# Waste Rock Dump Management and Stability Evaluation

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The management of mine waste dumps has historically been assigned mainly to the on-site mining operations. In recent years, focus has turned to a more scientific approach to waste rock dump management and the auditing of these manmade structures.

A risk-based classification study of mine waste dumps that was carried out by British Columbia in 1992 identified certain technical issues that would remain unsolved, particularly where pore water pressure developed in foundation materials, or poor quality fine-grained waste becomes saturated. Both of these above factors are adversely influenced by high dumping rates and dump face heights.

Designs for proposed new dumps should include detailed stability assessments for each stage of development, taking into account the variations in rock quality and the rate of dumping. Possible modes of failure should be rigorously evaluated.

A-risk based conceptual evaluation system to determine the likelihood of waste dump slopes being unstable was developed to quantify the risk. The proposed methodology established requirements for the scope of waste dump stability investigation by considering the following elements:
- Site conditions
- Design criteria
- Monitoring requirements
- Construction guidelines.

This methodology or risk-based design procedure is continuously developing to encompass the changing on site requirements for large mining operations that often span an extensive mining lease area.

A common-sense approach to evaluating and determining the risks associated with a particular waste rock dump or stockpile is used on many mining operations. This paper documents some of the procedures and approaches utilized for a basalt waste dump life-of-mine design analysis.

## INTRODUCTION

The kingdom of Lesotho is a small mountainous country, completely landlocked by South Africa. The diamond mine discussed in this paper is situated within the Maluti mountain range and is located at approximately 3100 m above sea level.

The mine is an open pit truck and shovel operation, and interest has been shown in the deposit since 1968. Mining commenced in 1972 and is still carried out to date.

There are two waste dumps in close proximity to the two open pit mining operations. The paper covers the slope stability analysis of the active dump as mining expands and the dump develops further. A phased rehabilitation programme will be implemented on the inactive dump. A layout of the open pits and the waste dumps is shown in Figure 1.
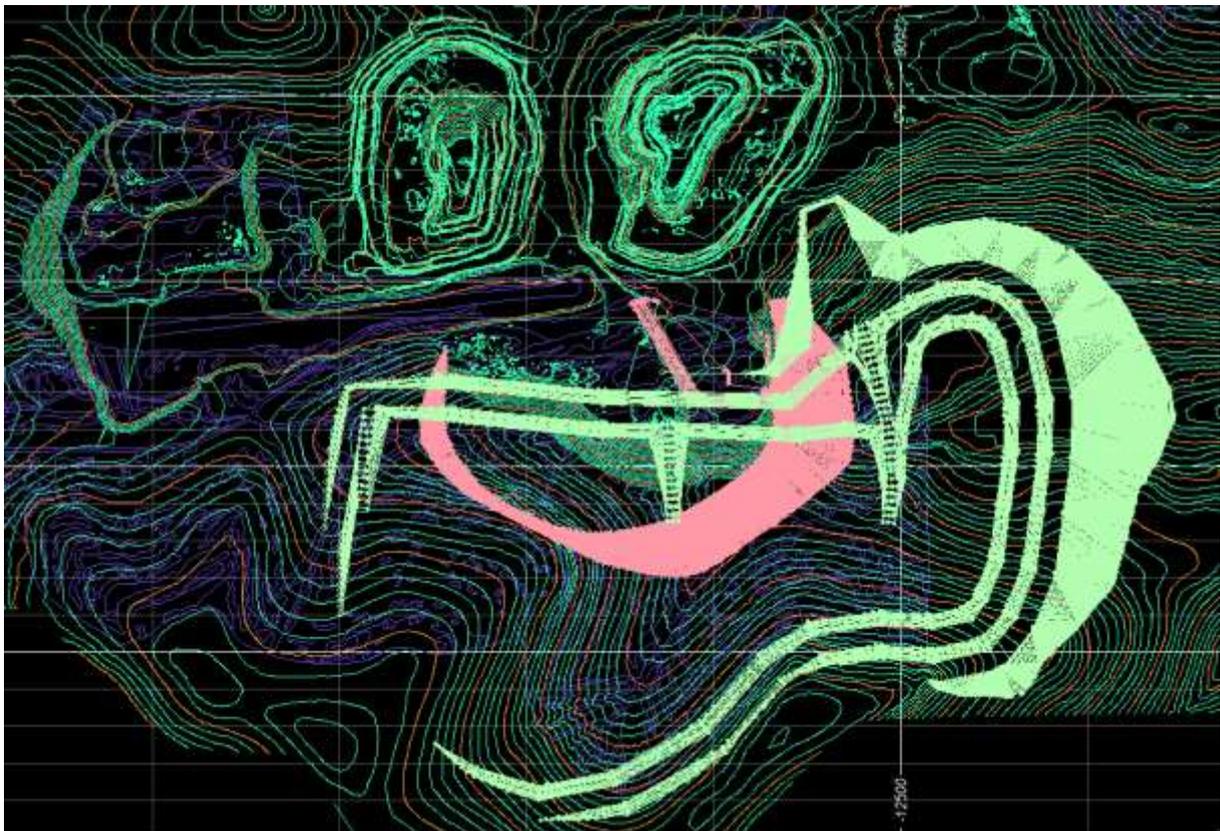


*Figure 1: Plan layout of the waste dumps and open pits.*

## GEOTECHNICAL INVESTIGATION

The geotechnical investigation was carried out to determine the waste material and foundation strength parameters. The foundation soil parameters were determined using existing soil maps, on-site observations, and information provided by staff on site responsible for stripping the foundation soil prior to dumping. A copy of the soils map is shown in
Figure **2**. Strength parameters were sourced from the Unified Soils Classification System (USCS) based on the assumptions made for the soil interface. No laboratory tests were carried out to determine the

strength parameters. It was further assumed that basalt would be found below the scant soil horizon and no further testing was conducted to determine the basalt strength parameters, as exploration data would adequately provide the information required.

No material tests were carried out for the dump materials, as material would inevitably be sourced from the crest or toe of the dump, and this would provide superficial analysis of the waste material only. Waste material being dumped consists predominantly of basalt, and extensive use was made of the technical data collected for the open pit stability evaluations. The exploration database, geotechnical database, and existing laboratory results were sourced from the mine site.



