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Geomorphology of thickened tailings beaches: insights from field deposition and full-scale trials

Behnam Pirouz [a,*], Sadegh Javadi Rudd [a], Keith Seddon [a]

[a] *ATC Williams, Australia*

Abstract

The tailings beach slope and profile are undoubtedly the most critical design parameters for thickened tailings schemes. The storage capacity, initial embankment and subsequent raise heights, water pond size and location, tailings storage facility (TSF) footprint and the long-term operational costs all depend on the actual achieved beach slope.

Realistic and accurate beach slope prediction would not be possible without a full understanding of the mechanisms governing the formation and development of thickened tailings beaches.

Observations from large-scale field deposition trials and full-scale TSFs across various mine sites have been used to develop a descriptive model that outlines the key processes and mechanisms involved in thickened tailings beach formation, their interactions, and their effects on the resulting overall beach slope. The model presented in this paper highlights the relative significance of sheet flow and self-formed channel flow in the formation and evolution of the beach.

The model is set in the context of the overall picture of thickened tailings beach development over time, and describes different stages of beach formation, the development of a plunge pool, flow mechanisms from the plunge pool, sheet flow and formation of channel flow, the progressive extension of self-formed channels over time, flow behaviour at the downstream end of self-formed channels, the interaction between sheet flow and channel flow that form and expand the overall stack footprint and beach slope.

Keywords: *thickened tailings, beach slope, sheet flow, self-formed channel, plunge pool*

1 Introduction

Thickened tailings disposal schemes, in the form of central thickened discharge (CTD) or down-valley discharge (DVD), have been utilised in the mining industry for the past 40–50 years as an efficient and cost-effective method of tailings management.

The concept was first introduced to the mining industry through the pioneering research conducted by Professor Eli Robinsky in the 1970s (Robinsky 1978).

Recent advancements in thickening technology – particularly the development of larger-diameter high-density and paste thickeners – have made this technique increasingly viable for large-scale mining operations.

A key factor in the successful implementation of the thickened tailings disposal technique is the accurate prediction of the achievable beach profile and overall slope during the design stage. This enables the designers to correctly estimate the required tailings storage facility (TSF) footprint and the height of the perimeter embankments. For a given TSF footprint, a steeper beach slope provides greater storage capacity and reduces the required embankment height.

[*] Corresponding author. Email address: behnamp@atcwilliams.com.au

Early research on tailings beach profiles dates back to the 1980s (Blight 1987; Williams & Meynink 1986) with a primary focus on the sorting of coarse and fine particles along the length of the beach, as well as the concavity of the beach profile (McPhail 1995).

The study of tailings beach profiles and slopes has been the focus of numerous investigations and debates over the years, with more recent research concentrating primarily on the prediction of non-segregating tailings beach slopes (Williams 2001; Pirouz et al. 2005; Pirouz et al. 2007; Fitton, 2007). Reviews of beach slope prediction models are provided in published literature in the past (Williams et al. 2008; Simms et al. 2011).

A clear understanding of the mechanisms and processes governing beach formation and evolution, as well as the key parameters influencing the beach profile and overall slope, is essential for developing reliable models capable of accurately predicting beach profile and slope.

Common observations and records from mine sites (Williams 2014) and large-scale field trials (Pirouz et al. 2015) of the thickened (non-segregating) tailings beach formation processes recognise 2 main mechanisms:

- The laminar sheet or fan flow, which is associated with deposition of solids on the developing beach.
- The self-formed channel flow, which is the mechanism that transports the tailings slurry for potentially long distances over the developing beach from the discharge point to the point of deposition.

There are 2 schools of thought regarding which mechanism controls the overall beach slope. One argues that the sheet/fan flow is the dominant mechanism for beach development and overall beach profile, while the other believes the transport mechanism in self-formed channels is the mechanism that dictates the overall beach profile.

One of the earlier studies to highlight the importance of self-formed channel hydraulics and the total transport model in determining the overall beach slope was published by Williams (2001) at the Paste and Thickened Tailings Conference in Pilanesberg. Since then, several researchers have developed beach slope prediction models that focus on the hydrodynamics of tailings slurry flow in the self-formed channel, rather than on the shear strength of tailings slurry and geomechanical properties of the deposited tailings in a stationary condition (Fitton & Slatter 2013; Pirouz et al. 2014; McPhail 2018).

