Cover placement on extremely weak, compressible tailings

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ABSTRACT

Increasingly, the successful reclamation of tailings impoundments involves placing permanent dry (soil) or wet (water) covers over the tailings to provide isolation and control of radiological, oxidation, and/or leaching effects. This paper reviews key issues related to the placement of dry (soil) covers on extremely weak, compressible fine tailings. The design and construction of soil covers on such tailings often presents a formidable challenge to the geotechnical as well as the environmental engineer due to the low shear strength, poor trafficability, and high settlement of underconsolidated tailings at the time of reclamation. The geotechnical issues to be considered include: (i) consolidation of near-surface tailings to achieve strength gains, improve trafficability, and allow safe placement of initial cover layer; (ii) stability of tailings slopes during dewatering of tailings ponds and/or cover placement, and (iii) long-term settlement of tailings and its impact on cover integrity and final surface shaping. The environmental issues to be considered include (i) management of contaminated (free) pond water; (ii) management of contaminated pore water expelled during tailings consolidation; and (iii) management of (uncontaminated) surface water on top of the cover. This paper summarizes recent experiences gained in evaluating alternative cover placement methods for a large uranium tailings reclamation project.

INTRODUCTION

This paper discusses the construction of a dry cover over very weak compressible tailings located in the slimes zone of tailings impoundments. The construction of soil covers on these slimes often presents a formidable challenge due to the low shear strength, poor trafficability, and high settlement of these underconsolidated tailings at the time of reclamation. It is concluded from this review that the geotechnical properties of the slimes have to be well understood in order to select the best strategy for placing a dry cover onto the slimes zone.

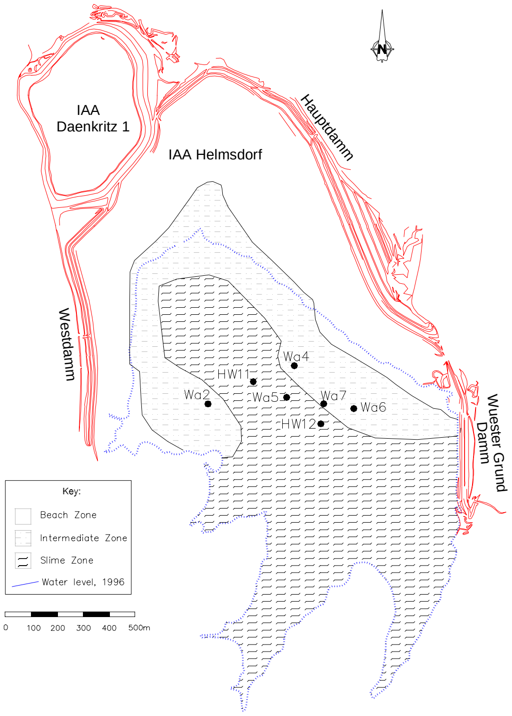


Fig. 1. Site plan for Helmsdorf tailings impoundment.

GEOTECHNICAL PROPERTIES OF THE SLIMES ZONE

The tailings deposits in most impoundments can be divided into at least three zones: (i) beach zone, (ii) intermediate zone, and (iii) slimes zone. Typical geotechnical parameters for these different zones are summarized in Table 1. The data are from a large uranium tailings impoundment ("IAA Helmsdorf") located in eastern Germany. Table 1 illustrates that the geotechnical properties of the tailings in these three zones differ substantially. Here we focus on the slimes zone which presents the greatest difficulties for placing a soil cover.

The slimes zone comprises much of the tailings area in the IAA Helmsdorf presently covered by water (Figure 1). Oedometer measurements in the laboratory indicated a high relative settlement of up to 28% for the slimes. From the tests a low coefficient of consolidation, C_v =1 to 4 x 10^{-7} m^2/s and very low vertical hydraulic conductivity, k_v in the order of 2 to 6 x 10^{-9} m/s were derived.

The low permeability of the slimes results in very slow consolidation under self-weight. As a result excess pore pressures and settlement may occur for many tens of years after tailings placement. In addition, these extremely soft, compressible layers of low permeability silts and clays generate high pore pressures when subjected to loading and behave as extremely weak, almost fluid, deposits. The poor consolidation properties of the slimes significantly complicate initial access and subsequent placement of a dry cover.

Table 1. Representative Geotechnical Properties of the different Tailings Zones in the Helmsdorf Impoundment (after Baugrund Dresden, 1995)

Geotechnical Parameter	Beach Zone	Intermediate Zone	Slimes Zone
Grain size			
d_{10} (mm)	0.02	0.01 - 0.002	<<0.001
d_{60} (mm)	0.1	0.08 - 0.008	0.005
d_{90} (mm)	0.25	0.1 - 0.04	0.03
Average Water Content, w_n	0.10 – 0.30	0.25 – 0.65	0.45 – 0.96
Atterberg Limits			
w_P	0.15	0.15 – 0.19	0.21
w_L	0.28	0.30 – 0.47	0.54
I_P	0.14	0.16 – 0.18	0.32
Dry Density, ρ_s (g/cm^3)	2.76	2.79	2.78
Bulk Density, ρ_n (g/cm^3)	1.95	1.78 – 1.93	1.64 – 1.78
Void Ratio, e	0.55 - 1.0	0.7 – 2.0	1.5 – 3.0
Total Shear Strength, τ (kN/m^2)	20 - ≥50	5 - 50	< 5 (surface) 5 – 20 (depth)
Coefficient of Consolidation, c_v (m^2/s)	1 to $2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$ to $2 \cdot 10^{-7}$	1to $4 \cdot 10^{-7}$
Compression Index, C_c	0.05 $^{(*)}$	0.20 $^{(*)}$	0.50 $^{(*)}$
Hydraulic Conductivity (m/s)	$1 \cdot 10^{-4}$ - $5 \cdot 10^{-7}$	$1 \cdot 10^{-9}$ - $5 \cdot 10^{-7}$ $^{(*)}$	$1 \cdot 10^{-9}$ - $2 \cdot 10^{-8}$ $^{(*)}$

$^{(*)}$ data derived from simulation of self-weight consolidation w/ calibration against in-situ void ratio profile (see RGC Report 028001/5)[3]

The poor consolidation properties of the slimes are readily apparent from field observations. Figure 2 shows two void ratio profiles observed in the centre of the slimes zone (at HW11 and HW12). The range of void ratios is significant in spite of the uniformity of material. A decreasing void ratio with depth is observed due to the higher effective stresses at greater depth. The large range in void ratio suggests that these very fine tailings are highly compressible. Simulation of the filling process using a nonlinear finite-strain consolidation model suggested that the tailings are significantly underconsolidated (see simulated excess pore pressures in Figure 2, see RGC, 1996).

