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Evaluating construction tolerances and tailings dam shape for closure using the CAESAR-Lisflood landscape evolution model

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Abstract

Variability in landform construction for closure has long been an uncertainty: downstream tailings dam slopes are designed with precision, while the earth moving equipment that build them vary in their ability to accurately replicate designs. As such, performance outcomes of the closure landform can be tied to the equipment used and/or operator experience, for better or worse. Unintended surface variations can lead to concentrations of surface water flow, gully formation, and excess erosion of the landform surface. A key concern is therefore how much variability in construction, or 'surface roughness' is acceptable, and does this level of acceptability change based on the complexity of the landform being constructed?

While many closure landscapes seek to maximise surface roughness and micro-topography for the associated microclimatic and biodiversity benefits, a concern with respect to surface roughness at closure, particularly on steep slopes, is that too much may lead to excess erosion. Controlling factors lend this problem well to investigation using a landscape evolution model (LEM); in this case the CAESAR-Lisflood LEM.

Using four different downstream sand dam designs with identical overall dimensions, one digital elevation model (DEM) of each was created with (a) low surface roughness and with (b) high surface roughness. A standardised precipitation database, grain size distribution, and parameters were used for all LEM simulations, such that variations due to surface roughness could be isolated. LEMs are often used to test computer-generated designs (i.e. smooth contours with no surface roughness), as well as existing landforms whose surfaces are replicated using light detection and ranging (LiDAR)-based DEM inputs (i.e. surfaces with substantial roughness). These two extremes have not previously been compared but have implications for the way LEM inputs are generated and assessed, the assumptions made during design, and for the degree of precision required in closure earthworks construction.

Results of the LEM testing indicate landform-scale topography provides superior erosion mitigation compared to micro-topographic variations, and that geomorphic landform designs are more resilient to surface variations than traditional designs, providing greater 'room for error' during construction.

Keywords: *CAESAR-Lisflood; construction tolerance; erosion; landscape evolution model; tailings dam; risk assessment; surface roughness*

1 Introduction

From the early stages of the mining lifecycle (Figure 1), mines are required to conduct impact assessments and to plan for closure; if not by the governing regulatory body, then by corporate guidance or the International Council on Mining and Metals, or ICMM (if the operator or parent organisation is a member company). Best practices dictate that closure planning shall commence at the earliest stage of planning and design for a new mine and include details on the expected final landform and surface rehabilitation as well as a risk assessment (International Committee on Large Dams [ICOLD] 2013; World Bank & International Finance Corporation 2002).

Of relevance, the Global Industry Standard on Tailings Management (International Council on Mining & Metals [ICMM] 2021) requires that:

- A robust design is developed that considers "… site conditions, water management, … and construction issues, and that demonstrates the feasibility of safe closure of the tailings facility" (Requirement 5.2).
- A risk assessment is used to inform the design (Requirement 5.4).
- The closure phase is designed with sufficient detail to demonstrate the feasibility of the closure scenario (Requirement 5.6).
- Risk assessments be undertaken and updated using best practice methodologies at a minimum every three years or whenever there is a material change to the tailings facility or the social, environmental, and local environmental context (Requirement 10.1).

Figure 1 Mining lifecycle as it pertains to tailings facilities (adapted from Al-Mamun & Small 2018)

To summarise, for operational tailings dams a design must be informed by risk assessments completed using best practices and must consider construction issues during design. Furthermore, the operator must demonstrate the feasibility of the closure scenario and update risk assessments and designs regularly. Given the strong correlation between topography and erosion, it follows that the erosion risk assessment should consider surficial construction issues; historically, this has not been the case. Typically, neither erosion assessments nor design have considered potential surface roughness associated with landform topography.

Erosion assessments have evolved substantially over the past 20 years. While the universal soil loss equation (USLE; Wischmeier & Smith 1978) was once considered to be the gold standard, several limitations relevant to post-mining landforms restrict its use in this realm. Over the last 30 years increased computing power and improved accuracy of topographic data have led to the development of three-dimensional (3D) implementations of USLE using Geographic Information System (GIS), software such as the Water Erosion Prediction Project (WEPP), 3D soilscape evolution models, and 3D landscape evolution models (LEMs).

Landscape evolution modelling of mine closure landscapes, particularly those with potential for high erosion such as sand tailings dams, is required by an increasing number of regulatory jurisdictions worldwide and is best available practice (BAP) for predictive erosion risk assessments. Two approaches are taken when using LEMs for an erosion assessment, depending on the stage of the tailings dam within the mining lifecycle:

1. For tailings dams not yet fully constructed (i.e. those in the design, construction, operational, or closure (transition) stage), current approaches include running a LEM with landform design/s exported directly from computer aided design software as a base. From this simulation, future landform performance is predicted.
2. For tailings dams already constructed (i.e. those in the closure (active care), closure (passive care), or post-closure stage) and where no further topographic changes are anticipated, existing topography is documented using Light Detection and Ranging (LiDAR) or other survey methods, and this digital elevation model (DEM) is used as a base to then predict future landform performance.

Uncertainty exists in the topography used in both of these scenarios listed above. In the former, computer aided design software produce DEMs with perfectly smooth topography; for example, a dam crest designed to be at an elevation 500 metres above sea level (masl) will have a uniform crest elevation of 500 masl, whereas in reality the constructed dam crest may fluctuate slightly with some areas lower or higher than designed due to vehicular traffic, equipment size and articulation, equipment operator experience level, foot traffic, and reclamation and/or revegetation specifications, etc. Therefore, erosion assessments completed with a perfectly smooth DEM may not be representative of reality.