The relevance of sheet flow processes and tailings shear strength to the overall beach profile and slope has been debated in the research by Williams (2014):

> *"Some practitioners are still reluctant to let go of the belief that shear strength – yield strength, in the context of the non-Newtonian behaviour of a thickened tailings slurry – must be at the heart of a slope prediction method. It is a reasonable prima facie position, but it happens not to be correct, in this author's opinion."* Williams (2014)

The same study also questioned the applicability of small-scale depositional flume and stack trials – formed through the deposition of discrete batches of tailings and governed by sheet flow mechanisms – to representing the full-scale stack profile. The research concluded that the overall beach slope of a tailings stack is governed by the limiting equilibrium channel slope required for a given tailings material to generate sufficient turbulence to achieve total transport.

The accuracy of the beach slope prediction model developed based on total transport self-formed channel hydraulics has been validated against actual record data from several operating mines (Williams 2014; Fitton 2018).

2 Definition of thickened tailings

Studies on the geomorphology and hydrodynamics of tailings beaches have shown that the achievable beach slope in any mine site is directly proportional to the tailings solids concentration (i.e. rheology) and inversely proportional to the discharge flow rate (Williams 2014; Pirouz et al. 2017). These are valid statements for what is known in the industry as thickened slurries.

In the context of tailings management and tailings beach formation and slope prediction, it is important to recognise that the term thickened tailings refers to tailings that have been processed – using high-rate, high-density, or paste thickeners – to a consistency that exhibits non-segregating behaviour upon deposition. Beyond certain limiting densities, referred to as the segregation threshold, tailings slurries become non-segregating and develop a measurable yield strength under static conditions (Williams 2014).

By definition, hydraulic sorting is not a concern for non-segregating tailings, as it is not anticipated to occur in such materials. If it does occur, it is expected to be minimal. No specific yield stress, viscosity, or solids concentration range is universally associated with non-segregating behaviour, as these characteristics vary from one tailings slurry to another.

It is well-established that the application of shear to a slurry mixture, such as the shearing that occurs as the slurry flows within a channel or pipe, can breakdown the yield strength. As a result, slurries that exhibit non-segregating behaviour under static conditions may become segregating when subjected to flow. The effect of shear on segregation behaviour has been investigated by one of the authors (Pirouz et al. 2008).

Both laboratory evidence (Pirouz et al. 2008) and field data from large-scale deposition trials (Pirouz et al. 2015) support the concept that when a tailings slurry is thickened to the so-called dynamic segregation threshold limit, the combined effects of slurry yield strength, turbulent forces within the self-formed channels, and gravitational settling of particles interact in a way that preserves the non-segregating nature of the slurry during flow (Pirouz et al. 2008, 2015). Under these conditions, as the tailings flow from the discharge point to the toe of the stack, total transport of solid particles occurs within the self-formed channels.

It should be noted that the beach profile of a stack formed from non-segregating thickened tailings typically has a concave shape; however, this characteristic is attributed to thickener performance and other factors (such as flow streams remerging on the beach) rather than hydraulic sorting or segregation of solid particles on the beach. The underlying reasons for the concave profile observed in non-segregating tailings beach have been discussed in detail in previously published studies by Pirouz et al. (2017) and Seddon et al. (2018).

3 Observations from field deposition and large-scale trials

Observations from numerous mine sites visited by the authors over the years indicate that when tailings – regardless of their tonnage, mineralogy or physical properties such as particle size distribution (PSD), solids concentration, and rheological characteristics – are continuously discharged from an outlet pipe or spigot, the flow always confines itself into a self-formed channel. This channel gradually extends in length over time and can reach several kilometres.

Figure 1 illustrates examples of flow channelisation observed across developing tailings beaches at several mine sites. As shown, the formation of flow channels occurs even in cases where no thickener is employed.

Figure 2 shows the development of the self-formed channel within a 10 m-long, straight, horizontal rectangular flume after approximately 2 hours of continuous tailings discharge from the upstream end, with the material freely exiting at the downstream end – flow-through flume test.

At a larger scale, the tailings beach profile appears to be formed by hundreds of meandering, self-formed channels.

The questions that may arise here are how the tailings are able to develop these self-formed channels when first discharged onto hard ground – whether it be a natural surface or a previously dried and desiccated tailings beach – and why such channels form at all.

