HEAP AND DUMP LEACH PILE STABILITY RATING AND HAZARD CLASSIFICATION SYSTEM©

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1 Introduction

Since the introduction of modern heap and dump leaching methods in the 1980s there have been numerous contributions in the literature by mining companies, individuals and consulting companies to the design, safe operation and closure of these leach facilities. However, unlike various guidance documents that have been developed and published for water dams, tailings dams and waste dumps by well-known organizations such as the International Committee on Large Dams (ICOLD), the Australian National Committee on Large Dams (ANCOLD), the Canadian Dam Association (CDA), the International Council on Mining and Metals (ICMM), and the Large Open Pit (LOP) project, there are no widely accepted guidelines or standards regarding the design, stability analysis or hazard/risk assessment of heap and dump leach facilities. This paper is intended to help close this gap with the introduction of a new classification system designed to assist practitioners with objective assessment and rating of the relative instability hazard of existing and proposed heap and dump leach facilities. This new Heap Stability Rating and Hazard Classification (HSRHC) system, applicable to both heap and dump leaching, has been developed based on an adaptation of the Waste Dump Stability Rating and Hazard Classification (WSRHC) system described in Chapter 3 of *Guidelines for Mine Waste Dump and Stockpile Design* (Hawley and Cunning 2017).

There is no generally accepted definition for the difference between a “heap” and a “dump” leach, and usage of the term dump leach varies considerably between industries (especially between gold and copper) and regions (e.g., North and South America). Generally speaking, and as used herein, heap leach facilities can process either crushed or uncrushed (run-of-mine [ROM]) ore. Heaps are stacked in relatively thin lifts (rarely more than 25 m per lift), with benches between lifts and relatively closely controlled geometry to optimize metal recovery. Modern heaps are always stacked on an engineered liner system. On the other hand, dump leach facilities are always ROM, stacked in relatively thick lifts, often with very high angle of repose slopes, and occasionally without an engineered liner system, relying on geologic containment. In this paper the term “heap” refers to ore piles for both heap and dump leaching and “heap leach facility” (HLF) also refers to both types of facilities.

Following its introduction in 2017, the WSRHC has been widely used by mining companies, consultants, academics and regulators as a screening tool for assessing the overall hazards of waste dumps and stockpiles and comparing the estimated hazard levels to other sites and facilities. In the absence of a similar tool focused more directly on HLFs, several practitioners have informally adapted the WSRHC to help establish key design attributes, assess the relative hazard level of alternative designs, and (in recent forensic investigations) evaluate HLF failures. The anecdotal conclusions from these adaptive studies are that the WSRHC system as it stands is useful for HLF

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application, but that the industry would benefit from a standardized and exclusively heap-leaching focused hazard assessment tool. Furthermore, given its proven utility, adaptation of the WSRHC, rather than development of a new, dedicated tool from scratch, is the logical path forward. The LOP project is an international research and technology transfer project focusing on the stability of large slopes associated with open pit mining. The LOP project is sponsored by industry in multi-year cycles, and the current cycle is called LOP IV. The LOP IV Sponsors agreed with this approach and funded the development of the Heap Stability Rating and Hazard Classification (HSRHC) system based on the WSRHC system, a short description of which is provided in the next section to set the background. This paper will form the basis for a chapter in the pending LOP book *Guidelines for Heap and Dump Leach Design and Operations*, which is slated for publication in 2027.

2 Waste Dump and Stockpile Stability Rating and Hazard Classification (WSRHC) System

Rating the stability and classification of the potential hazard of a given waste dump or stockpile using the WSRHC system requires the evaluation of 22 Factors categorized into 7 Groups, which are, in turn, used to define two indices: the Engineering Geology Index (EGI) and Design and Performance Index (DPI). The architecture of the WSRHC system is illustrated in Figure 1. The factors that make up the EGI are dependent on the conditions of the site, while the factors that define the DPI are primarily controlled by the geometric design and performance history of the facility.

Each factor is weighted according to its perceived overall importance, and a range of possible numerical values is assigned. Detailed guidance is provided for the selection of numerical ratings for each factor. Numerical ratings for factors from each index are added together to derive an overall Waste Dump and Stockpile Stability Rating (WSR). The maximum achievable WSR is 100, with higher WSR ratings signifying greater stability and lesser hazard. The range of possible WSR ratings is subdivided into five Waste Dump and Stockpile Hazard Classes (WHCs), ranging from “Very Low” to “Very High” as shown in Table 1.

The outcomes of a WSRHC classification may be presented and compared on an X-Y plot as illustrated in Figure 2, where the X-axis represents the DPI and the Y-axis represents the EGI. The color coding of the plot areas corresponds to the WHC. Negative values of both the EGI and the DPI are theoretically possible, and the X-Y plot can be extended into negative space if needed, although in practice, negative rating values are rare.

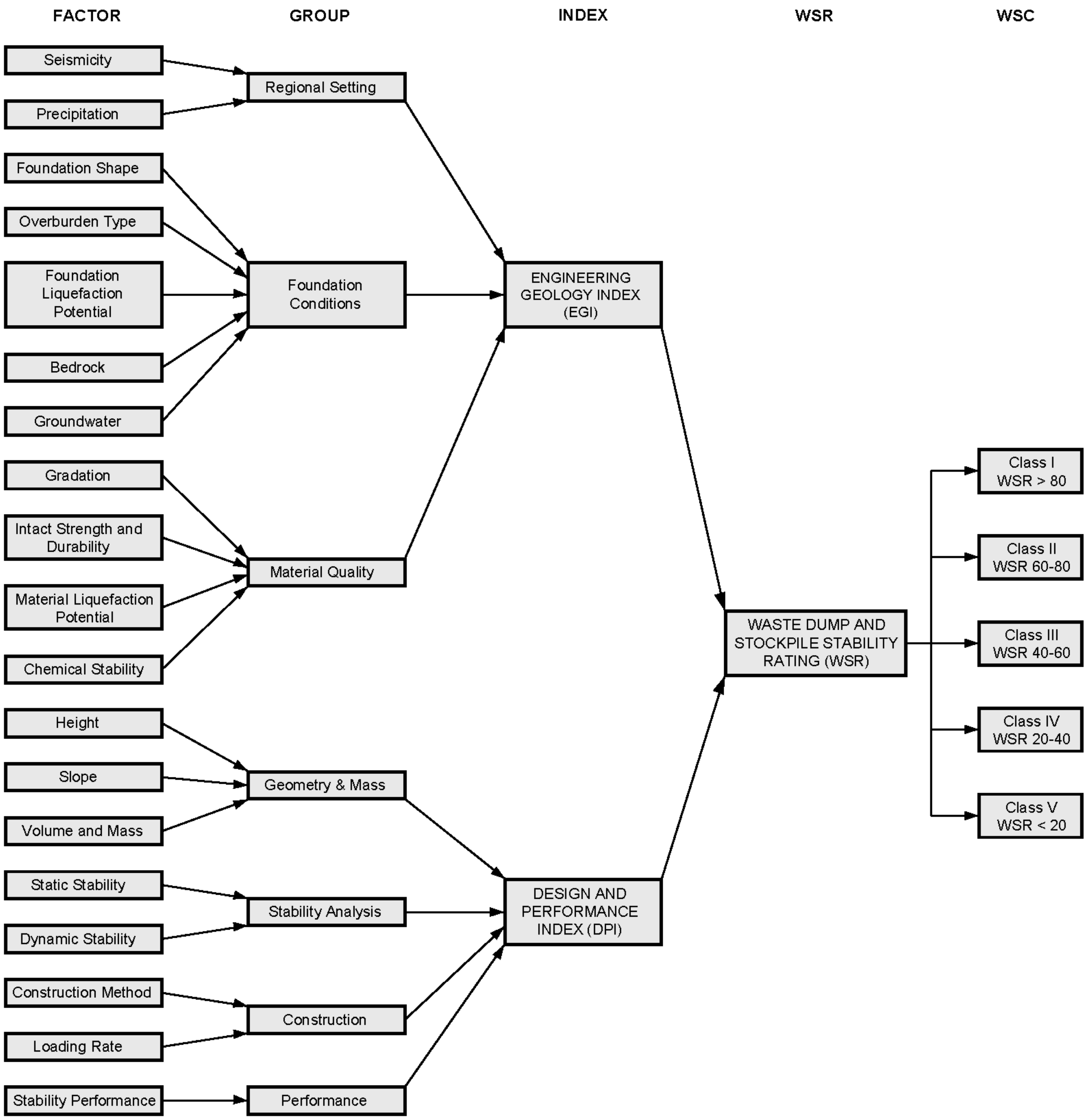

Figure 1: Architecture of the WSRHC system (after Hawley and Cunning 2017)

Table 1: Waste dump and stockpile stability ratings ranges and hazard classes (after Hawley and Cunning 2017)

WSR	WHC	INSTABILITY HAZARD
80-100	I	Very Low Hazard
60-80	II	Low Hazard
40-60	III	Moderate Hazard
20-40	IV	High Hazard
< 20	V	Very High Hazard

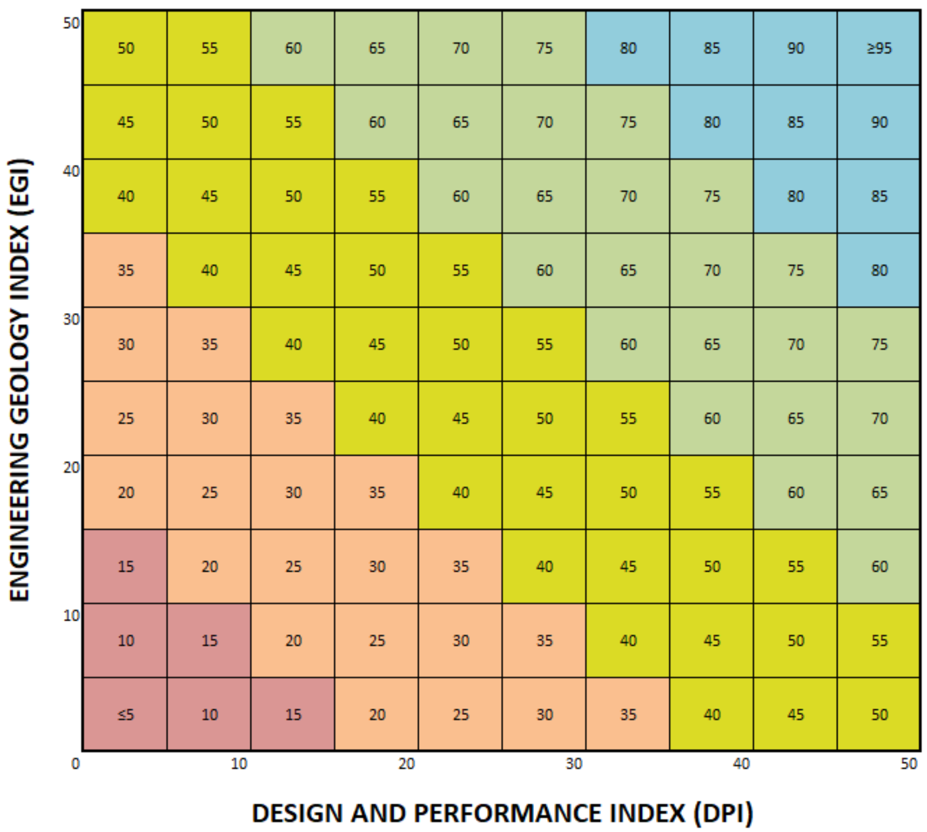

Figure 2: Waste dump and stockpile stability rating (WSR) and hazard chart (WHC) (after Hawley and Cunning 2017)

3 Heap Stability Rating and Hazard Classification (HSRHC) system

As indicated at the very outset, the term heap refers to ore piles that are constructed for both heap and dump leaching, although in some cases the unique attributes of these two types of facilities warrant separate discussions and different characterizations. The Heap Stability Rating and Hazard Classification (HSRHC) system described below retains the same basic architecture as the WSRHC and is intended to be applied to all types of leaching facilities: heap leaching, dump leaching, low-grade stockpile leaching, and leached ore dumps that are being actively re-leached, rinsed or disposed of on an engineered liner system. Note that leached or spent ore is typically called “ripios” at many South American operations, and that term is occasionally used herein. Where leaching has been completed and the remaining deposits are fully drained, practitioners are encouraged to compare the results of classifications using both the WSRHC and HSRHC systems.

As per the WSRHC, the HSRHC consists of two parts: the Heap Stability Rating (HSR) and the Heap Hazard Classification (HHC). The structure is very similar to the WSRHC and is illustrated in Figure 3. It requires evaluation of 24 key factors or attributes that affect stability, with additional sub-factors introduced under most of these factors. In many cases, the original WSRHC ratings have been redefined to better represent the unique attributes of heap or dump leach facilities. Factors have been organized into eight groups, with numerical ratings assigned to each factor. Of the eight groups, three are EGI and the other 5 are DPI. The sum of the ratings defines the HSR, which has a maximum possible value of 100, equally divided between EGI and DPI. A higher HSR rating indicates a more stable configuration. As with the WSRHC, negative HSR ratings are possible under certain hazardous conditions.

HSR values are subdivided into five heap hazard classes (HHCs). HLFs with a very high HSR (more than 80) are assigned to HHC I and are characterized as presenting a very low potential for instability (very low instability hazard). Conversely, those with a very low HSR (less than or equal to 20), including negative values, are assigned to HHC V and are characterized as presenting a very high potential for instability (a very high instability hazard). Intermediate classes (HHC II, III and IV) represent HLFs with intermediate potentials for instability, or intermediate instability hazards. As indicated above, the architecture of the system is the same as for the WSRHC system and is similar in concept to the Rock Mass Rating (RMR) system (Bieniawski 1976) and the Geological Strength Index (GSI) classification (Hoek et al. 2002), both of which have gained wide acceptance and are well understood by most geotechnical practitioners in the mining industry.

The HSRHC system is designed to strike a balance between complexity and utility. While the number of factors that must be evaluated may at first seem daunting, many are based on objective parameters that are self-explanatory and should be relatively easy to obtain or estimate from plans or records. Detailed benchmark descriptions are provided to help the user select values for the more subjective factors. It is strongly recommended that the Engineer of Record (EoR) or Designer of Record (DoR) participate in this process. To simplify use, the system has been coded into a macro-enabled Excel workbook with each group of factors separated out into its own worksheet. Key parameter ratings may be input directly into the individual worksheets, and the component indices and final stability rating value are calculated automatically. A complimentary copy of this spreadsheet can be downloaded from the LOP website.