*Figure 2. Soil distribution plan for the proposed dumping area.*

**FOUNDATION MATERIALS**

A site reconnaissance survey was carried out to determine the extent of the waste dumps, surrounding topography, water channels, and proximity to the open pits. Numerous photographs of the surrounding topography and the soils map provided were used to determine the depth and type of foundation soils likely to be encountered beneath the existing dump. A photograph of the surrounding topography is included as

*Figure* **3**. A plan of the soils map provided by the mine was superimposed onto the mine plan and is presented as

Figure **4**. As can be seen from the image, the thickness of the soil interface down the valley is approximately 500 mm. While it is probable that the soil within the valley may increase down-valley, it is unlikely that the soils interface beneath the dump will exceed 1.0 m.

*Figure 3. Characteristic setting of the valley slopes showing outcrops of bedrock.*
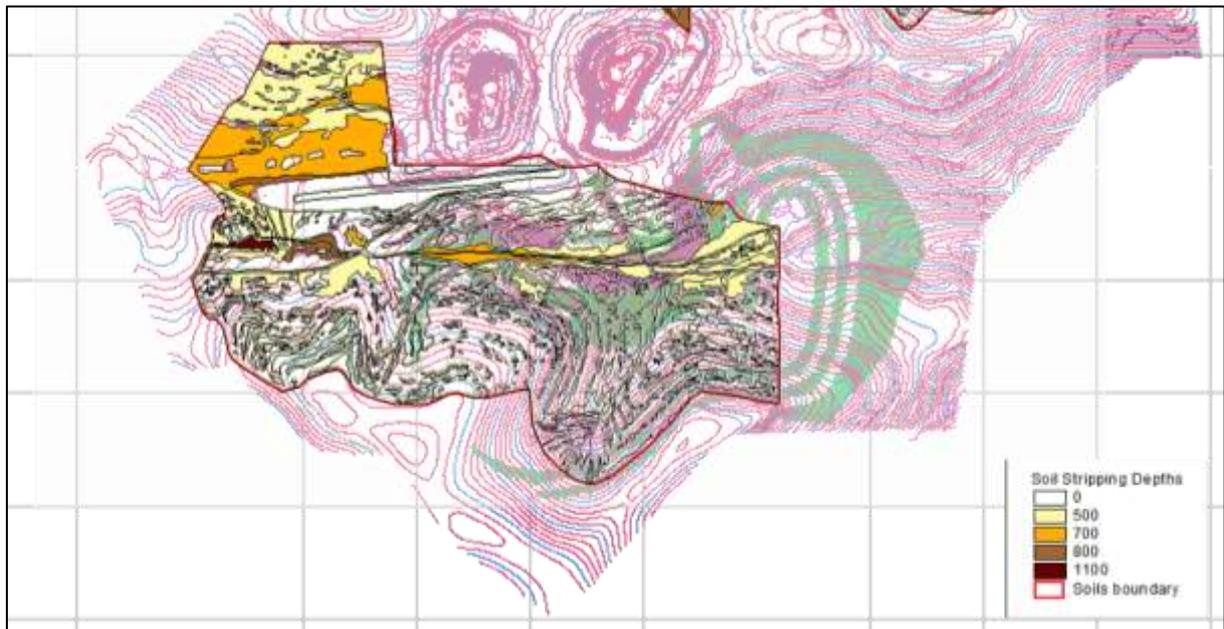


*Figure 4. The mine plan superimposed by the soils map.*

**WASTE ROCK DUMP DESIGN**

**Typical Foundation Profile**
A schematic presentation of the foundation profile as developed from the supplied designs, topography maps, observations and soils depth map is presented as
Figure 5. The assumptions made were that minor soil deposits would occur on valley slopes and these thicknesses typically range from zero to approximately 1000 mm in the base of the valley floor.
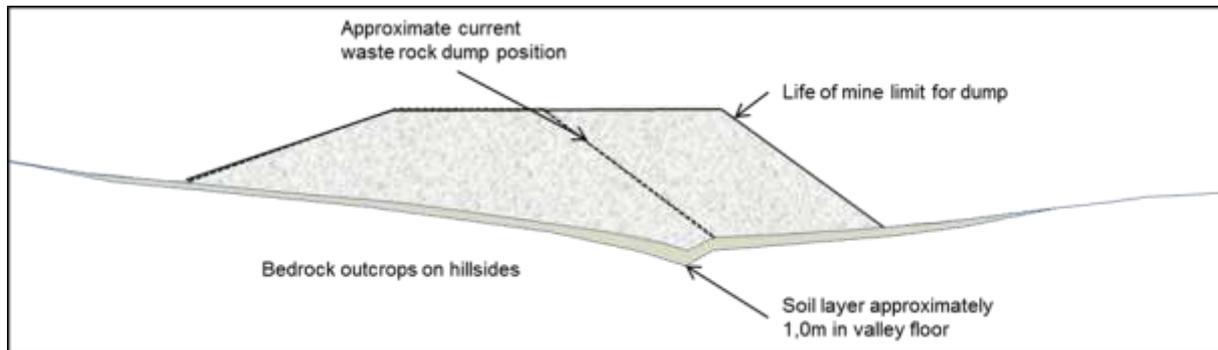


*Figure 5. Schematic presentation of a typical soil profile used for stability analysis.*

These measurements were derived from the soils map information, which provided typical depths as well as estimated soil types. Erosion of the softer soils and weathered materials would have occurred, and this 'hill wash' would be transported down the slopes into the valley floor beneath the dump. On site mapping of these soils has yielded the soils map shown in
Figure 2 and this map typically details thicknesses of approximately 1.0 m at valley floor level. No foundation trenches or foundation indicator tests were conducted on this site.

**Waste Dump Materials**
As it was not practical to sample the dumps, a decision was taken to analyse the waste rock based on the lithological characteristics of the material drilled for exploration/mining purposes. The logged cores were therefore analysed to gain information about the characteristics and composition of the waste rock. The exploration drill-hole logs were analysed from the exploration database.

