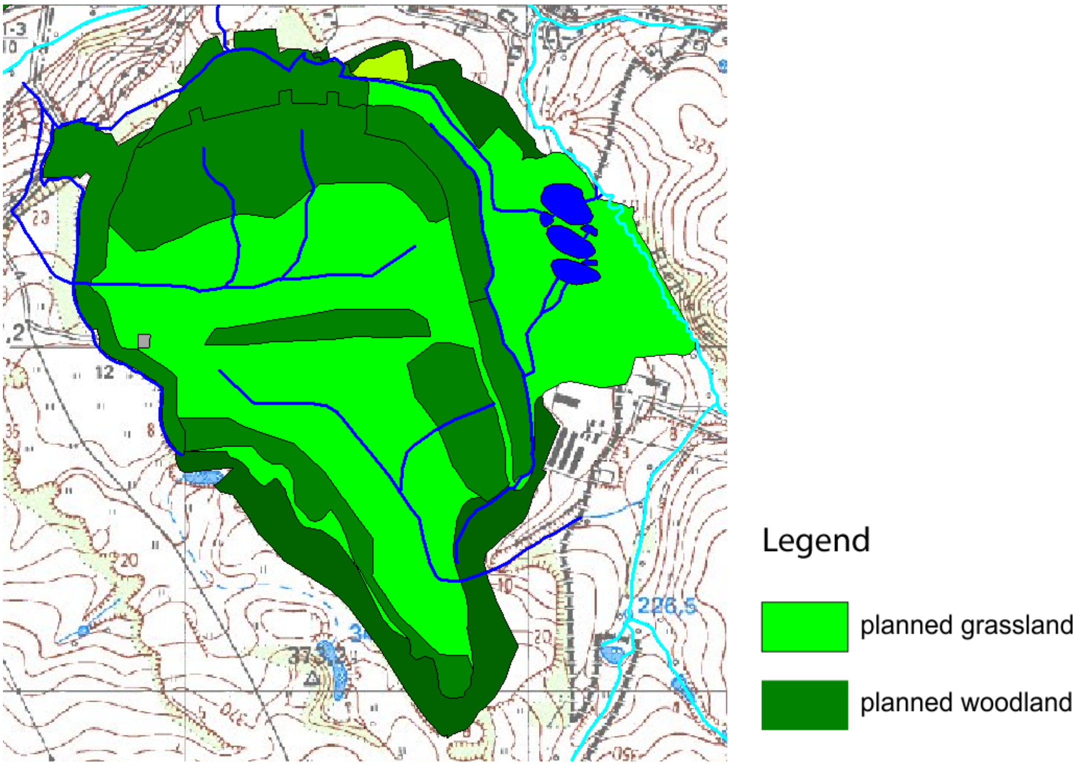


Figure 4 Vegetation on final cover according to accompanying landscaping plans

A quite simple and robust layer system was identified according to the principle of a store-and-release cover using the assistance of vegetation. With respect to the environmental impact, this cover system performed substantially equal to multilayer cover systems. To increase the performance of the final cover´s storage layer, its minimum thickness was increased from 1.5 to 2.0 m. In addition, the lowermost 0.5 m thick lift of this storage layer and the underlying interim cover layer or contouring layer are to be compacted as a sealing layer in a defined way (damp course). The lowest 0.5 m thick lift of the storage layer is also to impede rooting into the underlying compacted layer. The results and conclusions drawn from the geotechnical stability calculations with respect to long-term settings and erosion/suffusion risks corroborated the envisaged final cover configuration. The use of more expensive and in practice more difficult to handle sealing layer materials like loess clay or clay could in this case be avoided.