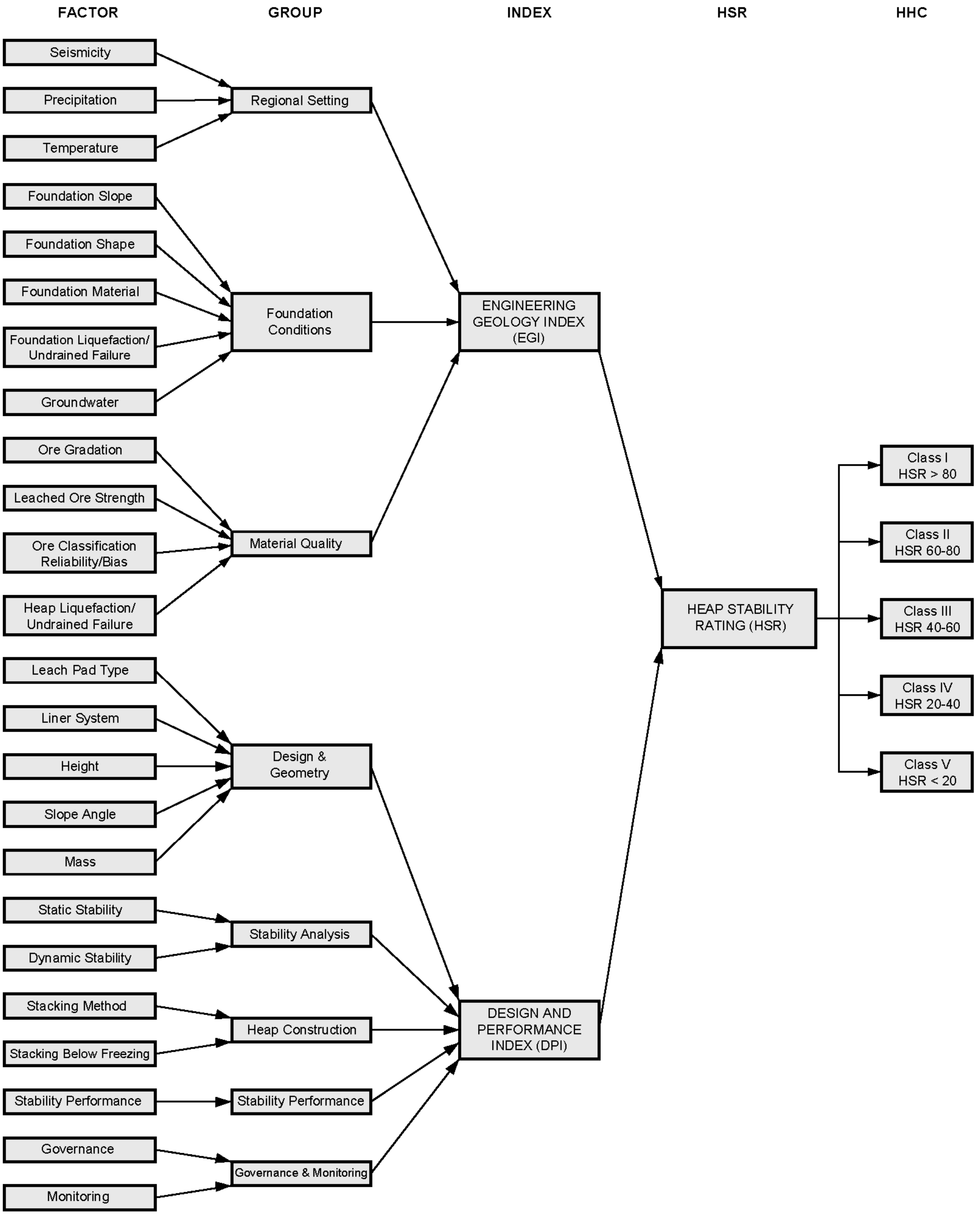

Figure 3: Architecture of the Heap Stability Rating and Hazard Classification (HSRHC) system

The numerical values assigned to each factor and group have been weighted to reflect their relative importance. As experience using the system is gained, adjustments to these weightings, to the individual parameter values and ranges, and perhaps even to the factor hierarchy and content, may be required to refine and improve the system. In this regard, direct feedback from practitioners about their experience using the draft system and suggestions for improvement were solicited during the preparation of the final paper and are reflected herein. This process is discussed in more detail in Section 4.10.1, Validation and Calibration.

The HSRHC system is intended not only to provide guidance for assessing the stability and hazard potential of leaching facilities, but also to serve as a consistent framework for compiling and cataloguing data that may ultimately support the development of a comprehensive global database of heap and dump leach facility designs and performance. It must be emphasized that the hazard is not an assembly of directly measurable parameters, and the essence of the HSHRC system, like any other hazard or risk assessment system, lies in the discipline of analysis and the engineering judgment it compels through the process of generating a numerical outcome. For example, if a facility receives a low Heap Stability Rating, an appropriate response may include revising the design, operational or monitoring practices to address the primary contributing factors, such as improving quality control of ore placement, applying more robust stability modelling methodologies, or reducing slope angles.

4 Stability Rating Factors

The following sections provide detailed descriptions of the various factors the HSRHC system comprises, and guidance in evaluating individual factor ratings. The factors are organized into eight groups as illustrated in Figure 3. Tables summarizing the factor descriptions and numerical ratings for each group and corresponding to individual worksheets in the companion Excel workbook, are shown in Tables 2 to 9. Some general rules of application of the HSRHC system are given below:

- In the case of dynamic heaps where the leached ore (ripios) is removed and dumped elsewhere, the ripios dump should be characterized as a heap or dump leach pile according to the HSRHC system if the dump is on a liner or subjected to further irrigation, and as a dump or stockpile as per the WSRHC system if it is unlined and not to be subjected to further irrigation. Alternatively, consider rating the hazard using both systems[5], comparing results, and adopting the more conservative of the two ratings. In both cases, special attention must be paid to undrained shear strength and liquefaction risks, especially for acid-leached ores which can undergo significant chemical degradation during and following the leaching process.
- In many cases, more than one sub-factor is shown for a given factor. Where it is possible to evaluate more than one of these parameters, or the user cannot decide between values or ranges, an average, intermediate or weighted rating value based on the judgment of the user should be chosen.
- Many of the factor ratings that combine to define the HSR are subject to variability throughout the development cycle of a heap or dump leach facility, including those used to reflect a site-specific understanding of the Regional Settings group factors, and the designer needs to be aware of this variability. As a rule, individual factor rating values that are representative of the least favorable conditions throughout the life cycle of the structure should be chosen. Alternatively, a range of rating values can be calculated based on the range of input values

[5] Some users of the WSRHC system have applied it to heap and dump leach facilities by including the effects of the liner system in the Foundation Conditions group (Foundation Material) and considering the leaching effects and saturation conditions in the Material Quality group. This is a crude but qualitatively useful approach.

for different factors to help understand this variability, allowing for a sensitivity analysis of the impacts of the siting and design alternatives on the resulting hazard classification. Another approach would be to prepare stability ratings and hazard classifications for each major development phase. This information may help to evaluate how the stability of the leach pile might vary throughout its development cycle, and to objectively identify critical phases.

- There are three conditions where the rating of a single factor can override the final Heap Hazard Class (HHC) decision based on the calculated Heap Stability Rating (HSR) and default the HHC to either Very High (HHC V) or High (HHC IV). Each of these is identified in the footnotes to the applicable table and summarized below:
  - In the case of liquefaction or undrained behaviour of the foundation (Table 3), if the rating is judged to be either High or Very High, the HHC is set directly based on the liquefaction and undrained strength rating as follows: if the Liquefaction or Undrained Failure Potential is judged as Very High, the leach pile should be classified as HHC V (Very High Hazard), regardless of the HSR. If the Liquefaction or Undrained Failure Potential is judged as High, the leach pile should be classified as HHC IV (High Hazard), unless the HSR is equal to or less than 20, in which case it should be classified as HHC V (Very High Hazard).
  - In the case of liquefaction or undrained behaviour of the material stacked in the heap or dump (Table 4), if the rating is judged as either High or Very High, the HHC is set directly based on the liquefaction and undrained strength rating as follows: if the Liquefaction or Undrained Failure Potential is judged as Very High the leach pile should be classified as HHC V (Very High Hazard), regardless of the HSR. If the Liquefaction or Undrained Failure Potential is judged as High, the leach pile should be classified as HHC IV (High Hazard), unless the HSR is equal to or less than 20, in which case it should be classified as HHC V (Very High Hazard).
  - In the case of Stability Performance (Table 8), if the Stability Performance is judged as Unstable, the leach pile should be classified as HHC V (Very High Hazard), regardless of the HSR. If the Stability Performance is judged as Metastable, the leach pile should be classified as HHC IV (High Hazard), unless the HSR is equal to or less than 20, in which case it should be classified as HHC V (Very High Hazard).

4.1 Regional Setting Group

The Regional Setting group (Table 2) includes factors that are related to the geographic location and climate of the site. The key factors in this category are seismicity, precipitation, and temperature. Unlike waste dumps and stockpiles, where temperature is generally not a critical issue, heap and dump leaching in cold climates brings in some additional challenges, both in terms of operational efficiency and stability hazards, making temperature a more important factor in Regional Setting. In contrast, hot and humid environments can accelerate material degradation (especially in contact with acid), thus impacting the Chemical Stability, Intact Strength, and Durability factors in the Material Quality group.

While this Group is called Regional Setting, the more site-specific these factors can be made, the more reliable the resulting ratings. For example, at the start of a project, maps of expected Peak Ground Acceleration (PGA) at a regional scale and the applicable National Oceanic and Atmospheric Administration (NOAA) Atlas are often used for preliminary economic assessments (PEAs). As the project advances, accepted modern practice requires that design and analysis efforts consider key inputs at an increasingly refined level. For example, site-specific seismic hazard and meteorological studies are usually completed, especially for projects with relatively high failure consequences. Advancing the HSRHC along with the design would also be good practice.

Other regional and climate factors, such as humidity and wind speed/direction, may also be important in the design (e.g., to optimize dust suppression and for snow and avalanche management), but either do not impact stability (e.g., wind) or are considered indirectly in other groups. The Regional Setting group has a possible rating range of -8 to 14 points, accounting for 12.3 per cent of the possible range of HSR values (including possible negative ratings).

Table 2: Regional setting factors and ratings

Factors[1]	**Ratings**				
Seismicity					
Expected Peak Ground Acceleration (g): based on DBE but not less than 1:475-year return period event/10% probability of exceedance in 50 years	> 0.4	0.2-0.4	0.1-0.2	0.05-0.1	< 0.05
Seismicity Rating	**-2**	**0**	**2**	**4**	**6**
Precipitation					
Average Annual Precipitation (mm)[2]	> 2,000	1,000-2,000	350-1,000	100-350	< 100
Precipitation Rating[3]	**-4**	**-2**	**0**	**3**	**6**
Temperature					
Months with average daily temperature < 0°C	> 5	4	2-3	1	0
Temperature Rating	**-2**	**0**	**1**	**1.5**	**2**
Regional Setting Rating[4]	**Minimum Possible Rating: -8**				**Maximum Possible Rating: 14**

Notes:

1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition.
2. Includes rainfall and snowfall converted to equivalent rainfall (i.e., Snow-Water Equivalent [SWE]). Where a site-specific SWE calculation is not available, use a nominal 10:1 conversion factor (e.g., 100 mm of snowpack yields 10 mm of melt water).
3. For sites that experience intense seasonal rainfall or rapid runoff events, decrease the rating value by 2 points. For example, if the site is subject to a moderate level of annual precipitation of between 350 and 1,000 mm but is also subject to rapid snowmelt and high runoff events during the freshet, the Precipitation Rating should be reduced to -2. Do not decrease the Precipitation Rating if it is already at the minimum (-4).
4. The sum of the ratings for the individual factors is the Regional Setting Rating.

4.1.1 Seismicity

In most mine settings, the design of HLFs must consider the potential impact of earthquakes. This has become standard practice internationally, with regulatory agencies in some jurisdictions, particularly those in high seismic risk zones (e.g., Perú, Chile and Türkiye), requiring that seismicity be explicitly considered. Accordingly, seismicity is included as one of the key stability factors in the Regional Setting group.

The Seismicity rating is evaluated according to the expected ground acceleration at the site. Table 2 considers the PGA from either the 1:475-year return period seismic event (also equivalent to the expected ground acceleration with a 10 per cent probability of exceedance in 50 years) or the Design Basis Earthquake (DBE) for projects sufficiently advanced to have a DBE. However, if the DBE PGA is less than that of the 1:475-year event, the higher PGA should be used. Note that these rating factors have been calibrated based on the 1:475-year seismic events and, thus, use of a stronger DBE may warrant reconsideration of the assigned values.

Values for earthquake design ground motion (EDGM) parameters should be developed from site-specific seismic hazard assessments that are routinely carried out to support the design of tailings dams, HLFs and other large or critical infrastructure components at the mine. Some jurisdictions and government agencies provide maps or interactive websites that can be used to estimate certain EDGM parameters at a given site to an acceptable degree of reliance, at least for initial infrastructure design (e.g., Giardini 1999; NRC 2013; USGS 2015).

The Seismicity factor has a possible rating range of -2 to 6 points, accounting for 4.5 per cent of the possible range of HSR values. From a structural stability perspective, potential earthquake impacts are also indirectly included in the assessment of liquefaction potential under the Foundation Conditions and Material Quality groups, and directly in the assessment of the overall Dynamic Stability and Deformation factor under the Stability Analysis group. When all these factors are considered collectively, and depending on site-specific circumstances, high seismicity could have a significantly negative impact on the HSR.

4.1.2 Precipitation

Heap and dump leach piles constructed in wet environments face operational issues such as leach solution dilution, inconsistent leachate flow, increased runoff potential, surplus solution accumulation, seasonally higher degrees of saturation within the heap, and the potential for clogging of the drainage system due to fines migration. In high precipitation regions, excessive rainfall may also cause stability issues and structural failures if not accounted for with the leach solution application (irrigation) rate.

The Precipitation factor is rated based on equivalent annual precipitation, including snowfall. This information is typically summarized in environmental impact assessments, general project descriptions, and site characterization reports. Most operating sites, and many exploration and closed sites, maintain climate stations that record precipitation data. Where practical, such data should be considered when selecting the Precipitation factor.

As in the case of waste dumps and stockpiles, total annual precipitation alone is not sufficient to describe the potential impact of precipitation on heap leach pile stability. Sites that are subject to strong seasonal variations (wet seasons or monsoons) with periods of intense rainfall, or rain-on-snow events during freshet periods that result in rapid snowmelt and high instantaneous runoff, are more susceptible to precipitation-related instability than those that receive uniformly distributed precipitation throughout the year or season. For sites subject to high rainfall intensity or runoff events (including freshet), the Precipitation rating should be reduced by 2 points. For example, if the site is subject to a moderate level of annual precipitation of between 350 and 1,000 mm but is also subject to rapid snowmelt , the Precipitation rating should be reduced from 0 to -2. If the Precipitation Rating is already at the minimum value of -4, no further downgrading to account for rainfall or runoff intensity should be applied.

The Precipitation factor has a possible rating range of -4 to 6 points, accounting for 5.6 per cent of the possible range of HSR values. Including Precipitation as an individual factor reflects the significant potential impact it can have on leach pile stability. In addition, high precipitation levels tend to result in higher natural groundwater levels that could indirectly and adversely affect both the Groundwater and Foundation Liquefaction/Undrained Failure factors in the Foundation Conditions group, and the Heap Liquefaction/Undrained Failure in the Material Quality group. This collective impact of precipitation on the HSR can be substantial, highlighting the importance of this factor.

4.1.3 Temperature

Temperature refers to ambient air temperature as a proxy for the risk of freezing within the heap, which can affect the ore, process solutions, and even foundation conditions if permafrost is present. Sub-freezing temperatures can be experienced due to high latitude (e.g., in the arctic and sub-arctic) or high elevation (e.g., the Andes). Several leach facilities have operated or are currently operating in locations that experience prolonged periods of daily average temperatures below freezing.

The Temperature factor has a possible rating range of -2 to 2, accounting for 2.2 per cent of the possible range of HSR values.

4.2 Foundation Conditions

This group (Table 3) includes factors that are related to the key physical attributes of the foundation or footprint of the leach pile. The factors in this group that are thought to potentially affect stability and are applicable to most leach piles are the topography (Foundation Slope and Foundation Shape), the nature of the foundation materials (Foundation Materials), the potential for foundation liquefaction or undrained failure (Foundation Liquefaction/Undrained Failure), and groundwater conditions (Groundwater). The Foundation Conditions group does not include the liner system, which is addressed in the Design and Geometry group (Table 5). For users who wish to apply both the WSRHC and HSRHC systems, such as recommended herein for ripios dumps, the WSRHC Foundation Condition group can be adapted to address the presence of the relatively weak components of the liner system.

The Foundation Conditions group has a possible rating range of -18 to 10 points, accounting for 15.6 per cent of the possible range of HSR values.

4.2.1 Foundation Slope

The slope of the foundation of a heap leach pad has a direct influence on the global stability and general performance of the structure. Leach piles constructed on steep foundations are much more likely to be unstable or to perform poorly from a deformation perspective than those constructed on flat foundations.

The Foundation Slope factor is characterized based on the average overall foundation slope angle. The foundation of the ultimate-stage heap leach facility may be flatter or steeper than its interim phases. While the Foundation Shape factor (see below) attempts to capture some of this variability, if the Foundation Slope factor varies widely by phase, it should be selected based on the least favorable overall slope angle throughout the development cycle of the heap, not just on the ultimate configuration, unless the classification is being done for closure purposes only or for individual phases of development. Average overall foundation slope angles can be measured directly from heap stacking plans and representative sections or profiles.

The Foundation Slope factor has a possible rating range of -2 to 2 points, accounting for 2.2 per cent of the possible range of HSR values.