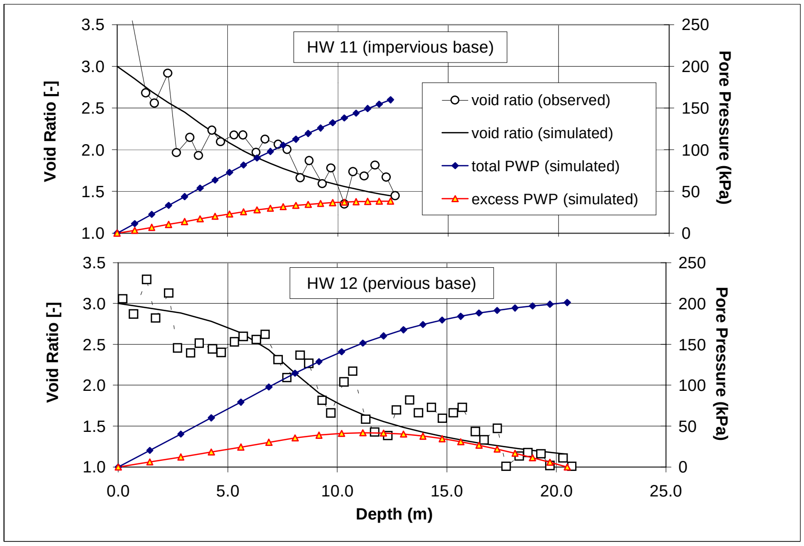


Figure 2. Profiles of void ratio and pore water pressure in slimes zone, Helmsdorf Impoundment.

Figure 3 shows various depth profiles of undrained (in-situ) shear strength, determined by shear vane testing from a floating platform, in the slimes zone of the Helmsdorf impoundment. These field measurements suggest that the undrained shear strength of the slimes is less than 5 kPa in the upper 2-4m and less than 10kPa in the upper 5-10m of the slimes deposit. Such low values of undrained shear strength are insufficient to support wheeled or tracked vehicles and conventional earth moving and placing techniques for cover layer placement. The very low undrained shear strengths observed in the upper layers of the slimes deposit are a result of the high void ratios and excess pore pressures (c. Figure 2), combined with the extremely low cohesion of the freshly deposited slimes. According to the effective stress principle the undrained shear strength is defined as:

$$\mathbf{s = c' + (\sigma - u) \tan \phi'} \qquad (1)$$

where: σ is the total stress, u the pore water pressure, and c' and ϕ' the effective stress parameters for cohesion and friction. Using equation (1), the undrained shear strength was estimated for a representative location of the slimes deposit (at HW11) assuming (i) no excess pore pressures and (ii) 60% excess pore pressures are present (see solid and dashed line in Figure 3, respectively). Representative values were assumed for the effective stress parameters (c'=0 and ϕ'=25°). A comparison of the field measurements and the calculated values suggests that the slimes are underconsolidated, i.e. high excess pore pressures must be present significantly reducing the in-situ shear strength of the tailings.

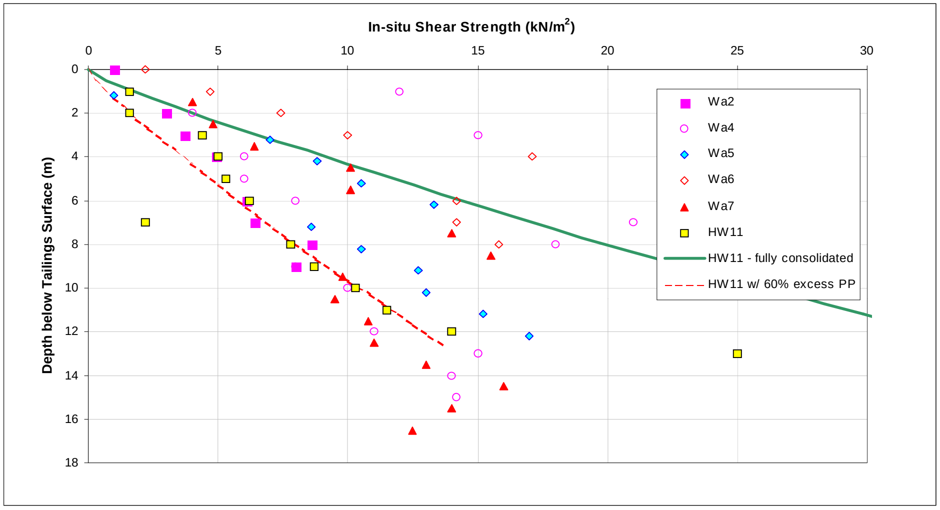


Figure 3. Undrained (in-situ) shear strength profiles in slimes zone, Helmsdorf Impoundment.

DESIGN ISSUES FOR RECLAMATION OF SLIMES ZONE

Several geotechnical and environmental issues have to be considered when planning the construction of a dry cover onto very weak, compressible tailings.

Environmental Issues

Dewatering of the free pond water is typically the first step of reclamation in the slimes zone. If the pond water is contaminated it will have to be pumped to a treatment plant and treated prior to discharge into the environment. In this case the allowable rate of pumping is often limited (either by treatment plant capacity or an allowable discharge limit). Until such time that a dry cover is placed onto the exposed slimes there is a potential for air-drying, which may lead to dust emissions. In the case of uranium tailings, exposed tailings further pose the risk for radon exhalation. While from an environmental point-of-view an expeditious covering of the slimes following pond drawdown is favored this may not be advantageous, or even possible, from a geotechnical point-of-view.

During consolidation of the highly compressible tailings in the slimes zone, large volumes of tailings pore water are released and flow out of the fine tailings. If this seepage is contaminated, it will have to be collected and treated past the closure date. Since most of the seepage from the slimes zone results from consolidation this process is typically very slow and can extend well past the date of final cover placement (Brouwer et al., 1994). The long-term collection and treatment of tailings seepage may comprise a substantial portion of the total cost of remediation.

In most cases the dry cover is placed to isolate the tailings, i.e. to prevent further infiltration into the tailings and therefore contaminated seepage out of the tailings. Clearly, the sooner after pond drawdown the low permeability cover can be placed the less seepage will have to be collected and treated. The different water quality of surface runoff flowing on top of the cover (from precipitation and run-on) and just below the cover (tailings pore water expelled to the surface by consolidation) may require the use of two separate drainage systems. These separate drainage systems may have to be maintained well past the day of final cover placement.

The amount of settlement during consolidation of the slimes influences the final surface shape of the tailings impoundment. Differential settlement is commonly observed in tailings impoundments, requiring a re-shaping of the tailings impoundment to maintain surface-runoff without any ponding.

Geotechnical Issues

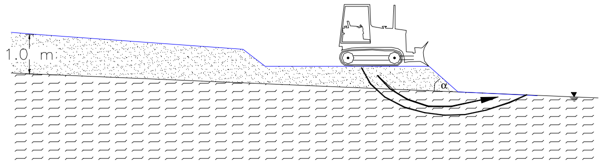
The extremely weak, compressible nature of the tailings in the slimes zone represents significant geotechnical challenges when trying to place a dry cover onto them (Sheng et al., 1998a). First, the low undrained shear strengths, in particular in the upper layers of the deposit (c. Figure 3), often prevent initial access with even light construction equipment. Second, the poor consolidation properties of the slimes also cause problems beyond initial access, i.e. during actual cover placement. The placement of a cover layer (even a thin layer of say 0.3m) represents a significant load, which is initially born by the pore water as excess pore water pressure. During consolidation these excess pore pressures gradually dissipate thus transferring the stress of the new load to the soil skeleton, resulting in an increase in effective stress and thus in-situ shear strength (Equation 1).