Figure 5 shows the cover design for both ponds A and B with respect to the different areas (sandy tailings beaches with relocated tailings on a first interim cover as well as fine tailings zones capped with interim cover and contoured). The final cover thickness varies from 2.0 m in sandy beach areas to 0.5 m in fine tailings areas. In fact, the functionality of the final cover incorporates underlying layers from interim covering and contouring with a minimum thickness of 2.5 m above fine and at least 3.0 m above sandy tailings.

sandy beaches

thick-ness [m]	initial woodland 	compaction degree
0.5	storage layer, veget. capaple	D_{PR} 88 - 92%
0.5	storage layer, waste rock	D_{PR} 88 - 92%
0.5	storage layer, waste rock	D_{PR} 88 - 92%
0.5	storage layer, waste rock	$D_{PR} \geq 95\%$
0.5	interim cover, waste rock, later defined compacted	$D_{PR} \geq 95\%$
0.5	interim cover, waste rock	
	tailings	

fine tailings

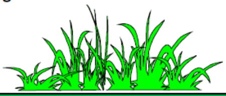
thick-ness [m]	grassland 	Compaction degree
0.5	storage layer, veget. capaple	D_{PR} 88 - 92%
0.5	contouring, waste rock, later solved with fangs	D_{PR} 88 - 92%
$\geq$ 2.0	contouring, waste rock	
	fine tailings	

Figure 5 Planned cross-sections of final cover

4 Preparative measures for final cover on Truenzig tailings facility

Since 2001 the contouring of Truenzig tailings facility has been implemented, involving dam flattening and plateau recontouring to construct a surface profile providing long-term stability. To accelerate the predicted settlements along the future main runoff diversion ditches during the construction period, fill materials were placed together with the use of vertical wick drains. The surcharge loading started in 2003 at pond A and in 2006 at pond B. These measures were combined with the installation of deep vertical drains, a horizontal drainage layer and associated drainage wells in the settlement-sensitive pond area along the main trench.

Based on the results of numerical calculations, it was decided to drive down vertical wick drains to depths varying from 5 to 27 m, considering that the deepest vertical drains should be driven down to no more than 90% of total tailings thickness. The pond foundation was not to be punctured, to prevent pollutant migration. The geotextile wick drains (width: 0.15 m, thickness: 0.01 m) were arranged in a triangular grid spacing of 3.0 m. With respect to the results of oedometer data, permeability and compressibility of the fine tailings were determined in relation to void ratios and water contents measured with depth. The individual drains were to act as sinks into which the tailings body would discharge via shorter drainage distances.

The embankment for surcharge loading in pond A was planned with a length of approximately 750 m and in pond B with a length of approximately 1,000 m. The maximum thickness of the embankments was constructed on a 25 m wide strip and with slopes ratios of v:h = 1:5 on both sides. The width of the embankment varied between 60 m and 135 m, depending on the total height of the surcharge loading. The maximum thickness of the embankment was from 3.5 m to 11 m. The intended height of the loading accounted for the equivalent loading of contouring, final capping, required settlement compensatory measures and an additional temporary preloading.

Comprehensive monitoring of the works by the geotechnical construction supervision was possible using instrumentation with pore water pressure sensors and settlement plates. The evaluation of the pore water pressure development related to the amounts of settlements was applied as the decision criterion for assessing the success of the construction work. Monitoring of the settlements behaviour and the pore water pressure development was carried out in the field, based on the evaluation of settlement points and pore water pressure measurement points with two or three depth-dependent staggered sensors.

The surcharge loading caused significant amounts of settlement, which were locally larger than the expected amounts. The surcharge loading also led to movements in a horizontal direction. Smaller settlement portions observed at the same time in areas adjacent to the embankment might be explained by delayed consolidation-related vertical deformations. Right from the beginning of loading on fine tailings, the pore water pressure increased as expected and likewise the stiffness of the tailings. Since the completion of the final surcharge loading, an almost linear increase in the amounts of settlement has been recorded. Since this time, a distinct bend and a subsequent decreasing course of the settlement curves can also be perceived. A reliable criterion for evaluation and verification of consolidation progress was the decrease of excess pore water pressures with time. The approach to determine the equivalent permeability for the region of deep vertical wick drains in the numerical calculations could be confirmed in this case.

The partial removal of the embankment for surcharge loading was approved by the authorities on the basis of the evaluation of the monitoring results. During the layer-wise removal of the embankment in pond A from 2006 to 2008 and pond B from 2008 to 2010, the excess pore water pressures completely vanished and settlement stability was achieved. All sequences were accompanied by an extensive monitoring of pore water pressures and settlements that continued during further remediation.