Table 3: Foundation Conditions factors and ratings

Factors[1]	**Ratings**				
Foundation Slope					
Average Overall Slope Angle (°)	> 32	25 - 32	15 - 25	5 - 15	< 5
Foundation Slope Rating	**-2**	**-1**	**0**	**1**	**2**
Foundation Shape[2]					
Section Shape	Convex on steep to very steep slopes	Convex on moderate slopes; concave or planar on steep to very steep slopes	Convex on gentle slopes; planar or concave on moderate slopes	Planar or concave on gentle slopes	Planar or Concave on flat or favorable slopes. Includes “flat” leach pads common to Chile’s Atacama Desert
Plan Shape	Slopes with a pronounced convex plan shape (‘nose’)	Large radius convex slopes	Planar slopes with no lateral confinement	Concave slopes and wide valleys that provide limited natural confinement	Narrow valleys or gullies that provide substantial natural confinement
Foundation Shape Rating	**-2**	**-1**	**0**	**1**	**2**
Foundation Materials					
Foundation Material Type[3]	ASCE Class F, or Type I: Highly organic soils; very soft-soft silts and clays; sensitive clays; thaw-unstable permafrost; very weak or highly clay altered, sheared/highly fractured rocks; phyllite; GSI/RMR < 20; Q < 1; adversely oriented faults/shear zones	ASCE Class E, or Type II: Soft to firm fine-grained lacustrine deposits, silts and clays, fine-grained residual and lateritic soils; loose sands and gravels; sedimentary or moderately weathered/altered rocks; moderately to intensely fractured; GSI/RMR 20-40; Q 1-4; adversely oriented joints	ASCE Class D, or Type III: Alluvial; loose to moderately dense sands, gravels; mixed-grained colluvial, moraine, glacial till; sandy residual soils; stiff fine-grained soils; moderately competent or fractured bedrock; slightly weathered/altered; GSI/RMR 40-60; Q 4-10	ASCE Class C, or Type IV: Competent talus deposits; dense, coarse-grained soils; highly weathered but coherent bedrock, GSI/RMR 60-80; Q 10-40	ASCE Classes A and B, or Type V: Very dense, mixed-grained moraine and other very hard or competent soils; perpetually frozen thaw stable soils with negligible potential for creep due to embankment loading; competent, unweathered bedrock; GSI/RMR>80; Q>40
Foundation Materials Rating	-4	0	2	3	4
Foundation Liquefaction/Undrained Failure					
Potential for Foundation Liquefaction/Undrained Failure[4, 5]	Very High;[6] very uniform; very loose; minimal plastic fines (-#200); open, clast supported structure; high void ratio; rounded clasts; saturated	High;[7] sensitive clays and extremely weak soils	Moderate or unknown	Low; but cannot be fully discounted	Negligible; well graded; dense; high content of plastic fines[8] (-#200); matrix supported structure; low void ratio; angular clasts; dry
Foundation Liquefaction/ Undrained Failure Rating	**−8**	**-6**	**-4**	**-2**	**0**
Groundwater					
Groundwater Conditions	Groundwater table at surface; active discharge, seepage; strong upward gradients; potential generation of high pore water pressure in foundation due to embankment or heap loading	Groundwater table 1-5 m below ground surface; limited potential for development of adverse pore water pressures in foundation due to embankment or heap loading	Groundwater table 5-10 m below ground surface; limited potential for development of adverse pore water pressures in foundation due to embankment or heap loading	Groundwater table 10-30 m below ground surface; negligible potential for adverse pore water pressures in foundation	Groundwater table at >30 m below ground surface; negligible potential for adverse pore water pressures in foundation
Groundwater Rating	**-2**	**-1**	**0**	**1**	**2**
Foundation Conditions Rating[9]	**Minimum Possible Rating: −18**				**Maximum Possible Rating: 10**

Notes:
1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition.
2. Choose the shape that best describes the geometry of the foundation in plan and section. Convex foundations steepen towards the toe in section and lack lateral confinement in plan; concave foundations flatten towards toe in section and provide lateral confinement in plan.

3. For ASCE soil Class A through F, see the ASCE site classification system (American Society of Civil Engineers 2022, chapter 20). For Types I through Type V, see Hoek et al. (2013) for a description of Geological Strength Index (GSI), Bieniawski (1976) for a description of RMR, and Barton et al. (1974) for a description of Q.
4. Evaluation of the potential for liquefaction or undrained failure of foundation soils may require detailed *in situ* investigations and specialized laboratory testing. If unknown or unsure, use a default value of zero (0) and consult a geotechnical specialist.
5. Liquefaction and undrained failure are both linked to loading rate and pore water pressure conditions within the foundation. The Foundation Liquefaction/Undrained Failure Rating should be based on the failure mechanism (liquefaction or undrained failure) that has the highest likelihood.
6. If the Foundation Liquefaction/Undrained Failure Rating is judged to be Very High, the heap should be classified as HHC V (Very High Hazard), regardless of the HSR.
7. If the Foundation Liquefaction/Undrained Failure Rating is judged to be High, the heap should be classified as HHC IV (High Hazard), unless the HSR is less than or equal to 20, in which case it should be classified as Very High Hazard.
8. The consideration of the effect of plastic fines on liquefaction and undrained behaviour is very complex. On the one hand, clays reduce hydraulic conductivity (permeability) and, in a leaching environment, can create layers with high degrees saturation, and saturation is required for either liquefaction or undrained behaviour. On the other hand, if the content of plastic fines creates significant cohesion, the risk of liquefaction can be reduced. However, materials with plastic fines are more prone to undrained behaviour than otherwise. Hence, the use of the plastic fines to dismiss the potential for liquefaction should only be done in consultation with an expert in undrained soil behaviour.
9. The sum of the ratings for the individual factors is the Foundation Conditions Rating.

4.2.2 Foundation Shape

The shape of the foundation of a heap leach pad may also have an impact on the stability and general performance of the heap. Two criteria have been identified to help characterize the degree of confinement afforded by the shape of the foundation: the nature of the vertical profile of the foundation as it appears in cross-section (Section Shape), and the plan shape as represented by the topographic contours (Plan Shape).

The Section Shape rating is determined by comparison of the vertical profile of the foundation to three idealized shapes: convex, planar and concave, and with reference to the overall steepness of the foundation slope. For leach pads that have a similar overall foundation slope, concave shapes in which the foundation slope progressively flattens from crest to toe generally result in better long-term stability than those with convex shapes (foundation slope progressively steepens from crest to toe, such as for a leach pad on a ridge line). Planar foundation slopes would logically fall between the concave and convex cases; however, if the foundation slope is gentle, there may be little difference between the performance of heap leach facilities constructed on concave and planar foundations.

The Plan Shape rating is determined based on the shape of the foundation in plan or map view. For leach piles constructed in narrow valleys or gullies that provide natural lateral confinement, the slopes on most sides of the heap are supported by favorable natural topography and thus those slopes tend to perform very well. However, the downgradient slope can be relatively high and founded on adversely sloping ground unless a buttress is provided at the toe. These issues are captured in part under the Leach pad Type factor of the Design and Geometry group (Table 5).

Users should select a Foundation Shape rating based on the descriptions of the Section Shape and Plan Shape parameters given above and summarized in Table 3. The Foundation Shape factor has a possible rating range of -2 to 2 points, or 2.2 per cent of the possible range of HSR values.

4.2.3 Foundation Materials

The term foundation material herein refers to any soil or bedrock material that may underlie the leach pad and liner, including residual soils derived from in situ weathering of bedrock below or transported deposits such as glacial till or moraines. Five Foundation Material types have been defined according to the ASCE site classification system (American Society of Civil Engineers 2022, chapter 20) Class A through E, as well as Types I through V according to the foundation conditions defined in the WSRHC system. For sites that include fill beneath the facility which could influence stability, engineered (structural) fill should be treated as ASCE Class C (Type IV). Non-engineered fill (including old tailings deposits, waste rock dumps, or leach piles) should be characterized as

ASCE Class D, E or F (Type III, II or I, respectively) according to the soil type representing the expected behaviour of the non-engineered fill.

ASCE Class F, or Type I: Highly organic soils, very soft to soft silts and clays, sensitive clays, and thaw-unstable permafrost. This type also includes very weak or highly clay altered, sheared or highly fractured rocks; phyllite; adversely oriented faults/shear zones; bedrock with a Geological Strength Index (GSI) (Hoek et al. 2013) of less than 20, a Rock Mass Rating (RMR) of less than 20, or a tunneling quality index (Q) (Barton et al. 1974) or less than 1.

ASCE Class E, or Type II: Soft to firm fine-grained soils such as lacustrine deposits; silts and clays, fine-grained residual soils; laterites and weathered saprolites; loose sands and gravels; lateritic soils; loose sands and gravels; fine-grained sedimentary rocks; moderately weathered or altered rocks; moderately to intensely fractured; bedrock with continuous joints or GSI/RMR 20-40 or Q 1-4.

ASCE Class D, or Type III: Alluvial deposits; loose to moderately dense sands and gravels including mixed-grained colluvial, moraine, and glacial deposits; sandy residual soils; stiff fine-grained soils layer; mixed-grain glacial deposits (moraine and till); moderately competent or fractured bedrock; lightly weathered/altered bedrock, or bedrock with GSI/RMR 40-60 or Q 4-10.

ASCE Class C, or Type IV: Competent talus deposits and dense, coarse-grained soils; engineered (structural) fills; highly weathered but coherent bedrock; GSI/RMR 60-80 or Q 10-40.

ASCE Class A and B, or Type V: Very dense, mixed-grained moraine and other very hard or competent soils; perpetually frozen thaw stable soils with negligible potential for creep due to embankment loading; competent, unweathered bedrock and bedrock with GSI/RMR>80 and Q>40.

Users should select a Foundation Materials rating based on the descriptions given above and summarized in Table 3. If the Foundation Materials vary throughout the footprint of the structure, an intermediate rating value should be chosen, weighted based on the expected distribution of the different foundation materials and their potential influence on stability. If the designer specifies that a weak surficial overburden layer is to be removed before or during construction, the Foundation Materials rating should be based on either the material that underlies the stripped layer or the backfill depending on which is expected to dominate stability. Similarly, if a lower quality soil layer is to be improved before construction, such as with dewatering, pre-consolidation or compaction, the post-improvement quality of the layer should be used to determine the rating.

The Foundation Materials factor has a possible rating range of -4 to 4 points, or 4.5 per cent of the possible range of HSR values.

4.2.4 Foundation Liquefaction/Undrained Failure

This factor is intended to address the layers within the foundation that have the potential to mobilize undrained shear strengths and, in the extreme, liquefy during loading (static or dynamic such as an earthquake). Soils susceptible to developing undrained shear strengths can experience sudden and significant loss of strength owed to the combination of increasing pore water pressure (reducing the effective confining stress) and strains (triggering strain softening).

Undrained foundation failure can occur when weak foundation soils are loaded too quickly. Rapid loading of saturated or near-saturated fine-grained soils with low hydraulic conductivity can increase pore water pressures within the soil faster than they can be dissipated by normal consolidation processes. These types of failures can occur quickly once the undrained strength of the soils is exceeded, and displacements can be very large. A recent, well-publicized example of an undrained foundation failure is the 2014 failure of the Mount Polley tailings dam in British Columbia (Morgenstern et al. 2015); while this was not a leach pile, it is nevertheless a relevant example. Undrained conditions and static liquefaction were also identified as part of the cause of the June 24, 2024, failure at the Victoria Gold Corp. (Eagle Gold mine) VLF in Canada (Smith and Konrad, 2025); while this was caused by conditions within the heap rather than the foundation, the geomechanics are the same. Peak strength reductions of 50 per cent from drained to undrained are not uncommon, and the reduction from peak drained to residual undrained strengths can be significantly greater.

Foundation Material types that are most susceptible to undrained failure include saturated or nearly- saturated, under- to slightly over-consolidated clays and silts. Mixed-grained, residual soils, saprolites and moraine, whose shear strength properties are often dominated by plastic clays and silts with low undrained strength, may also be susceptible. Under the right loading and groundwater conditions, even moderately strong Foundation Materials that behave as Mohr-Coulomb materials, whose shear strength behaviour is composed of both cohesive and frictional components, may be susceptible to significant loss of shear strength under undrained loading conditions.

Liquefaction, on the other hand, is a phenomenon in which the stiffness and the strength of the soil are suddenly reduced, often to near zero, and the soil behaves like a liquid due to a critical change in loading conditions (often called the trigger event). Under saturated or near-saturated conditions, loosely packed soils can contract under loading, resulting in pore water pressure increases and an associated decrease in effective confining stress, resulting in a near total loss of shear strength. Such critical change in loading resulting in high pore water pressures may be induced by cyclical shaking during an earthquake. Seismic shaking can also result in collapse of a loose, dispersed soil structure, which in turn can result in a sudden increase in pore water pressure, causing liquefaction. Earthquake-induced liquefaction is commonly referred to as dynamic liquefaction. Liquefaction may also be induced by high pore water pressures due to artesian flow conditions, rapidly rising phreatic levels, excess pore water pressures induced by construction activities including loading by heavy equipment, rapid advancement of heap stacking, or sudden loss of confinement such as with a local translational failure (static liquefaction) which triggered the Eagle Gold slope failure. Liquefied material behaves more like a fluid than a soil and is subject to rapid loss of strength and large displacements when unconfined. A good resource for estimating the undrained and liquefaction behaviour of soils and crushed ore is the modified NorSand model (Castonguay and Konrad, 2019; Smith and Konrad, 2025).

Foundation Materials that are most susceptible to liquefaction have several common attributes. They are typically composed of relatively uniformly graded materials (either *en masse* or interlayered). They are also usually loose (i.e., contractive), having a high void ratio and a relatively high degree of saturation, and for clayey soils have modest to low plasticity. Deposits of uniformly graded, loose, saturated silt and fine sand are often highly susceptible to liquefaction; coarser deposits of sand or gravel, and even cobble-sized material, may also liquefy under certain conditions. Conversely, materials that are dense (dilative), well-graded, unsaturated (i.e., less than about 80-85 per cent saturation) and contain appreciable amounts of clay and large angular particles have a relatively low susceptibility to liquefaction. However, sensitive clay deposits with high water content have been known to liquefy under certain loading conditions and, therefore, clay content by itself should not be construed as a liquefaction resistant characteristic. Further, high plasticity clays can have relatively low susceptibility to dynamic liquefaction, but they can suffer from cyclic softening.

If the Foundation Liquefaction/Undrained Failure Potential Rating is judged to be Very High, the heap should be classified as HHC V (Very High Hazard), regardless of the HSR. If the Foundation Liquefaction/Undrained Failure Rating is judged to be Very High, the heap should be classified as HHC IV (High Hazard), unless the HSR is less than or equal to 20, in which case it should be classified as Very High Hazard.

Users who are not experienced geotechnical practitioners should consult a geotechnical specialist before assigning Foundation Liquefaction/Undrained Failure ratings. The lowest rating category for this factor (Very High potential for liquefaction or undrained strength failure) has a high negative rating of -8, with the best-case rating being 0 points. The Foundation Liquefaction/Undrained Failure factor accounts for 4.5 per cent of the possible range of HSR values.

4.2.5 Groundwater

Groundwater levels, hydraulic gradients, and the hydraulic conductivities (loosely referred to as permeability herein) of the materials that compose the foundation, influence the pore water pressures in the foundation. Elevated groundwater levels and pore water pressures in the foundation can adversely affect the stability of the structure and can also create conditions (e.g., saturation) that increase the potential for foundation liquefaction failure. Heap and dump leach piles founded in groundwater discharge areas with upward gradients, such as valley bottoms or topographic lows, are more likely to experience elevated pore water pressures and saturated conditions than those founded in recharge areas with downward gradients, such as well-drained slopes or topographic highs. Construction of leach piles can also change the natural groundwater levels and flow regime by changing catchment areas or infiltration rates; hence, an evaluation of the groundwater conditions in the foundation needs to consider both the natural conditions and influence of construction. The potential impact of groundwater on the stability of the leach pile is rated on a range of the known or expected conditions ranging from very deep (the highest rating) to near the ground surface (the lowest), as discussed below and summarized in Table 3. Depth to groundwater should be taken at the seasonal maximum after construction of the facility.

