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'Free' water from thickened tailings

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Abstract

Recent trends in tailings disposal are aimed at disposal without 'dams'. Although tailings basins (and dams) can be designed, constructed, operated and closed safely and very economically, recent initiatives have focused on minimising the use of hydraulic structures for containing tailings. These initiatives have been (and should be) driven by decisions based on considerations for water supply and economic considerations associated with minimising risk from (1) the potential adverse environmental impacts with the 'free' water from thickened tailings, (2) having a dependable tailings management system for operating tailings dams, and (3) public perception with tailings dams. In most cases, water is the key factor in the evaluation of risk with tailings disposal. This paper will address some of the concepts used to estimate the quantity of 'free' water that is available from thickened tailings for recycling (if water shortage is a consideration) and to assess the potential risks for this 'free' water to cause adverse environmental impacts. Predictive flow modelling of thickened tailings, drainage, and the hydrologic settings in which thickened tailings are deposited is a key tool in quantifying 'free' water production. The movement of 'free' water from the thickened tailings will be discussed in the paper. Once the quantity of 'free' water is known, the associated risk may be evaluated more accurately. Two case histories will be presented that illustrate the concepts; one involving thickened tailings/paste from a soda ash facility in Wyoming, USA and one from flu gas desulpherisation (FGD) sludge from a coal-fired power plant in North Dakota, USA. General concepts for tailings disposal, with minimal use of 'dams' on projects that are currently under development, will also be discussed. The benefits, as well as the challenges of having 'free' water available within the thickened tailings during disposal will be addressed. Finally, 'free' water from thickened tailings and sludge must also be accounted for when evaluating the thixotropic characteristics of these materials. The role that salinity plays on thixotropy must be considered when designing containment structures for thickened tailings. This paper will discuss the thixotropy of thickened tailings and FGD sludge.

1 Introduction

Recent trends in tailings disposal are aimed at disposal without 'dams'. However, tailings disposal as a paste or dewatered tailings without 'dams' poses problems that are similar to those associated with conventional disposal into a sedimentation basin with containment dams. Although tailings dams can be designed, constructed, operated and closed safely and very economically, recent initiatives have focused on minimising hydraulic structures for the storage of tailings. These initiatives have been (and should be) driven by decisions based on considerations for water supply and the economics associated with minimising risk. There is risk in: 1) the potential for environmental impacts arising as the 'free' water from thickened tailings evolves and migrates; 2) having a dependable tailings management system for operating tailings dams; and 3) running afoul of public perception. In most cases, water (and especially the free water) is the key factor in the evaluation of risk in regards to tailings disposal.

By 'free' water, we mean fluid that is included within the interstices of tailings or paste at the time of disposal but post-emplacement, is able to migrate from the tailings or paste. We address some of the concepts used to estimate the quantity of 'free' water that is available from thickened tailings for recycling (if water shortage is a consideration) and to assess the potential risks for this 'free' water to cause adverse environmental impacts and concerns about dam safety. We discuss why predictive flow modelling of thickened tailings, drainage, and the hydrologic settings in which thickened tailings are deposited is a key tool in quantifying 'free' water production and movement. Once the quantity of 'free' water is known, the available water supply, the environmental risk and dam safety may be evaluated more accurately.

2 Concepts used to estimate free water generation

A simplified concept for estimating free water is illustrated in Figure 1. Free water will be generated in a sedimentation basin from the settling of the solids according to Stokes law. Stokes law describes, in simple terms, the settlement of solids in a fluid. For purposes of this discussion, the tailings/paste is assumed to have already settled in accordance with Stokes law and the resulting free water from this settlement has already been generated and removed (or otherwise used).