(a)

(b)

(c)

(d)

Figure 1 Examples of tailings flow channelisation at different mine sites. (a) Copper mine; (b) Zinc mine; (c) Gold mine; (d) Copper mine

Figure 2 Channelisation of tailings during beach formation in a large-scale continuous flow flume trial, Copper mine

The thickener type, discharge solids concentration, and fully-sheared yield stress of the tailings at each mine site are summarised in Table 1 for comparison.

Table 1 Thickener type and tailings properties

Mine site	Mineral	Type of thickener	Solids concentration (%)	Discharge flow rate (l/s)	Fully-sheared Bingham plastic yield stress (Ps)
Site a	Copper	Paste	68	870	20
Site b	Zinc	No	33	80	1.5
Site c	Gold	High-rate	60	120	10
Site d	Copper	Paste	58	640	40
Flume	Copper	Paste	67	18	40

It is a common observation by the authors at various mine sites that when fresh tailings are first discharged into a new area – whether onto natural ground or a previously deposited dried beach – the beach formation process begins with waves of sheet flow that advance and deposit a fresh layer of tailings across the surface. At this stage, no self-formed channels are present, as illustrated in Figure 3 (tailings slurry solids concentration = 54%, discharge flow rate = 100 l/s, fully-sheared Bingham plastic yield stress = Y = 12 Pa).

Figure 3 Stage 1 of beach formation. Sheet flow mechanism depositing a bed of fresh tailings

As time passes and tailings discharge continues, a plunge pool of specific size and depth gradually forms at the point where the incoming flow impacts the newly deposited tailings beach.

The size and depth of a plunge pool are primarily determined by the discharge flow rate and the velocity of the incoming tailings (Heng et al. 2012). Since the plunge pool is formed from tailings solids, the natural process adjusts the pool's size and shape to dissipate all of the kinetic energy of the incoming flow. A higher discharge velocity results in a correspondingly larger and deeper plunge pool. Consequently, the effects of the incoming flow's kinetic energy are confined to the plunge pool area, and the flow exiting the plunge pool carries no memory of the discharge velocity from the spigot. This process is shown in Figure 4.

As deposition continues, the tailings flow emerging from the plunge pool gradually concentrates into one or two preferred channels, while the remaining channels become blocked and cease to carry flow. The orientation of the dominant channel consistently follows the path toward the lowest point on the beach, corresponding to the steepest hydraulic gradient relative to the plunge pool. Figure 5 illustrates this stage of the beach development.

It should be noted that the deposition of tailings consistently occurs at the downstream end of the channel through the sheet flow mechanism, forming the bed for channel development and progressively advancing toward the further downstream areas of the beach. This is shown in Figure 5.

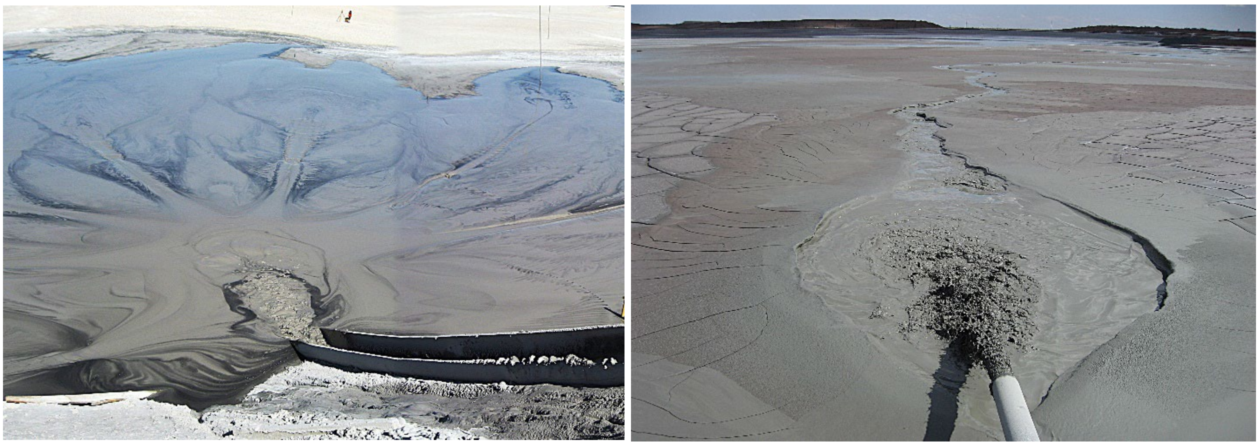

Figure 4 Stage 2 of beach formation. Plunge pool formation and the appearance of self-formed channels

