A Laboratory and Numerical Approach to Assess Ore Consolidation and Solution Distribution during the Ramp-up Period

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Abstract

Slow ramp up of initial irrigation rates is a commonly used scheme at the start of heap leaching to reduce ore consolidation and promote solution distribution. The phenomenon of ore consolidation during early irrigation is not well understood, and operators typically apply ramp-up irrigation schedules from experience. A combined approach using laboratory tests and numerical simulations has been developed to investigate ore consolidation and to optimize irrigation ramp-up schedules. Laboratory consolidation tests define the ore critical solution content, which is defined as the solution content at which the ore experiences major collapse/consolidation. Ore hydraulic properties are measured and applied in numerical solution flow models simulating various ore irrigation ramp-up schemes. The model-predicted solution content distributions are then evaluated to assess the leach solution content distribution laterally and vertically at different time steps under the irrigation ramp-up schemes. The relative observed differences help to identify ramp-up schemes that do not exceed the laboratory measured critical solution content and minimize the time needed to achieve the full target irrigation rate.

Results indicate ramp-up irrigation schemes can improve the solution distribution and reduce the potential to exceed the critical solution content. Solution redistribution from on/off irrigation schemes is more effective at minimizing ore solution contents at shallow ore depths and creating more uniform solution distribution than using constant low irrigation rates. We hypothesize that ramp-up irrigation minimizes shallow ore consolidation by allowing better solution redistribution over time, which creates a more uniform solution flow field that reduces the potential for reduced soil strength and ore collapse.

Introduction

Heap leaching is a cost-effective process to extract gold, copper, and other metals from low-grade ores. In addition to metallurgical properties and metal recovery rates, the leach ore particle size distribution, consolidation characteristics under loading, and the resultant hydraulic properties, are primary factors to consider for heap leach design and operations. Crushed ores (i.e., 0.5-inch diameter or smaller) typically yield faster and higher recovery rates due to a higher surface area to volume ratio; however, excessive fines generation can reduce permeability. Ore consolidation at depth within a heap can also significantly reduce leach ore permeability, increase solution bypass, and result in reduced recovery; the extent of consolidation and loss of permeability is a function of the ore physical properties, particle sorting, and overburden pressure (Milczarek et al., 2013; Guzman et al., 2013).

Agglomeration can be used to improve the permeability and strength of ores, by adhering the fine particles to the surface of larger particles and generating a low bulk density porous media consisting of large macro-pores between the agglomerated particles. The strength of agglomeration and its effect on the in-situ characteristics of the heap is not well understood, and frequently laboratory column results do not scale well to the field (Bouffard, 2005). Whereas gold and silver leach ores can use strong binders such as cement or lime to maintain agglomerate structure, copper leach agglomerates have a weak agglomerate structure (Lewandowski and Kawartra, 2009), and may experience loss of agglomeration and permeability due to gangue mineral dissolution and resultant ore decrepitation (Ghorbani et al., 2015).

Many crushed and agglomerated heap leach operations have observed shallow ore collapse directly under drip emitters at the heap surface and resulting metal recovery losses. To minimize this effect, these operations typically employ an irrigation ramp-up period to slowly wet the ore prior to initiating full irrigation rates. The phenomena of near-surface leach ore collapse and its effect on heap leach operations has not been well studied and is not observed with current consolidation-permeability testing methods. Column experiments by Briseño (2018) indicate that wetting of agglomerated copper leach ore at full irrigation rates resulted in shallow surface ore collapse, and that slow ramp-up wetting reduced ore collapse and improved solution distribution within the heap leach material. Because ramp-up wetting increases the leach-cycle time, better understanding of shallow leach ore collapse, and optimization of ramp-up wetting, could improve heap leach economics.

Within the soil sciences, collapsible soils have been extensively studied; Li et al. (2016) provided a summary review of loess (silty) soils in arid climates, which have a loose structure that is susceptible to collapse upon wetting. Soil collapse can be attributed to wetting reducing the strength of contact between particles and causing the soil structure to fail with particle rearrangement and loss of larger pore space. In general, significant collapse starts to occur at a critical water content, which varies depending on the initial water content and vertical stress under which the soil is wetted. As the soil water content increases beyond the critical value, significant volume change is experienced prior to reaching saturation. Li et al. (2016) cite several studies that observed full soil collapse prior to 70% of saturation. Whereby, mechanical elastoplastic breakage models have been developed to predict soil collapse, the parameters required by these models are hard to determine and simple constitutive relationships that can used to predict soil collapse have yet to be identified (Li et al., 2016).

