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Assessment of Leach Ore Dry Unit Weight and Hydraulic Performance

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Abstract

Proper design of a heap leach facility requires the development of a leach ore loading plan that can accommodate its ultimate capacity. The loading plan and associated capacity assessments will be more representative of actual field performance if they consider the variation in leach ore dry unit weight over time as the heap is loaded and the leach ore compresses under self-weight. That can be accomplished by careful evaluation of results from laboratory testing of representative samples of the leach ore.

Rigid wall permeability testing provides data about dry unit weight (and hence void ratio), saturated hydraulic conductivity, and vertical effective confining stress. These data can be fitted to relationships for compressibility (void ratio as a function of effective confining stress) and conductivity (saturated hydraulic conductivity as a function of void ratio) that were originally developed for self-weight consolidation of soft, fine-grained soils, e.g., tailings. The forms of those equations also typically fit laboratory test data from coarse-grained leach ore.

Once the compressibility and conductivity relationships are defined, incremental stress calculations with a spreadsheet allow for the development of: (1) profiles of dry unit weight and saturated hydraulic conductivity with depth in a unit area column of leach ore; and (2) the variation in depth-weighted average dry unit weight with average heap height. The average dry unit weight relationship may then be incorporated into heap loading plans and capacity assessments. Comparison of the planned leach application rate to the anticipated saturated hydraulic conductivity of the leach ore under the maximum heap height, assuming vertical percolation under unit hydraulic gradient, also provides a preliminary assessment of hydraulic performance.

Results for two case studies, including both a crushed and agglomerated copper heap and a run-of-mine gold heap, are presented. Actual results from mine production records compare well with predictions, although assessment of the run-of-mine gold heap required additional refinement to adjust for the effects of oversize material that could not be incorporated into the laboratory-scale testing.

Introduction

Proper design of a heap leach facility (HLF) requires development of a leach ore loading plan to include its ultimate capacity. The mine plan provides anticipated production in dry tonnes (or dry tons), while the assessment of the heap capacity is typically evaluated based on volume, which requires knowledge of the leach ore dry density (or dry unit weight) to relate the anticipated mine production to heap capacity. Often, the dry density (or dry unit weight) of the leach ore is assumed based on prior experience with similar projects, or estimated from the loose dumped dry density (or dry unit weight) achieved in bench-scale metallurgical column testing that may not consider the increase in density (or unit weight) resulting from an increasing depth of confinement. It is not uncommon for such initial assessments to significantly under- or over-predict the capacity of the associated HLF. The loading plan and associated capacity assessments will be more representative of actual field performance if they consider the variation in leach ore dry density (or dry unit weight) over time as the heap is loaded and the leach ore compresses under self-weight.

That can be accomplished by careful completion and evaluation of laboratory rigid wall permeability testing of representative samples of the leach ore. Testing conducted in accordance with standard procedures such as USBR 5600 or USBR 5605 (USBR, 1998; USBR, 1990) provides data relating dry density (or dry unit weight and, hence, void ratio), saturated hydraulic conductivity, and vertical effective confining stress. Abu-Hejleh and Znidarcic (1994) present relationships for compressibility (void ratio as a function of effective confining stress) and conductivity (saturated hydraulic conductivity as a function of void ratio) that were originally developed for self-weight consolidation of soft, fine-grained soils, e.g., tailings. The forms of those equations also typically fit laboratory test data from coarse-grained leach ore.

Once the compressibility and conductivity relationships are defined, incremental stress calculations with a spreadsheet allow the development of profiles of dry density (or dry unit weight) and saturated hydraulic conductivity with depth in a unit area column of leach ore and the variation in depth-weighted average dry density (or average dry unit weight) with average heap height. The average dry density (or average dry unit weight) relationship may then be incorporated into heap loading plans and capacity assessments, thereby enhancing the accuracy of those assessments by quantifying the variation in dry density (or dry unit weight) as the HLF is loaded to its capacity over time.

Comparison of the planned leach application rate to the anticipated saturated hydraulic conductivity of the leach ore under the maximum heap height, assuming vertical percolation under unit hydraulic gradient, also provides a preliminary assessment of hydraulic performance.

Analysis methodology

As noted, the detailed assessment of leach ore dry unit weight and hydraulic performance is conducted in two distinct phases. These comprise: (1) the development of leach ore compressibility and conductivity relationships from rigid wall permeability test results; and (2) the evaluation of leach ore performance as indicated by the behaviour in a unit area column.