In many instances a staged advancement of several thin cover layers is required, with provision to allow consolidation and strength gain at each stage, to avoid a rotational failure (slumping) or a bearing capacity failure near the advancing edge of the cover (Sheng et al., 1998b). Figure 4a/b illustrates these two potential types of failure during cover placement. Unfortunately, this dissipation of excess pore pressures and associated increase in the in-situ shear strength can be very slow. Vertical band drains (“wick drains”) may be required to accelerate consolidation during cover placement.

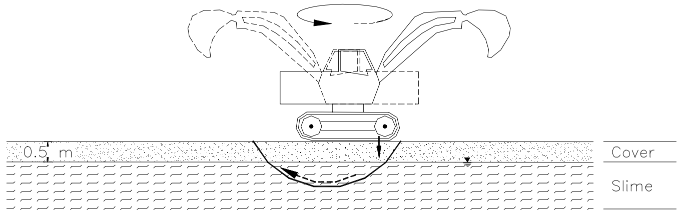
There is also a potential for a deep-seated rotational failure, involving freshly exposed slimes located on a slope (typically 2 to 5%) near the edge of the pond (Figure 4c). Such a failure (with or without a cover) can occur when the free pond water is pumped down much faster than the slimes can dissipate the resulting excess pore pressures. Installing deep vertical band drains that allow drainage of these tailings slopes may prevent deep-seated failures.

Another problem during cover placement is the potential of sensitive behaviour of the slimes, i.e. a strength loss of the slimes due to a sudden or cyclic loading (e.g. movement of a dozer or installation of band drains). Here the soil structure is partially destroyed and some of the effective stress carried by the soil skeleton is transferred back to excess pore pressures. Strength losses during cover placement have been observed in slimes zones at various sites (Sheng et al., 1998b). If a strength loss is observed in sensitive tailings during construction, the cover placement may have to be interrupted to allow dissipation of these new excess pore pressures. This can result in significant delays in the cover placement.

a) Rotational Failure near advancing edge of cover



b) Bearing Capacity Failure due to rotation of earth—moving equipment



c) Deep—seated failure due to rapid drawdown

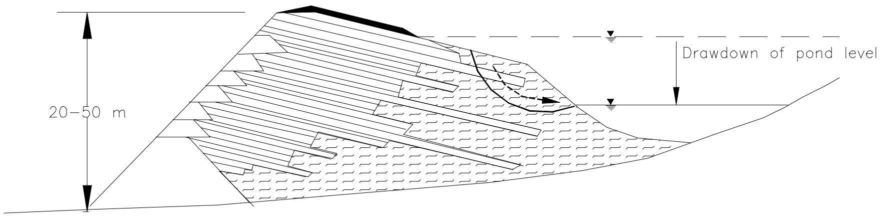


Figure 4. Schematic illustration of failure modes in soft tailings.

The large settlement of the fine tailings also raises geotechnical issues related to cover integrity and final surface shaping (Miller et al., 1990). The overall amount of settlement has a direct bearing on the amount of re-contouring required to achieve the desired final surface shape. Settlement tends to be much greater in the slimes zone than in the beach or transition zone. In those cases where the slimes zone is located in the center of the impoundment, significant cut and fill quantities may be required to maintain positive (gravity) drainage from the entire impoundment. In addition settlement is rarely uniform through the slimes zone owing to local differences in tailings thickness and/or consolidation characteristics. The resulting differential settlement can significantly compromise the integrity of the cover, in particular, if a complex multi-layer cover is used. If significant differential settlement is anticipated, an interim cover may have to be placed to allow initial settlement. The final surface shaping and placement of the multi-layer cover may only be done after most (say 90%) of settlement has been observed (Miller and Range, 1989).

TECHNIQUES FOR PLACEMENT OF DRY COVER

A review of the literature was done to identify techniques used for placing a cover on very weak compressible tailings (Table 2). The results of this review are summarized below.

Fill with Some Failure

If some degree of slope failure (with or without cover) can be tolerated than fill material could be placed in one of two ways. First, fill material could be hydraulically placed or dumped from a barge prior to dewatering of the pond. The pond water would then be drawn down and the exposed tailings re-contoured and covered. This method is straightforward and safe, but may require large volumes of fill (fill may penetrate and mix with the slimes) and is limited to those slimes still covered by water (to allow access for the barge). Second, fill material could be pushed into the slimes zone using conventional earth moving equipment (Neukirchner and Lord, 1998). In this scenario it is advantageous to draw the pond level down as quickly as possible. The rapid drawdown will induce pond slope failures that are likely to occur, and thereafter the remaining slopes will be more stable.

Table 2. Summary of Case Histories on Dry Cover Placement on very weak, compressible tailings and other soft soils.

Site	**Material Type**	**Material Properties**	**Reclamation Work**			**Reference**
			Field Tests/ Field Trials	Band Drain Installation	Cover Placement	
IAA Helmsdorf, Germany	fine uranium tailings	10-50% clay; MC.=0.45..>1.0 $C_v=1..4x10^{-7}$; $c_c=0.5$; $s_u<5..10$	subaqueous placement		1m soil cover on intermediate tails	Jakubick and Hagen, 1998 RGC Report 028001/1-6
IAA Culmitzsch A, Germany	fine uranium tailings	silts&clays; MC.=0.7..>1.5 $C_v=1..5x10^{-7}$; $c_c=0.65$; $s_u<5..10$	1m cover trial w/ var. drain spacing	1.5m spacing	1m soil cover on intermediate tails	Jakubick and Hagen, 1998 RGC Report 028005/1
Eagle Mine Superfund Site, Colorado	fine uranium tailings	silts&clays; MC.=0.5..>1.0 $C_h=10^{-5}..10^{-6}$; $c_c=0.5..0.7$; $s_u<5$	2 trials w/ variable geogrids		0.6-4m fill plus multilayer cap	Neukirchner & Lord, 1998
Ranger Uranium Mine, Australia	fine uranium tailings	silts&clay; MC.=0.35..>1.0 $C_v=3x10^{-7}$; $c_c=0.2$; $s_u=5..10$	2m cover trial w/ monitoring of s & u_e			Sheng et al., 1998a; Sheng et al., 1998b
Highland Reclamation Project, Wyoming	fine uranium tailings	$C_v=1..3x10^{-7}$; $c_c=0.8..1.0$;		deep drains w/ 3m spacing		Miller and Range, 1989
Montana Tunnel Mine, Montana	fine tailings	MC.=0.35..>1.0 $C_v=6x10^{-8}..5x10^{-7}$; $c_c=1.0$;		deep drains (4.6-6.1m sp)		Brouwer et al., 1994; Brown et al., 1998
Ergo Tailings Dam, South Africa	fine tailings	$C_v=1x10^{-7}..6x10^{-6}$ (lab & CPT) $C_h \sim 6x10^{-5}$ (in-situ load test)	test loading w/ coarse tailings			Scheurenberg, 1987
PMC Magnetite Dam, South Africa	fine tailings	silt; $C_v=2x10^{-6}..3x10^{-5}$ (lab) $C_h=3..6x10^{-5}$ (in-situ load test)	test loading w/ coarse tailings	deep drains w/ 10m spacing		Scheurenberg, 1987
Wostar Coal Mine, BC	fine tailings	non-plastic silt; MC=0.4-0.6; c=0, $\phi=30\text{-}34^{o;}$; $s_u=0\text{-}5.0$	field trial w/ 1.0-1.3m fill & strong geogrid		1-1.3m cover for u/s construction	Burwash et al., 1993
Schoeller Paper Mill, New York	sludge	MC.=1.0..>2.0; $k=10^{-6}..10^{-8,}$ $c_c=1.3\text{-}3.3$; $s_u=2.4..13.4$	1m test fill w/ monitoring of s_u & s			Peterson et al., 1990
Fraser River, B.C.	soft, clayey silt	silt w/ clay; $C_h \sim 1x10^{-5}$		2.1m spacing	8m preloading	Robertson et al., 1988
Missouri River, Nebraska	soft, alluvial clay	40-60% clay; M.C.=0.4..1.0 $C_v=10^{-7}..10^{-8}$; $s_u=10\text{-}40$		1m spacing	4.5m embank-ment fill	Lutenegger et al., 1988
Vera Cruz Ramp, Panama	clay	$C_v=5.4x10^{-8}$ (lab), c=0, $\phi=35^o$			4m embankment fill	Mattox and Fugua, 1991