In the case of tailings dams already constructed, LiDAR or other topographic surveys often have an accuracy of +/– 10 to 25 cm and up to 10 points per square metre. Accordingly, surface topography may be represented by more or less surface roughness in the DEM than in reality, both in terms of vertical and horizontal variation.

Given this inherent uncertainty in the topography used as a base for LEM erosion assessments, this paper sought to determine how localised topographic variation (surface roughness) would alter LEM results (i.e. erosion risk predictions), and whether the type of design (linear/traditional versus curved/geomorphic) affects the degree to which surface roughness makes a difference in erosion risk predictions. In essence:

1. Do sand tailings dams with high surface roughness result in different long-term erosion patterns relative to those with very little surface roughness?
   a. Where high surface roughness in the DEM could simulate a rough-graded landform, a landform with low construction accuracy relative to design, or low accuracy in the topographic data.
2. Are some hillslope or tailings dam shapes impacted differently by the inclusion of surface roughness?

2 The CAESAR-Lisflood LEM

LEMs have been used since the 1990s to evaluate landscapes and individual landforms (naturally occurring, anthropogenic, and synthetic) for mine closure at time-scales from individual storm events to 500,000 years (Hancock et al. 2016b). The CAESAR-Lisflood LEM is a reduced complexity model that simulates the fluvial processes contributing to surficial soil erosion: the model reads an hourly precipitation file and applies the depth each hour to the topographic surface (a gridded DEM), then routes surface water to adjacent downstream cells according to slope. Cumulative water depth and slope dictate flow velocity and thereby the grain sizes (if any) that are eroded or deposited. The smallest grain size within the grain size distribution used to represent surficial soil can be marked as having potential for suspension, which is also dictated by flow velocity. As such, three core inputs are required: an hourly precipitation dataset for the length of the simulation, a DEM of the surface topography, and a grain size distribution representative of the surficial soil, or in this case, sand tailings. These three main inputs are described below. Roughly 30 other parameters are further calculated or adjusted to complete parameterisation.

CAESAR-Lisflood has been evaluated extensively over a range of climates and geologies; It has been cross-validated with the SIBERIA landform evolution model, and calibrated using a range of methods including fall-out radionuclide (caesium-137), soil loss rates, gully size and void volume, historic topography and landcover projected to present conditions, and average discharge matching to measured discharge and calculated discharge (Coulthard et al. 2005, 2002; Hancock et al. 2011; Lowry et al. 2019; Martinez et al. 2009; Welsh et al. 2009). Version 1.9j of CAESAR-Lisflood was used for the simulations described herein. Furthermore, CAESAR-Lisflood has been used to assess the effectiveness of rip lines on a post-mining landform as an erosion mitigation technique (Saynor et al. 2019). The SIBERIA LEM has been used to evaluate variable surface roughness (Hancock et al. 2016a). However, the effect of surface roughness as it relates to variations in downstream dam design has not been investigated to date and is of interest due to the different geomorphically-based failure modes seen with each design.

3 Methods

In this study, the CAESAR-Lisflood LEM was used to simulate 50 years of extreme precipitation on fictional sand tailings dam designs. While the material properties and base climate information were gathered from the Athabasca oil sands region of Alberta, Canada, many other sand dams and indeed even dune sand from Alberta have very similar material properties. These simulations were intended to understand the relative impact of DEMs with varying depths of surface roughness and dam shape on LEM outputs. Exaggerated climate was used to illustrate failure mechanisms and trajectory; Accordingly, results are not considered to be site specific, but rather reflective of modelling and design decisions that could be taken on any site around the world.

3.1 Digital elevation models

Two DEMs were used for each simulation run, to represent the initial surface topography (surface DEM) and the lower limit of erosion (bedrock DEM). To develop the surface DEMs, four downstream dam surfaces were developed in AutoCAD with identical overall dimensions and exported. Surface roughness (Figure 2) was then added to these surface DEMs, such that they were representative of the overall shape but also had micro-topographic variations (surface roughness).

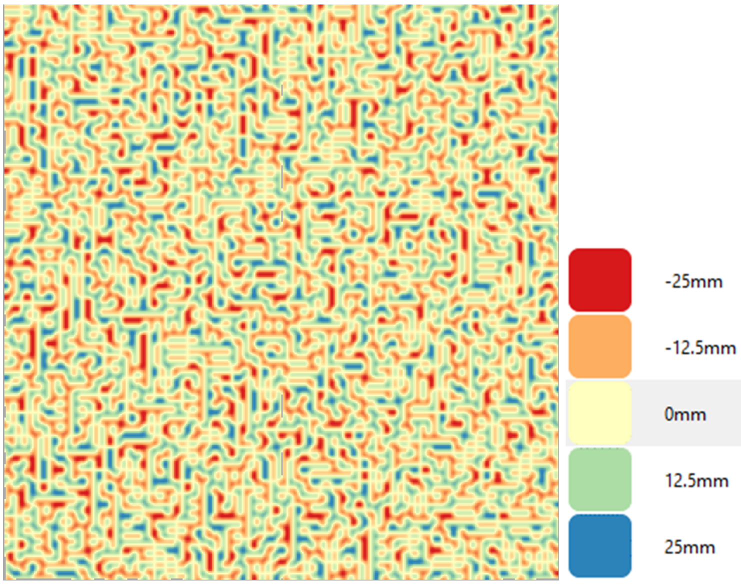

Figure 2 Graphic representation (500 m by 485 m) of low noise added to the DEMs to represent low surface roughness (+/– 25 mm). Legend indicates elevation differences from the DEMs (prior to addition of surface roughness)

To generate the surface roughness, Perlin noise was added to the surface. Perlin noise, as applied here, appears as a random system of elevation differences but with a consistent feature size. That is, the distance between a maximum elevation increase and decrease is relatively consistent across the surface. This closely matches the anticipated height variations of a physical surface where areas of higher or lower elevation are expected, as opposed to random height variations that are not correlated with adjacent points. An example of the Perlin noise added to the surface is shown below in Figure 2; the feature size (minimum dimension of an area of lower elevation) is approximately 2 m. Note that while Figure 2 shows a surface roughness of +/– 25 mm (i.e. low surface roughness), the same graphic would be representative of high surface roughness (+/– 150 mm in this study) with the legend values changed to -150, -75, 0, 75, and 150 mm, respectively, as the horizontal size of roughness was not altered for this study.