Based on the information deduced from the drill-hole logs, waste material distribution graphs were developed. The graphs take into consideration the percentages of waste rock and ore, *i.e.* the percentage ore was segregated from the waste rock to produce a waste rock chart. In the database the data is filtered to distinguish between kimberlitic and basalt/other material. The basalt/other material is further analysed to determine what percentages of which material make up the waste rock materials dumped. The results of the waste rock analysis are presented in Figure 6.
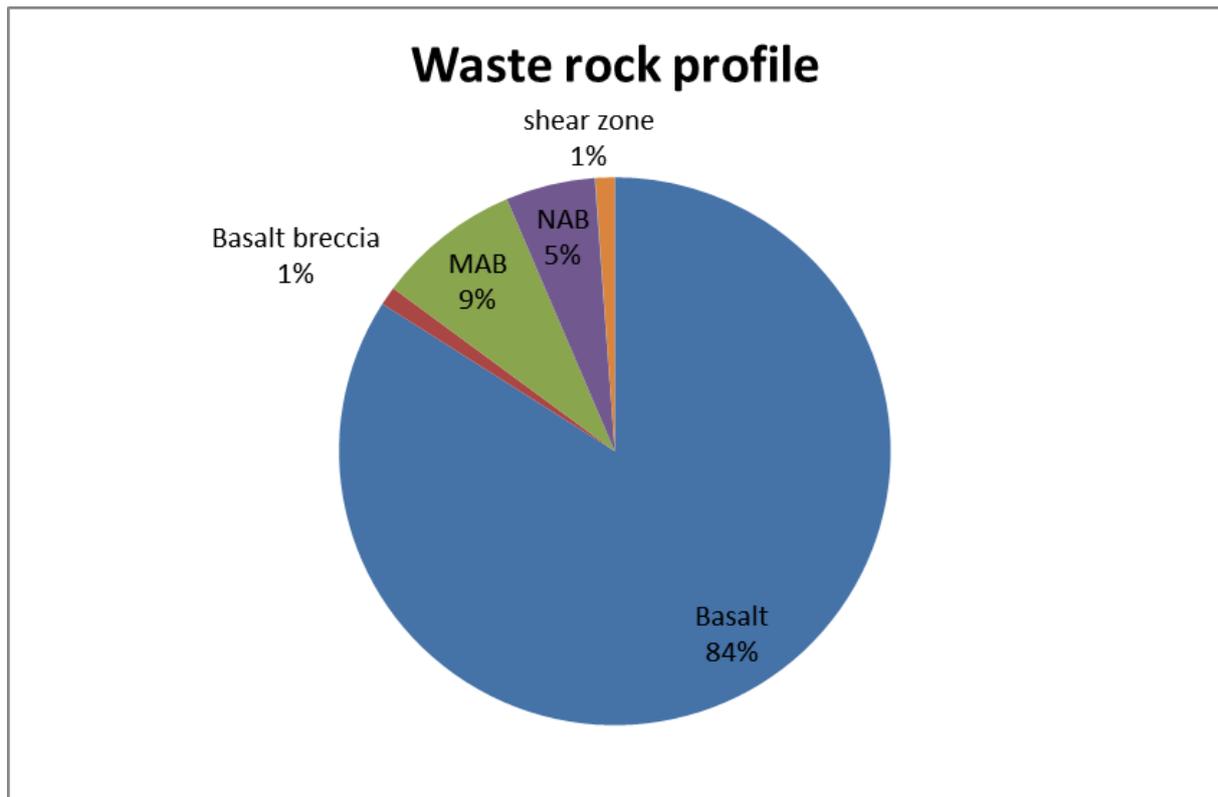
*Figure 6. Waste rock material composition.*

The evaluation indicates that the materials forming the dumps on this site are predominantly logged as basalt (84%), with minor percentages of shear zone, medium amygdaloidal basalt (MAB), non-amygdaloidal basalt (NAB), and basalt breccia. Materials will be mixed when dumped, and as a result of the waste rock material composition analysis, it was considered prudent to adopt the material strength parameters developed for basalt, and discard the minor influence the altered basalts may have on stability. Weaker materials may occasionally be dumped in a particular zone. This may result in localized instabilities within the dump, but in most cases these can be managed and rectified during the dumping process. Local failures or instabilities are likely to be observed and recorded during the recommended weekly visual inspections and mitigating measures can be established timeously.

**INPUT PARAMETERS FOR SLOPE STABILITY ANALYSIS**

To conduct the required analytical slope stability calculations, numerous input parameters are required. The following section describes the main input parameters required to populate the stability models, with the assumptions made.

**Foundation Materials**

The foundation material parameters are considered for further analysis. Strength parameters are assumed to fall within the CL-ML category of soils and were sourced from the Unified Soils Classification System (USCS). On-site examination of surface soils and thorough examination of the detailed soils maps confirmed the assumed soil types. The USCS classification uses values and deviations of rudimentary soil properties in a natural state. The CL-ML classification describes these soils as silt to clayey silt, inorganic, and low plasticity. Strength parameters for the foundation soils are included in **Error! Reference source not found.**. Exploration drill-hole data supports the assumption that basalt is found beneath the thin soils layer.

*Table I. Foundation soil strength parameters.*

| USCS classification | Soil type | Cohesion (kPa) | Friction angle |
|---|---|---|---|
| CL-ML | Silt to clayey silt, inorganic, low plasticity | 15 ± 10 | 30° ± 4° |

Note: These are assumed properties for the foundation soils encountered on the site.

As a conservative approach, the models were been analysed using mean values for cohesion and friction angle, applying the standard deviation and analysing the material parameters in the model statistically. The SLIDE models have been designated to report the global minimum, therefore the worst-case combination of cohesion and friction angle will be reported for the global minimum failure path. In addition, the foundation soils were analysed at a thickness of 1.0 m to simulate worst-case conditions.

**Waste Rock Material**
In developing the waste rock shear strength parameters, the Barton-Kjaernsli (1981) method was selected. This method is a further development of the empirical Barton-Bandis method widely used to model the strength parameters for large rock waste dumps. The Barton-Kjaernsli (1981) method is nonlinear and reflects the mechanical behaviour of high dumps more realistically than alternative methodologies. The parameters required to correlate the shear strength with the normal stress will be described more specifically. Furthermore, a comparison with the well-known Mohr-Coulomb strength model will also be carried out.