- Very shallow groundwater can be characterized by the following conditions:
  - The natural groundwater table is at or near the base of the heap or dump leach facility, which for a lined facility would be within about 1 m of the liner system. For facilities to be constructed on ground that will settle, the change in elevation over time should be considered.
  - The base or toe of the heap is located in a discharge or seepage area, or encroaches on a seasonal or perennial wetland, lake, stream or other fluid-impounding facility such as an unlined pond or reservoir.
  - There is a strong upward gradient in the base or toe of the leach pile heap or there is a potential for generation of high pore water pressures in the foundation due to leach pile loading.
- Shallow groundwater is characterized by conditions between Very Shallow and Moderate.
- Moderate groundwater can be characterized by the following conditions:

  - The maximum seasonal elevation of the groundwater table is 5 to 10 m below the base of the heap or dump leach facility and is not expected to rise appreciably because of facility construction.
  - Groundwater flow is either parallel to the slope or there is a downward gradient with limited to no potential for development of adverse pore water pressures in the foundation due to leach pile loading.
- Deep groundwater is characterized by conditions between Moderate and Very Deep.
- Very deep groundwater is characterized by the following conditions:
  - The groundwater table is at great depth, typically considered >30 m below the base of the heap or dump leach facility.
  - There is a strong downward gradient and negligible potential for adverse pore water pressures in the foundation.

Users should select a Groundwater rating based on the descriptions given above and summarized in Table 3. The Groundwater factor ratings range from -2 to 2 points, or 2.2 per cent of the possible range of HSR values.

4.3 Material Quality

The Material Quality group (Table 4) includes factors that are related to the physical attributes of the materials used to construct the leach pile and collectively determine the shear strength, potential to develop undrained conditions, deformational behaviour, and hydrological characteristics of the structure. The key factors in this category are the Ore Gradation, Leached Ore Strength, Ore Characterization Reliability/Bias, and Heap Liquefaction/Undrained Failure Potential.

Collectively, the Material Quality group ratings range from -14 to 26 points, accounting for 22.3 per cent of the possible range of HSR values.

4.3.1 Ore Gradation

The Ore Gradation or particle size distribution (PSD) of the leach material is a key factor in determining the frictional component of its shear strength, typically accounting for most of the shear strength of the ore material being leached. PSD also affects both saturated and unsaturated permeability as well as saturation conditions under irrigation and after draindown of the pile. In general terms, well-graded materials with a high percentage of coarse angular particles and a low percentage of fines tend to have higher shear strength and better drainage properties than poorly graded or fine-grained materials. Gradation is characterized using three indices: the particle size for which 80 per cent (by weight) of the material is finer (P_{80}), the fines content (per cent by weight passing through the #200 sieve, or 75 micrometers), and the plasticity index or PI (defined as the difference between the liquid and plastic limits, LL and PL, respectively, according to ASTM D4318). Fine-grained materials with a high LL (>50) and high PI (>15) typically have a high plastic clay content, lower strength, lower permeability, and are often strain-softening, especially under undrained conditions. Fine-grained materials with a low LL (<35) and a low PI (<10) are typically composed of low plastic clays and non-plastic silts and tend to have a higher shear strength; however, these materials can be of greatest concern for liquefaction when in a contractive, saturated or near saturated state.

The use of dry sieve methods for quick classification of crushed ore containing silt or clay can significantly bias the results towards a larger P_{80} and lower fines content (Rönnqvist, 2019). Smith and Konrad (2025) found that for the Eagle Gold HLF, the per cent passing the 1.25 mm sieve measured by dry sieving was a good proxy for the per cent passing the #200 sieve by wet methods.

Crushed ore, with a finer P_{80}, is generally more sensitive to the effect of fines, and especially plastic fines. In contrast, ROM and primary-crushed ore will generally have higher shear strength and permeability because of the presence of large, angular stones. There is some overlap in behaviour between the coarsest primary crushed ore and the finer range of ROM material, and users should be aware of this transition and use their best judgement to select the most applicable rating.

The gradation, plasticity, and durability of crushed ore can be significantly affected by adding an agglomerating agent to the crushed material before stacking; ROM and primary crushed ore are not suitable for agglomeration. For gold and silver ores, agglomeration is usually performed with the addition of both barren leach solution and Portland cement. The cement can provide significant and long-lasting improvements in strength and permeability, as well as reduce the plasticity of any clay minerals both by cation exchange and pozzolanic reactions. Further, there is significant latitude in the cement dosage used to improve agglomerate quality, limited largely by costs. As indicated in Table 4, agglomeration using Portland cement can increase the Ore Gradation Rating by 1 to 2 points, depending on the crush size and cement dosage. For acid leaching of copper, uranium, and nickel ores, Portland cement binders cannot be used but adding acid to the agglomerator can create similar effects as Portland cement, though there is less control on the effectiveness and longevity of the improvements.

Ore Gradation ratings can vary from -2 to 6, accounting for 4.5 per cent of the possible range in HSR values.

4.3.2 Leached Ore Strength

The shear strength of the leach pile material is also influenced by the intact strength and durability of the individual particles, particularly in high heaps where inter-particle stresses may exceed the intact strength of the material and result in crushing, and the potential for chemical degradation during the leaching process. In other words, the Leached Ore Strength rating serves as a proxy for how the physical properties may degrade over time.

Materials with poor mechanical durability could break down during placement or over time due to leaching processes. The leachate type and concentration also play a significant role. All these processes tend to result in the generation of additional fines (particles passing the #200 sieve) and change the gradation of the material. To help characterize leach pile materials based on intact strength and durability in conjunction with the leachate type/concentration, five material types have been defined in the following and summarized in Table 4. To the extent practical, the Leached Ore Strength factors should be estimated based on the properties of the ore after being exposed to several cycles of leaching for a conventional heap or dump, or a single[6] cycle for a dynamic heap.

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[6] A few dynamic HLFs stack and leach multiple lifts before unloading and starting the process over. For these facilities, the condition of the leached ore after the applicable number of leach cycles should be used.

Table 4: Material Quality factors and ratings

Factors[1]	**Ratings**				
Ore Gradation					
For crushed and ROM ore:					
P_{80} [2,3]	< 10 mm	10 - 18 mm Or Unknown	19 - 35 mm	35 - 75 mm	> 75 mm
% Fines[3]	> 30	20 - 30	10 - 20	5 - 10	< 10
Plasticity Index (PI)[4]	> 15	10 - 15	5 - 10	< 5	Non plastic
Agglomeration[5]	Increase rating by 2 points for agglomeration with Portland cement, or 1 point for agglomeration with acid			Increase rating by 1 point for agglomeration with either Portland cement or acid	
Ore Gradation Rating	**-2**	**0**	**2**	**4**	**6**
Leached Ore Strength					
Intact Strength and Durability[6]	Type 1 Extremely weak to very weak, highly degradable ore	Type 2 Weak, degradable ore	Type 3 Medium strength ore with moderate durability	Type 4 Strong, durable ore	Type 5 Very strong, extremely durable ore
Leachate Type and Concentration	Acid[7]; > 10g/l	Acid[7]; < 10g/l	Water or Alkali[8]	Alkali[8]	Alkali[8]
Leached Ore Strength Rating	**-2**	**0**	**2**	**4**	**6**
Ore Characterization Reliability/Bias					
Ore Characterization Reliability	No data on aged samples	Little data on aged samples	Some data on partially aged samples (1 leach cycle)	Data on samples aged (1-2 leach cycles)	Comprehensive data on long term aged samples
Sampling Statistics and Bias	No statistically significant sampling or known sample bias towards good quality rock	Little statistically significant sampling, known sample bias	Statistically significant sampling for at least 5 years, little data beyond 5 years	Statistically significant sampling for at least 5 years, some sampling >10 years	Statistically significant sampling for at least 10 years
Ore Characterization Reliability/Bias Rating	**-2**	**0**	**2**	**4**	**6**
Heap Liquefaction/Undrained Failure					
Susceptibility to Liquefaction or Undrained Failure[8,10]	Very High[11]	High or unknown[12]	Low	Very Low	Negligible
Average Irrigation Rate ($l/h/m^2$)[13]	> 15	10-15	5-10	3-5	< 3
Irrigation on the slope ($l/h/m^2$)[13,14]	Slope irrigation up to 100% of average	Slope irrigation up to 75% of average	Slope irrigation at 50-75% of average	Slope irrigation at < 50% average rate and with performance monitoring	Slope irrigation only with supporting geotechnical analysis and with performance monitoring
Simultaneous irrigation on the slope and near the slope	Unlimited without controls	Unlimited with controls in place	Rarely and with effective controls in place	Never	Never
Heap Liquefaction/ Undrained Failure Rating	**−8**	**−4**	**0**	**4**	**8**
Material Quality Rating[15]	**Minimum Possible Rating: -14**				**Maximum Possible Rating: 26**

Notes:
1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition.
2. P_{80} signifies the particle size at which 80% (by weight) of the material is finer (passing in a sieve analysis).
3. Based on gradation analyses of leached ore (ripios) residue under total solvent exposure during life of ore exposure to solvent (multiple leach cycles for multiple lifts of ore).
4. Plasticity Index (PI) is routinely measured on particles passing through #40 sieve. In the case of Run-of-Mine (ROM) ore with relatively low fines content, the impact of PI on the Ore Gradation Rating can be negligible; therefore, the PI factor should not be included for ROM ores except those with high fines.
5. Agglomeration with Portland cement can improve the physical properties of the crushed ore into the range of soil cement, if costs are not a factor. Given this, the user can increase the rating by more than the recommended 1 or 2 points for very high cement dosage if the improvements are supported by geotechnical testing. In no case should the Ore Gradation Rating exceed 6.
6. Under expected ambient climatic conditions and exposure to the leach solution for the expected duration in the heap or dump.
7. The acid is almost always H_2SO_4 for base metals but could be any other acid. The high concentration acid is generally used for nickel while the lower is common for copper and uranium.

8. Alkali leachate includes NaCN (gold and silver leaching) and carbonate (an option for uranium leaching).
9. Evaluation of the potential for liquefaction or undrained failure of leach pile material may require detailed and specialized laboratory testing. If unknown or unsure use a recommended default value of -4 and consult a geotechnical specialist.
10. Liquefaction and undrained failure are both linked to loading rate and pore water pressure conditions within the heap. The Heap Liquefaction/Undrained Failure Potential Rating should be based on the failure mechanism (liquefaction or undrained failure) that has the highest likelihood. If the susceptibility to liquefaction or undrained failure is unknown, consult a specialist for advice or chose between High and Very High.
11. If the Heap Liquefaction/Undrained Failure Potential Rating is judged to be High, the heap should be classified as HHC V (Very High Hazard), regardless of the HSR.
12. If the Heap Liquefaction/Undrained Failure Potential Rating is judged to be High, the heap should be classified as HHC IV (High Hazard), unless the HSR is less than or equal to 20, in which case it should be classified as Very High Hazard. Note that if the susceptibility of a heap to liquefaction/undrained failure is unknown, the facility defaults to a High to Very High (-4 to -8 rating) hazard; hence the importance of conducting a credible liquefaction/undrained failure assessment on the heap leach material early in the design process.
13. If the irrigation rate varies, use the highest rate sustained for longer than 30 days. For sites that use pulse irrigation, use the irrigation rate based on a 7-day average.
14. Near the slope means an exclusion zone within a horizontal distance from the crest equal to the toe-to-crest height of the slope measured vertically. For a 100 m high heap, any irrigation within 100 m of the crest would be considered “near the slope” for these purposes. For complex geometry a more complex analysis may be required to determine an effective exclusion zone. For example, for VLFs in a tight value and with steep slopes, the 3D flow effects can adversely concentrate flows near the slopes.
15. The sum of the ratings for the individual factors is the Material Quality Rating.

Type 1: Extremely weak to very weak, highly degradable materials, any rock that will significantly degrade when exposed to the leach solutions such that the shear strength or permeability are reduced by more than 20 per cent, and rock with a GSI<20, an RMR<20, or Q<1. Poorly indurated or weakly cemented rocks with very low intact strength (unconfined compressive strength [UCS] less than or equal to 5 MPa; Field Hardness less than or equal to R1 [ISRM 1981]); that break down easily when end-dumped on repose angle slopes, under bulldozer/haul truck traffic, or that are susceptible to crushing under anticipated static loading; and rocks that contain expansive clay minerals and are highly susceptible to slaking or freeze-thaw degradation. Weak, fine-grained, plastic and/or highly organic soils.

Type 2: Weak, degradable materials including any rock that will degrade when exposed to the leach solutions such that the shear strength or permeability are reduced by more 20 per cent during leaching. Type 2 also includes rocks with low intact strength (UCS 5 to 25 MPa; Field Hardness R1 to R2; GSI/RMR of 20 to 40; or Q of 1 to 4) and/or low slake durability, and moderate susceptibility to freeze-thaw degradation. This type also includes mixed-grained soils and medium-grained alluvium, except very coarse-grained alluvium and talus.

Type 3: Medium strength materials with moderate durability. Moderately strong rocks (UCS 25 to 50 MPa; Field Hardness R3; GSI/RMR of 40 to 60; Q of 4 to 10), with moderate slake durability, limited susceptibility to freeze-thaw degradation, and limited potential for crushing under anticipated static loading. Includes very coarse-grained alluvium and talus derived from durable rocks.

Type 4: Strong (UCS 50 to 100 MPa; Field Hardness R4; GSI/RMR of 60 to 80; Q of 10 to 40), very durable rocks with low susceptibility to freeze-thaw degradation, including coarse, durable, angular material composed of strong rock blocks.

Type 5: Very strong to extremely strong (UCS higher than 100 MPa; Field Hardness greater than or equal to R5; GSI/RMR>80; Q>40), extremely durable rocks with similar strength and durability. These materials would not be susceptible to freeze-thaw degradation, mechanical breakdown during placement, or crushing under the anticipated static loading.

Users should select a Leached Ore Strength rating between −2 and 6 based on an evaluation of the above factors. This factor accounts for 4.5 per cent of the possible range in HSR values.

4.3.3 Ore Characterization Reliability/Bias

A chronic issue in heap leaching, and even more so for dump and ROM leach facilities, is adequate characterization of the physical and geochemical properties of the ore before the facility has started operation. This has been at the root of many geotechnical problems as well as process issues. There are two key factors: the reliability of the characterization process for the ore body and the statistical significance of the test work, which also includes any bias inherent in the sampling and testing programs.

For ores that do not tend to degrade during leaching (including many gold oxide ores and some copper ores), adequate characterization reflects how well the geotechnical properties of the fresh ore, and its variations, have been identified. Since these programs are usually driven by the metallurgical investigations, the ore geotechnical characterization is often an extrapolation from that work. While this is useful, it is often incomplete. There is also the issue that from a process view, the average life-of-mine ore, combined with some preference for the pay-back period, tends to drive the studies. However, this may not produce suitable results for a geotechnical evaluation. One of the root causes of the large heap leach failure in the Yukon (Canada) in 2024 was inadequate management of the variability of the ore (Smith and Konrad 2025).

This matter becomes more problematic for ores which degrade chemically, as is common with copper ores and universal with nickel laterite ores (Smith and Christie 2015; Steemson and Smith 2009). In this case, steps should be taken to ensure that the sampling and testing are not biased towards fresh or unleached samples, or towards samples that are most geochemically stable under prolonged exposure in a heap or otherwise guided by metallurgical performance such as high metal recovery rates. For existing operations, *in situ* testing including drilling, sampling and Standard Penetration Test (SPT) and Cone Penetration Test (CPT) work, ideally supplemented with geophysical surveys such as resistivity, nuclear magnetic resonance (NMR) or down-hole neutron moisture content testing, is recommended.

Users should select an Ore Classification Reliability and Bias rating between -2 and 6 points based on an evaluation of the above factors. This factor accounts for 4.5 per cent of the possible range in HSR values.

4.3.4 Heap Liquefaction/Undrained Failure

Similar to foundations, some types of leach ore under certain conditions, such as seismic loading or static loading combined with high irrigation rates, could be susceptible to liquefaction or undrained failure. Materials that are most susceptible to liquefaction are typically composed of very loose, uniformly or gap graded materials that are either fully or nearly saturated. At the extreme, where the liquefaction potential is very high, a rating value of −8 was assigned to ensure that such conditions are appropriately flagged.

The potential for undrained behaviour in any leach pile depends largely on its degree of saturation. Saturation, in turn, is controlled by the *in situ* permeability of the ore and the applied irrigation rate, as well as an additional inflow due to rainfall or snowmelt. Where permeability is much greater than the irrigation rate, saturation beneath irrigated areas typically remains in the range of 50 to 70 per cent. For ore with lower permeability, or subject to higher irrigation rates, the degree of saturation can rise rapidly during active irrigation. Increased saturation can also occur in heaps with local barriers to solution flow such as zones blinded by fines migration or lenses of frozen material or intercalated snow. Heap materials with permeabilities less than about 1×10^{-3} cm/s generally operate at above 60 per cent saturation and can exceed 90 per cent saturation for permeabilities less than 5 $\times 10^{-4}$ cm/s (adapted from Milczarek et al. 2013 and Liu and Hashemzadeh 2017).