The four downstream dam slope topographies simulated were: Linear (constant slope gradient), Benched, Catena (or s-curved), and Geomorphic: Linear, Benched, and Catena had a constant cross-section across the dam width. The fourth, the Geomorphic design, had a variable cross-section due to the drainage network, whereby cross-sections alternate between Catena-shaped drainage course bottoms and convex ridges. All four dam designs were created with identical overall dimensions: 500 m wide by 485 m long (from crest to toe), and 60 m in height (the average slope from toe to crest of the slope is 1V:7H). DEMs with a resolution of 1 m (this results in 242,500 points to be modelled) were created first with no surface roughness, then were adjusted such that a version of each with low and high surface roughness was created. All eight surface DEMs are shown in Figure 3.

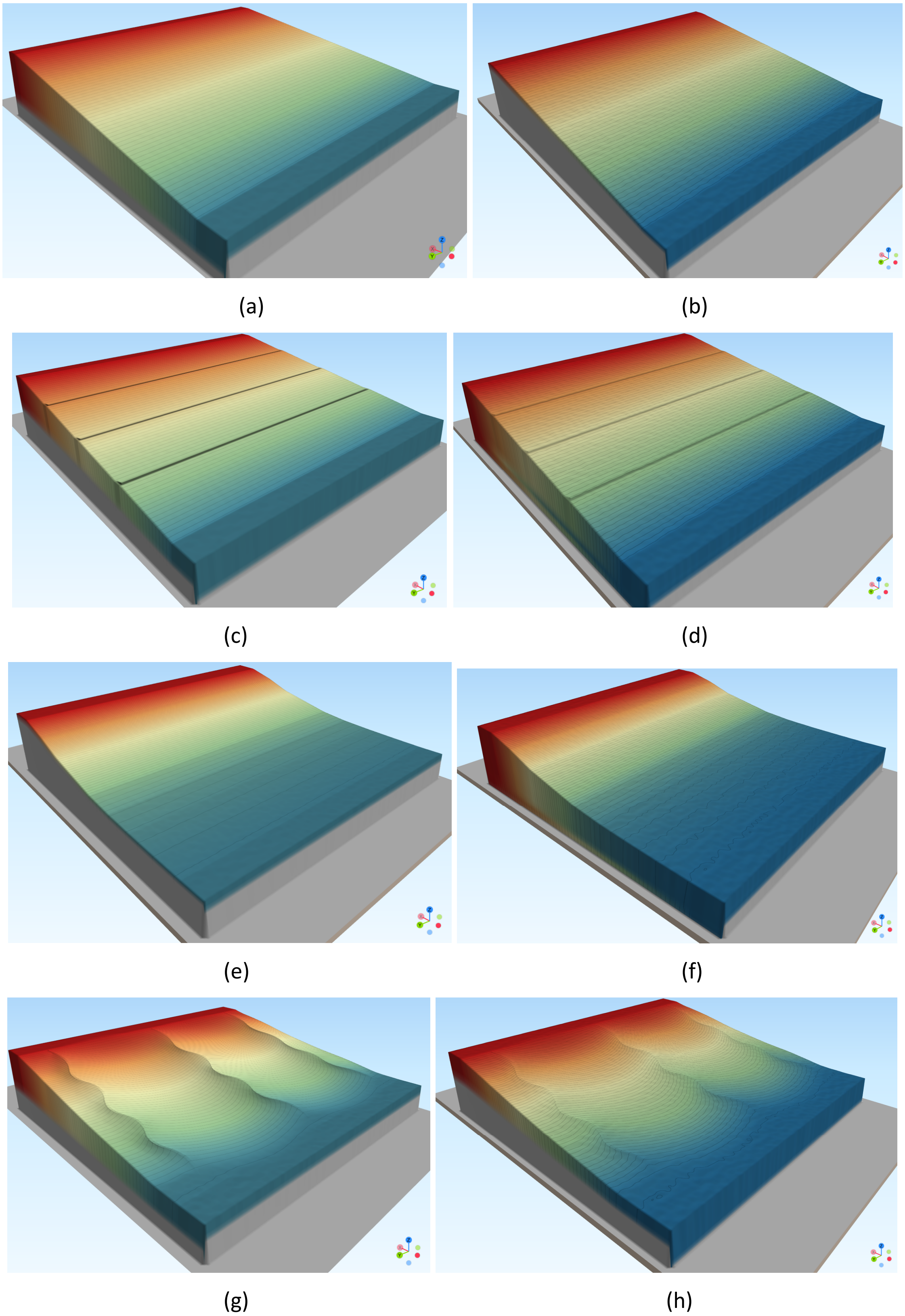

Figure 3 Axonometric views of surface DEMs with low surface roughness (left) and high surface roughness (right). (a and b) Linear; (c and d) Benched; (e and f) Catena; (g and h) Geomorphic

Bedrock DEMs were created with the same area as the surface DEMs, but with a uniform surface elevation equal to the lowest elevation within the surface DEMs (i.e. 0 m). No surface roughness was added to the bedrock DEMs.