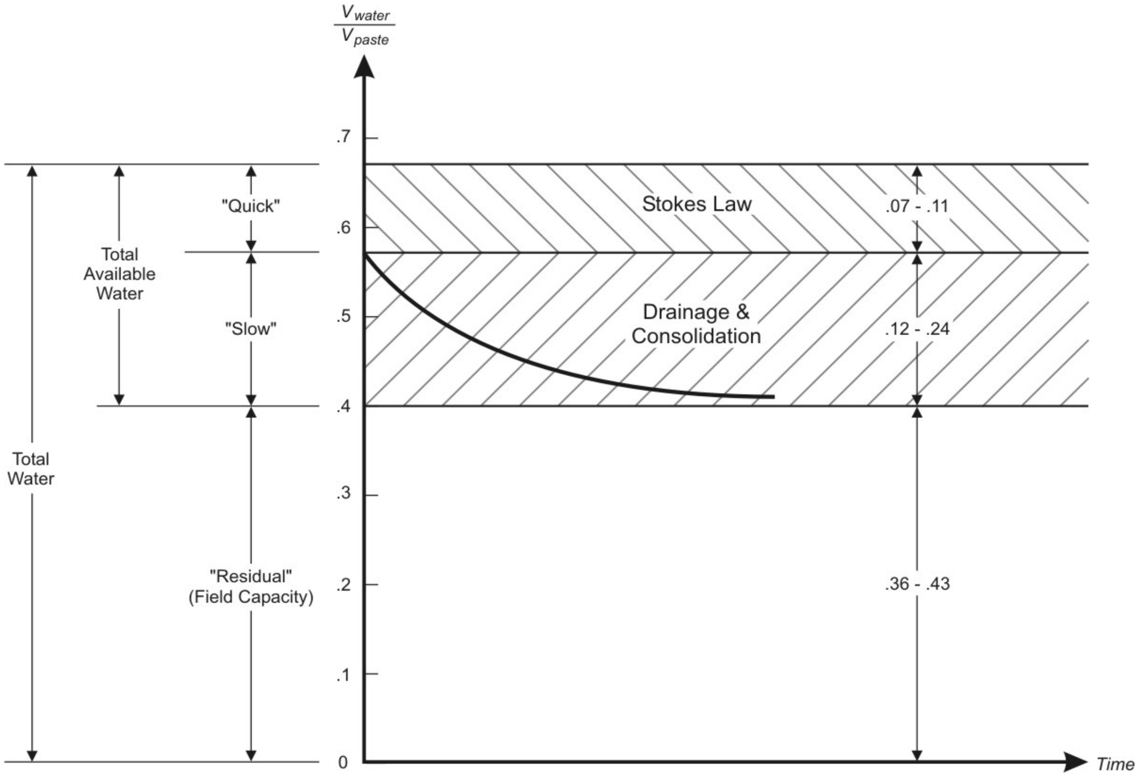


Figure 1 Illustration of simplified concept for estimating free water

After sedimentation has taken place, additional free water will become available by gravity drainage and by consolidation. A simplified method for determining free water available from tailings by gravity and consolidation was developed in the 1970s (Barr, 1978) and is discussed herein. More sophisticated methods are now available using computer techniques.

Free water from gravity drainage of the tailings/paste will take place until an equilibrium condition (herein called the 'field capacity') is approached. The field capacity is defined in general terms according to ASTM D2325, Test for Capillary-Moisture Relationships for Soils. An approximate way to calculate the volume of gravity water based on the field capacity of the material is shown on Figure 2. The