Whether loess soils provide an analogue to leach ore agglomerates deserves further study. Conceptually, an agglomerated ore that is stacked to achieve low bulk density conditions has a leach ore structure held in place via contact forces between the agglomerated particles. As the leach ore is initially irrigated, the leach ore solution content directly below the dripper increases rapidly. A rapid increase in solution content could decrease the shear resistance and the capillary tension that holds particles in place, in addition to potentially loosening the particles bound to the agglomerate surface, and result in a collapse (increased bulk density, reduced porosity) of the leach ore structure. Briseño (2018) observed that shallow leach ore collapse can propagate through the leach ore profile and result in differential settlement between the wetter and dryer zones, in addition to uneven solution distribution.

Consequently, the objective of an irrigation ramp-up schedule is to apply leach solution in intermittent (short time) intervals, which allows the solution sufficient time to redistribute and slowly wet the leach ore. Slow wetting reduces the potential for agglomerate structure collapse and should maintain more uniform hydraulic conductivity of the leach ore.

Once the leach ore is uniformly and fully wetted, its structure should be more stable to allow leach solution to be applied with full irrigation rates without further ore solution water content increase and ore collapse. Because the potential for collapse is dependent on the material properties of the leach ore and the irrigation rate, experimental methods to determine wetting and consolidation behaviour for agglomerated or non-agglomerated ores are needed to guide heap leach designs and operations to minimize ore collapse at the surface, maximize solution distribution throughout the leach ore profile, and minimize leach ore wet up time.

Methods

Four copper ore samples crushed to 0.5-inch diameter nominal particle size and with similar particle size distributions (Figure 1) were selected from a larger hydrodynamic testing program to evaluate hydraulic properties and potential ore collapse at shallow near-surface conditions. Sample S4 had the lowest (16%) and S3 had the highest (19%) passing #100 mesh.

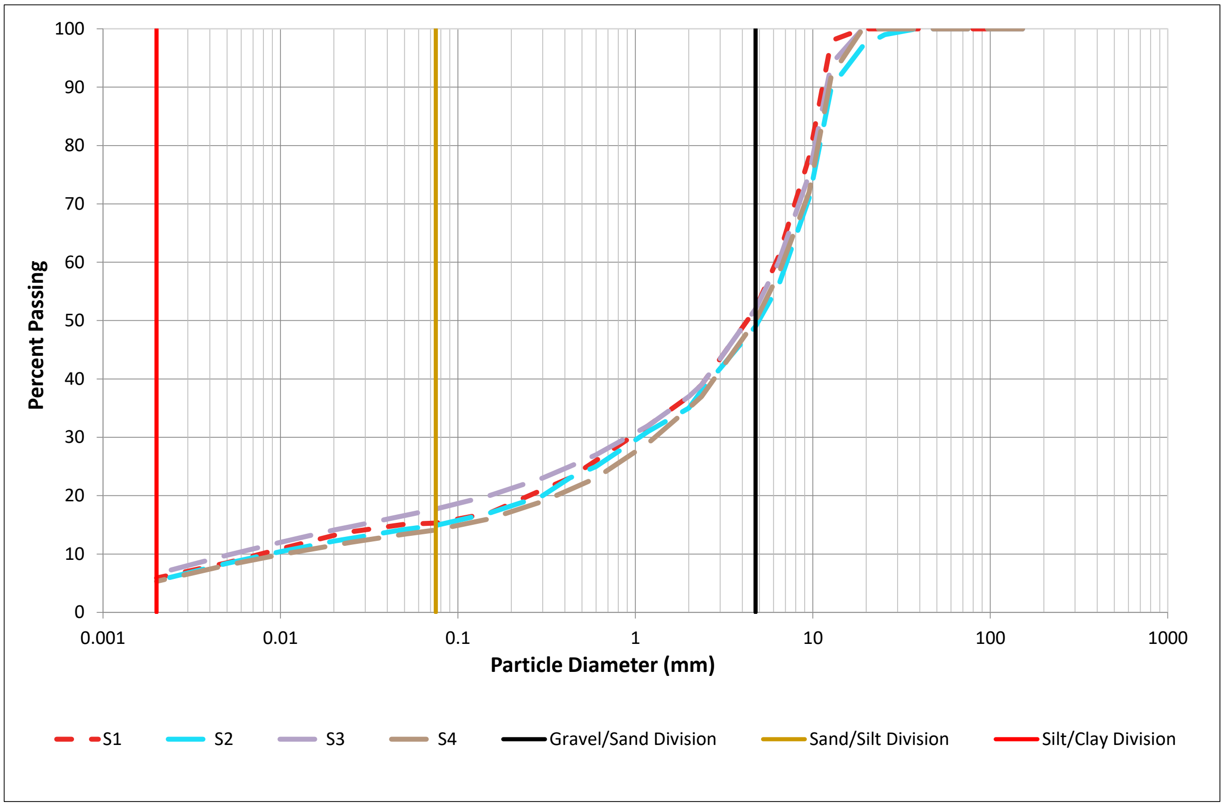

Figure 1: Ore sample particle size distribution

Laboratory test methods

Laboratory tests performed on the four ore samples included:

- Hydraulic properties: saturated hydraulic conductivity (Ksat), unsaturated hydraulic conductivity (Kunsat), and moisture retention characteristics (MRC).
- Leach ore stability: wet pack ore collapse tests.