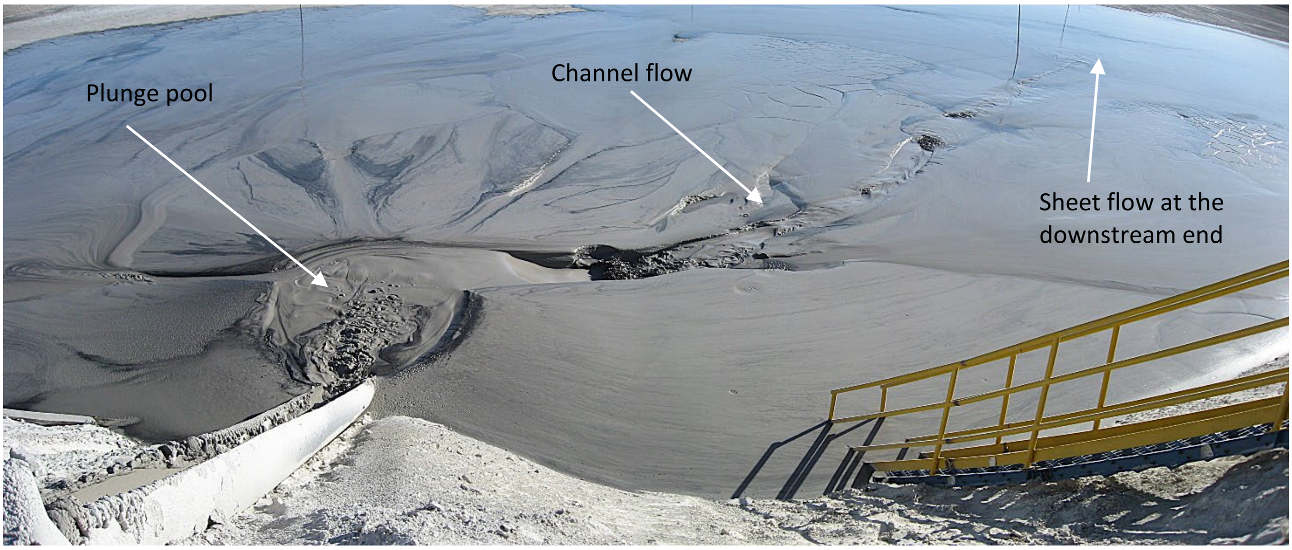

Figure 5 Stage 3 of beach formation. Establishment of the plunge pool and channelised flow in the preferred direction

As illustrated in Figure 6, the length of a well-established, self-formed channel can extend to more than 1 km on the beach (depending on the size of the TSF), with tailings continuing to flow within the same channel for several days as deposition proceeds and the channel progressively advances further downstream.

The lifespan of a tailings channel and the duration for which tailings continue to flow through a particular channel are primarily controlled by the size of the TSF and the ground elevation in the downstream area relative to the elevation of the plunge pool.

As time progresses, the self-formed channel functions as a transport conduit, conveying freshly discharged tailings from the plunge pool to newly developed downstream areas of the beach, where deposition occurs through the sheet flow mechanism.

Once the downstream areas of a channel have been filled with sufficient tailings and the beach level in these areas has risen adequately relative to the plunge pool level, the deposited tailings progressively block the downstream end of the channel, leaving no further space to accommodate additional tailings delivered by the channel for deposition. This blockage effect progressively migrates toward the upstream sections of the channel, causing the flow of tailings within the channel to become increasingly difficult. This is shown in Figure 7.

Figure 6 Stage 4 of beach formation. Further advancement of the tailings beach toward the downstream area

At this stage, the channel banks begin to overflow at multiple points and, quite suddenly, the channel breaches its banks in one or more locations. The resulting sheet flow waves spread outward from the breached sections, depositing fresh tailings and preparing the surface for the formation of a new self-formed channel toward other areas of the beach.

After a short period, a new channel develops, diverting the tailings flow toward a lower-lying area of the beach where the material can move more freely under the action of gravity.