calculation also implies that if the *in situ* moisture content is less than the field capacity, then the volume calculated is the amount of water that can be added to the soil-water system before free water is generated by gravity drainage.

$$V_g = \frac{\omega_g \gamma_d H}{100\gamma_w}$$

Where: V_g = volume of gravitational water released (cubic meter of water per square meter of disposal area surface) from the full height of the disposal site if the moisture content is constant over the full height of the disposal site or from the portion of the disposal site with a gravitational water content equal to ω_g.

ω_c = gravitational water in the waste expressed as a moisture content (%) of the difference between natural moisture content and field capacity.

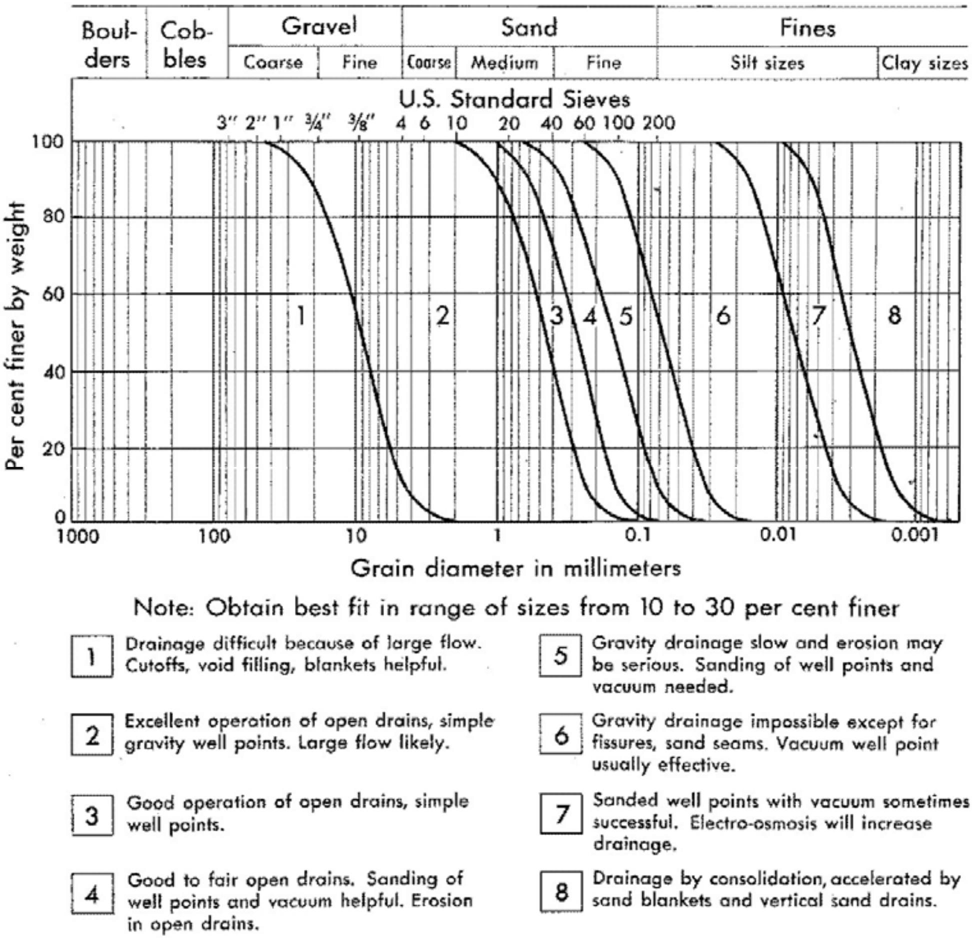
γ_d = dry density of the residual waste material (kg per cubic meter).