Symbol Index:
MC = Moisture Content; C_v = coefficient of vertical consolidation in m^2/s; C_h = coefficient of horizontal consolidation in m^2/s; C_c = compression index
s_u = total (undrained) shear strength in kPa; s = settlement; u_e= excess pore pressure

The early exposure of the slimes also allows for some initial surface strength gain due to air-drying. Figure 5 illustrates the increase in effective stress resulting from air drying, hence the increase in strength in the upper, particularly weal layers of the slimes. Placement of fill would then proceed cautiously using light equipment. Cover placement may have to be halted temporarily to allow further consolidation (Neukirchner and Lord, 1998). Air-drying can be enhanced by 'working' the tailings surface with amphibious vehicles and by planting vegetation to enhance evapotranspiration. This combination of air drying and 'trial and error' methods of advance appears to be the most common practice but is seldom documented. This trial-error approach may not always be suitable, however, due to uncertainties in the cover advance rate that can be achieved and uncertainties related to cover stability during construction.

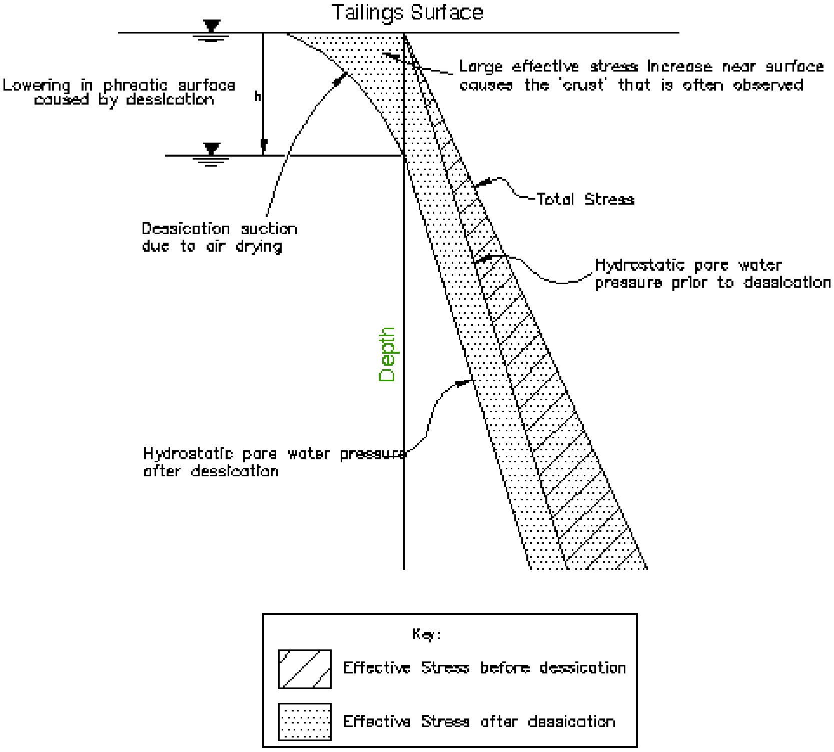


Figure 5. Increase in effective stress due to air drying.

Controlled Cover Placement without Failure

If a failure is to be avoided then the load during cover placement has to be reduced. There are three approaches to achieve a controlled cover placement without failure. First, the cover material can be placed in thin layers (say 0.3 to 1m) advanced with small light equipment, as illustrated in Figure 6a. A staged construction allows for the dissipation of excess pore pressures between placement of individual layers (e.g. Mattox and Fugua, 1991). Second, a lighter cover/fill material may be placed if such a source is available. For example, fly ash has been used as light fill material to cover soft tailings in the Mydlovari tailings impoundment in the Check Republic. Third, the cover material may be placed hydraulically using either a sub-aerial (spigot) or subaqueous discharge technique. Sub-aerial discharge is limited to those areas with tailings slopes of about 1 to 2% (Figure 6b). For areas with slopes greater than the sand beaching angle it would be necessary to contain the hydraulically placed sand behind a small retention berm (e.g. using sandfilled geotextile tubes) (Figure 6c). The sub-aqueously placed sand produces much steeper sub-aqueous beach slopes than for sub-aerial deposits (up to 10%) requiring a systematic movement of the discharge points to obtain a more uniform sand layer (Figure 6d). Initially only the buoyant weight of the sand contributes to the load on the slimes. Once some consolidation of the slimes has occurred under this first layer load, the pond can be dewatered. This results in the sand load increasing to reflect its total weight. The total weight of the initial layer can therefore be applied to the slimes in two increments with no construction equipment load.