Figure 7 Stage 5 of beach formation. Gradual blockage of the channel flow from the downstream deposition

Eventually, the downstream blockage effect extends upstream to the plunge pool, triggering the formation of a new channel from the plunge pool toward another section of the beach, as illustrated in Figures 8 and 9.

The mechanisms described herein for the formation and evolution of the beach are repetitive and recur continuously as the tailings discharge proceeds. As shown in Figure 9, once the influence of downstream deposition extends to the plunge pool, the tailings solids deposition at the base of the plunge pool causes a rise in its elevation, resulting in the development of a similar plunge pool at a higher elevation. This progressive sequence explains how the height of the tailings stack increases over time.

Figure 8 Stage 6 of beach formation. Sheet flow spills from the plunge pool to form a new channel toward a new direction

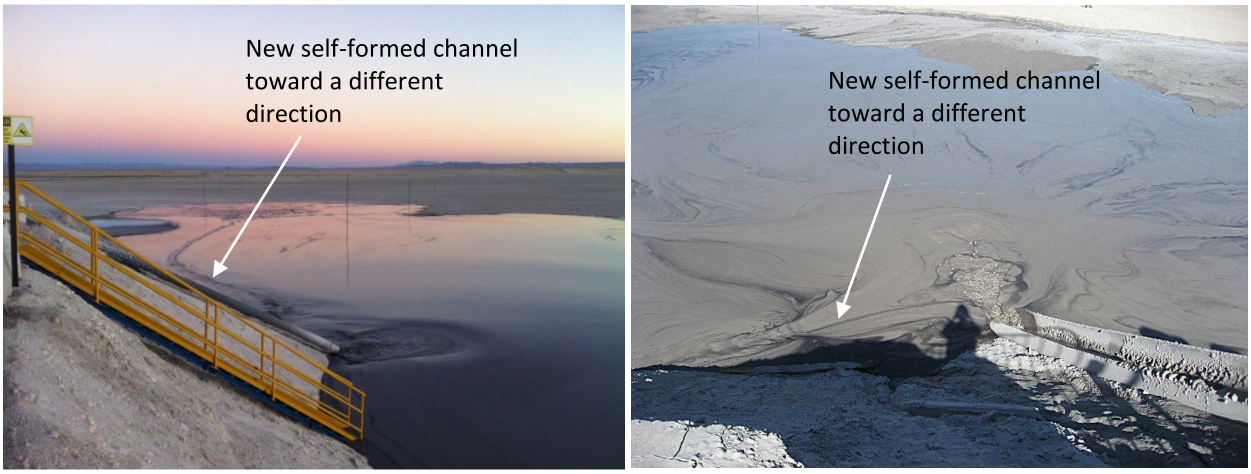

Figure 9 Stage 7 of beach formation. Formation of a new self-formed channel originating from the plunge pool and extending toward another part of the beach

The key findings from the observations of a developing beach can be summarised as follows:

- Tailings deposition always takes place by the sheet flow mechanism at the downstream end of the self-formed channel.
- Once a fresh layer of tailings is deposited on the developing beach by the sheet flow mechanism, the flow rapidly becomes channelised, concentrating within a self-formed channel.
- Very limited (if any) tailings deposition or solids settling occurs within a fully established self-formed channel. The flow within such a channel represents a steady-state total transport condition.
- The self-formed channel functions solely as a transport mechanism, conveying tailings across the developing beach to newly formed downstream areas and thereby expanding the beach footprint.
- Channelisation of the flow on the beach occurs because it provides a more energy-efficient mechanism for slurry movement than sheet flow, demonstrating nature's inherent tendency to adopt the most efficient (i.e. less energy-consuming) means of transport.

4 Thickened tailings beach formation descriptive model

Using insights from long-term observations of thickened tailings deposition schemes and large-scale field trials, a descriptive model is proposed that describes different mechanisms involved in beach formation and development and explains why the self-formed channel always appears when tailings flow is continuously discharged into a TSF.

The deposition of thickened tailings in any TSF always commences with sheet flow. The lateral expansion and forward progression of the sheet can be described as successive layers of slurry sliding over one another.