The potential for undrained behaviour leading to slope instability is not governed by saturation alone, but also by phreatic levels above the collection system and the pore water regime more generally including perched water or localized zones of saturation especially near slopes, and similar site-specific factors. For instance, there are many examples of heap leach facilities in higher rainfall sites such as northern Perú, Central America, and Ghana, that have found that surface water management practices can significantly influence slope stability. Given these complexities, users should either adopt a conservative rating for Heap Liquefaction/Undrained Failure Potential or undertake robust analyses to justify assigning a rating of 0 or higher.

Users should select a Heap Liquefaction/Undrained Failure Potential rating based on the material descriptions given in Table 4. Those that are not experienced geotechnical practitioners should consult with a geotechnical specialist before assigning a Heap Liquefaction/Undrained Failure Potential rating. To encourage practitioners to do so and explicitly address the issue of liquefaction/undrained failure potential, if the Heap Liquefaction/Undrained Failure potential is not known or has not been evaluated, a rating of −4 is assigned.

Occasional lifts of low permeability ore can create as great a hazard as if the entire heap were of low permeability ore. This was identified as a root cause of the 2024 Eagle Gold failure (Smith and Konrad 2025) and may have been a contributing or even controlling factor in the Çöpler, Türkiye failure of February 2024. A similar effect often occurs in heavily trafficked areas of a heap, such as buried haul roads. In cases with lifts of different permeability, a common guideline is to consider the “mean minus the standard deviation” as the default permeability for the purpose of stability rating. Note, however, that this approach does not address the risks inherent to perched water tables.

Users should select a Heap Liquefaction/Undrained Failure rating between -8 and 8 points, based on an evaluation of the above factors. This factor accounts for 8.9 per cent of the possible range in HSR values.

4.4 Design and Geometry

The Design and Geometry group (Table 5) includes factors that are related to the leach pad type, the liner system selected, the geometry, height, and capacity of the heap. Larger, deeper leach piles, and those with steeper overall slopes, tend to be more susceptible to instability, with higher volumes affected, greater potential runout, and more adverse impacts than smaller, lower and flatter structures. The *Guidelines for Mine Waste Dump and Stockpile Design* (Hawley and Cunnings 2017) used historical data from 16 waste rock dumps reported to have poor or very poor performance to weight the WSR factors for geometry and mass. This approach was the starting point to develop the HSR weighting system for the leach pile Design and Geometry factors, then adapted based on the authors’ experience, knowledge of poorly behaved facilities, and failures cited in the literature. The Design and Geometry factors were further refined based on the validation and calibration process for the HSRHC system as discussed in Section 4.10.1, which used multiple iterations of stability ratings for 115 facilities along with input from four mining companies and two consulting groups.

Collectively, the Design and Geometry group has a possible point rating range of -13 to 16 and accounts for 16.2 per cent of the possible range in HSR values.

4.4.1 Leach Pad Type

The Leach Pad Type can significantly affect the hazard ascribed to the facility, especially for the facilities typically at either end of the hazard classification range: valley leach facilities (VLF) at the high-hazard end and dynamic heaps (also known as on-off pads) at the low-hazard end. VLFs can create greater hazards due to several factors:

- The steep and complex foundation conditions inherent in such facilities, and these features often continue downstream of the VLF and can channelize any large failure.
- For the same tonnage and leach pad area, the largest slopes in a VLF will typically have a greater maximum ore depth than in a non-valley fill facility, creating more stress on and strain within the liner and solution collection systems.
- In a VLF, most or all of the solution flow is usually concentrated in a single, relatively confined internal drainage corridor, that can result in the saturation zone extending into the overlying lifts of ore.
- Impounding VLFs will typically have a considerable mass of saturated, contractive ore near the supporting toe of the largest slope.
- Most VLFs impound some solution behind the toe buttress or dam at least some of the time, which can create a similar hazard as a dam. A VLF is herein considered an impounding VLF if it is designed to impound solution and the operating procedures do not include robust controls to prevent pregnant leach solution (PLS) accumulation except in extreme storm events or process upsets (such as loss of pumping capacity).

Of the roughly eight significant heap failures in the modern history of the technology, three were impounding VLFs, although these types of leach pads constitute less than 3 per cent of all leach facilities, as estimated from the authors' experience and published data (Canadian Mining Journal 2020; Tectonic Metals Inc 2024). Each of these failures caused significant environmental impacts and resulted in the insolvency of the owner. There was also a large (but not catastrophic) slope instability triggered at another impounding VLF, induced by injection leaching and exacerbated by poor surface water management (Shelbourn 2014). Thus, impounding VLFs have been assigned the lowest Leach Pad Type rating of -4 points.

On the other hand, dynamic heaps are nearly always stacked to a maximum pile depth of less than 10 m, and any given lift of ore is only exposed to leach solutions, and thus subject to the related geochemical weathering, for one leach cycle rather than years or even decades common with conventional multi-lift heaps and dumps. For dynamic heaps, most of the geotechnical risks are transferred to the ripios dump. This results in dynamic heaps being assigned the highest Leach Pad Type rating of 4 points. As previously discussed, a ripios dump may be treated as a waste dump unless it is expected to be re-leached or is placed on a geomembrane liner, in which case this HSRHC system should be applied. Ideally, both systems should be used to rate ripios dumps, noting again that the WSRHC system requires some adaptations to the Foundation Conditions group to accommodate the liner system.

Users should select a Leach Pad Type factor rating of between -4 and 4 points. This factor accounts for 4.5 per cent of the possible range in HSR values.

Table 5: Design and Geometry factors and ratings

Factors[1]	Ratings				
Leach Pad Type					
Pad Type	Impounding Valley Leach Facility (VLF)[2]	Non-impounding VLF[2]	High Lift Heap or Dump[3,4]	Conventional Multi-lift Heap or Dump[5]	Dynamic Heap[6]
Leach Pad Type Rating	**-4**	**-2**	**0**	**2**	**4**
Liner System					
Geosynthetic clay liner (GCL) or geosynthetic/geosynthetic interfaces[7]	Within 1 times heap height of toe of heap	1-2 times heap height from toe of heap	> 2 time heap height from toe of heap	Geomembrane and low permeability soil	No liner, soil liner only, or geomembrane only
Liner System Rating	**-4**	**-2**	**0**	**2**	**4**
Height					
Overall (toe to crest) Height (m)	> 150	110-150	50-110	20-50	< 20
Thickness Over Liner (m)	> 140	100-140	50-100	20-50	< 20
Maximum Individual Lift Thickness (m)	> 50	25-50	15-25	8-15	< 8
Height Rating	**-1**	**0**	**1**	**1.5**	**2**
Slope Angle					
Overall (Toe to Crest) Angle (° or nominal horizontal : vertical)	> 30 (> 1.7)	27-30 (1.8:1)	24-27 (2.0:1)	12-22 (2.5:1)	< 20 (< 2:75:1) Or Dynamic Heap
Slope Angle Rating	**-4**	**-2**	**0**	**2**	**4**
Mass					
Mass (Mt)	> 250	100-250	20-100	5-20	< 5 Or Dynamic Heap
Mass Rating	**0**	**0.5**	**1**	**1.5**	**2**
Design and Geometry Rating[8]	**Minimum Possible Rating: -13**				**Maximum Possible Rating: 16**

Notes:
1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition.
2. Valley leach facilities (VLFs) involve placement of ore completely across narrow valleys with fill supported on opposing valley slopes. VLFs that create upstream impoundments are classified as Impounding VLFs; those that do not create impoundments or extensive runoff catchment, and diversion works are classified as Non-Impounding VLFs.
3. High single lift (>25m), repose angle heap and dump leach facilities, and Ripios[5] piles that are subjected to secondary leaching.
4. Ripios is a term used extensively in South America for leached/spent ore that is removed from dynamic leach pads and placed in a separate pile or dump. Ripios dumps should be classified as a HLF using the HSRHC system if placed on a liner and/or subjected to secondary leaching, and as a waste dump or stockpile using the WSHRC guidelines if placed on an unlined foundation and not subjected to secondary leaching. Note that acid leached ripios dumps (with or without secondary leaching or liners) can be at high to very high risk for liquefaction and undrained failures.
5. Conventional heaps constructed in lifts that are sequentially leached. Individual lift thickness is typically less than 15 m.
6. Dynamic heaps (also known as on-off leach pads) where a single lift of ore (typically less than 10 m thick) is placed and leached. Following leaching, the leached ore (Ripios) is removed, and the cycle is repeated.
7. The residual internal strength of the GCL, the residual strength of the interfaces between the geomembrane(s) and any other geosynthetics (GCL, geotextile, geonet, or geocomposites) in the liner system are often the lowest strength layers in a heap or dump leach and as such can significantly affect slope stability if located within the zone of influence of a slope failure.
8. The sum of the ratings for the individual factors is the Design and Geometry Rating.

4.4.2 Liner System

For nearly all heap and dump leach facilities with liner systems, the geosynthetic liner components represent one of the weakest layers in the system. When only a single geosynthetic is used, the interface of the liner and either the underlying soil or the overliner drainage gravel will be the weakest part of the liner and solution collection system.

Designs incorporating two geosynthetics in direct contact are increasingly common. The most frequent configurations are: (i) a geotextile installed over the geomembrane to protect against puncturing, (ii) a geonet or geocomposite installed between two geomembranes as a leak detection and recovery layer, and (iii) a geomembrane installed over a geosynthetic clay liner (GCL) to create a composite liner system. The latter is particularly common when sufficient quantiles of low-permeability soil are not locally available (*in situ* or borrowed) to serve as both a secondary seepage barrier and a geomembrane cushion layer. Each of these systems will have a relatively weak interface between the geosynthetics, which can be subject to significant strain softening (a reduction in strength from peak to residual under deformation or strain). Another factor adding to the liner system weakness is the relatively low internal strength of a GCL itself, which can result in shearing through the hydrated bentonite layer.

Shear strengths at critical interfaces vary considerably. Soil to geomembrane interfaces can range from about 25° (for gravelly soil) to 10-12° (for interfaces with clay liners)[7]. Geosynthetic–geosynthetic interfaces usually exhibit shear strengths well below 20° and can even be less than 10°, depending on the geosynthetic materials and the granular material with which they are in contact (Russel et al. 1998). In fact, some liner systems include a geotextile-geomembrane interface as a friction break to allow the ore to settle on steep slopes without creating excessive drag-down forces on the geomembrane.

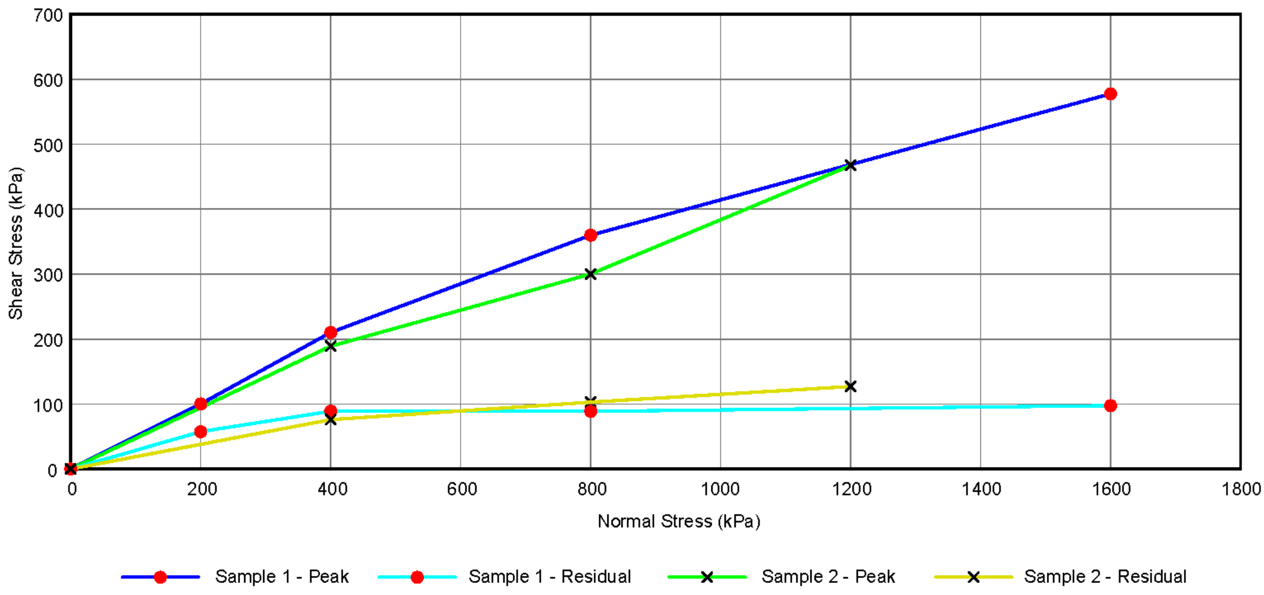


Figure 4: Peak and residual liner shear strengths for a geomembrane/GSL system (adapted from Smith and Konrad 2025)

Geomembrane–GCL interfaces are more complex. Their performance depends strongly on overburden load, the hydration and strain history of the GCL, and the particular product used. Notably, both catastrophic failures in 2024 (Çöpler and Eagle Gold) involved leach pad liner systems containing GCLs, and in both cases, concerns arose about the mobilization of very low shear strengths either along the geomembrane–GCL interface or within the GCL itself. In the extreme, with a saturated bentonite layer and large deformations fully mobilizing residual strengths, the internal

[7] As this discussion is intended only as an illustrative example, no distinction is being made in this passage between peak and residual or drained and undrained strengths.

strength of a GCL can be 6° or less; further, at high normal loads, GCLs and geomembrane-GCL interfaces often behave in laboratory testing as a cohesive material with near-zero friction angles as shown in Figure 4.

The influence of such weak layers on overall slope stability diminishes with increasing distance from an unsupported slope. For this reason, Table 5 accounts for both interface type and location relative to the slope (expressed as a proportion of heap height). Users should select a Liner System rating between -4 and 4 points based on the guidance in Table 5. This factor accounts for 4.5 per cent of the possible range in HSR values.

4.4.3 Height

Three parameters were chosen to characterize the height of the leach pile: (i) the overall (toe to crest) height measured vertically from the lowest point of the toe of the heap to the highest part of the top, (ii) the vertical height or thickness above the liner, and (iii) the maximum individual lift thickness or lift height. For heaps and dumps with a supporting buttress or for VLFs with a containment dam, the downstream toe of the buttress or dam should be considered the lowest point.

Users should select a Height rating between −1 and 2 points. This factor accounts for 1.7 per cent of the possible range in HSR values.

4.4.4 Slope Angle

The overall slope angle of the heap or dump is the angle measured from the horizontal from toe to crest of the leach pile. The other slope angles of interest tend to be inter-bench and inter-ramp, as shown in Figure 5. In evaluating slope hazards, slope angle is often more critical than slope height. Table 5 assigns ratings across a range from slopes steeper than 30° (1.7H:1V[8]) to slopes flatter than 20° (2.75H:1V). For Dynamic Heaps, the default rating is equivalent to heaps with slopes of less than 20°.

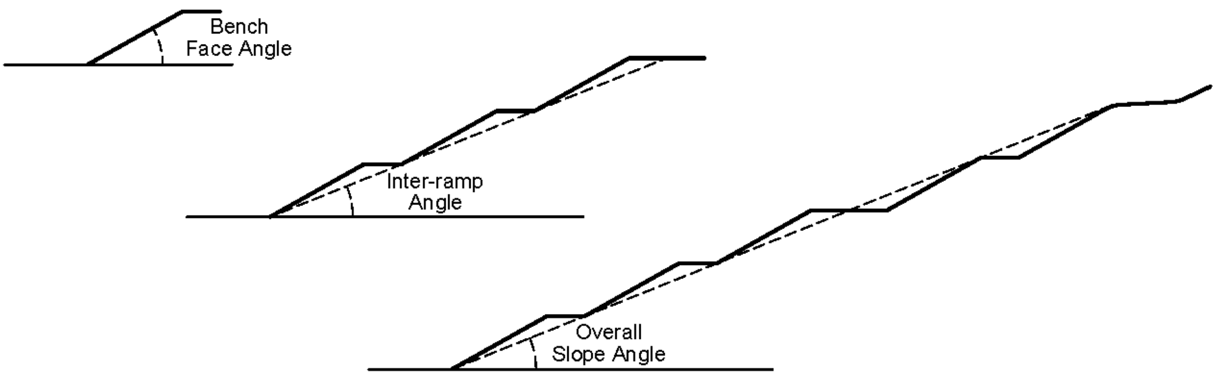


Figure 5: Relationship between inter-bench, inter-ramp and overall slopes

[8] The use of 1.7H:1V and 2.75H:1V signifies the ratio of horizontal (H) to vertical (V) distances from toe to crest.