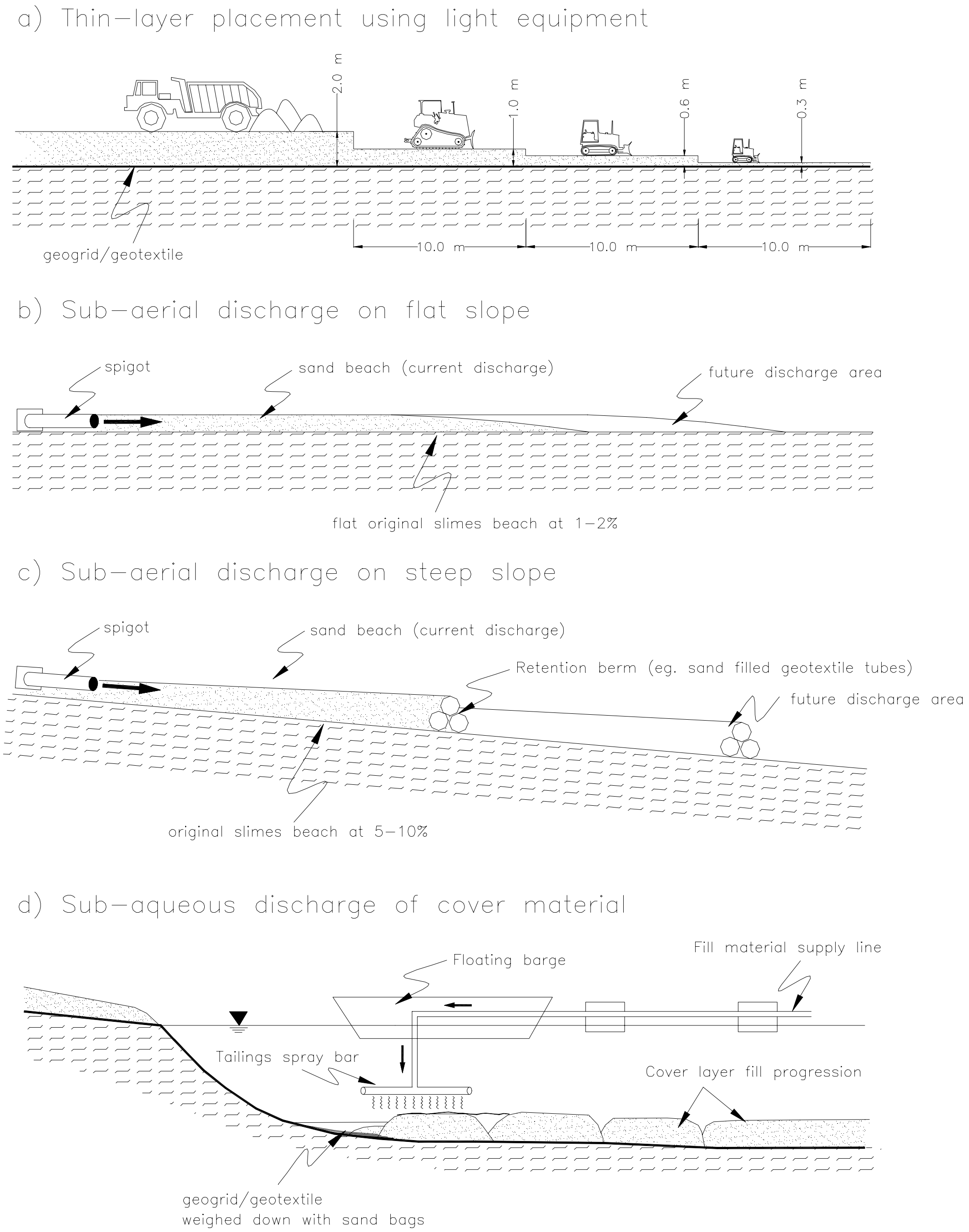


Figure 6a-d Methods of Controlled Cover Placement without Failure.

Measures to Enhance Tailings Strength

In most cases the near-surface shear strength of the slimes is too low to allow any of the above controlled placement techniques, in particular from the "dry", to be used without the risk of a slope or bearing capacity failure (Sheng et al., 1998a; Neukirchner and Lord, 1998). The most common and simple method to alleviate this problem is to place a geosynthetic tensile reinforcement element (geogrid or geotextile) directly onto the tailings. Geogrids and other reinforcing elements are commonly used for this purpose and the design methodology is well developed (e.g. Burwash et al., 1993; Peterson et al., 1990).

In addition, one of several measures can be taken to increase the shear strength of the tailings prior to and during cover placement (typically only the top 5-10m are critical to the stability during cover advance). First, the tailings may be dewatered prior to cover placement thus allowing dessication air-drying (Burwash et al., 1993, c. Figure 5). Weather, time and drainage/seepage conditions influence the effectiveness with which air drying can be achieved. Revegetation of the exposed slimes area may significantly enhance the depth to which the tailings can be dewatered due to root development.

Second, high permeability drainage elements, most commonly in the form of band drains, may be placed into the upper layers of the slimes. The band drains reduce the effective drainage path length (from the total tailings depth to half the horizontal spacing of the drains) significantly accelerating the consolidation process and allowing earlier access and faster advance rates during actual cover placement. Band drains are widely used to accelerate pore pressure dissipation and increase effective shear strength in soft clay foundations in earthworks construction (e.g. Robertson et al., 1998; Lutenegger et al., 1988). It is also increasingly being used in tailings impoundments to accelerate consolidation (e.g. Scheurenberg, 1987; Miller and Range, 1989; Brouwer et al, 1994; Brown et al., 1998).

Finally, in cold climates, it is common practice to place the initial layer once the surficial slimes are frozen (Neukirchner and Lord, 1998). Deep freezing, (to more than 1 m) allows heavy equipment to work directly on the tailings surface. Shallow freezing assists with placement of geotextiles and initial thin layer placement.

Design of Cover Placement – A Case Study

Wismut GmbH is currently overseeing the remediation of several tailings impoundments constructed during the post-war production of uranium by the former SDAG Wismut, a Soviet-East German state enterprise (Jakubick and Hagen, 1998). Based on a probabilistic risk assessment it was agreed with the regulator that a reasonable remediation is best achieved by placement of a dry cover over the tailings impoundments. The sequence of tailings remediation steps currently followed at WISMUT comprise: (i) removal of pond water, (ii) placement of an interim cover, (iii) tailings consolidation enhancement by de-watering, (iv) flattening of embankments and dams, (v) filling, grading and shaping of the tailings surface and (vi) construction of the final cover (Jakubick and Hagen, 1998).

Robertson GeoConsultants Inc. (RGC) was retained by Wismut GmbH to review and assess alternative options for placing a dry (interim) cover onto the slimes zone of the Helmsdorf impoundment (Figure 1). The Helmsdorf impoundment is the largest of the Wismut impoundments with 205 ha total surface area. Approximately half of that area is classified as intermediate and slimes zone (covered by water in 1996, Figure 1). It contains approximately 50 million tons of tailings, placed in the impoundment between 1957 and 1989 (Jakubick and Hagen, 1998).

The geotechnical properties of the slimes were first characterized by a detailed site investigation (Baugrund Dresden, 1995). Samples were taken from the slimes zone by drilling from a floating platform and using special vacuum sampling techniques and were analyzed in the laboratory. The results of this first geotechnical investigation are summarized in Table 1. A review of the data indicated that the consolidation parameters determined in the laboratory were not sufficiently accurate for prediction of future consolidation of the slimes. Instead, the consolidation parameters were determined by simulating the filling and self-weight consolidation in the slimes zone. In essence the filling of the impoundment represents consolidometer test at the field scale. The consolidation parameters (i.e. $e \rightarrow \sigma'$ and $k_f \rightarrow e$ relationships) were varied by trial-and-error until a good match with the current field conditions (void ratio profile) was obtained. This way the consolidation parameters were calibrated at the field scale providing greater confidence for later predictive modeling.

The simulation of the filling and self-weight consolidation requires the use of a non-linear finite strain (NLFS) model which accounts for the nonlinear consolidation properties of the slimes and the large strains occurring during settlement of these very compressible tailings (Schiffman et al., 1984; Caldwell et al., 1984). Figure 2 shows the void ratio and excess pore pressure profiles simulated for two slimes profiles in the center of the Helmsdorf impoundment using the NLFS model ACCUMV (Schiffman et al., 1992). The void ratios of both slimes profiles could be simulated very well using the same set of consolidation parameters ($e=-0.5 \cdot \log \sigma'(\text{kPa})+2.2$ and $e=1.8 \cdot \log k_f(\text{m/s})+17.2$). Unfortunately, measurements of excess pore pressures in the slimes deposit were not available for calibration at the time of the study. However, the high excess pore pressures simulated for the slimes deposit (Figure 2) are consistent with the low in-situ shear strengths observed in the slimes zone (Figure 3).