*Input Parameters*
The input parameters considered for the Barton-Kjaernsli methodology are the particle size distribution (PSD) of the waste rock, the uniaxial compressive strength (UCS) of the rock fragments, the compacted porosity ($n$) of the waste rock, the roundness (or angularity) of the fragments (R), and the basic friction angle ($\sigma_b$).

*Particle Size Distribution*
The Barton-Kjaernsli methodology utilizes the $d_{50}$ particle size as one of the input parameters. Preferably a robust knowledge of the particle size distribution is required, but regular PSD photographs are taken and fragmentation analysis carried out on site immediately after blasting, and this information was sourced to assist with the PSD analysis.

The PSD graphs incorporate seven PSD analysis results from the database. These results are presented in Figure 7. To validate the results further, a typical range of PSDs observed on similar operations elsewhere is shown for comparative purposes.
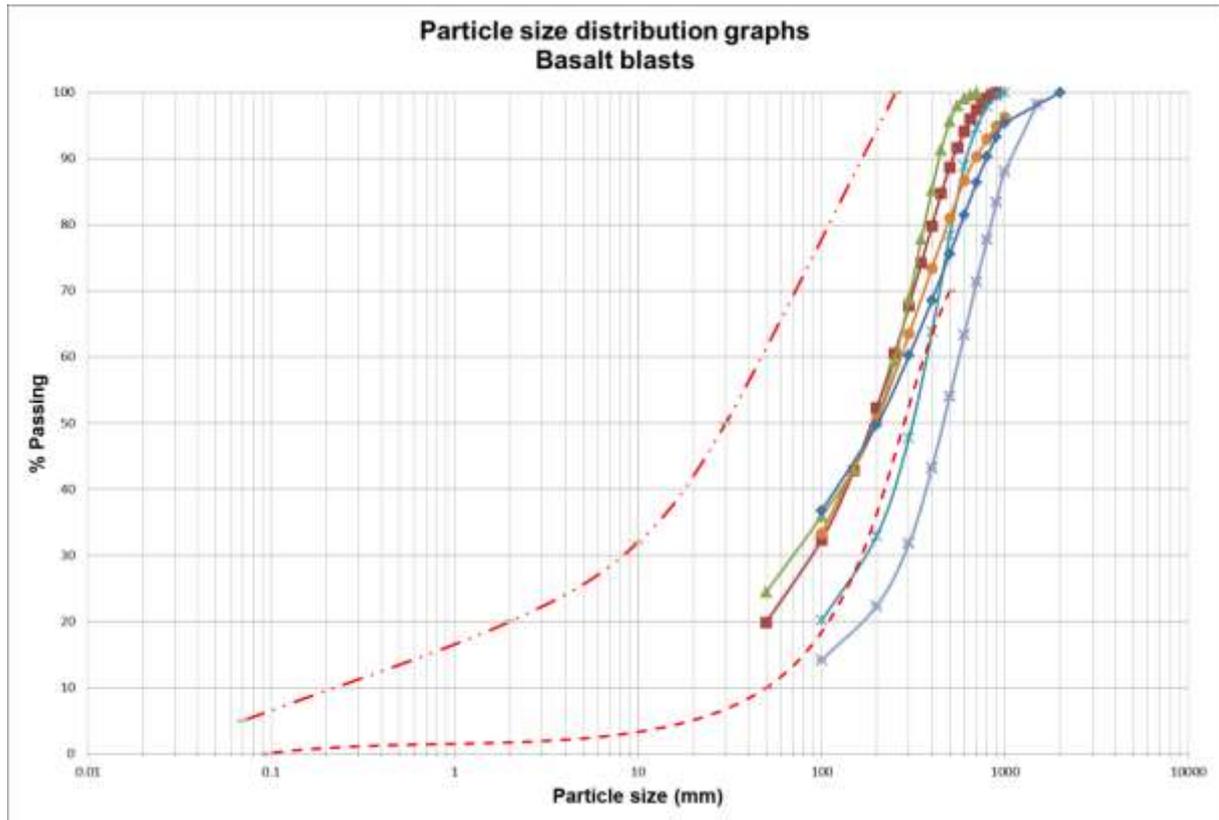
*Figure 7. Basalt particle size distribution curves.*

It should be noted that material segregation in line with the dumping procedure (end tipping) occurs. This leads to a certain variance in PSD. Generally, it can be accepted (and was observed) that the dump material will be coarser at lower levels and finer at higher levels. The PSD results obtained from the blast analysis fall on the coarse side of the typical PSD graph, and are considered reasonable.

### Unconfined Compressive Strength

The unconfined compressive strength (UCS) of the predominant waste material component is required for the Barton-Kjaernsli methodology. UCS strengths were sourced from the database providing strength information for pit design. UCS values were sourced from laboratory tests, and a mean value of 126 MPa was used for basalt.