Tests were designed to identify the saturated and unsaturated hydraulic properties and the approximate solution content at which collapse/consolidation may occur. K_{sat} and K_{unsat} were performed in dual wall permeameters using the methods described in Milczarek et al. (2013). MRC tests followed ASTM method 6836 – 02 (ASTM, 2008). Leach ore samples were agglomerated with raffinate and 10 kg/ton concentrated sulfuric acid at the optimal gravimetric solution content (GSC) between 5.8 to 7.2%. Ore samples were packed into 15-cm diameter, 5-cm high, rigid-wall Tempe cells. The packing bulk densities were targeted to represent a 1 m heap height from consolidation permeability tests.

Wet pack ore collapse/consolidation tests

Wet pack ore collapse tests consist of preparing agglomerated leach ore samples at different GSC using raffinate solution, packing the leach ore samples into 15-cm diameter by 30-cm tall dual wall permeameters and then compressing at increasing pressure steps from 0.5 to 6 m over burden pressure to determine the critical volumetric solution content (VSC) at which the maximum consolidation is observed. Leach ore samples were loaded into dual wall permeameters at an initial approximate bulk density of 1.5 g/cm^3 at GSCs of 5.6%, 7.8%, 9.5%, 12.2%, and 14.3%, which correspond to initial volumetric solution contents (VSC) of 8.4%, 11.7%, 14.2%, 18.2%, and 22.1%. The samples were then compressed at increasing pressures approximating 0.5, 1, 1.5, 2, 4, and 6 m overburden pressure. Bulk density changes were monitored with an automated system using pressure transducers to monitor the consolidation of the ore every five minutes.

Numerical modeling

Two-dimensional, axisymmetric variably saturated fluid flow in the leach ore was simulated using the finite element numerical code HYDRUS 2D/3D (Simunek et al., 2018). The focus of the numerical modeling was to identify ramp-up irrigation rates/schemes that would:

1. Minimize ore solution contents between 0 to 3 m depths during the wetting up phase.
2. Maintain VSC values below the critical solution content, defined as the solution content at which the maximum compression or maximum bulk density is achieved.
3. Maximize solution distribution between 0 to 3 m.
4. Obtain the most even wetting profile within the upper 50 cm of the domain.

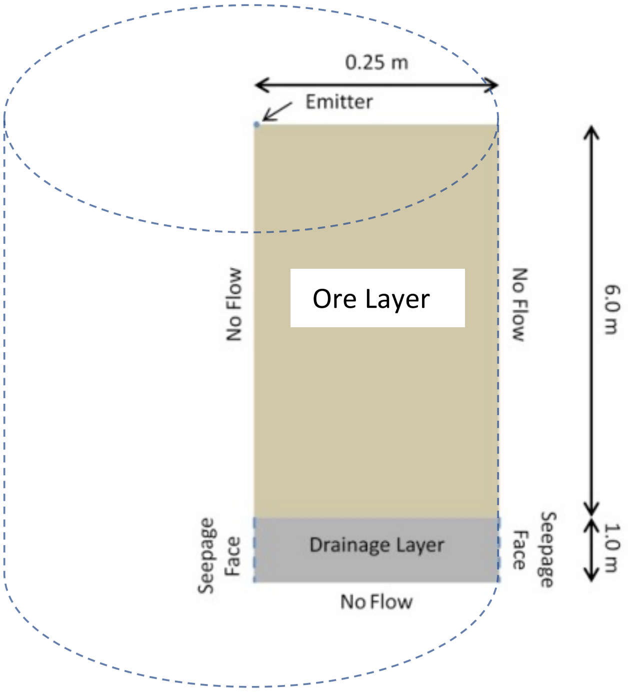

Figure 2: Schematic of model domain (not to scale)

A schematic representation of the model domain is provided in Figure 2. The model consisted of a 7 m high by 0.25 m radius domain with variable finite element grid spacing ranging from 0.01 m to 0.05 m, with finer grid cells near the location of the solution input (solution emitter). Ore hydraulic properties were assigned from the surface to a depth of 6 m below ground surface (bgs). A one-meter-thick drainage layer material type was assigned from 6 m to 7 m bgs (Figure 2).