As the laminar sheet moves and spreads laterally, its depth decreases, causing the slurry sheet to become progressively thinner. The laminar flow regime also promotes the development of a density profile within the slurry layer through the mechanism of zone settling, which in turn increases the solids content, shear strength, and viscosity of the lower layers. Eventually, the shear strength of the layer closest to the stationary bed reaches a level where it can no longer move with the overlying flow and comes to rest. The next layer of slurry, immediately above the now-stationary layer, then comes into contact with the bed, acting as the new moving layer, allowing flow to continue. Consequently, the thickness of the sheet flow gradually decreases as it advances and spreads laterally, until the topmost layer contacts the stationary bed and motion abruptly ceases, as illustrated in Figure 10 (Pirouz et al. 2005).

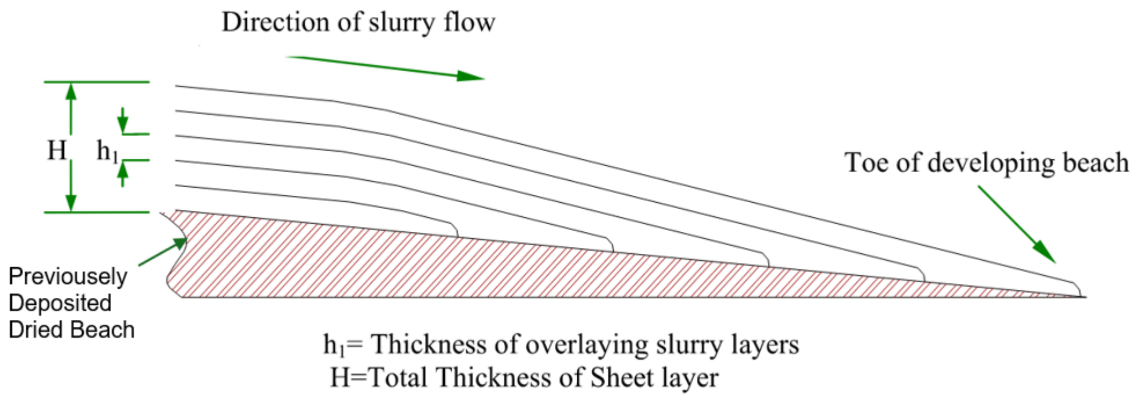

Figure 10 Flow of laminar sheet flow on the developing beach

The slope stability of sheet flow is well understood in geomechanics by the following formula (Williams 2001).

$$\mathrm{Sin}(i) = \frac{S_u}{\gamma d} \tag{1}$$

where:

i = slope angle

S_u = undrained shear strength

γ = slurry density

d = sheet flow thickness measured normal to the slope.

For a particular slurry with known undrained shear strength and density, the problem with the above equation is that the sheet flow thickness, d, is not known, so that with any assumed value for the sheet thickness, any equilibrium slope $\mathrm{Sin}\ (i)$ can be obtained.

As illustrated in Figure 10, the cessation of motion in a sheet flow – regardless of the discharge rate or total flow depth – does not occur abruptly across the entire flow depth (H). Instead, it initiates in the lowermost layer adjacent to the stationary bed and progressively propagates upward, affecting the flow, layer by layer. Consequently, in Equation 1, the sheet thickness should always be considered as the thickness of the first layer closest to the stationary bed i.e. $d = h_1$ (not the initial total depth $d = H$), irrespective of the original total flow depth. Therefore, in laminar sheet flow, the equilibrium slope at which the slurry layers come to rest results from a balance between the shear strength of the lower layers and the thickness of the layer adjacent to the stationary bed.

From this analysis, it can be concluded that, for a given slurry mixture discharged over a horizontal surface in discrete batches, both the thickness of the layers that come to rest, h_1 and the overall equilibrium slope $\text{Sin}(i)$, are independent of flow rate. These characteristics likely represent fundamental properties of the slurry governed by particle size, solids content, rheology, and the settling velocity of the tailings.

Figure 11 illustrates the scenario in which discrete batches of tailings with equal volumes are discharged one after the other onto a previously dried beach. Assuming that the only possible flow regime is laminar sheet flow, the first batch of slurry spreads over the surface in the form of slow-moving sheets and fans. The laminar sheet flow will advance to an ultimate distance $X_1 = V_1 \times t$ before the shear strength of tailings halts motion throughout the entire flow depth, layer by layer, as shown in Figure 10. Here, V_1 represents the flow velocity, which depends on the rheological and other properties of the slurry, and t represents the time required for the shear strength of the slurry to propagate through the entire flow depth – from the bottom layer to the top surface layer – bringing the uppermost layer of slurry to rest.