Compressibility and conductivity relationship development

In conducting laboratory rigid wall permeability testing of representative samples of a leach ore:

- Large-scale apparatus should be employed, e.g., 8-inch-diameter (USBR 5600) or 19-inch-diameter (USBR 5600) rigid wall permeameters, to permit inclusion of most, or all, of the material gradation, while maintaining an appropriate ratio of specimen diameter to maximum particle size, which is typically not less than 6:1.
- Plumbing that supplies water to the permeameter should be oversized such that hydraulic head losses in the apparatus are small relative to the hydraulic head losses in the specimen. If not possible, test results should be corrected for system head losses.
- Bead of hydrated bentonite should be placed at mid-height on the inside of the rigid wall permeameter to limit side wall leakage, i.e., preferential flow along the interface between the permeameter and the specimen, during permeability testing.
- Material should be placed loose in the rigid wall permeameter to simulate its initial condition in the field, and then subjected to a nominal seating load.
- Specimen should be inundated from the base to present a more uniform wetting front that moves upward through the specimen, and displaces more of the air from within the material.
- Initial saturated hydraulic conductivity of the material should then be measured via a constant head permeability test.
- Vertical effective confining stress on the specimen should thereafter be increased incrementally by means of a load frame and hydraulic jack with displacement measurements (from which dry density or dry unit weight are later calculated), and saturated hydraulic conductivity measurements should be taken at each load increment, once deformations are complete, to a maximum effective confining stress selected based on the anticipated maximum height of the HLF.

Resultant test data will include vertical effective confining stress, dry density (or dry unit weight and, hence, void ratio), and saturated hydraulic conductivity, from which the necessary compressibility and conductivity relationships can be developed.

Test data, compressibility (void ratio versus effective confining stress), and conductivity (void ratio versus saturated hydraulic conductivity) relationships can be developed using simplified curve fitting techniques proposed by John (1998) in accordance with the forms of the relationships suggested by Abu-Hejleh and Znidarcic (1994), which comprise:

Compressibility: $e = A(\sigma' + Z)^B$
Conductivity: $K = Ce^D$
where: e – void ratio
σ' – vertical effective confining stress
K – saturated hydraulic conductivity
A, B, Z, C and D – curve fitting parameters

with typical compressibility and conductivity relationships shown in Figure 1, along with their underlying laboratory test data.

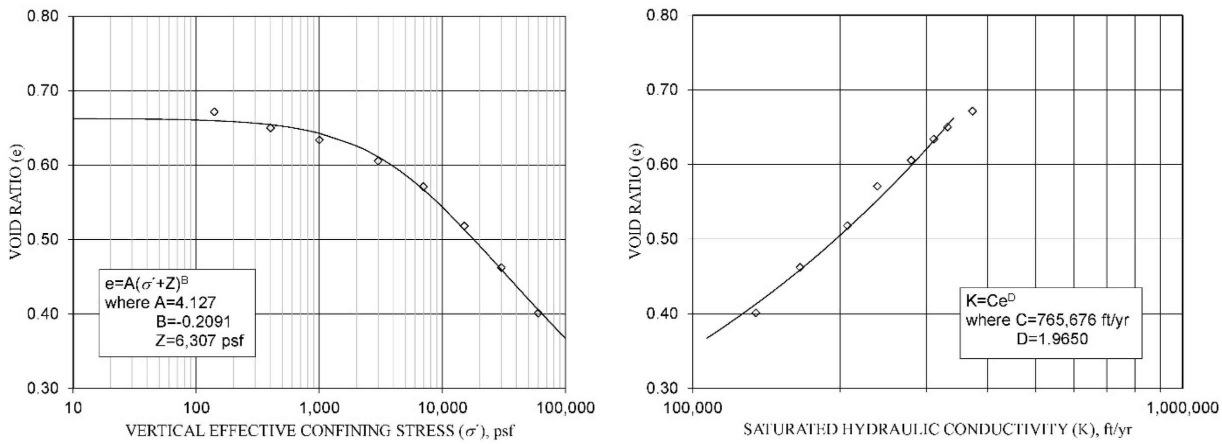

Figure 1: Typical leach ore compressibility and conductivity relationships

At the conclusion of the rigid wall permeability testing, it is also useful to establish: (1) the steady state, under leach moisture content at the project-specific target leach application rate; and (2) the draindown moisture content, i.e., the moisture content based on the water that will be held in the specimen against gravity, for use in later incremental stress calculations and/or HLF water balance assessments.