3.2 Rainfall

The rainfall record used for the simulations was composed of a 15-year hourly precipitation record for Fort McMurray, Alberta, Canada, adjusted for winter conditions, then looped to form a 50-year record. Statistical 24-hour design storms were inserted manually according to their return period, and lastly a 24-hour probable maximum precipitation design storm was included every 5 years, at year 1, 6, and so on. This method was not intended to simulate actual or probable conditions, but rather to accentuate failure modes and illustrate differences clearly. This dataset is more thoroughly discussed by Slingerland et al. (2022).

3.3 Grain size distribution

The grain size distribution (GSD) data was measured from 44 sand tailings samples collected from the downstream slope of a sand tailings dam north of Fort McMurray, Alberta. The average GSD of these 44 distributions was taken and separated into nine classes for use in the CAESAR-Lisflood modelling (Figure 4). The 0.075 mm fraction was permitted to act as suspended sediment within all simulations.

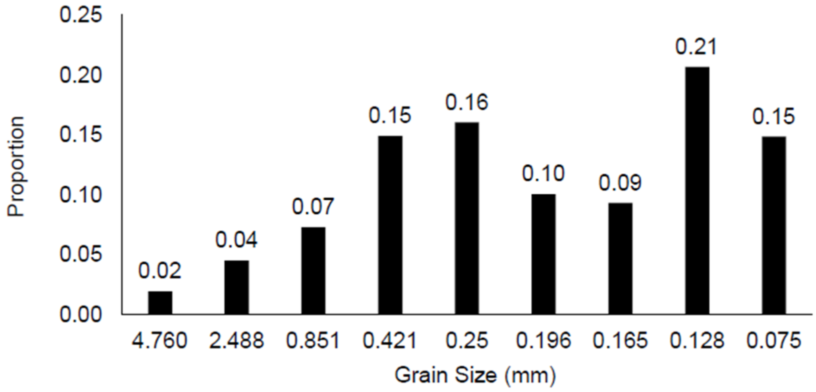

Figure 4 Particle size classes used in CAESAR-Lisflood simulations. From Slingerland et al. (2022)

For the Geomorphic dam design, a coarse fraction was used to mimic armouring down the central drainage pathways. CAESAR-Lisflood simulates the evolution of the GSD of each cell during the simulation and accepts an initial GSD for each cell which may very across the site (the buckets themselves cannot change). Within the drainage lines the GSD was modified to simulate a coarser material than the surrounding slope with 80% at 4.76 mm and 20% at 2.488 mm (Figure 5).

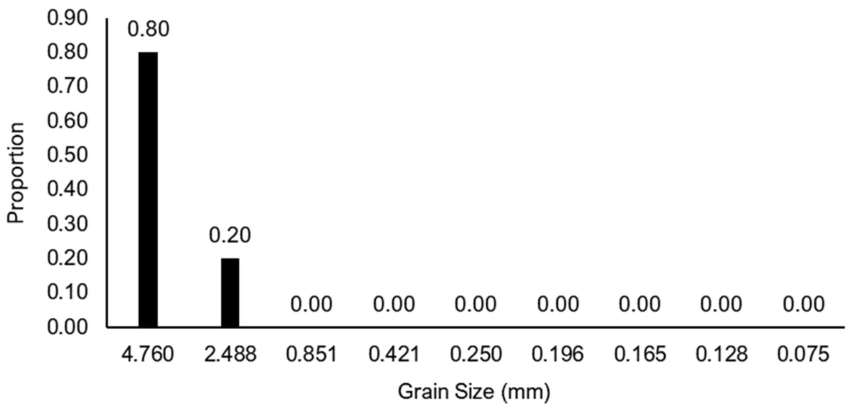

Figure 5 Particle size classes used in CAESAR-Lisflood geomorphic dam design simulations

3.4 Vegetation simulation and other parameters

Vegetation is simulated through a user-defined reduction in the proportion of erosion that is permitted to occur when vegetation is fully grown (time to full growth is also a user-defined input as is the maximum flow shear that the vegetation can resist), and also in part through the m-value which adjusts the water transport and storage associated with soils and vegetation. Small m-values produce a hydrograph with high-intensity peaks, while higher m-values produce longer duration, lower intensity hydrograph peaks. The m-value can be estimated based on relative forest cover or calibrated using a storm runoff hydrograph from the actual site. For this study, the m-value (0.01) was estimated based on forest cover. Additional parameters are listed in Table 1.

Table 1 CAESAR-Lisflood parameter values for sand tailings dam simulations

Input parameter	Value
Sediment transport law	Einstein
Maximum erode limit (m)	0.01
Active layer thickness (m)	0.2
Slope failure threshold (degrees)	40
Input/output difference (m^3s^{-1})	0.05
Courant number	0.3
Evaporation rate (m/day)	0.0034
Manning's n	0.0345
Vegetation critical shear (Pa)	177.23
Grass maturity (years)	15
Proportion of erosion when vegetation is fully grown	0.1

4 Results

Model results were evaluated both from a qualitative and a quantitative perspective: the qualitative allows for interpretation of risk and identification of failure modes, while the quantitative allows for numerical comparison and associated calculations (maintenance return period, for example).

As these landforms and the adjusted climate record are fictional, the results speak directly to the relative ability of various dam shapes (layouts and alignments) to perform under extreme rainfall events, and the role that relative DEM roughness plays in LEM results.