H = height of the residual waste in the disposal area with a gravitational water content equal to ω_g (meters).

γ_w = density of water (1,000 kg per cubic meter).

Figure 2 Volume of gravity water based on field capacity (Barr, 1978)

The amount of water derived from gravity drainage is generally based on the distribution of grain size, as illustrated in Figure 3. If the grain-size distribution is sufficiently small, no further water will drain by gravity and some additional driving force is necessary in order to generate more free water from the tailings/paste. Typically in a tailings basin or paste pile, as additional material is added, the increased weight of the tailings/paste (i.e. the lithostatic load) becomes the driving force that 'squeezes out' more free water. Higher pore pressures force water out of the void space until a new equilibrium condition is approached.



Note: Obtain best fit in range of sizes from 10 to 30 per cent finer

1 Drainage difficult because of large flow. Cutoffs, void filling, blankets helpful.

2 Excellent operation of open drains, simple gravity well points. Large flow likely.

3 Good operation of open drains, simple well points.

4 Good to fair open drains. Sanding of well points and vacuum helpful. Erosion in open drains.

5 Gravity drainage slow and erosion may be serious. Sanding of well points and vacuum needed.

6 Gravity drainage impossible except for fissures, sand seams. Vacuum well point usually effective.

7 Sanded well points with vacuum sometimes successful. Electro-osmosis will increase drainage.

8 Drainage by consolidation, accelerated by sand blankets and vertical sand drains.

Figure 3 Drainage capabilities of soils (Sowers and Sowers, 1970)

The amount of free water that can be generated through consolidation is estimated using laboratory test data obtained using methods such as those described in ASTM 2435, Standard Method for One-Dimensional Consolidation Properties of Soils. The pressure-void ratio curves are plotted in accordance with this ASTM Standard. The void ratio at saturation is Gw = Se, assuming full saturation or an S value of 1. The curves are then plotted as pressure vs. moisture content at saturation. Figure 4 shows an approximate way to calculate water derived from consolidation based on the consolidation properties of the tailings/paste. Of course, not all tailings or paste will generate free water from consolidation — the moisture content of the waste in situ needs to be at saturation for this to take place.

$$V_c = \frac{\omega_c \gamma_d H}{100\gamma_w}$$

Where: V_c = volume of consolidation water (cubic meter per square meter of landfill surface) released from the entire disposal site if the moisture content is constant throughout the site or from the portion of the disposal site at a consolidation water content of ω_c.

ω_c = consolidation water in the waste expressed as a moisture content (%) as the difference between the field capacity and the moisture content corresponding to the consolidation pressure from the consolidation graph.

γ_d = dry density of the residual waste material (kg per cubic meter).

H = height of the residual waste in the disposal area (meters).

γ_w = density of water (1,000 kg per cubic meter).

Figure 4 Volume of water based on consolidation test data (Barr, 1978)

Based on the above principals, we can conclude the following:

- Free water from tailings/paste will be generated if the in situ moisture content is at or above the field capacity of the waste.
- The amount of free water that is generated can be estimated using standard testing methods.

The volume of free water generated from tailings, paste and waste piles should be an important consideration because this water often has dissolved concentrations of waste constituents that exceed drinking water standards. As such, migrating free water from tailings and paste can represent a potential risk to water supplies and other environmental receptors such as streams, lakes, and wetlands. In some cases, the free water that is generated from tailings or paste represents a valuable water resource for meeting operational needs such as dust control and tailings slurry make-up. In both cases, more sophisticated methods for estimating free water using groundwater models for saturated and unsaturated flow may be appropriate.