### Size-dependent Equivalent Strength

The size-dependent equivalent strength is estimated based on the graph presented in Figure 8. The $d_{50}$ particle size and the UCS are used as input parameters. The $d_{50}$ size for the basalts analysed range between 150 mm and 450 mm. The range is shown in pale green in Figure 8. The minimum and maximum values are then read up to the curved line for triaxial tests and then across the graph to the $S/\sigma_c$ ratio, indicating 0.26 and 0.22 respectively. These two values are applied to the formulae used to generate the Barton-Kjaernsli failure curve. The green shaded area represents the values for this site.
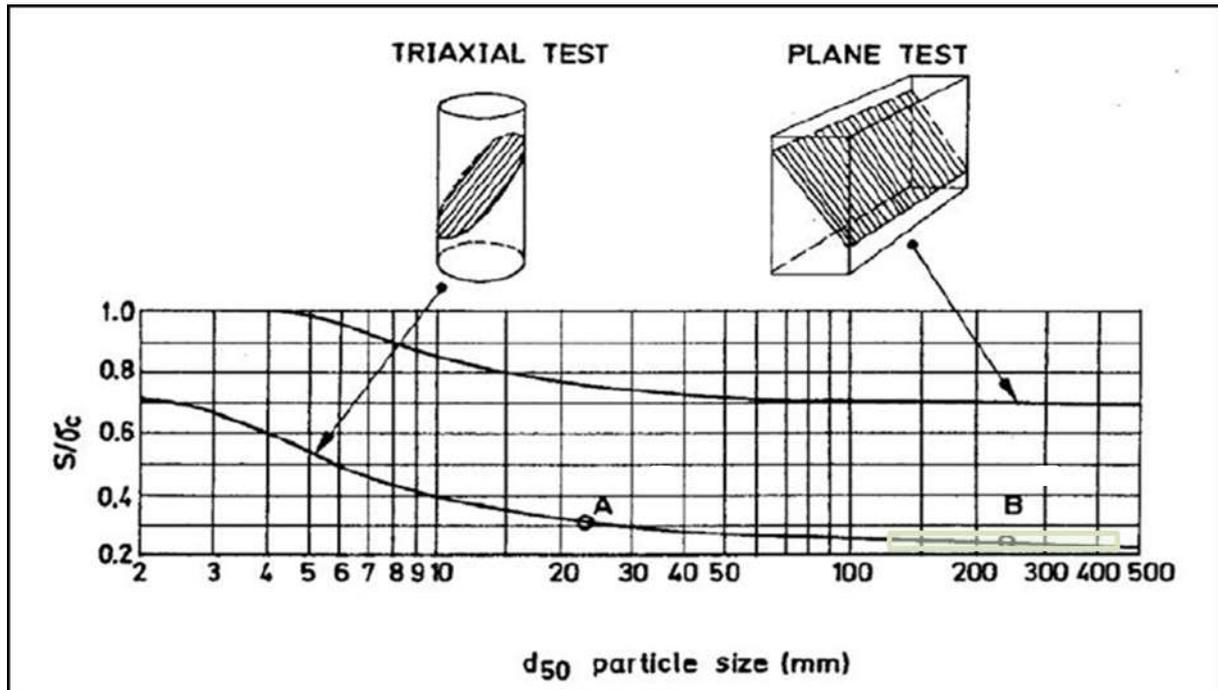
*Figure 8. Empirical S/UCS reduction factors for estimating S – D$_{50}$ particle size sourced from PSD curves.*

## Compacted Porosity

An assumed value for the compacted porosity was sourced from research undertaken to determine the range of porosity values that could be expected for basalt. Porosity estimates are used to determine the equivalent roughness (R) value. A conservative value from the range of porosity values has been adopted, considering the worst-case value feasible for this study.

## Equivalent Roughness

The equivalent roughness is determined by assuming a range of porosity values and adopting the lower bound, conservative value in combination with Figure 9. The roundness (R) for basalt waste material can be assumed as 'sharp and angular' on the basis that the material was blasted and minimal rounding would occur due to transportation and dumping. The range of porosity values obtained from literature review varies between 25% and 35% for basalt, and the porosity was considered to be 30% for the basalt on this site. The equivalent roughness is estimated as 7.5, as shown in Figure 9.
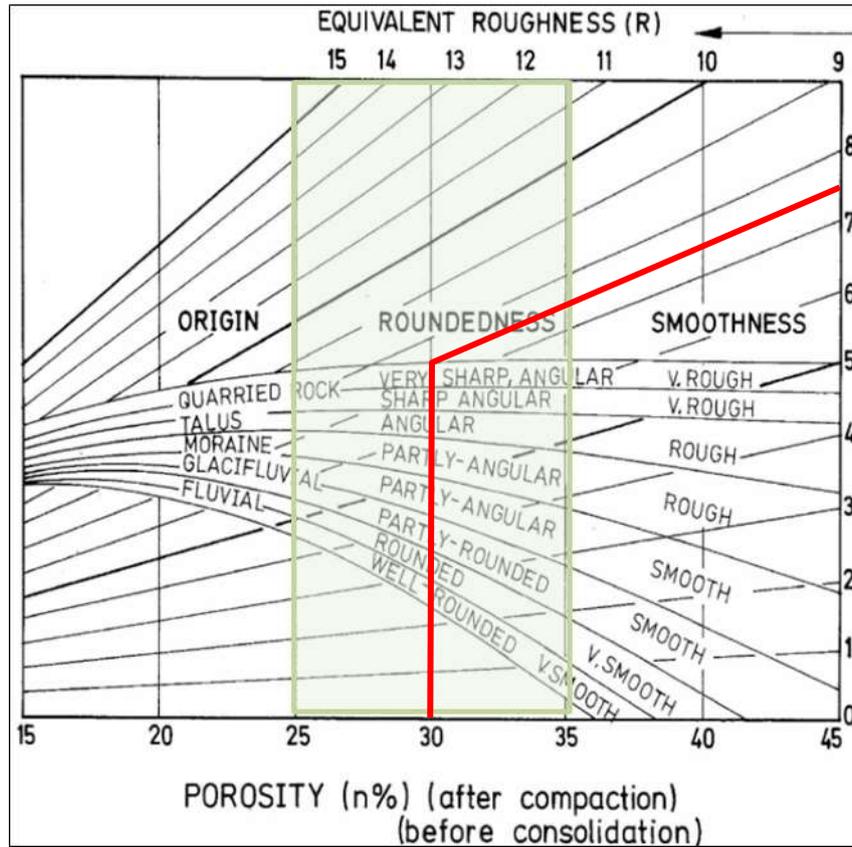
*Figure 9. Empirical scheme for estimating the likely R-value for rock fill.*

### Base Friction Angle

Detailed information regarding the value of base friction angle was sourced from the material strength parameters used for pit design. The estimates for the base friction angle of the basalt material were obtained from laboratory tests results presented in Table *II*II. The mean base friction angle was calculated as 37° with a standard deviation of 4. A normal distribution was assumed.

*Table II. Base friction angle form laboratory tests.*

| Hole ID | Depth (m) | Rock type | Base friction angle (°) |
|---------|-----------|-----------|-------------------------|
| 1 | 152.38–152.75 | Amygdaloidal basalt | 37 |
| 2 | 342.73–343.02 | Amygdaloidal basalt | 31 |
| 3 | 448.02–118.97 | Amygdaloidal basalt | 35 |
| 4 | 259.02–259.37 | Massive basalt | 37 |
| 5 | 271.02–271.42 | Massive basalt | 41 |
| 6 | 460.95–461.92 | Massive basalt | 40 |

### Unit Mass

Unit mass estimates were obtained from the pit design material properties. The unit mass used for basalt is 27 kN/m³.