The calibrated consolidation model was then used to estimate the total amount and rate of settlement due to placement of an interim cover with and without vertical band drains. The presence of vertical drains was approximated in the 1D model by simulating consolidation in individual, horizontal layers (RGC 1996a). Figure 7 shows the simulated relative settlement for an interim cover of 2m thickness assuming either no drains are used or deep vertical band drains (at a horizontal spacing of 4m) are used. The modeling results suggested that (i) the relative settlement would be in the order of 20% of the total thickness of the slimes deposit (i.e. up to 4.5m total settlement); and (ii) the use of deep vertical drains would accelerate the rate of settlement by more than an order of magnitude (i.e. from ~25yrs to ~1.2yrs to reach 90% settlement).

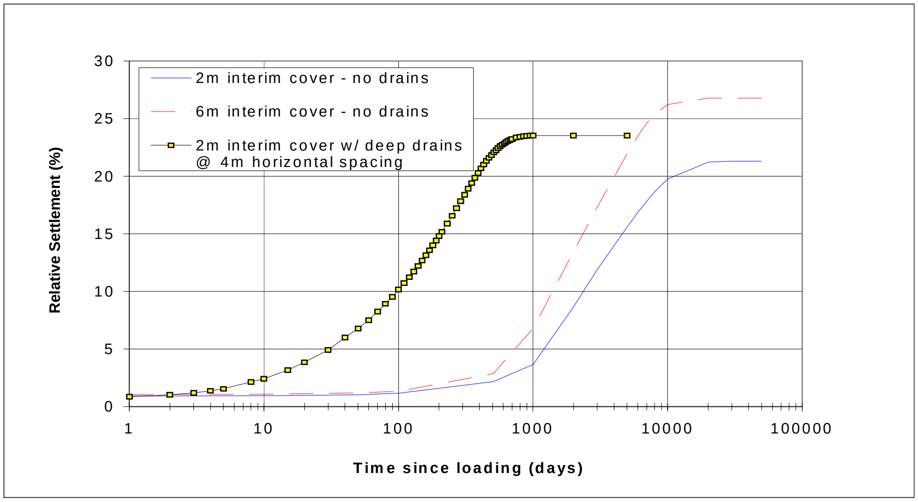


Figure 7. Simulated settlement (expressed as % of total tailings thickness) for different interim cover placement options.

The simulated values of relative settlement were extrapolated over the entire pond zone (intermediate and slimes zone) to estimate the volumes of contaminated pore water that would have to be treated and the volumes of fill material that would have to be placed prior to final cover placement. The total volume of pore water to be expelled from the tailings in the pond zone due to interim cover placement was estimated to be about 1.4 Mio m^3. The estimated settled tailings surface was used to develop a final surface plan. The maximum thickness of fill material (in the center of the slimes zone) was estimated to be about 6m. Consolidation modeling suggests that the placement of this additional fill material will result in some additional, albeit smaller, settlement of the slimes (c. Figure 7).

Preliminary stability calculations indicated that the undrained (in-situ) shear strength of the slimes is insufficient to support the placement of the planned 2m thick interim cover consisting of waste rock (total load about 36 kPa) even with the use of strong geosynthetic grid or fabric reinforcement (RGC, 1996b). It was concluded that for successful covering in a reasonable time frame it is necessary to adopt a construction and design approach which achieves and takes into account strength increases which occur as the cover placement proceeds (“effective strength design technique”). The use of band drains and surcharges to accelerate consolidation, and horizontal reinforcement to maintain stability during construction, makes it possible to control the excess pore pressure which is created in the compressible soil during cover placement (e.g. Mattox and Fugua, 1991).

The feasibility of a controlled placement without failure using thin-layer placement techniques was evaluated using a combination of consolidation and stability analyses (RGC, 1996b). Three different scenarios were evaluated which differ with respect to the horizontal spacing of the shallow band drains (all to a depth of 7m below top of tailings) and the timing of the layer placement (see Table 3). Figure 8 illustrates the thin-layer placement approach simulated here. In scenario 1 a very dense horizontal spacing of the vertical drains (at 0.8m spacing) is used to allow staged construction without prior consolidation. In scenario 2 and 3 the tailings are allowed to pre-consolidate by installing the band drains (at 1.5m spacing) from a barge floating on the tailings pond. In scenario 3, the pre-consolidation is enhanced by placing the first cover layer subaqueously (pre-loading due to buoyant weight). In all scenarios it was assumed that deep drains to the base of the impoundment are installed at 4m intervals to provide faster long-term settlement (Figure 8).

Table 3. Details of alternative cover placement scenarios.

Component	**Specifications**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Geosynthetic Reinforcement (Geogrid/Geofabric)	tensile strength = 15.8kN/m width	Yes	Yes	Yes
Deep Vertical Band Drains	depth = 12m	at 4.0m horizontal spacing		
Shallow Vertical Band Drains	depth = 7m	at 0.8m horizontal spacing(*)	at 1.5m horizontal spacing(2)	
Cover Layer 1	0.3m thickness	at t=14 days	at t=365 days(3)	at t=0 (4)
Cover Layer 2	0.3m thickness	at t=28 days	at t=379 days	at t=365 days
Cover Layer 3	0.4m thickness	at t=42 days	at t=393 days	at t=379 days
Cover Layer 4	1.0m thickness	at t=56 days	at t=407 days	at t=393 days
Completion of Interim Cover Placement	total of 2m thickness	after 8 weeks	after 1 year & 6 weeks	after 1 year & 8 weeks

Notes:
(1) installed using light pushing frame on geogrid reinforced tailings surface or long-boom installer from already completed interim cover
(2) installed using heavy rig from barge floating on tailings pond
(3) using subaerial or subaqueous placement
(4) immediately after installation of shallow band drains

For each scenario, the dissipation of excess pore pressures and settlement in individual slimes layers were simulated using the NLFS consolidation model. Figure 9 shows the simulated dissipation of excess pore pressures in a near-surface slimes layer (0.8 to 1.6m depth) during construction for the three scenarios examined. Figure 10 shows the respective Ru-profiles for the time of cover layer placement calculated from the simulated excess pore pressures and assuming the layers are advanced using a D7. The Ru-factor is defined here as the ratio of the total pore water pressure to the total stress acting on the soil (and thus depends on the weight of the machine used for advancing a given cover layer).