Although a single-lift heap typically stands at its angle of repose (about 36-38°), such single-lift failures rarely present a significant hazard. This condition is also common to nearly all heaps at their first lift, regardless of the eventual height. A hybrid case occurs when multiple lifts are stacked and leached; then the entire pile is removed once a modest height is reached (for example, four lifts), and the cycle repeated. Two operations, one copper mine in Chile and one gold mine in the USA, have recently applied this hybrid approach. In both cases, the ultimate toe-to-crest heap height remained modest, and the hazard ratings were essentially the same as for either a Dynamic Heap or a conventional multi-lift heap.

Users should choose the most appropriate Slope Angle rating between -4 and 4 by considering the overall context and site-specific conditions rather than relying solely on geometry. This factor accounts for 4.5 per cent of the possible range in HSR values.

4.4.5 Mass

The Mass factor should be estimated based on the bulk volume of the heap and an average in-place dry density of the stacked ore. The Mass or ultimate capacity of a heap ranges from the very small (<5 Mt) to very large (>250 Mt). Dynamic heaps should use the highest rating (2 points) regardless of the maximum tonnage that can be contained on the leach pad. This is to account to for the fundamentally lower hazard associated with a dynamic heap, where at any given time, each cell is at a different stage in its leach cycle: typically, one cell will have fresh ore being stacked, irrigation will be ramping up on another cell, a few other cells will be somewhere in their leach cycles, another will be off irrigation and draining, and one or two more will be under excavation or being off-loaded.

Users should select a Mass rating within the range 0 to 2 using the guidance in Table 5. This factor accounts for 1.1 per cent of the possible range in HSR values.

4.5 Stability Analysis

The Stability Analysis group (Table 6) is intended to capture and contrast differences in the results of objective stability analyses and the underlying Design Acceptability Criteria (DAC). A variety of analytical techniques may be used to model slope stability. These analytical techniques typically calculate a specific index value that represents stability, most commonly a Factor of Safety (FoS) or a Strength Reduction Factor (SRF). Both approaches are commonly used, with numerical techniques such as the finite element method (FEM), the finite difference method (FDM), and other techniques that apply the SRF becoming more popular.

While Table 6 considers an equivalence between FoS and SRF, this may not always be the case. FoS and SRF depend on many factors, including the specific analysis technique used, the complexity of the model, the critical failure path and, in the case of certain numerical models, the *in situ* stress conditions and the stress path. A detailed assessment of these differences is beyond the scope of this paper. Practitioners that are unable to make an informed decision whether SRF is reasonably equivalent to FoS based on the specifics of the analysis, should, as appropriate, consult with a geotechnical specialist to validate the decision.

Table 6: Stability Analysis factors and ratings

Factors[1]	Ratings				
Static Stability[2,3]					
Factor of Safety (FoS) or Strength Reduction Factor (SRF)[4]	< 1.2 or no supporting stability analysis	1.2-1.3	1.3-1.5	> 1.5	Dynamic Heap[4]
Analysis Method: Limit Equilibrium (LEM), Finite Element (FEM), or Finite Difference (FDM)	Two-Dimensional (2D) LEM or more advanced modelling			3D LEM, 2D FEM, or 2D FDM	N/A
Static Stability Rating	**-4**	**-2**	**2**	**3**	**4**
Dynamic Stability and Deformation[2,3,5]					
Factor of Safety (FoS) or Strength Reduction Factor (SRF)[4]	< 1.0 or no supporting stability analysis	1.0–1.05	1.05–1.15	> 1.15	Dynamic Heap[6]
Dynamic model displacement at pipelines or liner level[7]	> 150 cm Or unknown	75-150 cm	50-75 cm	25-50 cm	<25 cm
Dynamic Stability and Deformation Rating	**-4**	**-2**	**2**	**3**	**4**
Stability Analysis Rating[8]	**Minimum Possible Rating: -8**				**Maximum Possible Rating: 8**

Notes:
1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition.
2. For both Static Stability and Dynamic Stability and Deformation, it is assumed that there is at least a moderate level of confidence in the input parameters and that the analysis results are credible and reasonable. If this is not the case, use ratings of -2 for the applicable factors.
3. Multi-bench or Global. Generally, the FoS for single bench failures is relatively low given the angle of repose slope angle between benches.
4. Stability index values shown are based on FoS. If the stability analysis results are presented in terms of SRF, the practitioner must decide whether SRF is reasonably equivalent to FoS based on the specifics of the analysis. Consult with a geotechnical specialist to make this determination. This table shows three significant digits for FoS results; this is used here only to split the range and is not intended to suggest that analysis results should be interpreted as having three significant digits.
5. For dynamic heaps with only a single lift of ore on the pad, assign the maximum possible rating.
6. If pseudo-static analyses are used to evaluate dynamic stability, an appropriate reduction in the design peak horizontal acceleration should be applied. Consult with a geotechnical specialist to make this determination.
7. Displacement modelling is only necessary for this rating if the FoS<1.1. As an example, for a heap with a dynamic FoS<1.0 and an estimated displacement of 50-75 cm, the rating would be the average of -4 and 2, or -2 points.
8. The sum of the ratings for the individual factors is the Stability Analysis rating.

The Stability Analysis factors have been grouped into two categories: overall Static Stability, to capture the expected stability behaviour of the structure under conditions of normal static (gravity) loading, and overall Dynamic Stability and Deformation, to capture the expected stability behaviour under earthquake loading conditions. The typical acceptability criteria for these cases are different. For both of these categories, rating ranges are expressed on the basis of deterministic (FoS and SRF) values. The use of Probability of Failure (PoF) is rare in this application and thus has not been included in Table 6; for users who prefer the PoF approach, there are published correlations with FoS and guidance for using PoF (Christian et al. 1994; Canadian Dam Association 2019; Duncan 2000; Chapter 8 of Hawley and Cunning 2017). Considering that many heap and dump leach piles in operation, under construction or in the planning stages, are in moderate to high seismic activity zones, Static Stability and Dynamic Stability and Deformation factors have each been assigned 50 per cent of the overall rating.

Possible Stability Analysis rating values range from -8 to 8 and account for 8.9 per cent of the possible range in HSR values.

4.5.1 Static Stability

The Static Stability rating should be determined according to Table 6 based on the results of either 2D or 3D Limit Equilibrium Method (LEM) or numerical modelling using conventional analysis techniques such as FEM or FDM. Considering that many heap and dump leach piles in operation, under construction or in the planning stages, are in moderate to high seismic activity zones, Static

Stability and Dynamic Stability and Deformation factors have each been assigned 50 per cent of the overall rating.

The rating values given in Table 6 assume that there is at least a moderate level of confidence in the input parameters and that the analysis results are credible and reliable. If the confidence in the input parameters is low, or the results are judged to be unreliable or lacking in credibility, a lower rating value should be assigned. To qualify as having a moderate level of confidence, the results should be reviewed and accepted as reasonable and reliable by a geotechnical specialist.

The Static Stability factor has a possible rating range of -4 to 4 points and accounts for 4.5 per cent of the possible range in HSR values.

4.5.2 Dynamic Stability and Deformation

The Dynamic Stability and Deformation rating should also be determined according to Table 6 based on the results of either pseudo-static LEM analyses or, preferably, simplified or advanced deformation modelling techniques. Where pseudo-static analyses are used to evaluate dynamic stability and deformation, the design peak horizontal acceleration should be adjusted for the site and heap period such as that suggested by Bray et al. (2018).

As with Static Stability, the rating values for Dynamic Stability and Deformation given in Table 6 assume that there is at least a moderate level of confidence in the input parameters and that the analysis results are credible and reliable. If the confidence in the input parameters is lower, or the results are judged to be unreliable or lacking in credibility, a lower rating value should be assigned. To qualify as having a moderate level of confidence, the results should be reviewed and accepted as reasonable and reliable by a geotechnical specialist. If no analysis has been conducted, a default rating of -2 should be assigned.

The thresholds for displacement were set based on common practice in the industry to limit deformation along the liner system or at critical infrastructure at between 30 and 100 cm based on consequences such as torn liners and disrupted solution handling systems.

The Dynamic Stability and Deformation factor has a possible rating range of -4 to 4 points and accounts for 4.5 per cent of the possible range in HSR values.

4.6 Heap Construction

The Heap Construction group (Table 7) considers two primary factors: the method used to stack the ore and the number of months annually when ore is stacked at average ambient temperatures below freezing. These two factors collectively have a possible rating range of -2 to 8 points, accounting for 6.0 per cent of the possible range in HSR values.

4.6.1 Stacking Method

The Stacking Method factor is designed to capture key differences in ore placement and leach pile development. Four parameters are considered: (i) the stacking method (truck versus conveyor), (ii) stacking direction (upslope, downslope, or on-contour), (iii) the mass loading rate expressed as average tonnes per day per metre of crest length (t/d/m), and (iv) the crest advancement rate expressed in square metres per day (m^2/d), calculated as the product of the average lineal crest advance rate (m/d) and the lift height (m).

In the WSRHC system, the crest advancement rate is applied to all waste dumps. However, in heap and dump leaching, thinner lifts (as defined in Table 7) often improve both geotechnical stability and hydrogeological performance. Under the WSRHC system, the crest advancement factor could unreasonably penalize thin-lift stacking. To avoid this, the HSRHC system applies the crest advancement factor only to high-lift, run-of-mine dump leach facilities, where slower advancement rates contribute to strength gain and improved performance.

The Stacking Method parameters are divided into Crushed Ore Heap stacking and ROM/Dump Leach stacking to address the unique issues of each. The Stacking Method factor has a possible rating range of 0 to 6 points, accounting for 3.4 per cent of the possible range in HSR values.

Table 7: Heap Construction factors and ratings

Factors[1]	**Ratings**				
Stacking Method					
Option 1: Crushed Ore Heap	Truck Dump, lifts > 75 m	Truck Dump, lifts 50-75 m	Truck Dump, lifts 25-50 m	Conveyor Stack or Truck Dump, lifts 15-25 m	Conveyor Stack or Truck Dump, lifts < 15 m
Option 2: ROM/Dump Leach[2]	End Dump lifts, > 100 m or Dump Sort & Push lifts > 125 m	End Dump lifts, 75-100 m or Dump Short & Push lifts 100-125m	End Dump lifts, 50 -75 m or Dump Short & Push lifts 75-100 m	End Dump lifts, 20-50 m or Dump Short & Push lifts 30-75 m	End Dump lifts, < 20m or Dump Short & Push lifts < 30 m
Both Option 1 and Option 2:					
Stacking direction	Primarily downhill	Some downhill	On-contour	Uphill with very limited on-contour	Uphill only
Mass loading rate (t/d/m)	> 250	75-250	25-75	7.5-25	< 7.5 Or Dynamic Heap
Lift Advancement Rate[4] (m^2/d): to be considered only for high lift ROM dump leaching	> 500	150-500	50-150	15-50	< 15
Stacking Method Rating	**0**	**1.5**	**3**	**4.5**	**6**
Stacking Below Freezing					
Period of Active Stacking below 0°C (months per year)[3]	> 3	3	2	1	0
Stacking Below Freezing Rating	**-2**	**0**	**1**	**1.5**	**2**
Heap Construction Rating[5]	**Minimum Possible Rating: -2**				**Maximum Possible Rating: 8**

Notes:
1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition.
2. Select the method that best describes the stacking. Where the stacking operation includes attributes of more than one method, choose an intermediate rating.
3. Months of stacking with average daily temperature <0°C for more than half the month.
4. Crest Advancement Rate (m^2/d) = average daily rate of crest advancement (m/d) multiplied by average lift height (m). This factor should only be applied to traditional high lift ROM dump leach facilities.
5. The sum of the ratings for the individual factors is the Heap Construction Rating.

4.6.2 Stacking Below Freezing

This factor reflects the duration of ore stacking under freezing conditions. When ore is placed, its temperature is expected to approximate the average ambient temperature at the time of stacking. In cold climates, the greatest heat demand occurs in winter when frozen ore must be warmed above 0°C to allow leach solution to percolate. If the mass of sub-zero ore exceeds the capacity of the irrigation solution to supply heat, the solution itself can freeze—disrupting uniform solution distribution, leading to perched water and irregular, concentrated flow paths within the heap. These conditions can elevate pore water pressures and promote undrained behaviour. Spring thaw introduces additional complications, as melting zones may further disrupt solution flow and create weak layers withing the heap.

4.7 Stability Performance

The Stability Performance group is intended to capture the actual, documented stability performance of existing leach facilities either at the subject mine or reasonable, nearby analogs (based on geology, geotechnical and hydrogeologic properties). Five stability performance categories have been defined according to the following list and are summarized in Table 8.

Unstable: One or more slope failures significantly affecting operations or causing significant environmental releases or damaging the liner or solution collection systems, or mass movement of >100,000 t; or a history of significant ponding, side slope seepage, subsidence, internal erosion (e.g., sand boils), or other factors suggesting high degrees of saturation within the heap or dump; or a history of slope deformations in the highest or Red alert level.

Metastable: Leach piles that have experienced frequent or occasional smaller multi-bench or inter-ramp failures with mass movement of up to 100,000 t; moderate impact to operations or small environmental releases, or local and repairable damage to the liner system; a history of any ponding or minor side slope seepage; or a history of slope deformation in the Yellow or first alert level.

Stable: Heaps or dumps that have experienced only minor bench failures or deformation along ramps and the heap crest that are incidental to operations with no damage to the liner or solution distribution system; all movement remained within containment, although minor effects on the solution collection system may result in minor solution quantities leaving containment; very rare slope movements exceeding the Green or normal condition.

Very Stable: No notable failures of any size, no history of side slope seepage or ponding on top of the heap other than temporary after large storm events or pipe breaks, no history of Red alerts and only rare Yellow alerts for slope movement.

Excellent Stability: No history of Yellow or Red alerts, no slope failures other than incidental movement during ore placement or due to pipe breaks, no ponding or side slope seepage under any conditions, and no other evidence of elevated saturation levels.

For sites with no applicable performance history, a Stability Performance Rating of 0 should be assigned. A key distinction from the WSRHC system is the latent risk of liquefaction and undrained behaviour that may occur in heap and dump leach facilities but is uncommon in waste dumps. As previously discussed, the prerequisite conditions are the presence of contractive granular materials, universally present to some degree in crushed-ore heaps and occasionally in ROM heaps or dumps, together with a high degree of saturation (typically ≥85 per cent). In the absence of a trigger, such as a strong earthquake, loss of toe support, or a rapid rise in phreatic levels, these conditions may persist for years without incident. Accordingly, performance assessments should incorporate evaluation of both (i) the occurrence and spatial distribution of contractive materials, determined preferably through drilling and CPT investigations but also via laboratory testing or constitutive modelling such as NorSand (Castonguay and Konrad 2019; Smith and Konrad 2025), and (ii) evidence of saturated strata, identified through geophysical surveys, piezometric or tensiometric monitoring, surface ponding, slope seepage, or routine testing of ore placed on the heap or dump. An assessment on the Degree of Stability should be based on results of monitoring, inspections and performance records. For sites with a history of Unstable or Metastable performance but where the new facility, expansion or significant retrofitting of the existing facility incorporates design, operating or monitoring improvements that specifically and significantly address these past performance issues, the Stability Performance Rating value can be increased one or two categories but not beyond the Stable category with the rating of 0 points (i.e., from -10 to -5 or 0 for Unstable, or from -5 to 0 for Metastable).