**Barton-Kjearnsli (1981) Input Parameters**

Table III summarizes the input parameters used to determine the Barton-Kjaernsli (1981) strength parameters, and includes the results for the A and b factors in MPa. Parameters A and b are used to calculate the nonlinear strength envelope used in the SLIDE slope stability analysis.

*Table III. Input parameters for the Barton-Kjaernsli methodology.*

| Material | Barton-Kjaernsli Nonlinear shear strength relationship | | UCS (MPa) | $\phi b$ | $d50$ (mm) | Porosity % | R | S MPa | Rock unit density kN/m³ |
|---|---|---|---|---|---|---|---|---|---|
| | A | b | | | | | | | |
| Basalt (fine) | 1.0473 | 0.8808 | 126 | 37 | 150 | 30 | 7.5 | 32.76 | 27 |
| Basalt (coarse) | 1.0222 | 0.8815 | 126 | 37 | 450 | 30 | 7.5 | 26.46 | 27 |

**Phreatic Surface**

The presence of a phreatic surface influences the effective stress in the system and most often leads to a reduced factor of safety (FOS). A good understanding of the location of a phreatic surface is therefore essential. No detailed measures are in place to determine the location of a phreatic surface for the dump analysed. Using engineering judgement, considering site observations and available meteorological data, the following applies:

- The catchment areas of the dumps are limited to the dump surfaces only. Any infiltration is limited to rainfall or snowmelt
- Evaporation is significantly higher than precipitation (annual S-pan evaporation: 1050 mm *vs* annual precipitation 761 mm)
- No ponding was observed on the dump surface during the site visit
- Oversize material naturally segregates down- slope during the dumping process (Figure 10), and this will assist with water drainage through the dump. The oversize material at the base of the dump will facilitate seasonal water accumulation in the stream as the dump migrates over the low-lying area
- Failures after heavy rain have been reported by the mine operators while dumping down-valley.

Based on the above considerations, assumptions are that the dumps are free- draining under expected rainfall conditions and that no phreatic surface is likely to develop within the dump. Oversize material is presented in Figure 10.

*Figure 10. Oversize material segregates down to the toe of the waste rock dump.*

**Rock Waste Shear Strength Parameters**

The nonlinear shear strength envelope derived for the basalt waste material on site, as well as shear strength envelopes obtained from similar waste rock materials, is shown in Figure 11.
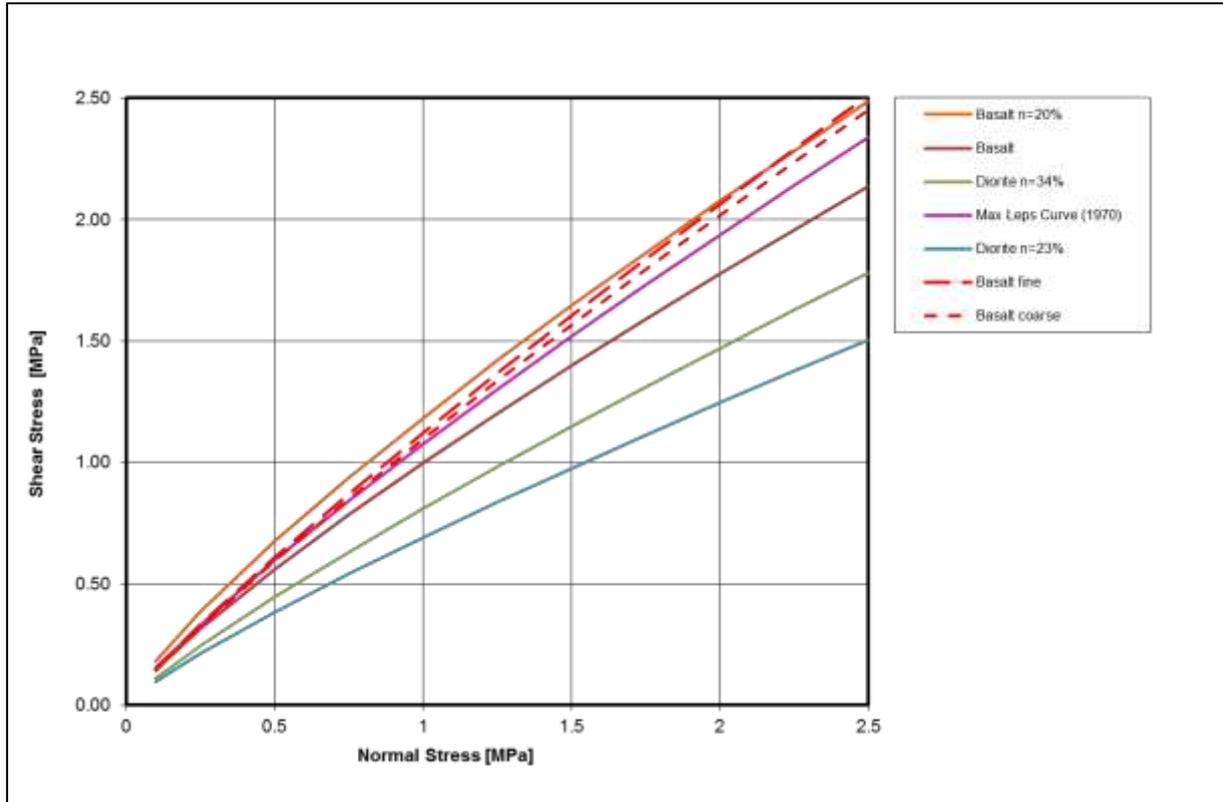
*Figure 11. Comparison of estimated basalt waste rock shear strengths.*

The basalt strength envelope sourced for this site is compared to similar mine sites, and the following observations are made:

- The coarse and fine basalts present similar results

The basalt material falls within the normal acceptable range for basalt dumps.

**Classification of Waste Rock Dumps**

Waste rock dumps can be compared to many other natural or engineered slopes or structures that are permanently developing. Because these structures continue to develop, minor local instabilities can be remediated in line with the management of the dump. Furthermore, the dumps are often in remote areas where consequences of a failure are minor or even limited to economic aspects only.