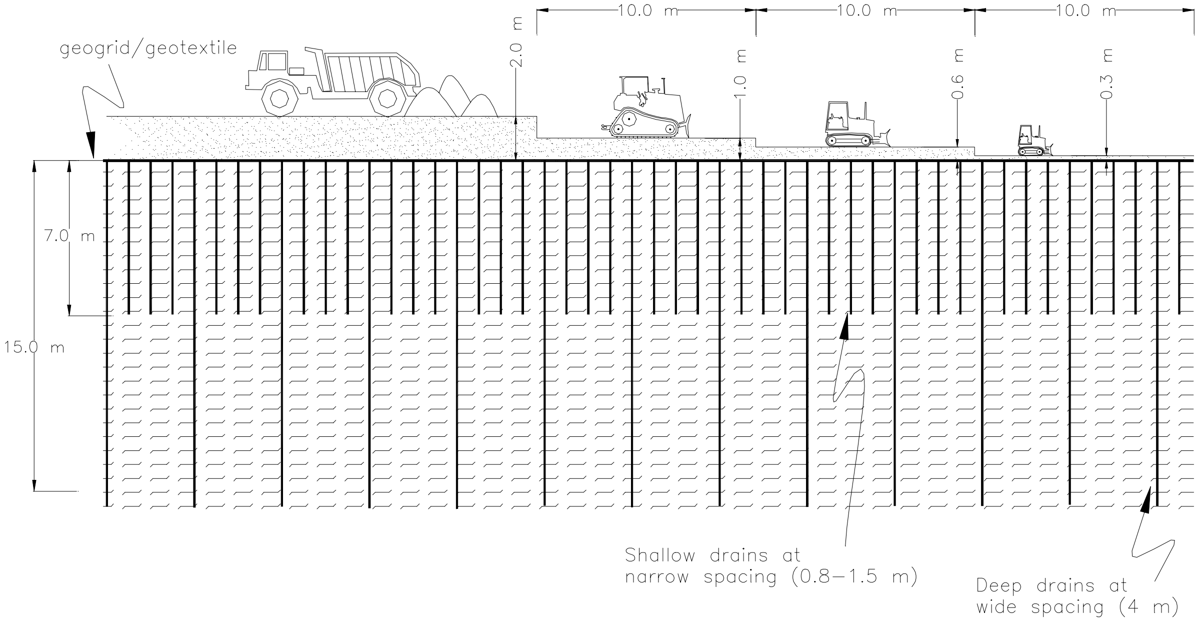


Figure 8. Schematic illustration of thin-layer placement showing shallow and deep drains and geogrid reinforcement.

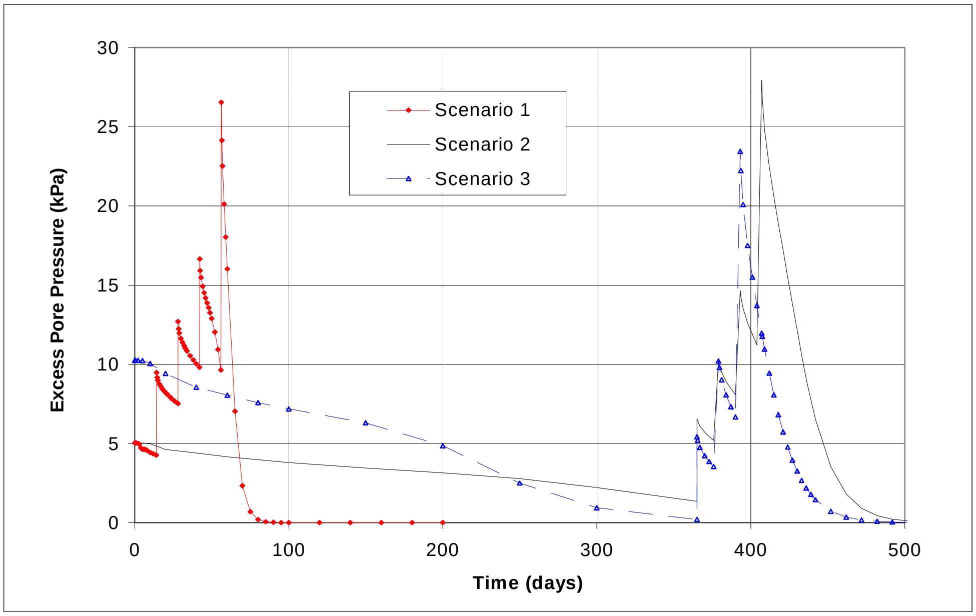


Figure 9. Simulated excess pore pressures in near-surface layer during construction for three alternative cover placement scenarios

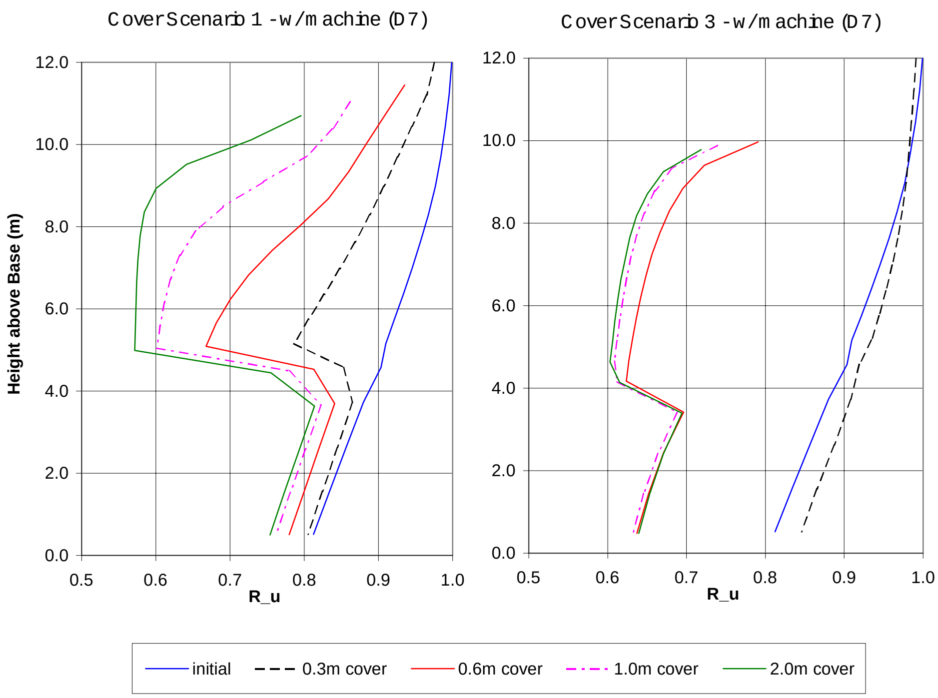


Figure 10. Calculated Ru profiles for scenario 1 and scenario 3 assuming the use of a D7 for cover placement.

The calculated Ru profiles were then imported into a slope stability model (SLOPE/W) and the stability simulated for critical times of construction, i.e. at the times of cover placement. The slope stability was evaluated for each layer advance using different machine loads and different tailings slopes (see RGC Report 028001/6 for details). Figure 11 shows a typical model set-up and the slip circle with the lowest factor of safety for scenario 2 (assuming a D3 is used for final layer placement on 5% slope).