Table 8: Stability Performance factors and ratings

Factors[1]	**Ratings**				
Stability Performance					
Degree of Stability[2] (select the lowest rating between the two categories)	Unstable[3]	Metastable[4]	Stable or no history	Very Stable	Excellent stability
Past Physical Instability	Slope failures significantly affecting operations or causing significant environmental releases or damaging the liner or solution collection systems, or mass movement of > 1 x 10^5 t	Frequent or occasional smaller multi-bench or inter-ramp failures with mass movement of up to 1 x 10^5 t; moderate impact to operations or small environmental releases or local and repairable damage to the liner system	Minor bench failures/ deformation along ramps and heap crest operationally incidental, no damage to liner or solution distribution system, all movement remains within containment, although minor effects on the solution collection system may result in minor solution quantities leaving containment	No notable failures of any size	
Past evidence of future physical instability	A history of significant ponding, side slope seepage, subsidence, internal erosion (e.g., sand boils), or a history of slope deformations in the highest or Red alert level	A history of any ponding (other than incidental and temporary) or minor side slope seepage; or a history of slope deformation in the Yellow or first alert level	No history of ponding or side slope seepage, very rare slope movements exceeding the Green (normal) condition	No history of side slope seepage or ponding other than temporary after large storm events or pipe breaks, no significant history of Red alerts and very rare Yellow alerts for slope movement	No history of Yellow or Red alerts, no slope failures other than incidental movement during ore placement or due to pipe breaks, no ponding or side slope seepage under any conditions, and no other evidence of elevated saturation levels
Stability Performance Rating	**-10**	**-5**	**0**	**5**	**10**
Stability Performance Rating[5]	**Minimum Possible Rating: -10**				**Maximum Possible Rating: 10**

Notes:

1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or the user cannot decide between two ratings, select an average or intermediate rating that best represents the overall condition. For Stability Performance, use the rating which corresponds to the lowest value indicated by either the Past Physical Stability of the Past Evidence of Future Physical Instability unless there have been significant changes in design or operations addressing the past performance issues.
2. An assessment on the Degree of Stability should be based on results of monitoring, inspections and performance records. For sites with a history of Unstable or Metastable performance but where the new facility or expansion incorporates design, operating or monitoring improvements which specifically and significantly address these past performance issues, the Stability Performance Rating value can be increased one or two categories but with the maximum rating of 0 points (i.e., from -10 to -5 or 0 for Unstable, or from -5 to 0 for Metastable).
3. If the Stability Performance is judged to be Unstable, the heap leach facility should be classified as HHC V (Very High Hazard), regardless of the calculated HSR.
4. If the Stability Performance is judged to be Metastable, the heap leach facility should be classified as HHC IV (High Hazard), unless the HSR is less than or equal to 20, in which case it should be classified as HHC V (Very High Hazard).
5. The sum of the ratings for the individual factors is the Stability Performance Rating.

The Stability Performance rating ranges from -10 to 10 points, accounting for 11.2 per cent of the possible range in HSR values. If the facility is judged Unstable, it must be classified as HHC V (Very High Hazard) regardless of the HSR; if judged Metastable, it must be classified as HHC IV (High Hazard), unless the HSR is ≤20, in which case classification defaults to Very High Hazard. The 20-point range of possible ratings is sufficient to alter any facility's hazard classification by at least one category (e.g., from Moderate to either Low or High) solely based on Stability Performance.

4.8 Governance and Monitoring

In 2016, the ICMM published a position statement on tailings governance framework which sets forth six key elements:

- Accountability, responsibility, and competency
- Planning and resourcing
- Risk management
- Change management
- Emergency preparedness and response
- Review and assurance

The Governance and Monitoring group factors in Table 9 are intended to capture the ICMM framework as it applies to heap and dump leaching. Collectively, they have a possible rating range of -6 to 8 points, accounting for 7.8 per cent of the possible range in HSR values.

Consistent with the observations for the Stability Performance group, the 14-point spread between minimum and maximum attainable scores is sufficient to alter hazard classifications by one category, thereby demonstrating the capacity of the HSRHC system to inform design and operational decision-making. To evaluate this effect, a validation and calibration exercise was conducted on a subset of 31 projects with classifications ranging from Low to Very High. When these projects were assigned the maximum possible score for Governance and Monitoring, all sites originally rated as Moderate were reclassified as Low, half of those rated as High were reclassified as Moderate, and 40 per cent of the sites rated Very High were reclassified as High. In aggregate, two-thirds of the sites experienced a reduction in hazard classification solely as a consequence of increased Governance and Monitoring scores, underscoring the material influence of this factor on overall hazard assessment and, by extension, on risk reduction.

The Governance and Monitoring factors have been adapted from Chovan et al. (2021), the recommendations presented in the Eagle Mine forensic report (Smith and Konrad 2025) and the experience of the authors. Where Table 9 uses terms like "industry standard," "comprehensive TARPs," and "multitiered," Chovan, Smith and Konrad can provide more detailed guidance. Further, "industry standard" should be informed by guidelines such as The Mining Association of Canada (2019) and ICMM (2016).

4.8.1 Governance

Governance, in this context, considers both past performance and existing capabilities, by way of compliance (Legal), worker and management preparedness (Training, Accountability and Responsibility), and oversight (Post-incident investigations, Third-party Reviews, Risk Assessments, and Construction Quality Assurance, as well as engagement of an EoR or DoR). Collectively, these capabilities and practices can have dramatic effects on any project. For this reason, Governance was assigned a range of ratings from -3 to 4 and accounts for 3.9 per cent of the maximum possible range of HSR values.

4.8.2 Monitoring

An effective monitoring program is essential for the successful operation of any complex geotechnical system and can also lead to improved management of any complex facility. For these reasons, Monitoring was assigned the same range of ratings as Governance (-3 to 4 points) and therefore also accounts for 3.9 per cent of the maximum possible range of HSR values as well.

Of particular note, the Monitoring factor expressly includes a parameter related to artificial intelligence (AI) integration, as AI is poised to reshape risk management for a broad range of industrial processes, including mining and mineral processing. In heap and dump leaching, two domains stand out for AI integration: (i) structured hazard classification systems such as the HSRHC, and (ii) geotechnical and hydrogeological performance monitoring.

Table 9: Governance and Monitoring factors and ratings

Factors[1]	**Ratings**				
Governance					
Legal	Frequent serious compliance issues	Occasional serious compliance issues	Minor and rare compliance issues	Only non-serious compliance issues	No material compliance issues
Training	Little or ineffective training	Below industry standard or not fully implemented	Industry standard or better, but only partly implemented	Better than industry standard, fully implemented	Best industry practice; fully implemented
Accountability and Responsibility	Not clearly defined or ineffective	Clear/effective, but only partly implemented; or fully implemented but not clear/effective	Industry standard operating procedures (SOP) with EoR and DoR participation as appropriate, including effective reporting systems and a multitiered management system including site teams and corporate review	Better than industry standard with continuous improvement, broadly adopting the recommendations of Chovan et al. (2021), The Mining Association of Canada (2019) or equivalent, and significant involvement of the EoR and DoR	Comprehensive, well-planned, fully implemented, audited; fully adopting the recommendations of Chovan et al. (2021), The Mining Association of Canada (2019) or equivalent
Post-incident investigations	None or ineffective	Rare, inconclusive, or recommended remediation/controls not implemented	SOP but limited implementation/ verification of effectiveness of remediation/controls	SOP with EoR engagement, timely/full implementation/ verification of effectiveness of remediation/controls	SOP with EoR engagement, third-party review of high hazard incidents; timely/full implementation/ verification of effectiveness of remediation/controls
Third party reviews	None or ineffective	Inconsistent reviews with limited follow-up	Independent technical review of critical components and practices	Independent Technical Review Board (ITRB) in place but limited engagement or incomplete follow-up	Independent Technical Review Board (ITRB) in place, well engaged with comprehensive follow-up
Risk assessments	None or ineffective	Not to industry standard, overly focused, or recommended mitigative measures/controls not implemented	Industry standard; recommended mitigative measures/controls not fully/timely implemented	Industry standard; recommended mitigative measures/controls fully/timely implemented	Industry standard; recommended mitigative measures fully/timely implemented. Special treatment of catastrophic hazards
Construction quality assurance	None or ineffective	Contractor or owner Construction Quality Control (CQC) and third-party Construction Quality Assurance (CQA)	Contractor or owner CQC and third-party CQA without audits or participation by the EoR	Robust third-party CQC & CQA without audits but with some EoR oversight	Robust third-party CQC & CQA with audits and significant EoR oversight
Governance Rating	**−3**	**-1**	**1**	**2**	**4**

Factors[1]	Ratings				
Monitoring[3]					
Triggered Action Response Plans (TARPs)	None or ineffective	TARPs not adequately developed, or the effectiveness of the critical controls are not verified	Comprehensive TARPs based on risk assessments, but no external review but effectiveness of critical controls not fully verified	Comprehensive TARPs based on risk assessments and developed in consultation with EoR, not independently reviewed	Comprehensive TARPs based on risk assessments and developed in consultation with EoR with third-party review
Monitoring and TARPs include surface ponding and side slope seepage	None or ineffective	Very limited or threshold values not well considered, frequency less than daily	Ponding or seepage only but with well-considered frequencies and thresholds	Both ponding and seepage measured and reported daily, thresholds qualitatively[4] established	Both ponding and seepage measured and reported daily, thresholds quantitatively[5] established
Slope Deformation	None or ineffective	Very limited, low precision, or infrequent (e.g., interferometric synthetic aperture radar [InSAR] only); little or no redundancy	Daily surface monitoring using high-accuracy ground-based instruments (e.g., prisms, LiDAR) with little or no redundancy	Surface and subsurface monitoring using multiple systems with near-real-time reporting	Surface and subsurface monitoring using multiple systems with near-real-time reporting, third-party review
Pore Water Pressure	None or ineffective	Very limited, poorly considered placement, none located in zones critical to slope stability and within 5 m vertically of the liner system	Some piezometers in key locations including near the liner system (within 5 m) and at various elevations in the heap	Comprehensive piezometer network with frequent monitoring and clear reporting system	Comprehensive piezometer network with frequent monitoring, clear reporting system, third party review
Moisture Content and Saturation Levels	None or ineffective	Implied from lab testing and irrigation rates	Seepage modelling supported by lab testing with periodic field verification (drilling, CPT, etc.)	Soil moisture gages/ tensiometers, geophysical surveys (resistivity, NMR, etc.), periodic drilling or CPT	Thorough understand of all areas critical to slope stability
AI Integration into data collection, processing and analysis	No use of AI or advanced analytics	AI or other automated tools are in place but are unverified or poorly integrated; outputs not reviewed by engineers; implementation is inconsistent across disciplines	Some application of AI for data screening or visualization; limited protocols for model validation and transparency; human oversight exists but integration with decision-making is ad hoc	AI tools actively used for anomaly detection and predict trend analysis; results regularly reviewed by qualified engineers; clear policies for data quality and oversight are in place	AI-enabled monitoring, predictive modelling, cross-domain data fusion; models trained on representative datasets; transparent with independent review; outputs integrated into operational decisions.
Monitoring Rating[6]	−3	-1	1	2	4
Governance & Monitoring[2]	**Minimum Possible Rating: -6**				**Maximum Possible Rating: 8**

Notes:
1. Select a rating for each factor. Where more than one criterion is shown for a given factor, or user cannot decide between two ratings, select an average or intermediate rating that best represents the conditions.
2. The sum of the ratings for the individual factors is the Governance and Monitoring Rating.
3. To qualify for the top two ratings (2 or 4 points) the monitoring system must substantially comply with the applicable recommendations of the Mining Association of Canada (MAC) Developing an Operation, Maintenance, and Surveillance Manual for Tailings and Water Management Facilities (2011, or the latest update) or other applicable criteria.
4. Qualitatively established means no specific link to the stability or deformation modelling, or past stability performance on this site, but rather based on general experience and benchmarking.
5. Quantitative thresholds are determined by modelling, specific performance at this site, or robust benchmarking to other sites with similar key drivers.
6. AI tools such as anomaly detection, predictive modelling, and data fusion can enhance monitoring and risk management, but their value depends on data quality, model transparency, and human oversight. Higher ratings in Table 9 require not only the presence of AI systems but also evidence that they are validated, explainable, and integrated into governance frameworks, with outputs reviewed and acted upon by qualified engineers. This requirement recognizes that AI adoption strengthens monitoring while maintaining professional accountability.

Within the HSRHC framework, AI can strengthen predictive power by detecting subtle patterns in the EGI and DPI scores, extracting knowledge from unstructured reports, and supporting scenario testing. These capabilities would allow hazard classifications to evolve dynamically in response to real-time monitoring and simulated events, while still anchored in engineering judgment. In performance monitoring, AI can be particularly valuable for analyzing the vast datasets generated by radar, light detection and ranging (LiDAR), piezometers, and other sensors. Machine learning can detect early warning signs of instability, such as the precursors observed in the failures at Eagle Gold and Çöpler, and integrate diverse datasets into coherent risk profiles. These outputs can inform real-time dashboards, predictive simulations, and streamlined compliance reporting under standards such as CDA (2019) and GISTM. However, Governance remains critical, and AI systems must be transparent, validated, and subject to professional oversight to avoid “black box” decision-making. In this regard, Table 9 includes AI-specific criteria such as data quality, model explainability, and integration of AI insights into operational decisions. In sum, AI will not, and should not, replace engineering judgment; however, it will likely become an essential tool for improving classification accuracy, early warning capabilities, and proactive risk management in heap leach operations. Nevertheless, just as geotechnical engineers learn from past experiences and take corrective measures to modulate judgments and future actions, the importance of continuous human feedback regarding AI interpretations, recommendations or decisions cannot be overemphasized.

4.9 Heap Stability Rating

The aggregate of the rating values for each group of factors described above for the two indices, EGI and DPI, is defined as the heap stability rating (HSR). Table 10 provides a convenient format for summarizing and aggregating the ratings for the different factors, groups and indices.

In addition to calculating the overall HSR, the worksheet calculates two component indices: the EGI and the DPI. The EGI is equal to the sum of the Regional Setting, Foundation Conditions and Material Quality group ratings (Tables 2 through 4), and represents factors that are related to the site location and geological conditions, and that the designer has limited ability to influence other than through site selection. The DPI is equal to the sum of the Design and Geometry, Stability Analysis, Heap Construction, Stability Performance, and Governance and Monitoring group ratings (Tables 5 through 9) and represents factors the designer has some or even significant control over. The maximum EGI and DPI rating values are each 50 per cent of the maximum possible HSR.

Table 10: Heap leach pile stability rating summary

Facility Details:							
Facility Identifier:							
Index	**Group**	**Factor**	**Factor Rating**	**Group Rating**	**Index Rating**	**HSR**	**HHC[1,2]**
Engineering Geology Index (EGI)	**Regional Setting** (-8 to 14 points) [12.3% of HSR]	Seismicity (-2 to 6 points)					
		Precipitation (-4 to 6 points)					
		Temperature (-2 to 2 points)					
	Foundation Conditions (-18 to 10 points) [15.6% of HSR]	Foundation Slope (-2 to 2 points)					
		Foundation Shape (-2 to 2 points)					
		Foundation Materials (-4 to 4 points)					
		Foundation Liquefaction/Undrained Failure (-8 to 0 points)					
		Groundwater (-2 to 2 points)					
	Material Quality (-14 to 26 points) [22.3% of HSR]	Ore Gradation (-2 to 6 points)					
		Leached Ore Strength (-2 to 6 points)					
		Ore Characterization Reliability/Bias (-2 to 6 points)					
		Heap Liquefaction/Undrained Failure (-8 to 8 points)					
Design and Performance Index (DPI)	**Design & Geometry** (-13 to 16 points) [16.2% of HSR]	Leach Pad Type (-4 to 4 points)					
		Leach Pad Liner System (-4 to 4 points)					
		Height (-1 to 2 points)					
		Slope Angle (-4 to 4 points)					
		Mass (0 to 2 points)					
	Stability Analysis (-8 to 8 points) [8.9%]	Static Stability (-4 to 4 points)					
		Dynamic Stability and Deformation (-4 to 4 points)					
	Heap Construction (-2 to 8 points) [5.6% of HSR]	Stacking Method (0 to 6 points)					
		Stacking Below Freezing (-2 to 2 points)					
	Stability Performance (-10 to 10 points) [11.2%]	Stability Performance (-10 to 10 points)					
	Governance & Monitoring (-6 to 8 points) [7.8% of HSR]	Governance (-3 to 4 points)					
		Monitoring (-3 to 4 points)					

Notes:
1. Assign HHC based on HSR values as follows (except as set forth in Note 2):
   HSR ≥80; HHC=I (Very Low Hazard)
   HSR ≥60, <80: HHC=II (Low Hazard)
   HSR≥40, <60: HHC=III (Moderate Hazard)
   HSR≥20, <40: HHC=IV (High Hazard)
   HSR<20; HHC=V (Very High Hazard)
2. There are three conditions where the HHC is set as High or Very High directly regardless of the HSR:
   Foundation Liquefaction/Undrained Failure Potential is High or Very High (Table 3, Notes 6 and 7)
   Material Liquefaction/Undrained Failure Potential is High or Very Hight (Table 4, Notes 10 and 11)
   Stability Performance is Unstable or Metastable (Table 8, Notes 3 and 4)

4.10 Heap and Dump Hazard Class

For descriptive purposes and to simplify comparison of different possible alternative configurations or design approaches for a given heap or dump leach facility, and in recognition of the somewhat subjective nature of the rating scheme, the possible range of HSR values has been subdivided into five categories or heap hazard classes (HHCs) as shown in Table 11.