Typically used FOS values are therefore lower than those suggested by various national and internal codes or institutions for natural or engineered slopes. Well-accepted recommendations initially presented in a paper prepared for the British Columbia Mine Dump Committee (1991) are given in Table IV. It can be seen that alternate acceptable FOS values are given (Case A and B). This approach allows scope to consider uncertainties; for instance, input parameters or the analysis method and the associated consequences of instability.

*Table IV. Guidelines for minimum design factors of safety.*

| Stability condition | Suggested minimum design values for factor of safety | |
|---|---|---|
| | Case A | Case B |
| Stability dump surface<br>Short-term condition (during construction)<br>Long-term (reclamation/abandonment) | 1.0<br><br>1.2 | 1.0<br><br>1.1 |
| Overall stability (deep-seated stability)<br>Short-term (static)<br>Long-term (static)<br>Pseudo-static (earthquake)[2] | <br>1.3–1.5<br>1.5<br>1.1–1.3 | <br>1.1–1.3<br>1.3<br>1.0 |
| Case A:<br>Low-level confidence in critical analysis parameters<br>Possibly aggressive interpretation of conditions, assumptions<br>Severe consequences of failure<br>Simplified stability analysis method (charts, simplified method of slices)<br>Stability analysis method poorly simulates physical conditions<br>High level of confidence in critical failure mechanism(s) | | |
| Case B:<br>High level of confidence in critical analysis parameters<br>Conservative interpretation of conditions, assumptions<br>Minimal consequences of failure<br>Rigorous stability analysis method<br>Stability analysis simulates physical conditions well<br>High level of confidence in critical failure mechanism(s) | | |

1. A range of suggested minimum design values is given to reflect different levels of confidence in understanding site conditions, material parameters, consequences of instability, and other factors.
2. Where pseudo-static analyses, based on peak ground accelerations which have a 10% probability of exceedance in 50 years, yield FOS < 1.0, dynamic analysis of stress-strain response, and comparison of results with stress-strain characteristics of dump materials is recommended.

## STABILITY ASSESSMENT

SLIDE version 6.0 (Rocscience) was used to assess the stability of the slopes for each sector. SLIDE is a two-dimensional analytical slope stability program used for evaluating the stability of circular and non-circular failure surfaces in soil and rock slopes. The algorithm analyses the stability of quasi-circular slip surfaces using vertical slice equilibrium methods. In this report, the Bishop simplified method was used.

5000 potential failure surfaces were generated using the non-circular path search method in order to identify the lowest FOS.

The slope geometry was developed after analysing numerous sections through the dump. Current, two-year, five-year and life-of-mine sections were analysed, and the stability assessed at each planned milestone. Two sets of markers were set to constrain the failure surface to certain areas and to exclude unrealistic failure surfaces.

The following normal and special loading conditions were assessed:
- Normal loading – modelling completely drained conditions without any surcharge loads
- Special loading conditions:

- Modelling an assumed phreatic surface in the weaker soil layer immediately above the natural base rock encountered in the foundations beneath the dump

- Modelling completely drained conditions considering a seismic hazard. Calculations have shown that only a horizontal acceleration affects the results. Any vertical acceleration is therefore neglected

- Both local and global factors of safety were analysed by setting the limits of each model accordingly. The limits set are described in the relevant sections.

## EVALUATION OF RESULTS

As discussed, and based on the current information available, the author is of the opinion that the safety of the dumps should in general be assessed using the acceptance criteria defined for Case B as recommended by the British Columbia Mine Dump Committee Guidelines and included as Table IV. The recommended FOS given for Case B is lower than for Case A. The lower acceptance criteria might consequently affect the assessment of specific dumps and potentially the design of any required remedial measures.

The selection of Case B parameters is justified for this operation as the analysis methodology is applied with confidence. Data-sets supplied by the mine are small, but additional information sourced from similar operations reflects that the data falls within acceptable limits used in comparison. On-site conditions and assumptions have been applied conservatively in general, and the consequences of failure will have a limited effect on current mining operations. The stability analysis methods applied are well accepted by the mining industry and have been rigorously applied to cover all anticipated circumstances. The stability analysis methodology is considered to follow physical conditions accurately. Confidence in the stability analysis results is good, and engineering judgement has been applied to understand the critical failure mechanisms. These mechanisms have been applied during the analysis phase of the project.

### Additional Considerations

Fluid flow in dumps controls the distribution of pore water pressure within the waste rock dump, which may in turn control stability.

A typical dump structure profile is included in Figure 12, and as is observed on site, a rubble zone is formed at the base of the dump by natural segregation of material during the dumping process. This coarse rubble zone forms a drain at the base of the dump and discharges from the toe. The compacted traffic surface restricts infiltration into the dump from rainwater and snowfall.
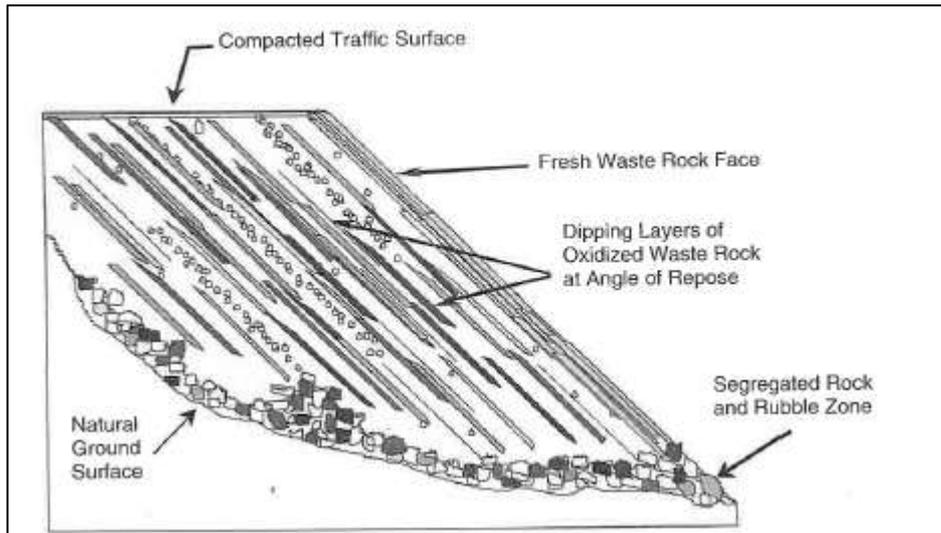
*Figure 12. Typical structure of a waste rock embankment.*

A typical flow regime within a dump is presented in Figure 13, and models utilized to simulate anticipated ground water conditions reflect this typical behaviour.