Measured saturated and unsaturated hydraulic parameters were used to estimate the van Genuchten parameters needed for the numerical modeling via the RETC code (van Genuchten et al., 1991). Solution flow into the model domain was simulated as a variable flux point source representing a single emitter applied to the domain through a 5 cm radius with 1.5 L/hr solution flux. The bottom boundary of the model and the side boundaries of the leach ore were assigned as no flow boundaries. The side boundaries of the drainage layer were assigned a seepage face boundary, allowing solution to exit from the model when the drainage layer becomes saturated (Figure 2). Initial conditions were set to the agglomerated ore solution content at 0.06 GSC or 0.09 VSC for both ore and drainage layer.

To guide the ramp-up schemes design for modeling, the following schemes were considered. A no ramp-up scheme and a slow ramp-up scheme (15 days) were first selected for the test. Scheme 1 was designed to be similar to the slow ramp-up scheme but with an accelerated schedule (15 days versus 8 days ramp-up period).

To evaluate whether we could improve the solution distribution by lowering the irrigation rate, Scheme 2 (7 days) was designed to have an identical daily average irrigation rate as Scheme 1 but with half the dripper irrigation rate and half the on/off period time.

To evaluate the irrigation distribution by reducing the irrigation amount for each irrigation period but faster ramp up, Scheme 3 (4.25 days) was designed to have an accelerated ramp-up schedule with shorter (a) and regular (b) on/off times.

Scheme 4 (12 days) was designed to have a similar scheme at the early ramp up but accelerated toward the end.

The HYDRUS model was then used to simulate six ramp-up irrigation schemes, as shown in Table 1.

Table 1: HYDRUS simulation ramp-up schemes

Scheme	Ratio	Duration (h)	Cumulative time (h)	Cumulative irrigation (cm)	On period (h)	Off periods (h)	Irrigation rate during on periods (L/m²/h)
No ramp-up	N/A	216	216	130	216	0	6.00
Slow scheme	1/48	24	24	0.30	0.5	23.5	6.00
	1/24	72	96	2.10	0.5	11.5	6.00
	1/8	96	192	9.32	0.5	3.5	6.00
	1/4	48	240	16.5	0.5	1.5	6.00
	1/3	48	288	26.2	0.5	1	6.00
	1/2	72	360	47.8	0.5	0.5	6.00
	Full rate	48	408	76.7	48	0	6.00
Scheme 1	1/32	48	48	1.20	0.5	15.5	6.00
	1/16	48	96	2.71	0.5	7.5	6.00
	1/8	24	120	4.51	0.5	3.5	6.00
	1/4	24	144	8.12	0.5	1.5	6.00
	1/2	24	168	15.3	0.5	0.5	6.00
	Full rate	48	216	44.2	48	0	6.00
Scheme 2	1/32	48	48	0.90	0.25	3.75	3.00
	1/16	48	96	2.71	0.25	1.75	3.00
	1/8	24	120	4.51	0.25	0.75	3.00
	1/4	24	144	8.12	0.25	0.25	3.00
	1/2	24	168	15.3	24	0	3.00
	Full rate	48	216	44.2	48	0	6.00
Scheme 3 a, b (15[a] and 30[b] min on period)	1/8	54	54	4.06	0.25[a] 0.5[b]	1.75[a] 3.5[b]	6.00
	1/4	24	78	7.67	0.25[a] 0.5[b]	1.75[a] 3.5[b]	6.00
	1/2	24	102	14.9	0.25[a] 0.5[b]	1.75[a] 3.5[b]	6.00
	Full rate	48	216	43.7	48	0	6.00
Scheme 4	1/48	24	24	0.30	0.5	23.5	6.00
	1/24	72	96	2.10	0.5	11.5	6.00
	1/16	48	144	3.91	0.5	7.5	6.00
	1/8	48	192	7.52	0.5	3.5	6.00
	1/4	48	240	14.7	0.5	1.5	6.00
	1/2	48	288	29.2	0.5	0.5	6.00
	Full rate	48	336	58.0	48	0	6.00

Results

Laboratory testing results

Hydraulic property testing

The estimated van Genuchten parameters are provided in Table 2, based on the measured MRC data and saturated and unsaturated hydraulic conductivity measurements at 3 m equivalent heap height. Drainage layer hydraulic parameters were estimated from the GSA database of hydraulic properties.