As shown in Figure 11, each new batch of slurry – flowing as overriding laminar rolling waves – increases the beach slope slightly after coming to rest. This incremental steepening, in turn, increases the velocity of the next overriding layer, allowing the newly discharged tailings to travel farther downstream.

This procedure is valid only if the slurry batches are discharged with a time interval Δt. The time interval Δt must be sufficient for the previous batch of tailings to lose its excess water and gain enough shear strength so that the subsequent batch cannot remobilise it.

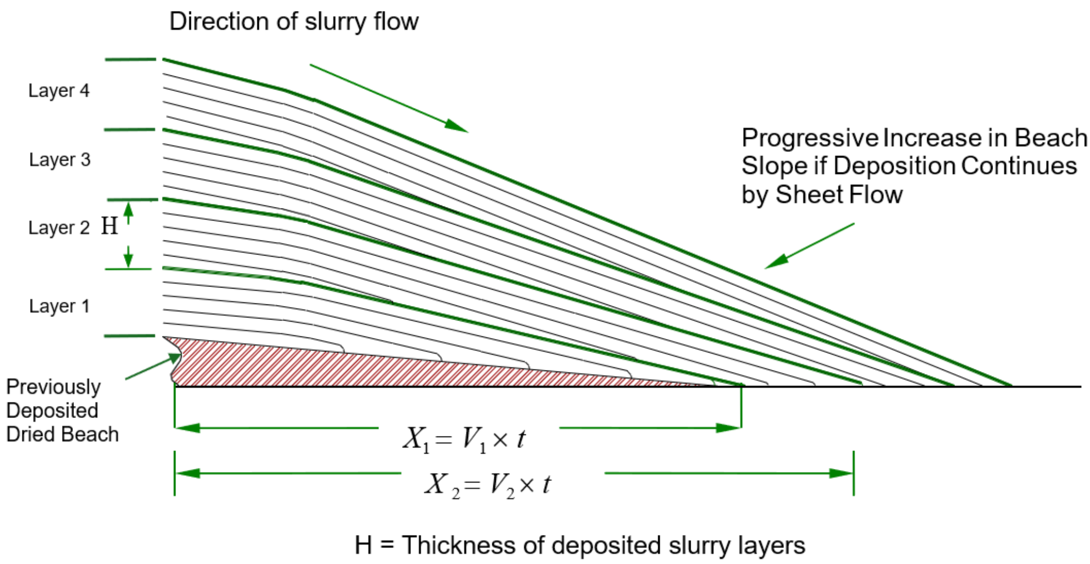

Figure 11 Tailings beach formed by deposition of discrete batches of tailings and sheet flow mechanism

The beach slope formed by discrete batch deposition of tailings under a sheet flow mechanism is initially controlled by the material's yield stress (shear strength) and gradually increases until it is ultimately governed by the material's angle of repose.

Figure 12 shows an example of a tailings beach formed by batch deposition, and the sheet flow mechanism exhibiting a very steep slope, approaching 40˚, which is comparable to the material's angle of repose.

Figure 12 Tailings beach formed by deposition of discrete batches of tailings and sheet flow mechanism (C = 60% solids, fully-sheared Bingham plastic yield stress = 10 Pa)

However, in practice, tailings deposition into a TSF is a continuous process. Consequently, the tailings flow inevitably becomes channelised on the beach shortly after deposition begins. A self-formed channel develops as soon as a sufficiently thick bed of freshly deposited material is established.

As shown in Figure 13, the overall slope of the beach formed by continuous tailings discharge and the self-formed channel hydraulic mechanism is significantly flatter than that formed by discrete batch discharge through the sheet flow mechanism governed by the shear strength of the steeled material.