Tests conducted on coarse dumps indicate that these structures remain predominantly unsaturated. Field observations also suggest that the coarser layers form the principal or preferred pathway for seepage through the dump due to surface infiltration. Surface infiltration is naturally mitigated during the construction of dumps by the compaction of material by traffic moving across the surface and compacting placed material, as well as differential compaction within the dump due to loading and material settlement.
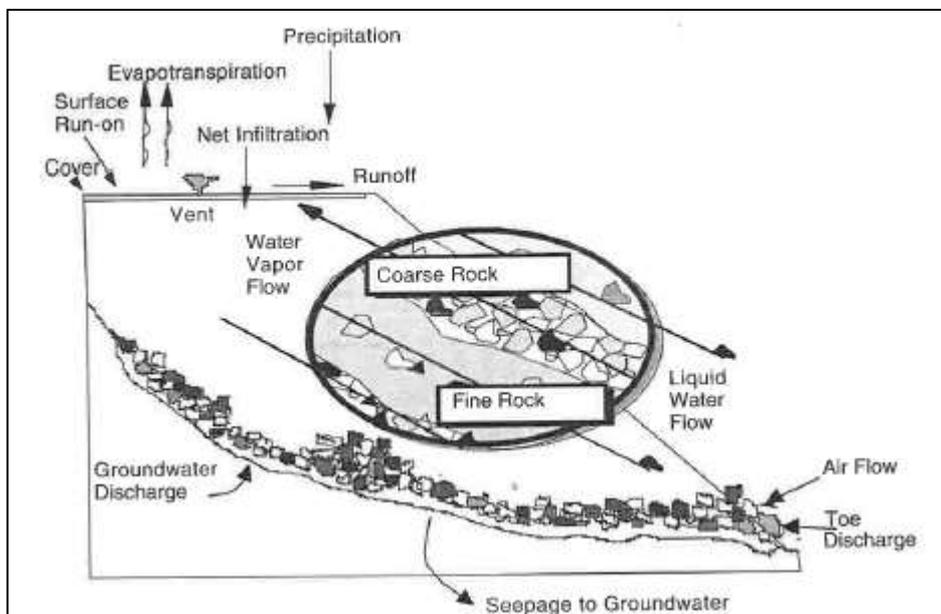


*Figure 13. Typical water/fluid flow diagram for waste rock dumps.*

While the typical flow diagram addresses the flows through the dump, storm water surface management remains a crucial part in the proactive management of the stability of dumps. The following considerations are highlighted:

- Surface water flows can erode a dumping platform and face if directed over the crest. The methodology employed to alleviate water flow over the crest include:
  - Construction of a berm to prevent storm water flow over the crest.
  - Limit water on the surface of dumps to only direct precipitation or snow melt – do not discharge any waste water onto the surface of the dump.
  - Grade the surface of the dump to assist with drainage of water off the surface towards the access road – a 2 % gradient away from the crest will suffice.
- Surface conditions such as depressions or irregularities should be avoided, as these are more likely to accumulate water and exacerbate infiltration.
- In extreme cases, the surface of the dump can be crowned along the centre line of valley fill dumps to divert runoff water away from the valley and down slope on either side of the dump.

## STABILITY RESULTS

The results calculated are discussed, and include local and global / deep-seated failure surfaces. Results include:
- Dry analysis – local and global analysis
- Saturated conditions along the soil interface – global analysis
- Seismic considerations with a saturated soil interface – global analysis.

The worst condition (lowest FOS) is reported for the 2015 dump position for the south section. That position presents the dump at its lowest point along the valley and the highest at approximately 170 m in a single lift. The result is recorded on the lower value for the accepted range, but still falls within acceptable limits.

Caution should be exercised when dumping down-valley, as previous instabilities have been recorded during this method of dumping. The old dump has reached its lowest down-valley point in the southern direction, and it is unlikely that additional instability will be recorded as a result of down-valley dumping operations. The eastern section will continue dumping down-valley, although the gradient is ≤10°. Monthly scanning monitoring of the surface, toes, and particularly in the valley is recommended. Removal of soft sediments along the valley floor is strongly recommended prior to dumping. Should the soil thickness along the valley floor be equal to or less than approximately 500 mm, it may be prudent to rip the foundation material rather than remove it. This will assist with drainage along the valley, as the natural segregation of material during the dumping process will result in large boulders rolling down the dump and landing in the ripped material to form a natural drainage channel along the valley floor.

## SUMMARY AND CONCLUSIONS

- A geotechnical investigation was carried out for the foundations and dumps using field observations, *in-situ* tests, test pits, and laboratory testing. Results of this investigation identified an interface layer above the bedrock in the foundation. The interface layer varies and is described as sandy silt to silty gravel. The estimated general thickness of this layer was 1.0 m
- Input parameters used for slope stability assessment include:
  - Waste dump material parameters derived from the Barton–Kjaernsli method
  - Interface material properties obtained from the soils map and assumptions made on site
  - Foundation material properties were assumed using the USCS system – further investigation would require improved definition of these parameters by means of test trenches and foundation indicator tests

- A phreatic surface was assumed to exist along the dump foundation interface only, and the models were not analysed for a completely saturated condition. It is assumed that a phreatic surface is unlikely to build up any significant pore water pressures within the dumps as the waste rock is predominantly coarse, strong basalt, and is most likely to remain free draining
- The guideline used for the mine operation stability analysis is sourced from a paper prepared for the British Columbia Mine Dump Committee (1991). These guidelines compare favourably with the guidelines for pit slope stability used during the pit design phase, and are recognized worldwide as an industry-acceptable guideline
- The dump profiles generally comply with the stability standards presented. Long-term erodibility of the dump surfaces is not considered a risk with a significant consequence.

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