Table 2: Leach ore and drainage layer van Genuchten hydraulic parameters

Sample	Saturated hydraulic conductivity	Unsaturated hydraulic parameters				
		Saturated solution content	Residual solution content	Alpha	N	L
	(cm/s)	(cm^3/cm^3)	(cm^3/cm^3)	(1/cm)	(–)	(–)
S1	2.00E-03	0.250	0.07	0.080	1.500	–2.0
S2	1.50E-02	0.270	0.09	0.700	1.400	–1.0
S3	8.00E-02	0.265	0.075	0.500	1.200	–2.0
S4	6.50E-02	0.233	0.06	0.536	1.224	–1.0
Drainage layer	3.10E-01	0.330	0.08	1.150	1.470	–2.9

Wet-pack leach ore consolidation tests

Wet pack leach ore consolidation tests determine the critical VSC at which the ore structure collapses. This is identified by the solution content at which a sharp increase/decrease in the bulk density is observed. To reduce the potential for ore collapse, the leach ore VSC should be kept lower than the critical VSC during the ramp-up period. Figure 3 show the results of the wet pack consolidation tests at five solution contents and six estimated heap heights (0, 1, 1.5, 2, 4, and 6 m) for each of the samples.

With the exception of Sample S3, all samples showed increasing consolidation with solution content and increasing depth in the heap profile (Figure 3). Of note, the lowest and greatest consolidation were observed at the shallowest and deepest ore depths respectively, but for each specific ore, the critical VSCs were similar, regardless of ore depth. Samples S1 and S3 had critical VSCs of at least 0.22 cm^3/cm^3, except for S3 the critical VSC above 4 m depth was approximately 0.19 cm^3/cm^3. Samples S2 and S4 had critical VSCs of 0.20 and 0.19 cm^3/cm^3, respectively. At solution contents higher than the critical VSC, sample bulk densities decreased with the increasing solution content.