3 The role of models in tracking the fate of free water

Numerical groundwater flow models are commonly used to predict the movement of water in the saturated zone from sources to discharge areas. In a tailings/paste disposal setting, they can work hand-in-glove with drainage and consolidation calculations. Numerical groundwater models can be used to better conceptualise the overall groundwater system or they can be more rigorously applied as a predictive tool to evaluate the movement of free water and quantity its availability. Commonly used codes include MODFLOW (McDonald and Harbaugh, 1988) and FEFLOW (WASY, 2004).

The most common approach used in the employment of groundwater flow models to tailings/paste emplacement is to decouple the problem of free-water evolvement from the prediction of the movement/migration of the free water. In other words, gravity drainage and free water generation due to consolidation are assumed to take place independently of larger scale groundwater flow. In this scenario (shown on Figure 5), free water from the tailings/paste becomes a source of additional water to the groundwater flow system but the groundwater flow system (in particular, the location of the phreatic surface) does not influence how much and when free water is generated. Free water from the tailings/paste is added to the groundwater flow system in much the same way as infiltrating precipitation is treated. These assumptions are most applicable to settings in which the tailings/paste is placed several feet or more above the water table.

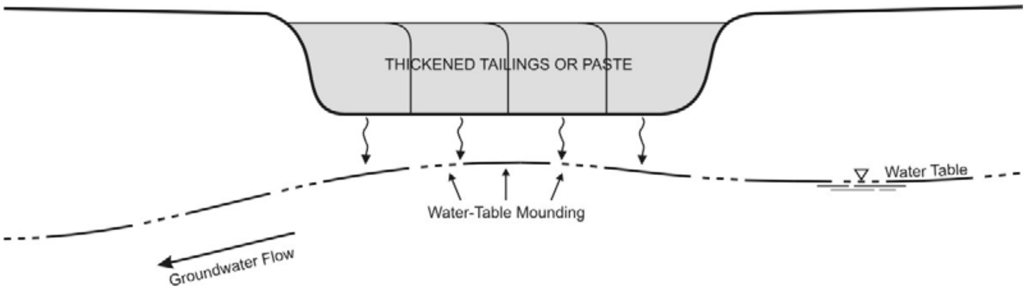


Figure 5 Water table passing through

The application of groundwater flow models to free-water movement can become more complicated in settings were the water table is initially near the bottom of the tailings/paste or where the water table moves up into the tailings/paste zone due to mounding caused by the generated free water or by some other circumstance (e.g. climatic changes, changes in regional pumping, etc.). In these situations (shown on Figure 6), the groundwater flow system directly influences the degree of saturation of the tailings/paste and the ability of the tailings/paste to drain or consolidate. Groundwater may actually flow through portions of the tailings/paste. The result is really not thickened tailings anymore but rather, a traditional tailings basin. The thickened tailings or paste becomes less as source and more a porous medium through which groundwater flows.

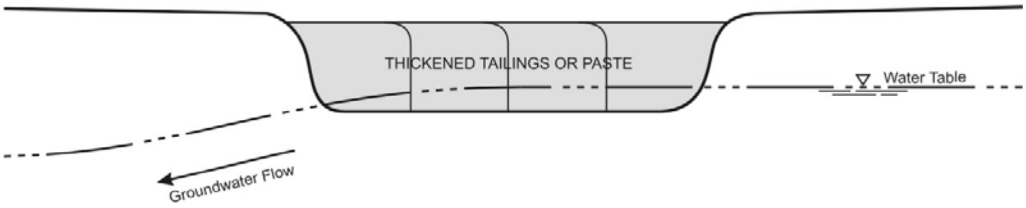


Figure 6 Water table mounding

Depending on one’s perspective and bias, groundwater flow models are typically either too simple (and fraught with uncertainty) or too complex (and fraught with uncertainty).

4 Case histories of paste/dewatered tailings/waste

Two case histories are presented that illustrate the concepts; one involving thickened tailings/paste from a soda ash facility in Wyoming, USA and one from FGD sludge in a coal-fired power plant in North Dakota, USA. The benefits, as well as the challenges of having ‘free’ water available within the thickened tailings during disposal will be addressed.

4.1 Soda ash thickened tails

Soda Ash (sodium bicarbonate) is an important additive in glass making and is used as a softening component in laundry detergent. It is mined extensively in the Green River Basin, Wyoming, USA, where it was deposited as part of an extensive Eocene evaporate deposit. Mining takes place underground and above-ground processing involves milling, drying, and transmission of tailings as a slurry into large basins. Efforts to minimise tailings volume have led to a mix design for underground and surface disposal of tailings as a paste.

Standard testing methods, previously described, were employed to determine the appropriate mix for the paste. A slump cone was used to evaluate the relationship between paste consistency and moisture content. Figure 7 shows the slump cone testing and the moisture contents of wet, average and dry paste states. Based on the slump test data, the material appears to have some structure for stability as the tailings becomes drier.