5 Final cover construction

In 2004, the final covering (Figures 6) began in areas where recontouring had been completed. It started at the flattened North dam and on the tailings beaches (so-called contouring hills no. 1 to 3) in the north of pond A, where the relocated dam material consisting of tailings of the autostable northern tailings dam was placed on top of the tailings beaches, capped with an interim cover. During cover implementation requirements according to the tailings properties (sandy beaches or fine slimes), the underground conditions on the rebuilt tailings, the minimum overlaying of 2.5 m above the tailings surface and the composition of the cover material, especially in the 0.5 m top layer, were constantly verified.

During implementation of the above measures, a quality assurance programme was put in place to ensure the performance of the final cover during the design period. As the final covering was under way, defined quality parameters were verified for the underlying interim cover. The top layer of the interim cover was qualified as sealing layer (damp course). Compaction degrees of more than D_{Pr}=95 % were needed. If this parameter was not attained, the compaction with soil compactors was continued. The layer thickness of the interim cover was verified during construction. Based on the results of quality assurance measurements, permission for final cover construction was obtained.

(a) (b)

Figures 6 Final cover during construction

The cross sections for tailings beaches and fine slimes were constructed to meet specific requirements. The cover material was trucked to the site from a nearby mine dump (mixed-grained soil). Degrees of compaction as well as the observation of the layer thickness and the material properties of the cover material were of paramount importance during that stage. The individual layers were constructed with different compaction degrees from D_{Pr}=88 % to 92 % to satisfy the two main criteria of storage capacity and erosion stability. In cases where the relatively low compaction degrees of underlying layers were not successfully demonstrated, these layers were pre-ripped by a bulldozer with ripper teeth. The completion of final covering is scheduled for 2013. Runoff diversion from the last partial area of the tailings facility to the receiving stream is envisaged to be accomplished in 2014.

6 Evaluated monitoring of the Truenzig final cover

Settlement measurements with the settlement deformation network (SDFN) and soil hydrological measurements were performed in addition to the quality assurance programme measurements during final cover construction. Measurements of pore water pressure, seepage water level and environmental (radiological) conditions performed during past remediation measures were continued.

The settlement measurements were carried out on a monthly basis since the beginning of contouring and were extended into the period of final covering. The complete SDFN network, arranged in a grid spacing of 100 m, was adapted to final cover works on both ponds of the Truenzig tailings facility. The measurement points were vertically extended according to the thicknesses of the construction materials. The vertical displacement readouts were evaluated in profiles. At a certain point in time after completion of the construction work, the measurement intervals were extended to three or six months, respectively. The results show deformations of the tailings surface associated with the vertical loads. They also indicate the establishment of a stable cover surface after completing final cover construction. The relative constant layer thickness is also demonstrated by these results. A reduction in thickness in the wake of possible local settlements did not occur so far. Any possible short-term local settlements simply demonstrate a temporary condition of the storage layer in the initial stage of vegetation growth. With the establishment of full vegetation, the storage layer will undergo a minor increase in volume due to root penetration. The final cover was matched to the site's long-term conditions, so a sufficient thickness of the storage layer of ≥ 2 m is expected.

A soil hydrological monitoring station (MS) was installed on the contouring hill no. 3 on top of the northwestern tailings beaches of pond A to verify the remediation efficiency of the final cover. The MS, installed in 2006, consists of a large lysimeter with an effective surface area of 240 m² to record the amount of seepage, a soil hydrological measurement place with various soil sensors to record the dynamics of soil water in the cover and an automatic weather station. The lysimeter measurements recorded surface runoff, the lateral flow within the storage layer and the percolation through the sealing layer. The hydrological measurement place is recording water contents and soil suction with time domain reflectometry probes installed at various depths of the storage and sealing layers as well as the soil temperatures. The weather data from the automatic weather station were matched with those of the regional station of the German weather service. The MS monitoring data have been evaluated since March 2006 to track long-term trends of the soil water balance of Truenzig final cover. Water contents determined at different depths and in various layers are shown in Figure 7 (Roscher et al., 2013).