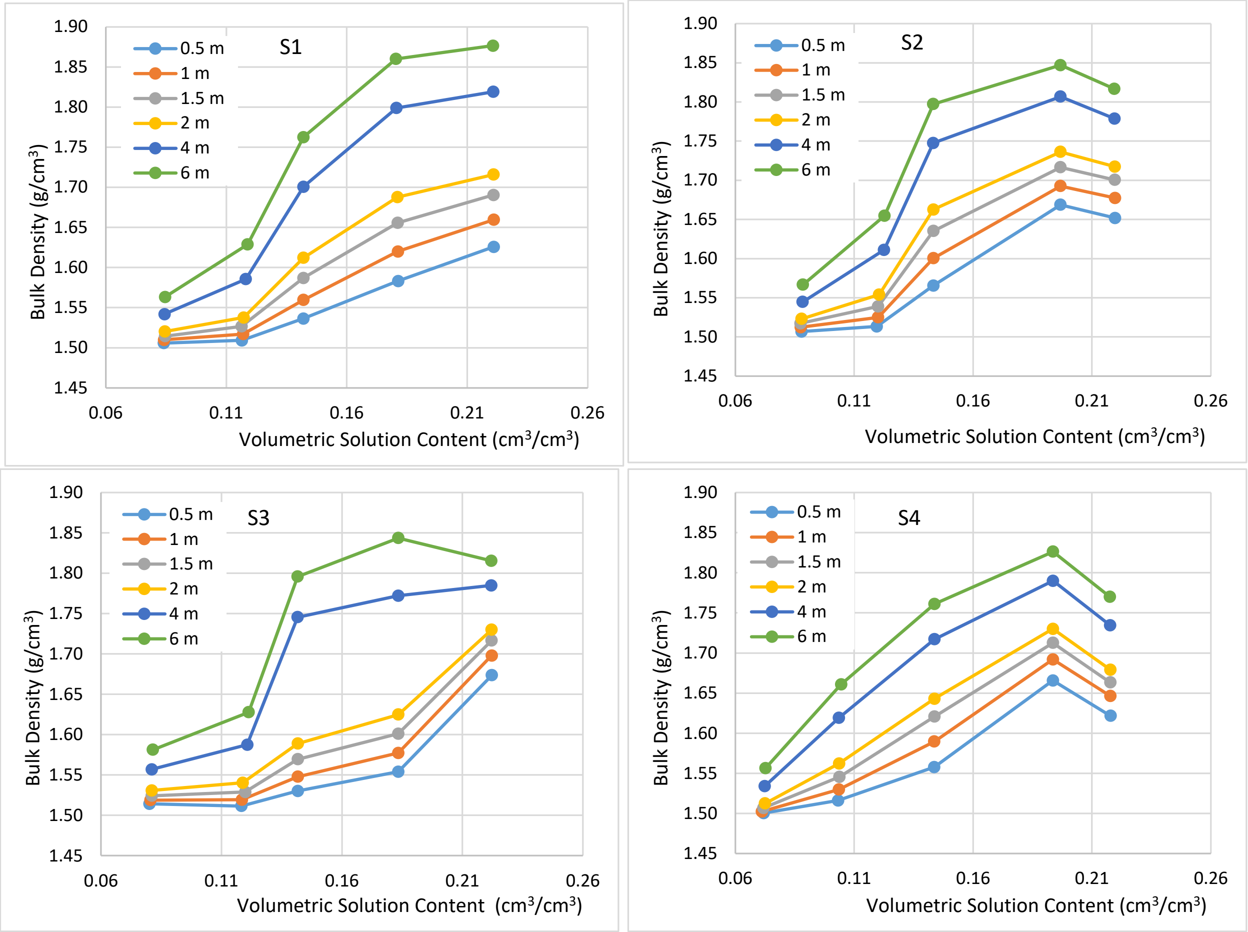

Figure 3: Solution content vs. dry bulk density at estimated depths within the heap

Numerical modeling results

The wet-pack consolidation results identified critical VSC values of 0.22, 0.20, 0.22, and 0.19 cm^3/cm^3 for samples S1, S2, S3, and S4, respectively. Unsaturated flow modeling results were interpreted by analyzing the predicted VSC distribution within 1 m of the surface to determine whether the irrigation ramp-up scheme exceeded critical VSC values for the leach ore being simulated. The time periods and corresponding cumulative irrigation at which the critical VSC is exceeded were identified for each simulated scheme and compared to determine the optimum irrigation ramp-up scheme(s).

Simulated VSC profiles from 0 to 3 m below the emitter after 18 cm of cumulative irrigation are shown in Figure 4. For the no ramp-up scheme, the critical VSC is exceeded to depths greater than 80 cm for all four ores. Schemes 1 to 3 generally show more similar wetting depth profiles to the no-ramp scheme. The Slow scheme and Scheme 4 were predicted to have lower VSCs throughout the profile than the other schemes and generally with lower VSC than the critical VSC below the depth of 20 to 50 cm; in addition, the depth of solution penetration is greater, indicating that these slower ramp-up schemes provide more uniform solution distribution throughout the profile. These solution distribution characteristics were maintained as cumulative irrigation increased (data not shown).