Leach ore performance evaluation without oversized material

Given the compressibility and conductivity relationships as defined above, incremental stress calculations can be completed with a spreadsheet to define the distributions of dry density (or dry unit weight) and saturated hydraulic conductivity versus depth in a typical unit area column of leach ore. As conceptually illustrated in Figure 2, the calculations involve a coordinate transformation.

1. Distribution of vertical effective stress is calculated as a function of depth in the "z" dimension, i.e., depth in a conceptual unit area column of leach ore solids with the volume of pore air and pore water removed, based on one of several assumptions regarding the influence of the pore water within the leach ore.
2. Distribution of void ratio with depth is then calculated from the vertical effective stress distribution and the previously established compressibility relationship.

3. Depths in the "x" dimension, i.e., actual depth in a unit area column of leach ore, are calculated from the depths in the "z" dimension and the associated void ratios.

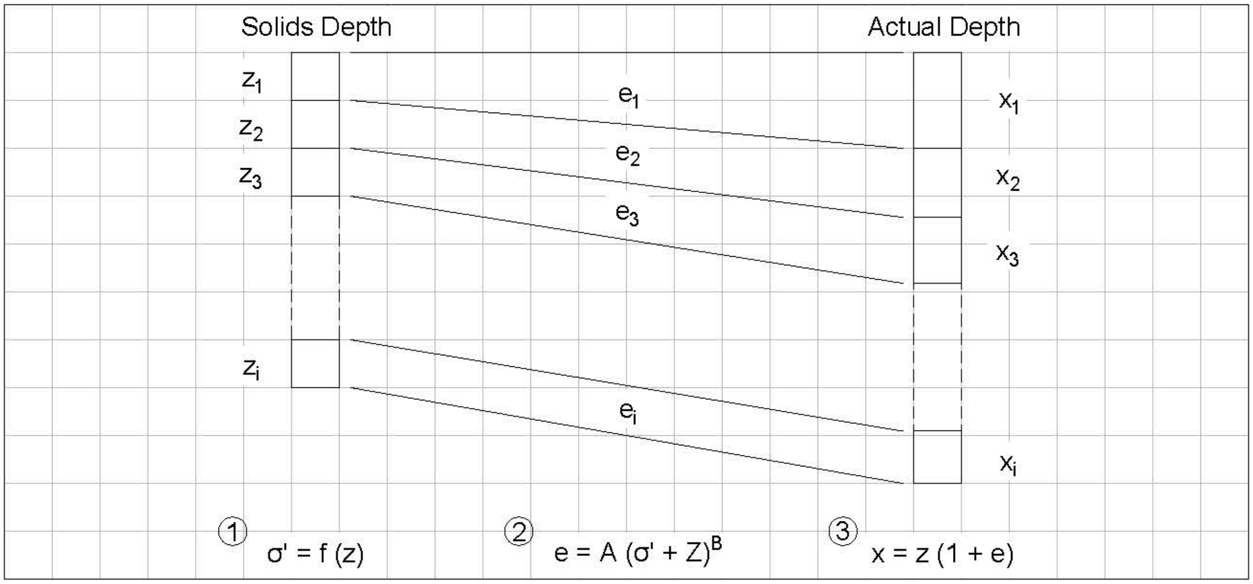

Figure 2: Coordinate transformation concept

The calculation of the vertical effective stress profile in the "z" dimension is dependent upon the effect of the pore water, if present. The simplest case comprises a dry unit area column without pore water, and, thus, with zero pore pressure throughout the unit area column. In that case:

Dry Material: $\Delta\sigma' = G_s * \gamma_w * \Delta z$

where: $\Delta\sigma'$ – vertical effective confining stress increment
G_s – particle specific gravity
γ_w – unit weight of water
Δz – solids depth increment

Another situation would comprise a saturated unit area column with hydrostatic pore pressures below a phreatic surface at the top of the unit area column. In that case:

Saturated Material: $\Delta\sigma' = (G_s*\gamma_w - \gamma_w) * \Delta z$

where: $\Delta\sigma'$ – vertical effective confining stress increment
G_s – particle specific gravity
γ_w – unit weight of water
Δz – solids depth increment