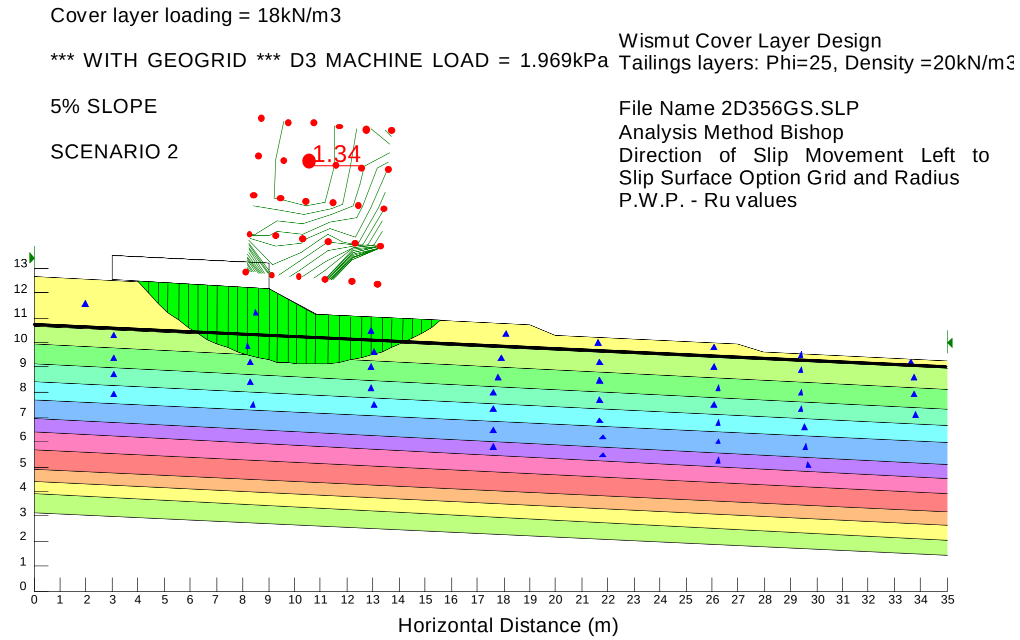


Figure 11. Slope stability analysis for scenario 2 assuming 5% slope and use of D3 for placing fourth cover layer.

It was concluded from the slope stability analyses that the placement of the first layer is generally the most critical one. For construction entirely ‘in the dry’ (scenario 1) it would be necessary to install shallow band drains at 0.8m horizontal spacing and use very light placement equipment such as Bobcats. If band drains were installed from the pond surface and drainage occurred for a year prior to cover placement (scenario 2), the spacing of the drains could be increased to 1.5 m. With the installation of band drains as well as the placement of a 0.3 m initial cover layer by hydraulic means (scenario 3) it was possible to use larger placing equipment. The effect of steeper beach slopes, as occurs on the pond side slopes, was found to be substantial. Modeling results suggest that it would be necessary to use smaller placement equipment or more geosynthetic

An interesting finding of this study was that the deformation (settlement) simulated for the incremental cover loads were at times greater than the incremental layer thickness. Consideration of these deformations in the stability analyses indicated that this has a significant stabilizing effect (Figure 12). It is concluded that with such large settlements the deformed geometry should be considered explicitly in the stability analysis.

The consolidation and stability analyses were found to be very sensitive to the model input parameters, in particular the nonlinear relationships of $e \rightarrow \sigma'$ and $k_f \rightarrow e$. It was concluded that field tests to determine field parameters and field trials to test placement techniques at the field scale are essential to verify these initial modeling results. Several field tests and field trials are currently being undertaken in the slimes zone of the Helmsdorf impoundment (and other Wismut tailings impoundments). The results of these field trials and tests will be used to update the consolidation and stability models in order to improve the accuracy of predictions for final design purposes.

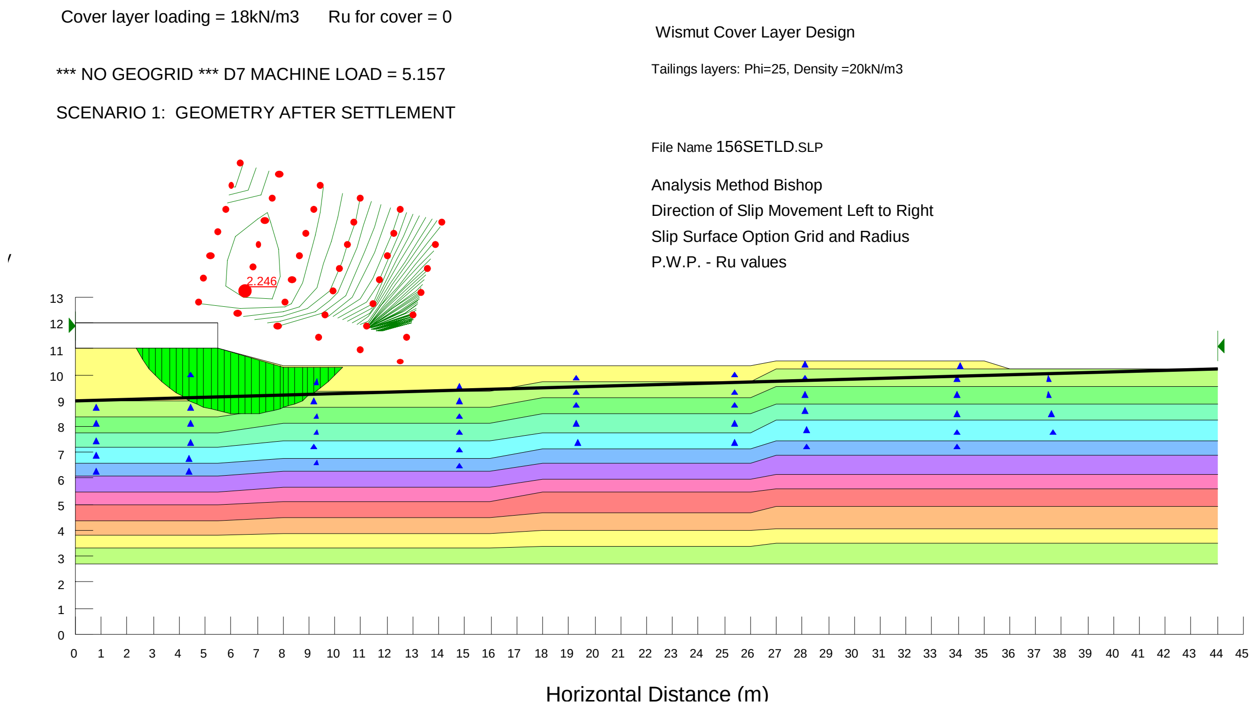


Figure 12. Stability analysis with explicit representation of estimated settlement due to cover placement.

CONCLUSIONS

The construction of soil covers on very weak, compressible fine tailings ("slimes") often presents a formidable challenge due to the low shear strength, poor trafficability, and high settlement of these underconsolidated tailings at the time of reclamation. The optimal technique (or combination of techniques) for placing a dry cover will vary from site to site and is influenced by the environmental and geotechnical circumstances as well as cost and availability of materials and equipment used for cover placement. Experiences from a large uranium tailings reclamation project indicated that a good understanding of the geotechnical properties of the slimes are essential for selecting the most suitable strategy for cover placement. The combined use of consolidation and slope stability modeling was found to be a powerful tool for initial selection of cover placement equipment and cover advance rates. Field tests and field trials are currently under way to confirm initial modeling results and to finalize the cover placement design.

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