4.1 Qualitative results

Each of the simulations resulted in some surficial change to the dam slope; however, the range of changes varied substantially across the four dam designs. In general, the patterns of erosion are as would be expected based on the topography. Linear and Catena designs produced widespread erosional features (Figure 6) and widespread deposition at the toe of the dam slope. The Linear design developed deeper erosional features than the Catena design, and correspondingly lead to substantially more deposition of sediment at the toe as compared to the Catena design. Additionally, due to the low slope gradient at the toe in the Catena design, much of the eroded material was deposited prior to reaching the toe of the slope. This has implications for maintenance of basal channels, for sites that have these to collect runoff and seepage: including a buffer or low gradient area prior to the basal channel will result in a reduced frequency for channel dredging, albeit maintenance on the slope of the dam will remain as vegetation will have greater potential for removal and burial.

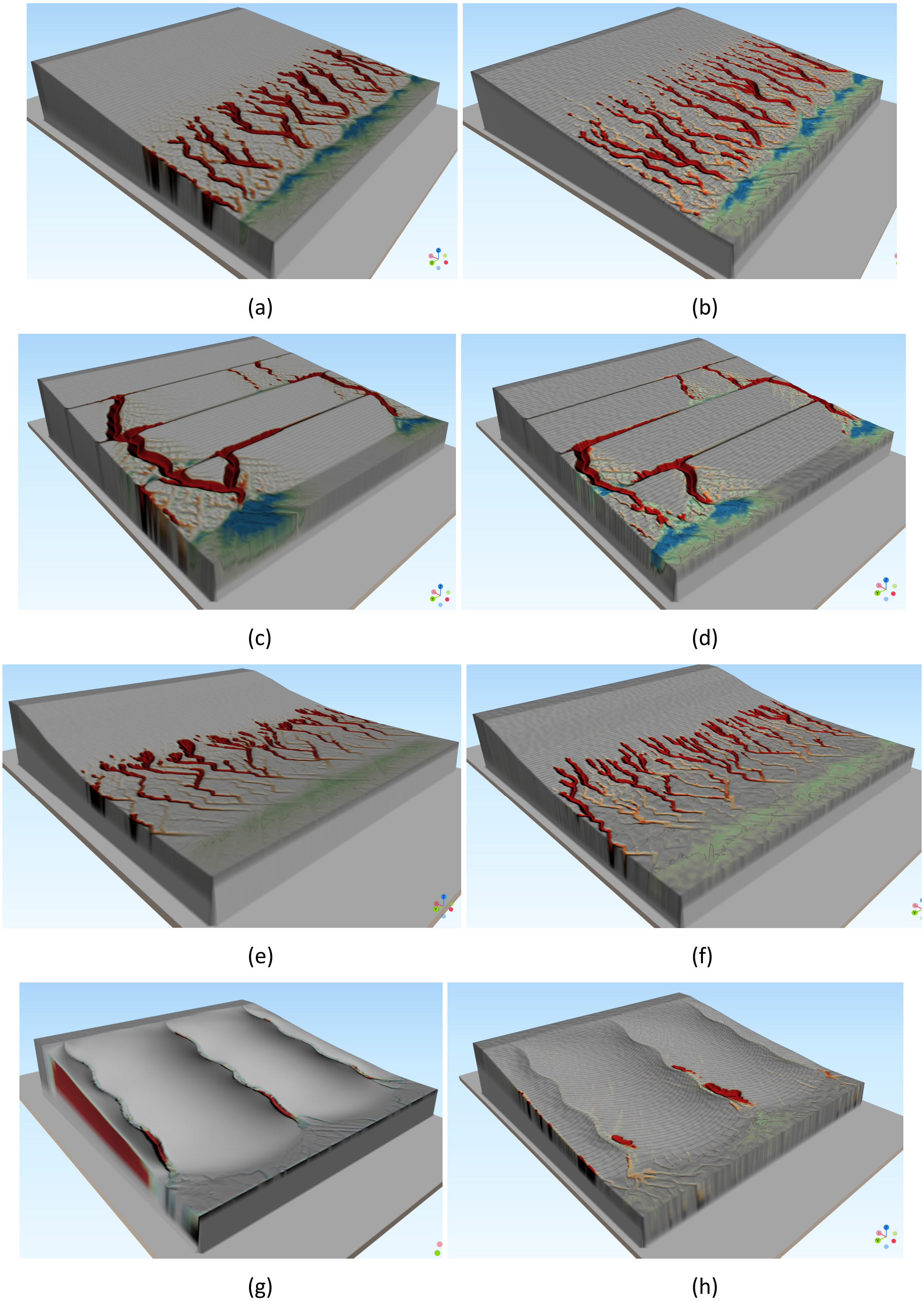

Figure 6 Axonometric views of dam slopes at the end of the simulation. With minimal: Low surface roughness: (left) and high surface roughness (right). (a and b) Linear; (c and d) Benched; (e and f) Catena; (g and h) Geomorphic

The Benched design failed in an expectedly catastrophic form for both low and high roughness DEMs, similar to what is seen on Benched slopes in reality: water ponded on the benches until a low point led to overtopping and downstream gully formation. Rather unexpectedly, more than one large gully developed.

Despite having near-equal catchments for each 'level' of benching, some benches developed one and some developed more than one gully, and most of these continued to develop over the 50-year simulated time frame, rather than runoff concentrating in one of these gullies over time. This is in contrast to the results of similar 'stress testing' modelling completed using no surface roughness where only one main gully formed and the benches each drained towards that singular feature (Slingerland et al. 2022), reproduced in Figure 7. The benefit of having more gullies, or drainage routes, is that the contributing drainage area is consequently smaller; this is possibly one reason why the single gully formed on Benched slopes in Slingerland et al. (2022) and was so much larger and deeper than those that developed in this simulation. This is one example where the inclusion of surface roughness may produce more realistic results, as minor surface undulations are likely to create small drainage divides on benches such that more erosional features develop.