Most commonly, an HLF is operated with the leach ore in an unsaturated state under a fixed leach solution application rate. For these analyses, it has been assumed that the gravimetric moisture content of the leach ore is constant with depth. It should be noted that moisture content is defined herein as a percentage of the dry mass of the material present. This differs from the definition of moisture content commonly used in metallurgy, which is defined as the percentage of the total mass of the material present. Under the assumption of unsaturated material (i.e., pore pressures are approximately zero) at a constant gravimetric moisture content with depth, vertical effective confining stresses can be defined as follows:

Moist material: $\Delta\sigma' = G_s * \gamma_w * \Delta z * (1 + w/100)$

where: $\Delta\sigma'$ – vertical effective confining stress increment
G_s – particle specific gravity
γ_w – unit weight of water
Δz – solids depth increment
w – gravimetric moisture content (percent by dry mass)

As noted previously, the gravimetric moisture content of the material under leach was assumed to be constant with depth. Although that may not be strictly correct, it is a reasonable assumption, because it results in slightly higher degrees of saturation deeper in the leach ore as the dry unit weight increases with depth and the void ratio decreases. That trend is to be expected, since the capillarity of the deeper, denser leach ore should be higher as well. Given the generally coarse, granular nature of most leach ores, these analyses have also assumed that self-weight compression of the leach ore occurs quickly such that time rate effects do not have to be considered, i.e., this behaviour comprises immediate compression and not time rate consolidation of a porous media.

Once the effective stress profile in the "z" dimension is established, the void ratio at each point within the unit area column of solids can then be calculated from the compressibility relationship defined previously, i.e., $e = A(\sigma' + Z)^B$, and the actual depth of each increment of material in the "x" dimension can be calculated as:

$\Delta x = \Delta z * (1 + e)$

where: Δx – actual depth increment
Δz – solids depth increment
e – void ratio

which completes the desired coordinate transformation. The actual depth at each point within the unit area column is then calculated by summing the overlying incremental actual depths. Note that it is often necessary for mass conservation to adjust the initial "z" dimension increments on an iterative basis to yield the correct actual depth of unit area column in the "x" dimension.

Once profiles of vertical effective confining stress and void ratio are established over the correct actual depth of the unit area column, dry density (or dry unit weight) can be calculated at each depth as follows:

$\rho_{dry} = G_s * \rho_w / (1 + e)$

where: ρ_{dry} – dry density
G_s – particle specific gravity
ρ_w – density of water
e – void ratio

$\gamma_{dry} = G_s * \gamma_w / (1 + e)$

where: γ_{dry} – dry unit weight
G_s – particle specific gravity
γ_w – unit weight of water
e – void ratio

The saturated hydraulic conductivity at each point within the unit area column can then also be calculated at its actual depth in the "x" dimension from the conductivity relationship defined previously, i.e., $K = Ce^D$.

Given the distribution of dry density (or dry unit weight) with actual depth in the "x" dimension within a unit area column of leach ore, the variation in overall average dry unit weight with increasing average heap height can be developed, which illustrates changes as the facility is loaded over time. For each average heap height considered, the corresponding overall average dry density (or average dry unit weight) comprises the depth weighted average value for the overlying leach ore from the dry density (or dry unit weight) profile in the "x" dimension as illustrated in the later case histories.

Under the assumption of vertical infiltration at unit hydraulic gradient, the saturated hydraulic conductivity of the leach ore may be compared to the planned leach application rate to assess the anticipated hydraulic performance of the leach ore. If the saturated hydraulic conductivity of the leach ore is expected to remain well above the planned leach application rate at the maximum depth of burial, the leach ore may be expected to remain freely drained throughout leach operations.

Leach ore performance evaluation with oversized material

Unadjusted results from laboratory-scale tests conducted on material from which an oversized fraction had been removed can under-predict the average dry density (or average dry unit weight) as compared to actual production-scale data. This is most likely due to the effect of the oversize particles that were excluded from the laboratory permeability testing.