Figure 8 shows the plot of the mix design as a function of moisture content, illustrating that even the "dry" mix has a moisture content above the liquid limit and will behave as a liquid when it is transported and deposited. This, in fact, was the case in practice.

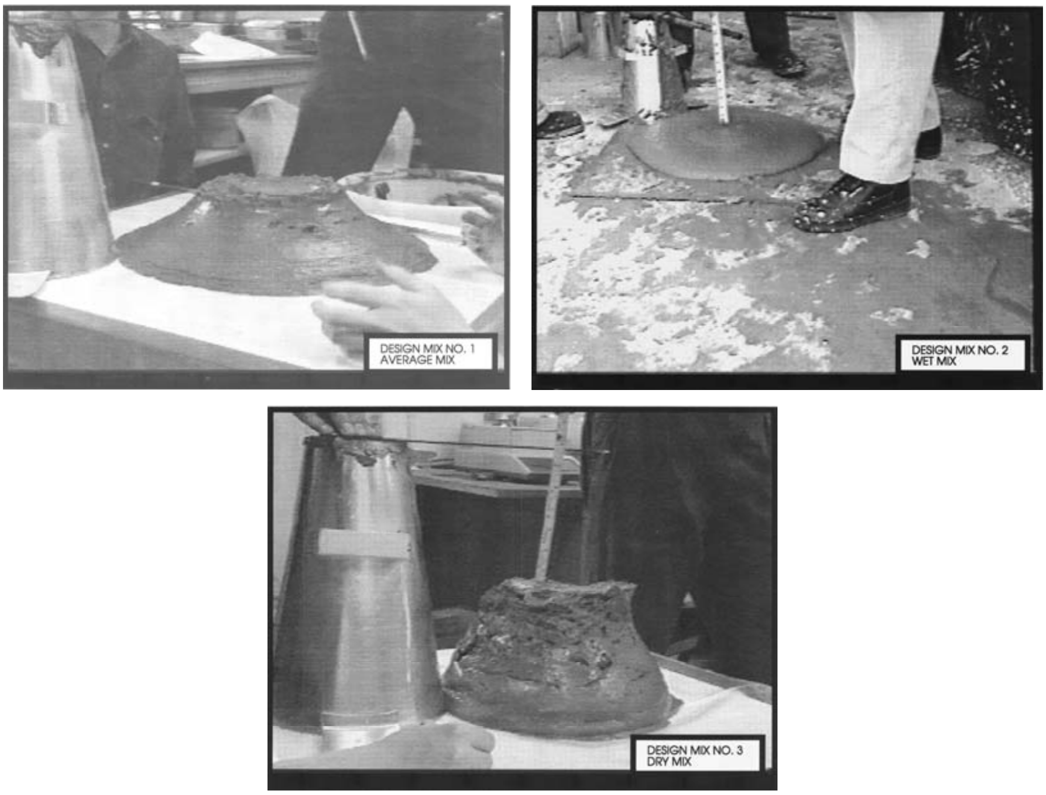


Figure 7 Slump cone tests

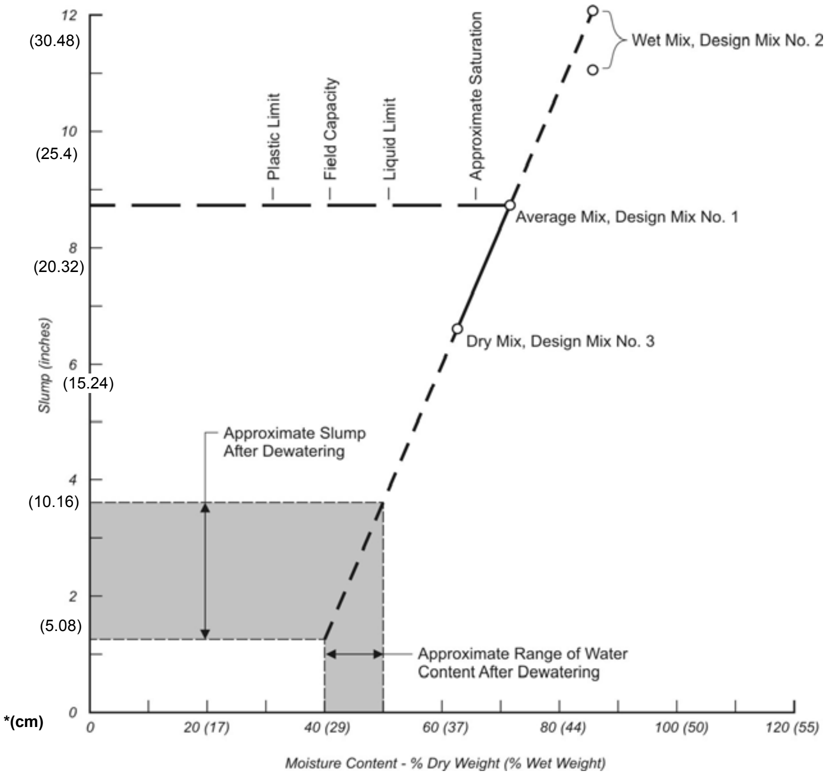


Figure 8 Mix designs versus moisture content

Because the paste material is above the liquid limit, surface disposal of tailings requires containment dams. These containment dams were constructed on the existing tailings delta to contain tailings until they became dewatered via drainage and consolidation within the basin. The paste containment was designed to allow the free water to be used in dust suppression by allowing the free water to seep through the pervious delta material, under the containment dams and onto to the delta, thereby keeping the delta wet and minimising dusting from the basin.

Evolvement of free water from the thickened soda ash tailings also had to be factored into the overall basin water balance and seepage collection system. As drainage and consolidation generated free water, downward seepage contributed to the groundwater mound that had been established underneath the basin from years of conventional tailings disposal. Increased seepage resulted in increased hydraulic head and overall increases in lateral seepage toward a nearby river. An existing multi-layer MODFLOW groundwater flow model of the basin and surrounding area was used to predict the effects of additional water from the thickened tailings to the overall groundwater flow system (Figure 9). The estimated rate of free-water evolvement into the basin formed the basis for increased hydraulic head estimates as input into the groundwater flow model. Using this model, the flow paths of the free water could be predicted and a determination could be made as to the adequacy of the existing seepage collection systems on future interception of affected groundwater.