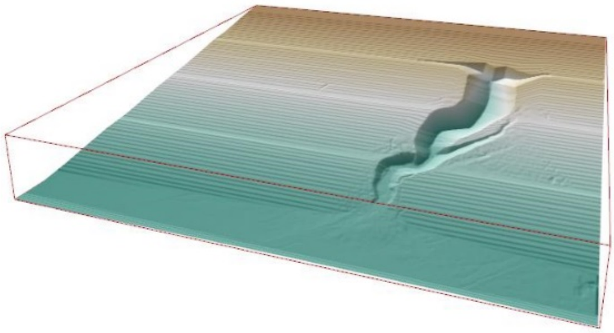

Figure 7 Single large gully formed in the Benched design (without any surface roughness) from Slingerland et al. (2022)

As would be expected with concentrated drainage pathways, concentrated areas of deposition also occurred at the base of the Benched designs. Two and three locations of concentrated deposition, forming fan-like structures developed in the low and high roughness iterations, respectively. In natural terrain these would be called alluvial fans, with the coarser particles dropping out first at the top of the fan and finer materials dropping out at the base.

The Geomorphic designs were subject to the least amount of erosion, and subsequent deposition downstream. No gullies developed on the landforms, and erosion and deposition were concentrated in the undulating drainage channels themselves. These drainage channels were designed with a Catena longitudinal cross-section to encourage reduction of flow speed with increasing catchment area in the downstream direction; as such it is not surprising that much of the eroded sediment would largely remain captured in the bottom third of the drainage courses.

Optimally, the Geomorphic design would include these undulating channels as well as some branching channels potentially, depending on the substrate and the slope gradient. This would increase the drainage density (length of drainage channel divided by drainage area) and therefore reduce erosion further.

4.2 Quantitative results

Cumulative tailings/surficial sediment loss was measured over the length of the simulation (Figure 8). Results can be grouped into three main categories: (1) Those that had high initial spikes followed by high erosion, (2) high initial spikes, followed by medium-high erosion, and (3) low initial spike followed by low erosion. The Linear and Benched designs fell into category 1, the Catena designs into category 2, and the Geomorphic into category 3. The main differences between category 1 and 2 were the earlier reduction in soil loss rate which would lead to an earlier geomorphic equilibrium, whereas those in category 2 continue to erode at a high rate. In contrast, the Geomorphic designs reduce to a very low soil loss rate quickly, and the design with minimal (low) roughness iteration reaches an equilibrium sooner than the increased (high) roughness iteration.

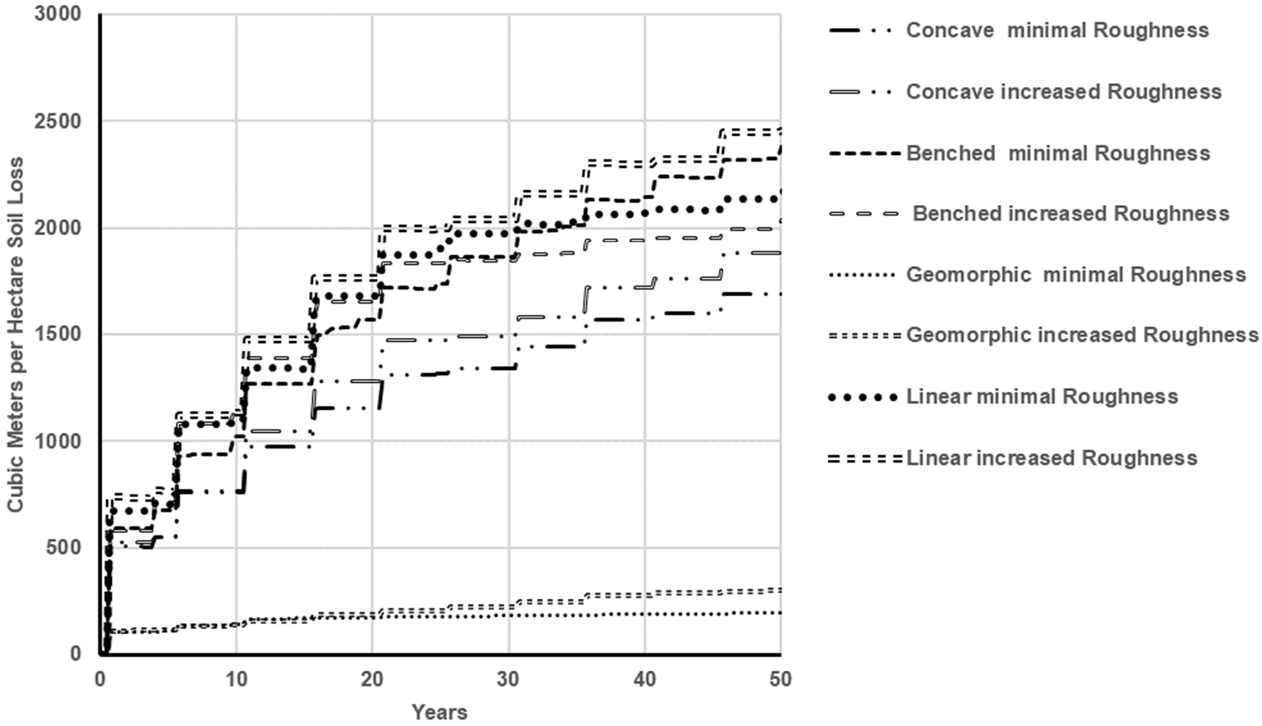

Figure 8 Cumulative sediment loss over the simulated time frame

From Figure 8, it is evident that in terms of long-term performance of the constructed dam slope, surface roughness has less impact on soil loss and corresponding maintenance requirements, than the dam design does. Increasing surface roughness (in the case of the Benched design) or diligently ensuring very low surface roughness (in the case of all other designs) will have much less of an impact on overall performance over the long-term, compared to choosing the appropriate dam shape to construct. This speaks to the dominance of landform-scale characteristics over micro-topographic characteristics in terms of long-term performance. This is particularly relevant, as approaches such as integration of 'micro-topographic' diversity and features are often written into closure plans as an erosion mitigation measure. A more impactful erosion mitigation measure would entail landform-scale earthworks to provide a geomorphically mature hillslope shape.