Laboratory derived dry densities (or dry unit weights) developed as described above can subsequently be adjusted for the effect of the oversized fraction by application of a procedure (ASTM D4718), which is commonly used to rock correct Proctor compaction test results for the effect of oversized material, but can be applied to other, similar circumstances. The rock corrected dry unit weights are calculated as:

$$\gamma_{dry,c} = 100 * \gamma_{dry,f} * G_s * \gamma_w / (\gamma_{dry,f} * P_c + G_s * \gamma_w * P_f)$$

where: $\gamma_{dry,c}$ – rock corrected dry unit weight
$\gamma_{dry,f}$ – dry unit weight of the finer fraction
G_s – particle specific gravity
γ_w – unit weight of water
P_c – percent of oversize fraction by weight
P_f – percent of finer fraction by weight

The rock corrected laboratory-scale test results often match the production-scale data well. Updated void ratios can subsequently be calculated at each depth within the profile in the "x" dimension as follows:

$$e=G_s*\gamma_w/\gamma_{dry}-1$$

where: e – void ratio
G_s – particle specific gravity
γ_w – unit weight of water
γ_{dry} – dry unit weight

with updated saturated hydraulic conductivity values then developed from the updated void ratios and the conductivity relationship defined previously, i.e., $K = Ce^D$.

Case history results

Although the author has applied this approach to numerous HLFs, two projects are presented herein as case histories because sufficient production data were available to provide some verification of the performance predicted based on laboratory-scale testing. These included: (1) a crushed and agglomerated copper heap; and (2) a run-of-mine gold heap.

As illustrated in Figure 3, the fresh and spent samples of the crushed and agglomerated copper ore comprise a well graded gravel with sand (GW) when sieved dry (i.e., agglomerates intact); however, the effect of agglomeration can be seen in comparing those to the wet sieved gradations (i.e., agglomerates destroyed) where the increased fines content shifts the classifications to a poorly graded gravel with silt and sand (GP-GM) and a silty gravel with sand (GM), respectively. It should also be noted that the fresh and spent gradations are similar, which would seem to indicate little or no decrepitation of the leach ore after one leach cycle, although those effects may be more pronounced after multiple cycles or a greater depth of burial under subsequent lifts of leach ore. Figure 3 further illustrates the gradation of the run-of-mine gold ore, i.e., a poorly graded gravel with silty clay and sand (GP-GC), before and after removal of the oversized fraction.

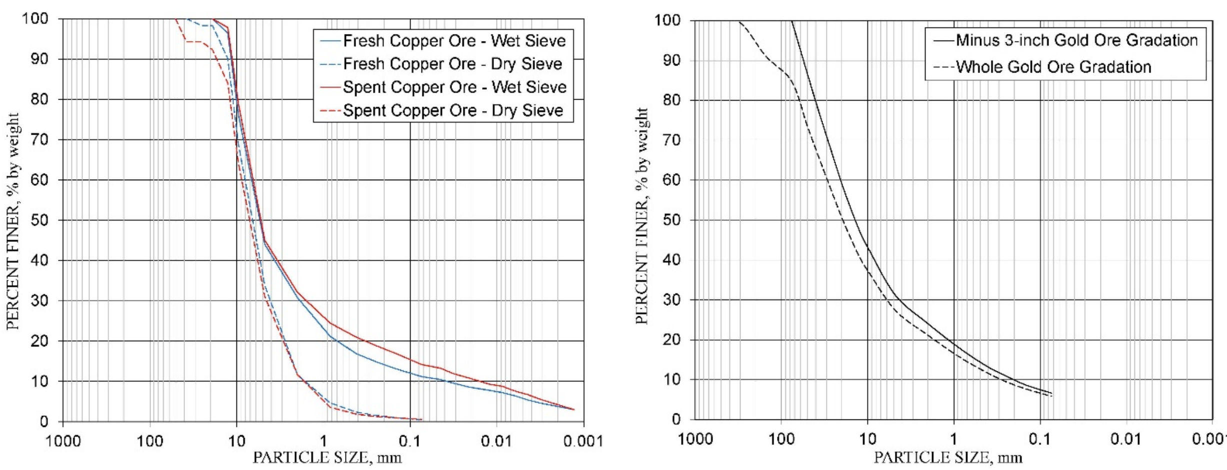

Figure 3: Copper and gold leach ore gradations

Figures 4 and 5 depict the compressibility and conductivity relationships for the copper and gold leach ores that were derived as described previously. The copper leach ore laboratory testing included rigid wall permeability testing of both fresh and spent ore specimens. Given that the results were not markedly different, they were interpreted together, which is further evidence of little or no decrepitation within that particular copper ore. The gold leach ore laboratory testing also includes results from two separate trials.