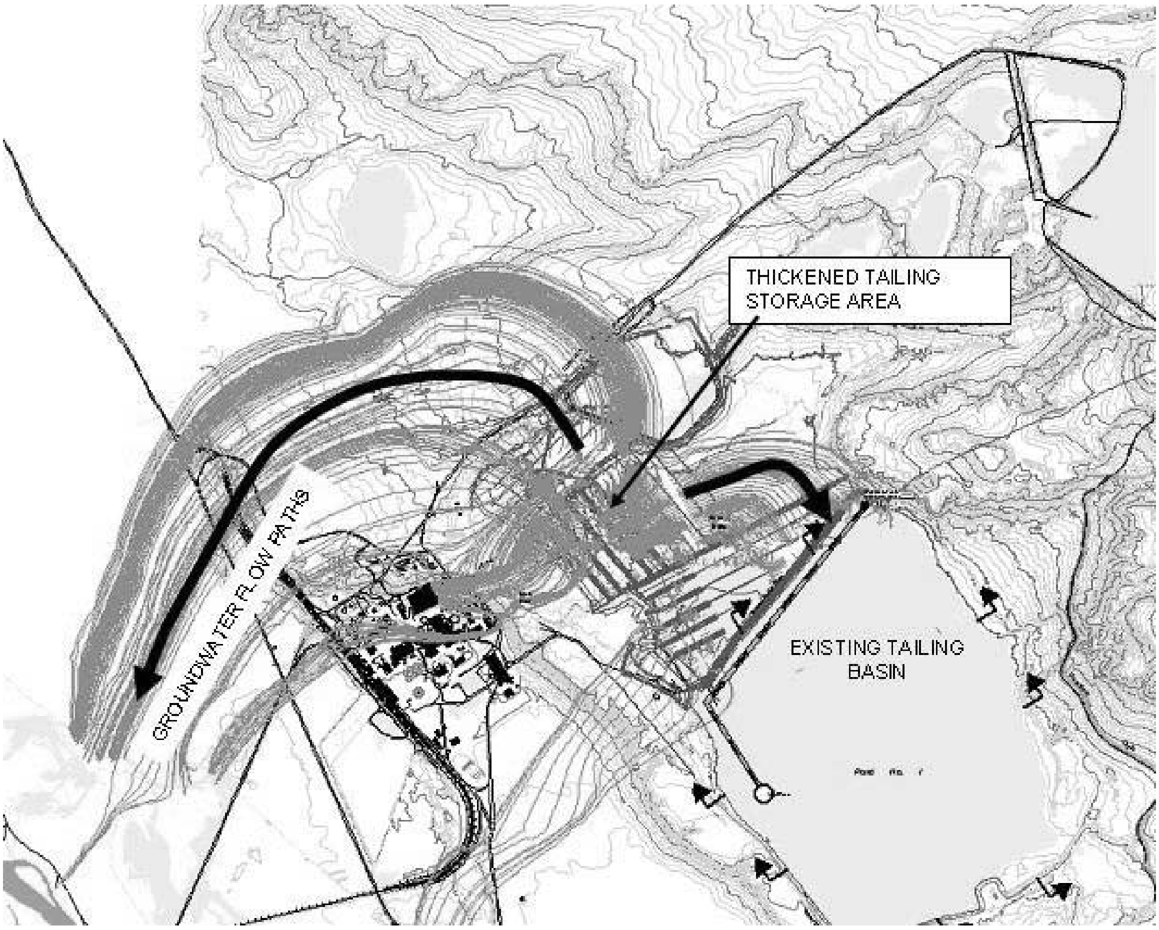


Figure 9 Groundwater flow model

4.2 Flu gas desulpherisation (FGD) sludge

At a coal-fired power plant in North Dakota, USA, flu gas desulpherisation (FGD) sludge is a waste residual that is temporarily retained in a basin until it can be excavated and hauled to nearby coal strip mines. The sludge was found to be initially stable during excavation from the basin but would suddenly collapse into a semi-liquid form as it was being loaded onto trucks for transport. When the FGD sludge reached the strip mine, it was reduced to essentially a semi-liquid. This semi-liquid form greatly impeded disposal because the low strength of disturbed FGD sludge was insufficient for truck traffic.

Testing of the FGD sludge was performed to define the various moisture relationships. Table 1 shows the moisture content relationships and density of the sludge. Based on these data, it was evident that free water would evolve and the FGD sludge would need to be dewatered if trucks were to be used to haul the material to the strip mines. Transport by other methods would present similar problems.

Table 1 FGD sludge moisture content relationships

	FGD Sludge	
	Sample @ Decant Area	**Sample @ Disposal Pit**
1. Moisture content (%)		
a. Laboratory test sample	162.8	50.3
b. Field capacity: 1/3 bar (gravity water)	130	48
c. Consolidation: mid layer	Not used	45
2. Dry weight (kg/m^3)	421.3	1,091.0

To dewater the FGD sludge prior to excavation and transport from the basin, a drain system was installed in the basin. This system dewatered the sludge by gravity drainage and consolidation until the moisture content was sufficiently low to allow for excavation and hauling without liquefaction.

In the strip mine, another drain system was also installed to dewater the sludge further and for a trafficable surface to develop. The drain system removed the remaining free water to a sump where it was pumped to an evaporation pond. Some sludge had already been placed in the strip mine prior to the drain system being installed. A drain system was installed above the existing sludge in alternating layers of waste and drainage material to capture the free water. This free water was discharged by gravity and consolidation into a sump where it was pumped to the evaporation pond. The drains were spaced in such a manner to promote dewatering quickly enough to allow for truck traffic over the sludge. Figure 10 shows the cross section of the strip mine with the sludge and drains.