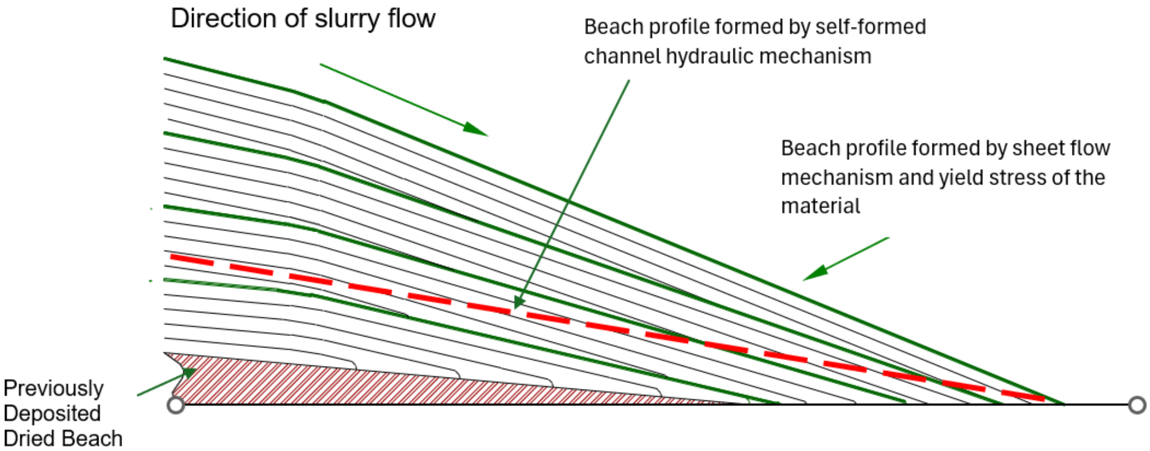

Figure 13 Slope of beach formed by continuous discharge of tailings and self-formed channel hydraulics

The tailings slurry naturally chose to confine itself within a narrow self-formed channel and travels across the beach through this pathway, as it represents a more efficient way of transport. In doing so, less gravitational energy is required to convey the material from one point to another, resulting in a flatter overall beach slope.

A key proposition derived from the descriptive model presented for thickened tailings beach formation and development is that the overall beach slope is primarily governed by the slope of the self-formed channel.

In other words, at any location along the developing beach, deposition by the sheet flow mechanism continues until a self-formed channel develops. The emergence of this channel prevents further material deposition at that location and interrupts the progressive steepening of the beach that would otherwise occur through continued deposition. The slope of the self-formed channel is considerably flatter than that of the beach formed under shear strength control of the deposited material.

Therefore, any model aiming to accurately predict the beach slope should focus on the hydraulics of the self-formed channels conveying a non-Newtonian fluid, rather than on the geomechanical properties of the tailings solids (Pirouz et al. 2014).

5 Conclusion

Using the findings from previous research, field observations from operating mine sites, and data from large-scale deposition trials, a descriptive model has been developed to explain the formation of thickened tailings beaches and the mechanisms governing their development.

The proposed model explains why the tailings flow becomes channelised on a developing beach and suggests that any accurate prediction model for beach slope should be based on the hydraulics of self-formed channels.

The model recognises the following fundamental features and mechanisms in the formation and evolution of thickened tailings beaches:

- A plunge pool forms at the impact zone where the discharged tailings flow meets the beach surface. The size and depth of the plunge pool are determined by the velocity of the discharged flow, ensuring that the dynamic energy of the tailings jet from the spigot is fully dissipated. As a result, the effect of the spigot discharge velocity does not extend beyond the plunge pool. In other words, the discharge velocity from the spigot has no impact on the overall beach slope or profile.
- The laminar sheet flow, which is always associated with tailings solids deposition, provides a fresh bed of tailings for the channelisation of the flow.
- Self-formed channel flow, which acts as a transport mechanism to carry the tailings slurry from the plunge pool to the downstream area of the beach. The direction of the flow is always toward the area of the beach that has the lowest level.
- The flow within the self-formed channel is a steady-state, total transport flow, with its slope governed by the hydrodynamic behaviour of the non-Newtonian fluid and particle transport mechanism within the channel.
- Channelisation of the flow almost inevitably occurs on the developing beach during continuous tailings discharge into a TSF, as it provides a more efficient mechanism for the tailings slurry to travel on the beach.
- The overall profile and slope of the tailings beach are governed by the slope of the self-formed channel rather than by the shear strength of the deposited tailings.
- The slope of the self-formed channel is considerably flatter than the sheet flow slope, which is determined by the yield stress of the tailings.
- The prediction of thickened tailings beach slope should be treated as a hydrodynamic problem rather than a geomechanical problem.
- Any trial conducted to study beach formation and slope, whether in the field or laboratory, should involve the discharge of a continuous flow of tailings sustained for a sufficient duration to allow channelisation to develop.

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