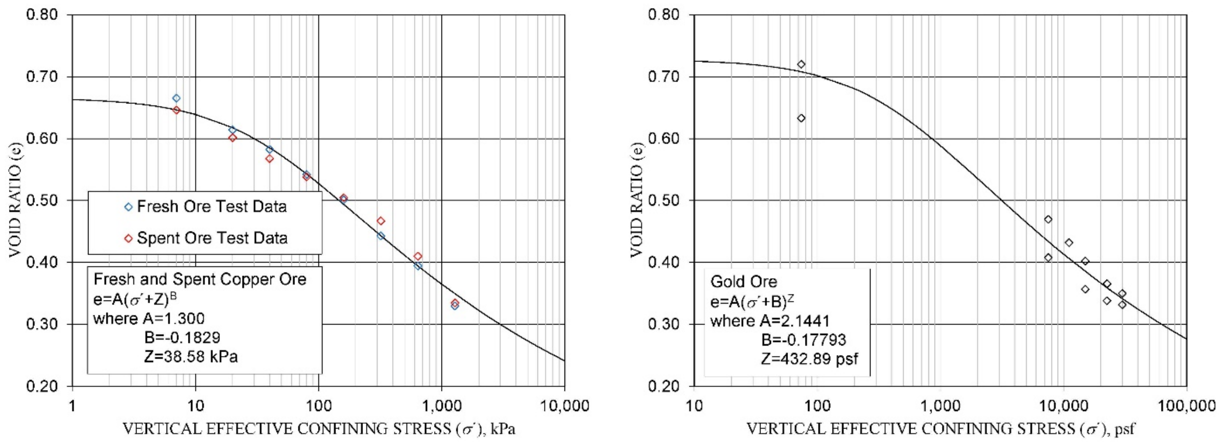

Figure 4: Copper and gold leach ore compressibility relationships

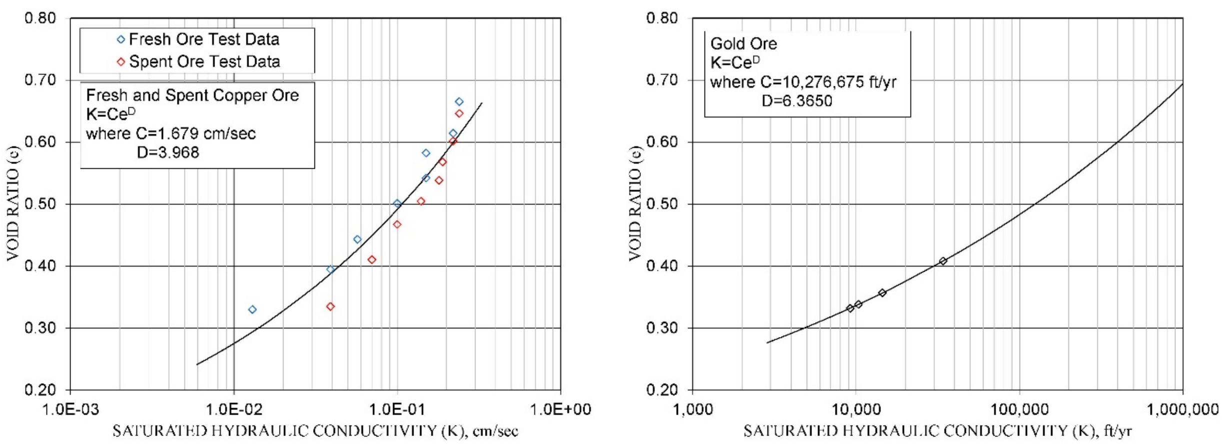

Figure 5: Copper and gold leach ore conductivity relationships

As a result of the incremental stress calculations described previously, Figure 6 depicts the variation in dry density (or dry unit weight) with actual depth within unit area columns of the copper and gold leach ores under their planned leach application rates. The results for the run-of-mine gold ore have been adjusted for the effects of the oversize material removed from the laboratory test specimens using the methodology described previously in this paper.

Figure 7 depicts the variation in leach ore average dry density (or dry unit weight) with average heap height for both the copper and gold HLFs that were developed from the density (or unit weight) profiles shown on Figure 6. To assess the accuracy of these predictions, dry densities (or dry unit weights) were calculated from production records at one or more different times during the operation of the copper and gold HLFs. Given three-dimensional topography of the heaps and their underlying liner systems, comparison of the two surfaces via AutoCAD Civil3D provided the volume and two-dimensional area of the HLFs at the time of the heap surveys. Volume divided by area provided estimates of the average height of the heap, and average dry densities (or dry unit weights) were calculated by coupling the volumes with the known production (i.e., leach ore dry tonnage placed on the heap) as of the dates of the various surveys. Good agreement is noted between predicted average dry densities (or average dry unit weights) based on laboratory test results and values calculated from production records.