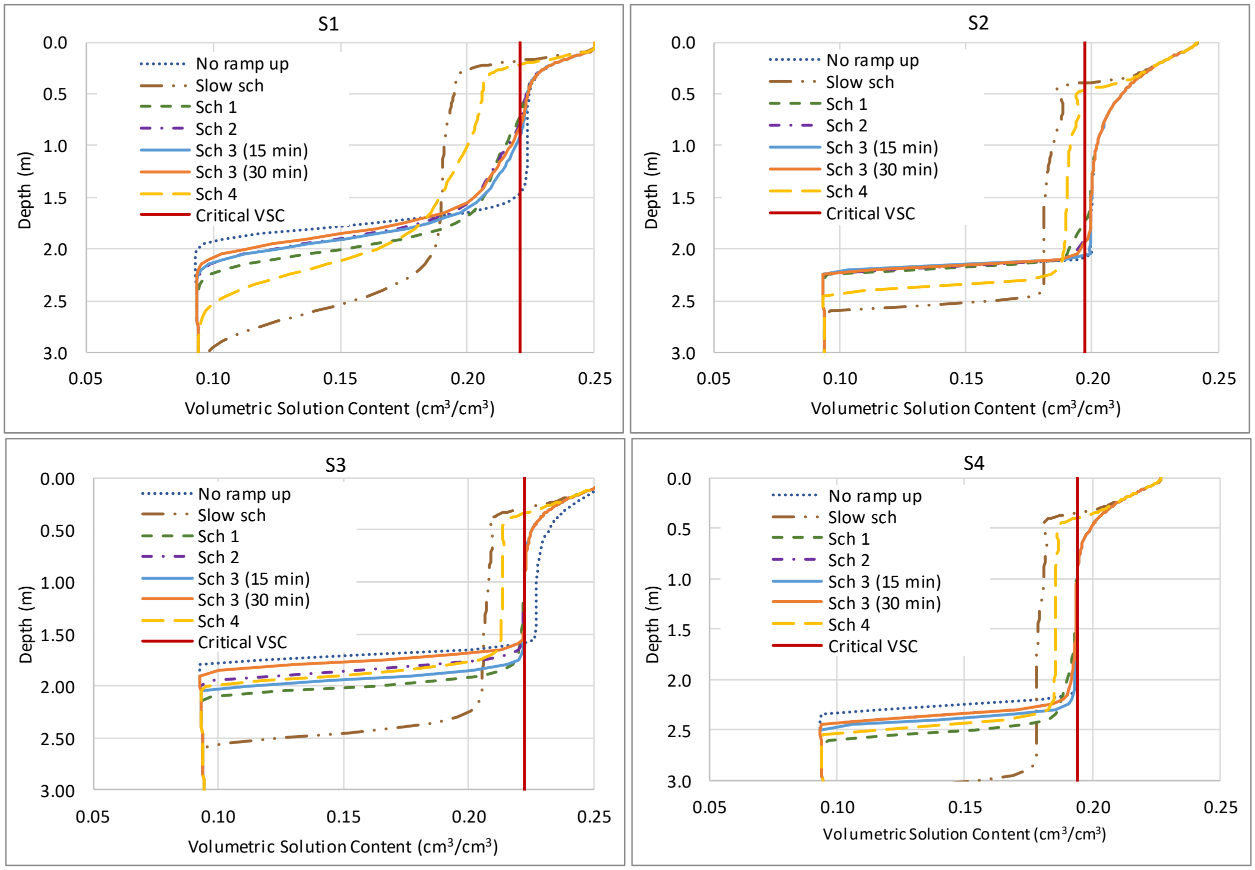

Figure 4: Model predicted solution content below the emitter at cumulative irrigation of 18 cm

The predicted horizontal distribution of VSC at depths of 15 cm and 30 cm bgs after cumulative irrigation of 10.2 cm are shown in Figure 5 for all four ores. The predicted VSCs are higher and less evenly distributed for the no ramp-up scheme compared to the ramp-up schemes. With the exception of S1, Scheme 2 showed lower and more evenly distributed horizontal VSC values at the 15 cm depth than all other model scenarios.

The no ramp-up scheme and Scheme 3b (30 min) showed the highest VSC horizontal values, whereas the Slow scheme and Scheme 4 showed intermediate predicted VSCs below the emitter and lowest horizontal VSC values. At 30 cm bgs, all schemes show more even lateral distribution than at 15 cm depth. The no ramp scheme and Scheme 3b (30 min) had the highest VSC and with the majority of the profile over the critical VSC. Schemes 1, 2, and 3a had the intermediate VSC with a much lower percentage profile over the critical VSC. Scheme 4 and the slow ramp-up scheme had the lowest VSC and most of the profile was lower than critical VSC.