A qualitative hazard description is associated with each hazard classification to help convey its relative potential for instability. These descriptions, ranging from Very Low Hazard to Very High Hazard, may be useful in qualitative and comparative risk assessments. For qualitative and semi-quantitative risk assessments, the hazard classifications may serve as proxies for the likelihood or probability of occurrence. It may also be instructive to plot HSR results on the chart in Figure 6. This chart illustrates the relative weighting of the EGI and DPI indices and facilitates comparison of different heap and dump leach facilities, as well as possible alternative configurations or development phases for a given project.

The HSRHC system can also be used as a guide to the level of effort required to investigate, design and construct leach piles. Leach piles with lower stability ratings, or ones that fall into higher hazard classes, logically ought to require more investigative and design effort, and more care and monitoring during construction and operations, than leach piles with higher stability ratings, or those that fall into lower hazard classes. Table 12 provides recommendations regarding the appropriate level of effort for the site investigation and characterization, analysis and design, and construction and operation stages in the life cycle of a heap or dump leach pile based on the HSR and HHC.

Table 11: Summary of heap stability ratings, hazard classes and relative instability hazard

HSR	HHC	INSTABILITY HAZARD
≥ 80	**I**	Very Low Hazard
≥60 to <80	**II**	Low Hazard
≥40 to <60	**III**	Moderate Hazard
≥20 to <40	**IV**	High Hazard
< 20	**V**	Very High Hazard

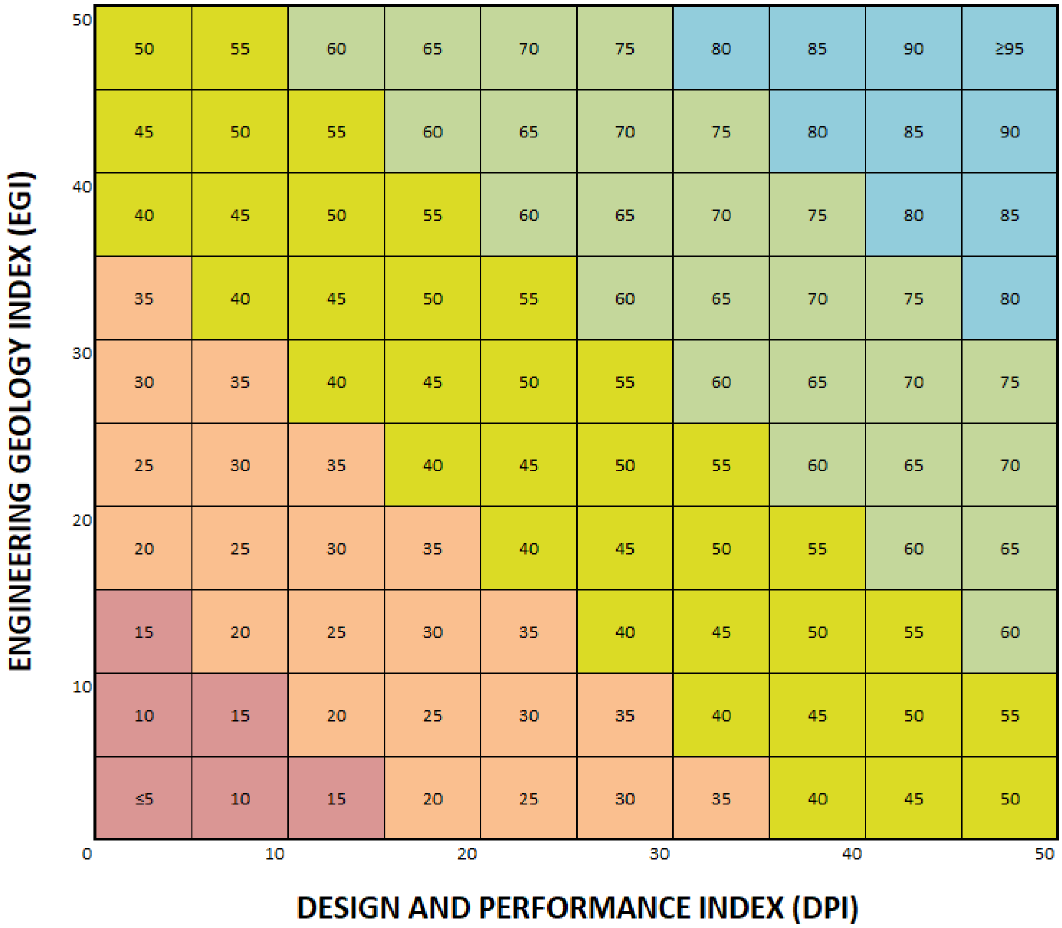
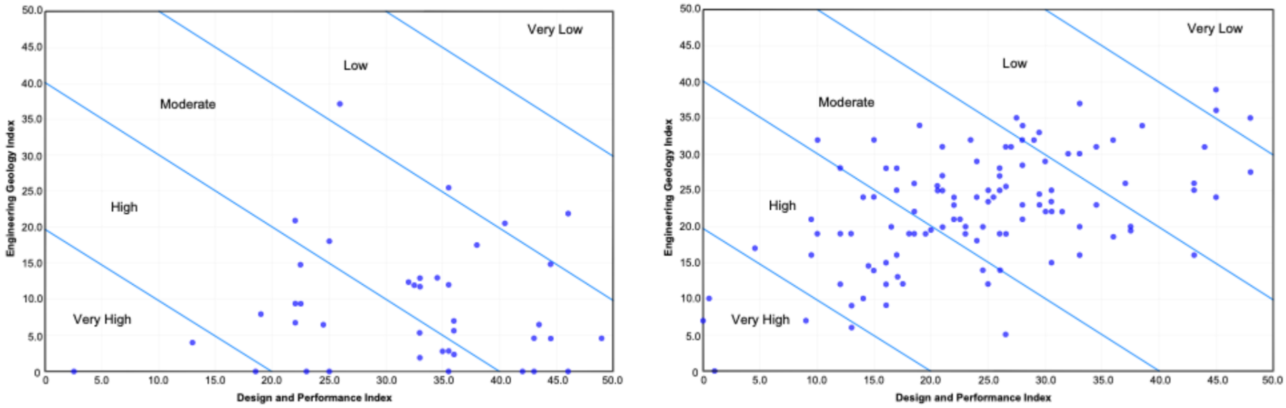


Figure 6: Heap stability rating (HSR) and heap hazard class (HHC) chart

4.10.1 Validation and Calibration

The validation of the rating and classification system was conducted through a structured, iterative process to enhance accuracy, transparency, and consistency with both engineering judgment and historical performance. Hazard classifications and stability ratings were solicited from the authors and LOP sponsors, and 75 heap and dump leach facilities were analyzed against expected outcomes based on professional experience and observed performance (Figure 7). Facilities showing discrepancies between assessor judgment and the HSRHC classification were examined in greater detail, with attention to the EGI (Tables 2-4) and the DPI (Tables 5-9) scores to identify sources of misalignment. Similar detail was applied to HSRs which were within a few points of the threshold to a higher or lower HHC. In addition, the distribution of HSRHC results across hazard categories was compared with the WSRHC outcomes (Figure 3.5, Chapter 3, Hawley and Cunning 2017), which further informed revisions. From this set, 31 facilities spanning the full hazard range were selected for detailed iterative calibration.

The calibration process involved: (i) detailed reassessment by the authors, with factor adjustments to address perceived imbalances; (ii) consultation with contributing sponsors to refine ratings; and (iii) systematic adjustments to the EGI and DPI, including normalization of their maximum possible ratings at 50 (increasing EGI by six points while reducing DPI accordingly), reassignment of certain factors, such as leach pad type and liner system, from the EGI group to the DPI group, and modification of minimum and maximum values for specific factors driving variance. Following these adjustments, all the previous facilities were re-analyzed, and additional facilities were added. The final system was further evaluated against recent failures in Türkiye and Canada, as well as less severe historical incidents, confirming that the revised classifications aligned with expectations and reinforcing the system's validity and practical utility as a hazard assessment tool. Figure 8 presents the EGI and DPI distributions and HHCs for 115 HLFs using the final rating system. The distribution of the 115 HHCs is: 3% Very Low, 16% Low, 64% Moderate, 27% High and 5% Very High Hazard.



Figures 7 and 8: EGI and DPI distribution before (left) and after (right) calibration. Note that for Figure 7 all EGI values less than zero are plotted as zero.

4.10.2 Hazard Classification and Risk Assessments

The Heap Stability Rating and Hazard Classification system does not constitute a risk assessment; rather, it is intended to inform and complement such assessments. Its greatest utility lies in qualitative and semi-quantitative contexts, where hazard classification may serve as a proxy for the likelihood of failure. For example, a facility classified as Moderate Hazard is expected to have a lower probability of failure than one classified as High or Very High Hazard.

Identifying the principal drivers behind a hazard classification offers insight not only into potential failure causes but also into likely failure consequences—insight that should be regarded as indicative rather than definitive. For example, a facility classified as Very High Hazard primarily because of liquefaction potential would be expected to produce major downstream impacts if failure occurred. Integrating this understanding into risk assessments—together with knowledge of the downstream environment, including the presence of workers or communities, critical water resources, or public infrastructure—improves consequence evaluation and preparedness. Conversely, recognizing that a facility carries a Very High Hazard classification can inform downstream land-use planning, justify protective infrastructure, and influence design trade-offs. In this way, the stability rating and hazard classification framework becomes not only a diagnostic tool but also a guide for proactive, risk-informed decision-making.

Table 12: Recommended level of effort based on HSR and HHC

Stability class		Level of Effort		
Heap Hazard Class (HHC)	**Instability Hazard**	**Investigation and Characterization**	**Analysis and Design**	**Construction and Operation**
I	Very Low Hazard	No special work required. Advance the project according to the level of study. For example, Front-end Loading FEL-0 to FEL-4 (Kennedy and Nelson, 2003; Merrow, 2011), Association for the Advancement of Cost Engineering (AACE International, 2016) Cost Class 5 to 1, or Canadian National Instrument 43-101 (Canadian Securities Administrators, 2011) Preliminary Economic Assessment (PEA), Pre-feasibility Study (PFS), or Feasibility Study (FS).		Normal site preparation for the type of facility and site conditions; conventional CQC and CQA; standard instrument and visual monitoring with basic trigger action response plan (TARP); periodic inspection by experienced geotechnical specialist and the EoR.
II	Low Hazard			
III	Moderate Hazard	Advance the project according to the level of study (e.g., FEL 0 to 4, AACE Cost Class 5 to 1, or NI43-101 PEA, PFS, FS). Increase the level of effort for the key drivers for the HHC III classification. For example, if uncertainty about the Foundation Conditions (Table 3) is a key driver, then perform additional geotechnical investigations of the foundation area, and consider either relocating the facility to a more favorable site or including ground improvement in the design (e.g., dewatering and removing poor quality foundation materials).	Moderate Hazard facilities should include Independent Peer Review (IPR) with engagement of the EoR during the design stage. Perform more robust characterization and analyses of the key factors driving the Moderate Hazard classification. For example, if Stability Performance (Table 8) is key to the elevated hazard class, increase the rigor of both the Ore Classification Reliability/Bias (Table 4) and Stability Analysis (Table 6). If the Design and Geometry (Table 5) factors are key drivers, consider changing the Leach Pad Type, Leach Pad Liner System, Height, and Slope Angle.	Continue the IPR and EoR engagement through construction, commissioning, and any major expansions. Follow industry standard (or better) construction practices including CQC, CQA, EoR and third-party review of the critical components, and where applicable with special attention to the factors driving the hazard classification. Implement Governance and Monitoring systems consistent with or better than the middle class of Table 9 (a Governance rating of at least 1, and a Performance Monitoring rating of at least 1).
IV	High Hazard	All projects with an HHC of IV should, to the extent practical, implement Governance and Monitoring systems consistent with the Maximum Possible Rating for Governance and Monitoring (Table 9). In no case should a High Hazard project advance to construction and commissioning, or continue to operate, with individual ratings for Governance and Monitoring of less than 2 each (4 combined). Perform trade-off studies to evaluate the costs and benefits of relocating the facility to improve the EGI or revising the design and operational criteria to improve the DPI and reduce the HHC; if the HHC is reduced, perform the additional level of effort appropriate for the new HHC. In the alternative, identify the key drivers for the HHC IV classification and evaluate options to (i) improve performance (including Governance and Monitoring), (ii) better understand the risks, and (iii) mitigate consequences of failure.	All HHC IV sites should have an independent geotechnical review board (IGRB) or an independent technical review board (ITRB), with expertise included in the key drivers of the relevant HHC. Complete best-in-class analyses for the critical behaviours, including as applicable advanced stability modelling (such as 3D LEM or 2D FEM), seepage modelling, and thermal modelling for cold climate facilities. Consider upgrading analyses related to the key drivers for the hazard classification, such as improved stacking methods and increased minimum stability Factors of Safety if Stability Performance is a key driver. Critical components should include both higher than standard Factors of Safety and redundancy.	Follow best practices for construction, CQC, CQA, and third-party review of critical components. Implement Governance and Monitoring systems consistent with either of the top two categories in Table 9 (a Governance rating of at least 2, and a Monitoring rating of at least 2). EoR engagement and the IGRB or ITRB review should continue through construction, commissioning and operations. Further, the recommendations of generally accepted and peer reviewed papers, reports guidelines and standards, such as Smith and Konrad (2025), the Global Industry Standard for Tailings Management (ICMM, 2020) and its supporting implementation documents, or the Canadian Dam Association (CDA, 2019) should be implemented as applicable. For the critical components, establish verifiable critical controls including detailed instrument and visual monitoring with redundancy; well-defined and site-specific TARPs; frequent inspections and review by an experienced geotechnical specialist.

Stability class		Level of Effort		
Heap Hazard Class (HHC)	**Instability Hazard**	**Investigation and Characterization**	**Analysis and Design**	**Construction and Operation**
				Monitoring should include piezometers in the heap and other methods to determine phreatic levels and degrees of saturation, temperature gages for cold climate facilities, routine testing of fresh ore stacked on the heap and leached ore, and redundant slope monitoring such as ground-based LiDAR or conventional survey techniques, and InSAR systems.
V	Very High Hazard	All projects with an HHC of V should implement Governance and Performance Monitoring systems consistent with the Maximum Possible Rating for Governance and Monitoring (Table 9). In addition, engagement of the EoR and third party reviewers should begin during this phase of work.	Follow the recommendations for HHC Class IV facilities. Additionally, perform 3D modelling for the critical slopes and, if the supporting data is inadequate to support advanced modelling, complete additional geotechnical investigations as indicated. Consider incorporating downstream improvements to mitigate consequences of any failure, such as relocating facilities away from the runout zone and more robust monitoring of any receiving waters. In additional to higher Factors of Safety and redundancy of key components, the system should include an appropriate level of resiliency[9] as set forth in ICMM (2020) and CDA (2019).	Follow the recommendations for HHC Class IV facilities. Additionally, implement Governance and Monitoring systems consistent with the top category in Table 9 (a combined Governance and Monitoring rating of 8). To the extent that construction of any components of the facility is related to the HHC V classification, provided enhanced peer review, more robust design criteria, governance and monitoring.

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[9] As used in this context, resiliency refers to the ability of a system or facility to withstand, absorb, adapt to, and recover from disruptive events (such as extreme seismic loading or flood conditions) while continuing to perform its critical functions. Resiliency is distinct from stability (resistance to failure, generally as measured by FoS) and reliability (the inverse of probability of failure, often active through redundancy and FoS); resiliency emphasizes response to and recovery from an extreme event and includes consideration of factors such as effectiveness of critical controls.

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