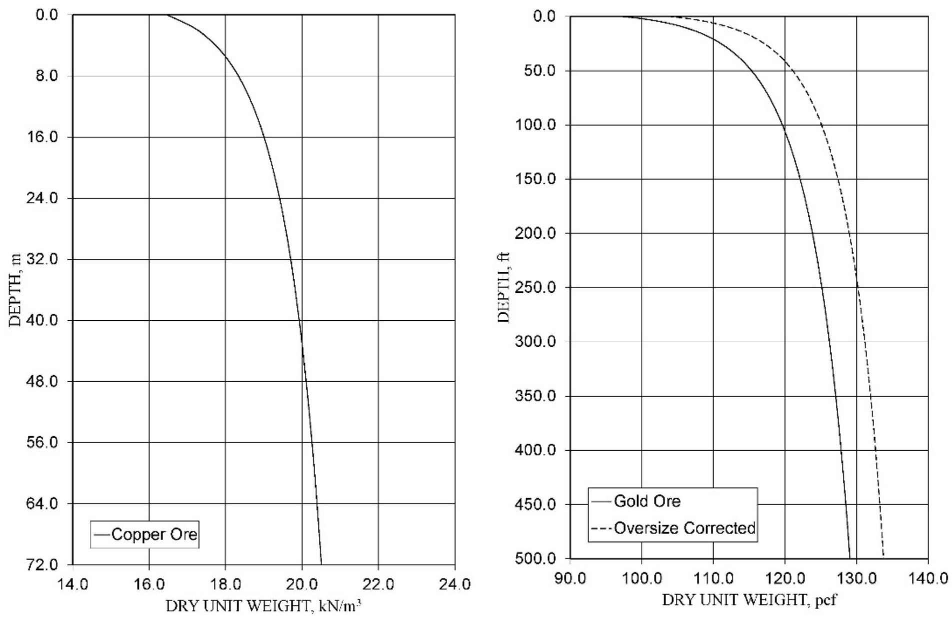

Figure 6: Copper and gold leach ore dry density (or dry unit weight) profiles

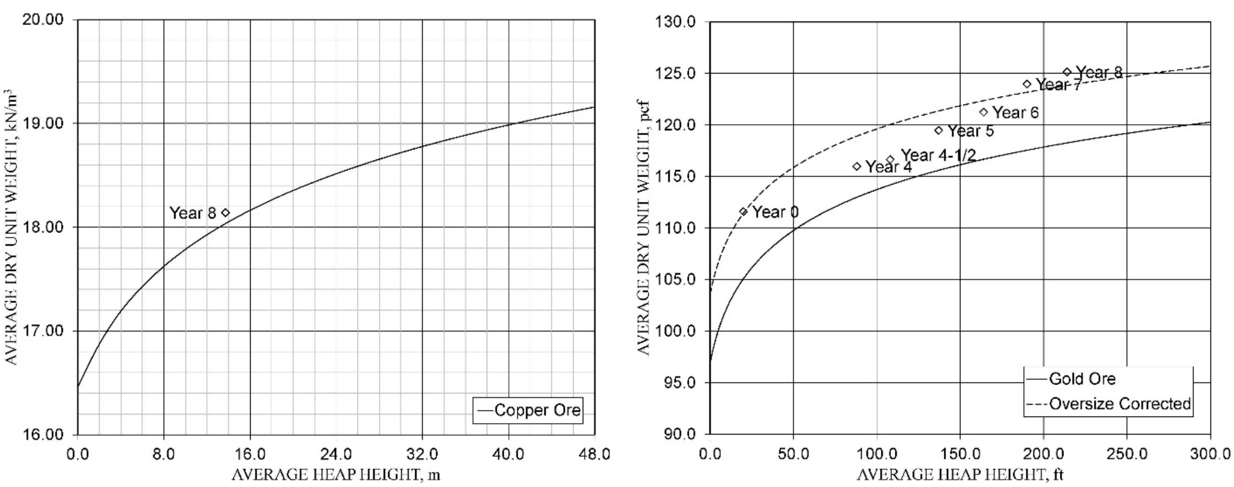

Figure 7: Average dry densities (or dry unit weights) with average heap height

Figure 8 presents comparisons of the saturated hydraulic conductivity profiles for the copper and gold leach ores with their respective planned leach application rates under the assumption of vertical infiltration at unit hydraulic gradient. Since the saturated hydraulic conductivities remain well above the planned leach application rates at the maximum depth of burial, the copper and gold leach ores are expected to remain freely drained and perform well throughout leach operations. It should be noted that the copper HLF is an aerated facility with interlift liners, and while project assessments did evaluate the counter current flow of air upward from low pressure blowers and process solution downward from the drip irrigation system at the heap surface, discussion of those assessments is beyond the scope of this paper.