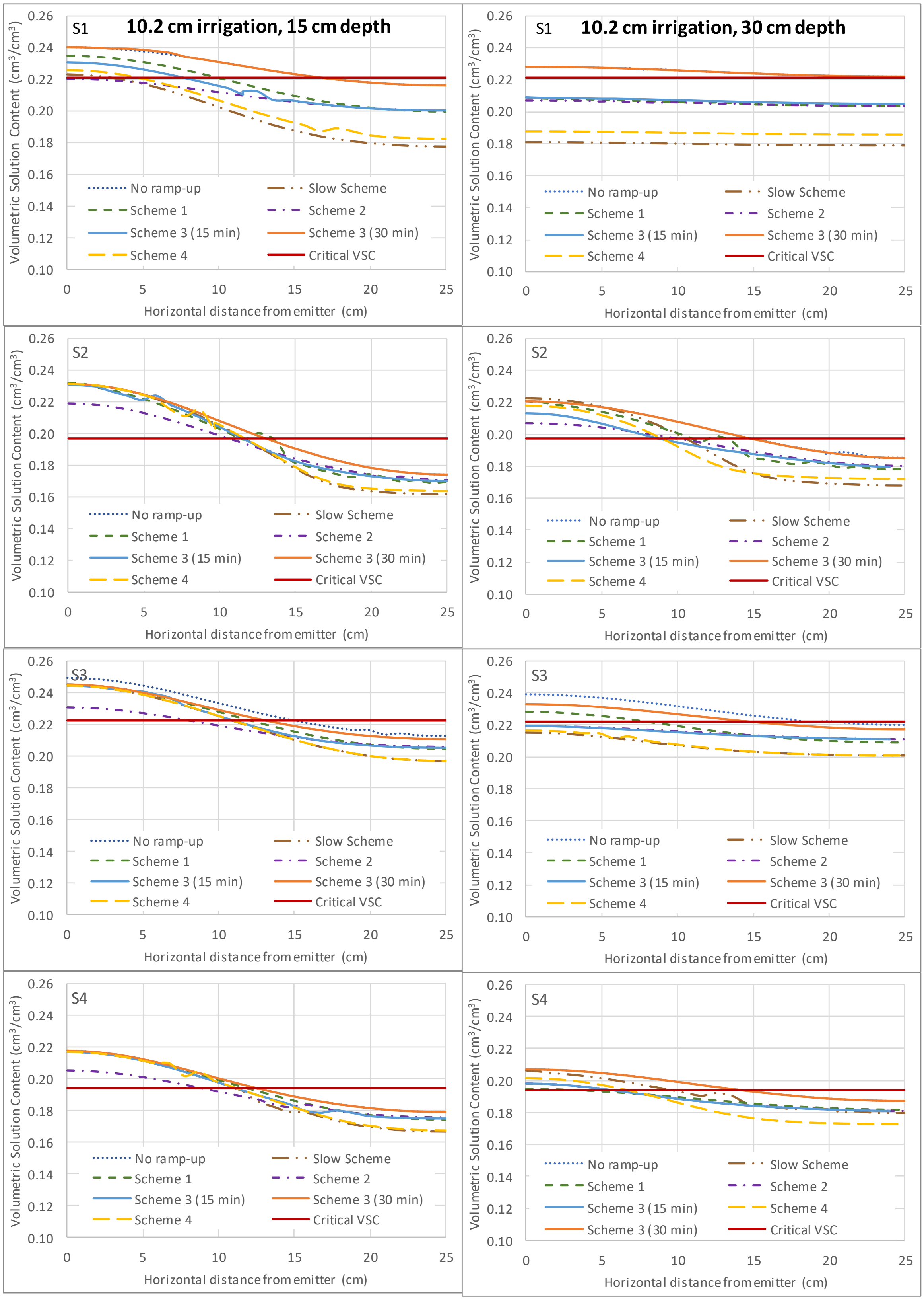

Figure 5: Predicted VSC horizontal profile for four ores at 10.2 cumulative irrigation at 15 cm (left) and 30 cm (right) depth

Overall, shorter on period cycles (Scheme 3b, 15 min) and/or lower irrigation rates (Scheme 2) could result in better redistribution of solution and less potential for ore collapse. Although Scheme 2 and Scheme 3b (15 min) could achieve an approximately 50% reduced ramp-up time than the Slow scheme, 15-minute on periods or lower irrigation rates may not be practical. Scheme 4 showed lower VSC values at the 15 and 30 cm depths and similar horizontal VSC distributions to the Slow scheme at later irrigation steps, indicating that similar leach ore wetting results could be achieved with Scheme 4 and a reduced ramp-up time (288 hours vs. 360 hours).

Conclusions

Hydrodynamic laboratory tests and wet pack collapse tests were performed on four copper leach ore samples, and unsaturated flow modeling was used to determine optimum irrigation ramp-up schedules that will minimize ore collapse at the surface, maximize solution distribution throughout the leach ore profile, and minimize leach ore wet up time.

The wet pack testing results indicate that VSC values exceeding 0.22, 0.20, 0.22, and 0.19 cm^3/cm^3 for ore samples S1, S2, S3, and S4, respectively, resulted in ore collapse and loss of agglomeration structure. These observed VSC critical thresholds were used to evaluate the unsaturated flow irrigation ramp-up models.

Unsaturated flow modeling results showed the predicted critical VSC directly below the emitter was exceeded from 0 to 1 m bgs for all four simulated ores for all but Scheme 4 and the slow ramp-up scheme. Model predicted VSC values from the slow ramp-up scheme and Scheme 4 were less than the critical VSC at depths of 20 to 50 cm bgs or greater for all ores.

Simulated VSC profiles from 0 to 1 m below the emitter at 10.2 cm of cumulative irrigation indicate that Schemes 1, 2, and 3 have similar wetting depth profiles. The sow ramp-up scheme and Scheme 4 were predicted to have lower VSCs below the emitter than the other schemes for all 4 ores at depths greater than 40 cm bgs. After 10.2 cm of irrigation, the no ramp-up scheme and Scheme 3b showed the highest VSC horizontal values, whereas the slow ramp-up scheme and Scheme 4 showed intermediate predicted VSCs below the emitter and lowest horizontal VSC values.

Simulated results for the slow ramp-up scheme and Scheme 4 were very similar. This indicates that similar leach ore wetting results could be achieved with Scheme 4 at a reduced ramp-up time (288 hours vs. 360 hours). The shorter but more frequent 15-minute on periods for Scheme 3a also resulted in lower VSC values below the emitter and a more uniform horizontal distribution, compared to Scheme 3b (30 minutes). Although Scheme 2 and Scheme 3a (15 min) could achieve an approximately 50% reduced ramp-up time, 15-minute on periods or lower irrigation rates may not be operationally feasible.

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