Statistics for the final, post-simulation dam slope and toe were attained from statistical analysis of the elevation difference output files generated by CAESAR-Lisflood and are presented in Table 2. While the Linear, Catena, and Geomorphic designs all saw greater total volumes of sediment removal with high surface roughness (compared to their low surface roughness counterparts), the Benched design was opposite this trend: the low surface roughness version resulted in greater total soil loss than the high surface roughness version. This is likely due to the different failure mechanism (overtopping) in the Benched design relative to the others. When a large volume of water overtopped into a low roughness downstream slope, the flow was able to eliminate minor topographic changes, then converge two gullies into one with high flow (as seen in Figure 6). In contrast, the high roughness version led to gullies remaining separated with moderate flows in each, and relatively reduced erosion potential. Additionally, the low surface roughness iteration resulted in elongation of one of the large gullies, substantially increasing the soil loss.

In terms of erosion (total and maximum depth), the Geomorphic designs had the lowest erosion while Linear and Benched designs had the highest. Linear designs had the most total sediment removed, while Benched designs had the deepest gullies. The maximum depth of erosion within the Geomorphic design was 3.17 and 4.52 m for low and high surface roughness, respectively; however, it is expected that these values would be diminished by the dense vegetation prone to develop in the high-moisture areas within the drainage pathways.

Erosion depths have particular importance due to many mines' reliance on cover systems at closure. Cover systems can be expensive to construct in part due to the rigorous quality control and diligence in construction, but also because cover materials can be difficult to source, and transport costs can be high when these materials do not naturally occur nearby. It is therefore often desirable to construct the thinnest cover possible.

Table 2 Summary of elevation changes at the end of simulations for dam slopes with minimal (2.5 cm) and moderate (15 cm) surface roughness

Design	Linear		Benched		Catena		Geomorphic	
Roughness (cm)	+/– 2.5	+/– 15	+/– 2.5	+/– 15	+/– 2.5	+/– 15	+/– 2.5	+/– 15
Maximum depth of erosion (m)	7.70	6.33	9.73	9.11	6.68	7.31	3.17	4.52
Total sediment removed (m^3)	49,855	56,615	55,293	41,334	39,037	42,450	3,749	7,126
Maximum depth of deposition (m)	1.53	1.75	2.01	2.09	0.52	0.62	0.31	0.51
Total sediment added to toe (m^3)	11,033	12,422	12,171	12,248	5,799	6,125	575	1,850
Mean elevation change (m)	0.16	0.18	0.18	0.12	0.14	0.15	0.013	0.02
Standard deviation of elevation changes	0.71	0.71	0.96	0.80	0.54	0.57	0.11	0.23

With respect to deposition (total deposition at toe and maximum depth), similar trends were seen with Linear and Benched designs leading to the greatest, and Geomorphic designs resulting in the lowest totals and depths. Deposition depths are important due to frequent reliance on basal channels for interception of seepage from dam toes and for collection and directing runoff from the dam toe. Basal channels are generally 2 m or more in depth and are dredged when they can no longer convey the targeted design storm without overtopping. As such, deposition depth is tied directly to the frequency of maintenance: where high deposition is noted, dredging is likely to be required more regularly to avoid overtopping of basal channels and to ensure site-wide water management plans function as intended. Low deposition, as seen in the Geomorphic design, likely requires little to maintenance.

Across Linear, Benched, Catena designs, all have mean elevation changes between 0.14 and 0.18 m; mean elevation change is an order of magnitude higher for these compared to the Geomorphic options, reflecting the reduced surface changes in the Geomorphic designs. Standard deviation is a measure of variation across the surface, which is why the Benched designs have a high standard deviation: these designs had low surface change except where very deep gullies formed. In contrast the Linear and Catena designs have moderate standard deviations reflecting the consistency of changes on the dam slope, and the Geomorphic designs have low standard deviations reflecting the minimal changes that occurred.

A final note on the statistics is the total soil removed in comparison to the total soil added to the toe of the dam slope. The volume of soil that was removed, minus the volume of soil deposited, is equal to the volume of soil entering downstream environments and is therefore of interest. Across all designs except for the Geomorphic designs, we see very high volumes (10,000's of cubic metres) of sediment being release into downstream environments. The qualitative and quantitative results indicate that the Linear and Benched designs are elongating their respective downstream dam slopes by depositing more soil at the toe, such that drainage lines evolve towards having a concave cross-section. In contrast, the Catena and Geomorphic designs already have concave cross-sections along their drainage lines, so sediment redistribution is more about minor refinements towards equilibrium (in this case, steepening sections rather than elongating the already elongated toe).

5 Discussion

Surface roughness can represent different realities in LEMs: for constructed landforms it can represent the intentional (or unintentional) smoothness or roughness introduced, or it can represent accuracy (or lack thereof) within the survey data. This study sought to determine the influence that surface roughness has on LEM results, and how different hillslopes or downstream dam shapes respond to varying levels of surface roughness. In Section 4, it was observed that landform shape provides a greater control on long-term surface erosion than the introduction of micro-topographic features (surface roughness), which are often touted as an erosion mitigation measure in mine closure plans submitted to regulators.