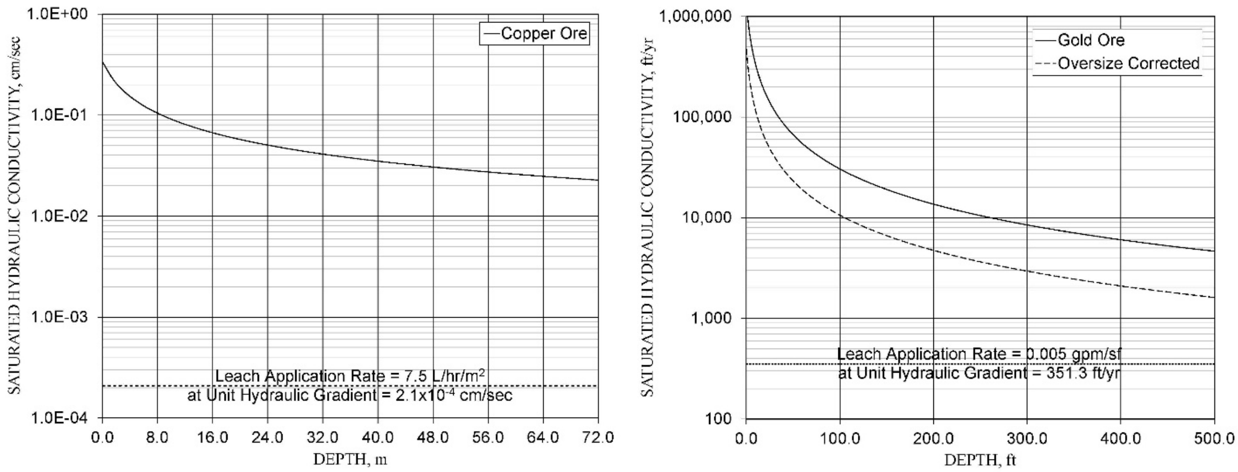

Figure 8: Copper and gold leach ore saturated hydraulic conductivity profiles

Conclusion

Rigid wall permeability test results typically include data relating dry unit weight (and hence void ratio), saturated hydraulic conductivity, and vertical effective confining stress. When carefully completed on representative samples of leach ore and adjusted for removal of oversize material if necessary, those test results can be fitted to relationships for compressibility (void ratio as a function of effective confining stress) and conductivity (saturated hydraulic conductivity as a function of void ratio) for leach ore that were originally developed for self-weight consolidation of soft, fine-grained soils, e.g., tailings.

Once the compressibility and conductivity relationships are defined for the leach ore, incremental stress calculations with a spreadsheet, with proper consideration of pore water conditions, allows the development of profiles of dry density (or dry unit weight) and saturated hydraulic conductivity with depth in a unit area column of leach ore and the variation in depth-weighted average dry unit weight with average heap height. Development of a HLF loading plan, to include its ultimate capacity, is enhanced by considering the variation in leach ore average dry density (or average dry unit weight) over time as the HLF is loaded and the leach ore compresses under self-weight. Furthermore, comparison of the planned leach application rate to the predicted saturated hydraulic conductivity of the leach ore under its maximum height, assuming vertical percolation of process solution under unit hydraulic gradient, provides an assessment of anticipated hydraulic performance.

Results were presented for two case studies including both a crushed and agglomerated copper heap and a run-of-mine gold heap. When rigid wall permeability test results on representative samples of the copper and gold leach ores were interpreted as described herein, the predicted variation in average dry density (or average dry unit weight) with average heap height compared well with actual results from mine production records. Hydraulic performance of both HLFs during production has been good, as predicted by the interpreted laboratory test results, based on observed conditions under the planned leach application rate, e.g., little or no ponding on the surface of the HLFs, no observed seepage on the sides of the HLFs, no phreatic surface development within the HLFs where solution levels could be monitored with installed instrumentation (e.g., vibrating wire piezometers), and process solution recovery in line with expectations.

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