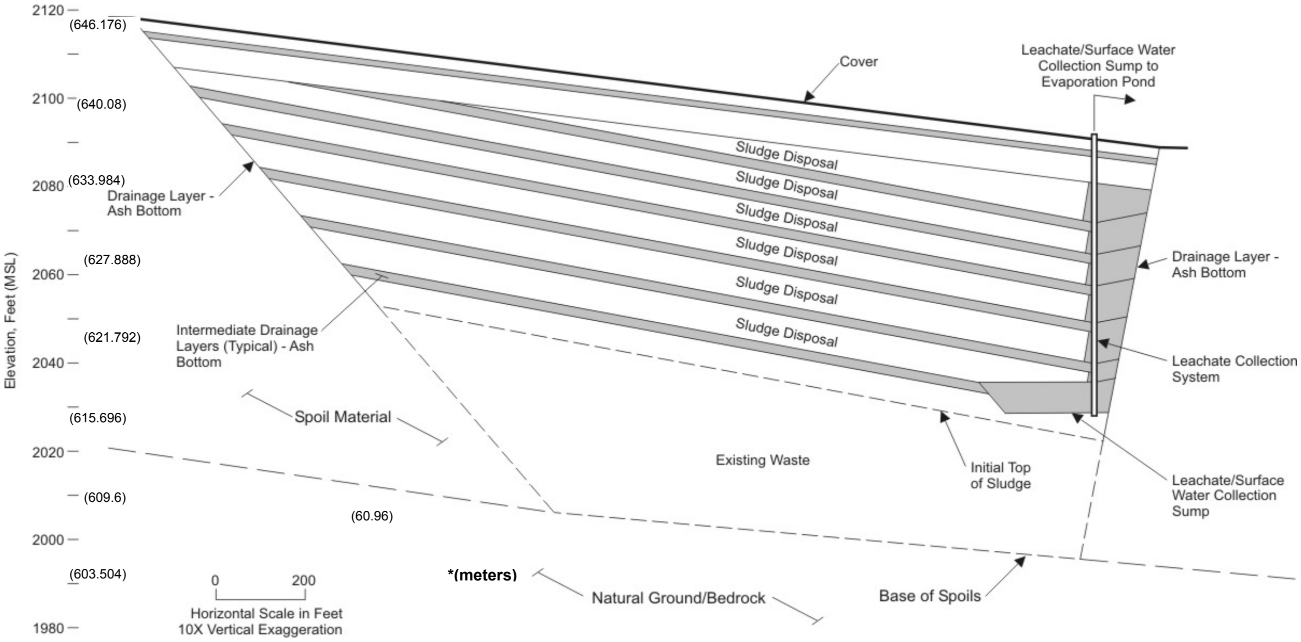


Figure 10 Pit cross section

As new waste was added, the existing waste consolidated and formed a layer that impeded downward flow of the fee water that evolved above it. The consolidation process decreased the permeability of the sludge but the build-up of pore pressures within the lowermost consolidating sludge also contributed to the creation of a nearly impervious barrier.

The relatively simple methods for determining the amount of free water, as described at the beginning of this paper, were found to reliably estimate how much free water would evolve from the FGD sludge and formed the basis for sizing sumps and evaporation ponds. The drainage systems and evaporation pond performed as intended and this site is now closed and reclaimed.

5 Special case of sensitivity and thixotrophy

Sensitivity, in general terms, is the loss of undrained strength when an undisturbed sample is remoulded. The causes of sensitivity are described in Mitchel (1976). Thixotropy is the property whereby a material stiffens while at rest and softens or liquefies upon remoulding (Mitchel, 1976). Materials with these properties change to liquid under shearing stress, e.g. when shaken, and return to the original state when at rest. The change is completely reversible: no change in water content or composition occurs. The sensitivity and thixotropic characteristics of thickened tailings and sludge need to be accounted for when evaluating the tailings/waste disposal methods. Although formal analyses of the thixotropy or the geochemistry related to sensitivity of the tailings/waste materials in the above examples were not performed, the thixotropic characteristics along with the causes of sensitivity were recognised and accounted for in the designs.

The examples provided herein contained ‘salt’ within the matrix. This salt tended to ‘bind’ the particles together causing an apparent strength to the structure. In both the soda ash thickened tailings and in the FGD sludge, the material would ‘stand-up’ and appear relatively stable under static conditions. In both cases, however, movement or transportation of the material caused the particles to separate and liquefy. In the case of the soda ash tailings, containment dams were required to contain the tailings for further dewatering. In the case of the FGD sludge, the dewatering in the initial basin was designed to allow for excavation and transportation of the waste and further dewatering in the final disposal area that would accommodate truck traffic.

The thixotropic nature and the causes of sensitivity of tailings/paste material are important when addressing the use of thickened tailings or paste for containment. In general, although the paste or thickened tailings will appear to be stable for containment on its own, the thixotropy of the material may result in a liquefaction of the containment and subsequent release of the tailings if disturbed or moved. Thus, properly designed containment dams and/or properly designed drainage systems are required to minimise the risk of instability of the dewatered tailings/paste.

6 Conclusions

A tailings or waste that has been dewatered or made into a paste will generate free water when disposed of. As such, the benefits of having a dewatered tailings/paste may or may not be greater compared to conventional tailings disposal using dams that are properly designed and constructed to contain tailings/wastes and collect seepage. In no way should one assume that forming tailings or waste into a thickened material alleviates the need to analyse, manage, and collect seepage — seepage will result as free water evolves from these materials. Furthermore, the causes of sensitivity and the thixotropic characteristics of the dewatered tailings/paste may be such that the apparent strength from a dewatered tailings/paste cannot be relied upon for stability and containment dams may be necessary to physically control the solid materials.

Recent trends in tailings disposal are toward disposal without ‘dams’, but a ‘dam-less’ (no pun intended) approach may only be applicable to a limited number of situations. Therefore, the driving considerations for use of conventional tailings disposal in sedimentation basins versus dewatering/paste disposal should be based on considerations for: 1) having an available and manageable water supply from dewatered tailings versus clear water in a sedimentation basin and 2) the economics associated with minimising risk. Sources of risk include: 1) environmental impacts of the ‘free’ water versus seepage water; 2) having a dependable tailings management system for operating tailings dams safely using thickened tailings/paste versus containment dams; and 3) adverse public perception. In general, it appears that the public perceives that a dewatered tailings/paste is safer and has less environmental impact than conventional tailings disposal.

We recognise that there are other considerations for having tailings/waste dewatered or made into a paste. For example, thickened tailings/paste has the potential for reducing the basin volume if sedimentation is difficult to promote or if the tailings/waste can be disposed of in a non-segregated manner as a dewatered tailings/paste at less cost compared to conventional sedimentation methods. However experience has shown us that it is important to consider both conventional tailings disposal by sedimentation with containment dams and a dewatered/paste tailings/waste when evaluating tailings/waste disposal methods. The benefits of both should be evaluated and decisions should be based on water needs, economics, and safety along with public perceptions.

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