This study also sought to determine how the various designs would respond to varying degrees of surface roughness. Low surface roughness variations for each of the four designs were run as well as high surface roughness designs, with the high surface roughness being 600% more across maximum and minimum elevations compared to the low surface roughness. The corresponding proportional changes (high relative to low surface roughness results) are provided in Table 3.

Table 3 An increase from low to high surface roughness (600% increase) produced the following percent changes (negative values are in italics)

Design	Linear	Benched	Catena	Geomorphic
Maximum depth of erosion (m)	*18%*	*6%*	9%	43%
Total sediment removed (m^3)	14%	*25%*	9%	90%
Maximum depth of deposition (m)	14%	4%	19%	65%
Total sediment added to toe (m^3)	13%	1%	6%	222%
Mean elevation change (m)	13%	*33%*	7%	54%
Standard deviation of elevation changes	0%	*17%*	6%	109%

Table 3 illustrates that the 600% increase in surface roughness did not correspond to an equal change in erosion and deposition, nor was the change always positive: in some cases an increase in roughness lead to a decrease in erosion or deposition. In general, low to moderate correlations (1 to 33%) were seen in Linear, Benched, and Catena designs, while the Geomorphic design resulted in the greatest proportional changes (43 to 222%). To determine whether high proportional change within the Geomorphic design was simply due to the low erosion and deposition, the absolute changes were assessed (Table 4).

Table 4 Actual change in values resulting from an increase from low to high surface roughness (negative values are in italics)

Design	Linear	Benched	Catena	Geomorphic
Maximum depth of erosion (m)	*1.37*	0.62	0.63	1.35
Total sediment removed (m^3)	6,760	13,959	3,413	3,377
Maximum depth of deposition (m)	0.22	0.08	0.10	0.20
Total sediment added to toe (m^3)	1,389	77	326	1,275
Mean elevation change (m)	0.02	0.06	0.01	0.01
Standard deviation of elevation changes	–	0.16	0.03	0.12

Table 4 indicates that the highest absolute change in statistics resulting from the 600% increase in surface roughness was seen in the Linear and Benched designs; however, the Geomorphic design also had high changes. In particular, the maximum depth of erosion, and deposition increased substantially. In contrast, the Catena design saw the least amount of changes from an increase in roughness.

These results speak to the relative resiliency of these various dam and hillslope shapes to variations in construction or in survey accuracy. In absolute terms, we can expect Linear, Benched, and Geomorphic designs to be most reliant on construction accuracy and note that the Catena design can take some variation and roughness in the construction without substantial reduction in performance. Additionally, this should be considered in terms of the performance, which saw better performance from Linear, Catena, and Geomorphic designs when they had low surface roughness, and better performance from the Benched design when it had high surface roughness. A summary table outlining how to achieve the best results from each of these designs is provided in Table 5, and two examples follow.

Table 5 Characteristics required to achieve highest possible performance for each design

Design	Linear	Benched	Catena	Geomorphic
Optimal surface roughness	Low	High	Low	Low to high
Construction and LEM tolerance	Low	Low	High	Low

For example, best performance for the Benched design will be achieved with high surface roughness, and this design is sensitive to surface variability, so erosion risk assessments done using LEMs should be done with an accurate topographic survey and construction should be completed with attention to detail such that the final landform is constructed accurately relative to the design. Deviations in construction relative to the design are likely to produce performance that varies from that predicted with the LEM.

As a second example, best performance for the Geomorphic design will be achieved with low surface roughness, but excellent results can also be achieved with high surface roughness. When conducting an erosion risk assessment with a LEM, however, there is low tolerance for deviation from as-built conditions as the modelling results can be substantially different with altered surface roughness. Similarly, if the landform is constructed with a different surface roughness to that simulated with the LEM, performance will be different from those predicted with the LEM. While performance will be excellent for the Geomorphic design with any level of surface roughness, it is still important to run the LEM with accurate surface roughness.

6 Conclusions

This work sought to answer two questions: (1) how does surface roughness influence LEM results and long-term erosion risk? And (2) how are sand hillslope or tailings dam shapes impacted by surface roughness? To answer these questions, four tailings dam designs were developed into digital surfaces and given two levels of surface roughness: one version of each design had low surface roughness (+/– 25 mm), and another version had high surface roughness (+/– 150 mm). They were then run through the CAESAR-Lisflood LEM for 50 years which exposed the surfaces to extreme precipitation events and background events.

Results indicated that an increase in surface roughness did not necessarily result in a positive feedback loop: increasing surface roughness led to a decrease in erosion on the Benched design, but for all other designs this led to an increase in erosion. This is a substantial finding given the propensity for reliance on micro-topographic relief and introduction of surface roughness as erosion mitigation at closure.

Where a design is being developed digitally with the intent to long-term assess erosion risk using a LEM, these results suggest that most landform shapes would benefit from an estimate of surface roughness to be included as this will alter the LEM results. Only the Catena design did not have marked changes in performance with a change in surface roughness. Similarly, where a topographic survey is being used as a base for LEM erosion assessments, the accuracy of that survey has a marked impact on LEM results, and care should be taken to verify the data and attain the highest accuracy possible, as slight deviations from reality can result in disproportionate LEM predictions.

Furthermore, results indicated that the landform-scale design had far greater impact on both short- and long-term performance and erosion risk, than surface roughness did. The Geomorphic design in particular had one order of magnitude less erosion over 50 years than any of the other designs and reached a geomorphic equilibrium within the simulated time frame whereas none of the others did. In short, landform-level changes are superior at mitigating erosion than micro-topographic variations.

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