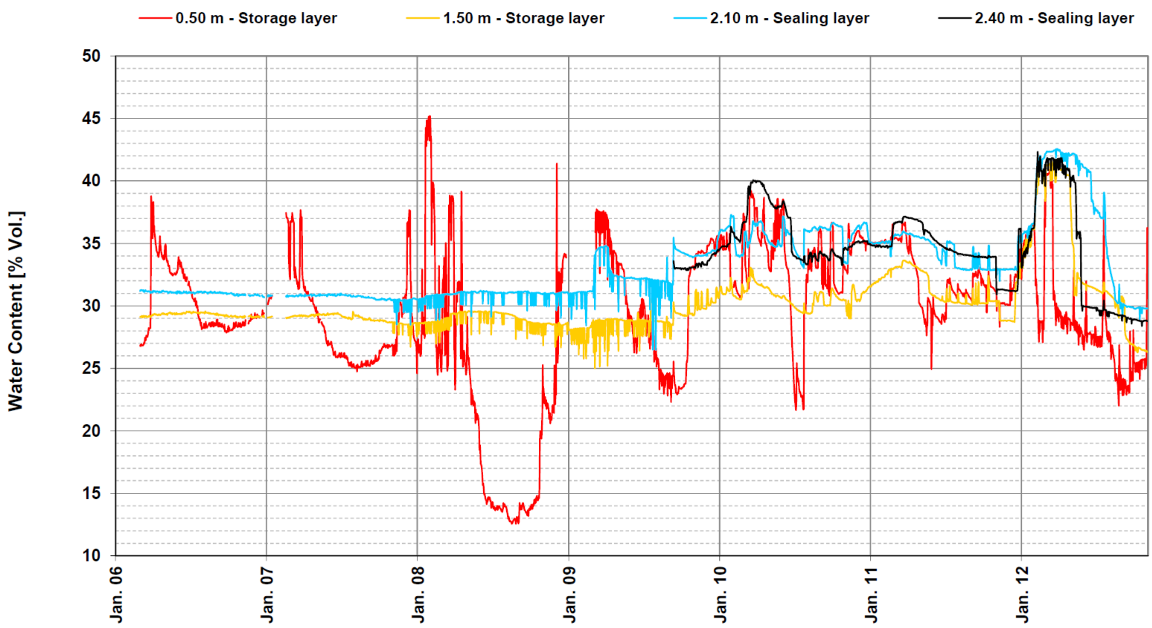


Figure 7 Daily average of water contents evaluated in Truenzig monitoring station

Soil water contents measured in the upper storage layer (0.50 m) show the typical annual cycle, partly dominated by extreme meteorological events. The annual minima and maxima increased from 2006 to 2008. This difference was smaller in the following years. The permanent wilting point of 7.0% vol. for the placed cover material was not reached over the whole investigation period. This may indicate that an effective storage layer exists to allow the normal growing of part of the system's vegetation. The water content at lower measurement points (1.50 m for storage layer and 2.10 m for sealing layer) was nearly constant until 2009 with approximately 30% Vol., and later it increased to more than 40% Vol. water content in the spring of 2012. The results could be interpreted to indicate that a drying up of the sealing layer did not occur. The measuring point in the sealing layer at a depth of 2.40 m was defective until September 2009. Subsequent data from this measurement point confirmed the investigation results, indicating an intact status of the sealing layer.

7 Conclusions

To accelerate the predicted settlements during the construction period, fill materials were placed and vertical wick drains installed as preparative measures for final covering at the Truenzig tailings facility. This allowed a stable surface to evolve as a basis for subsequent cover placement activities. Then a quite simple and robust layer system was constructed according to the principle of a store-and-release cover using the assistance of vegetation. Only natural mineral materials were used, to ensure long-term stability. According to the insight gained by the water balance modelling, vegetation established on the final cover included woodland on tailings beach areas and grassland in the central fine tailings areas.

The results of the monitoring station measurements during the last seven years indicate an intact cover system. Water content in the storage layer was always below the permanent wilting point of the cover material. The shape of the curve for water contents over the years shows a real evapotranspiration performance during the report period. The function of the sealing layer is preserved by the storage layer's function, and drying up was prevented during the monitoring period. With respect to the performance of the final cover at the Truenzig tailings facility, the cover option implemented provided a functionality nearly equal to multilayer cover systems.

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