A METHOD TO ASSESS THE FEASIBILITY OF INJECTION LEACHING ON HEAP LEACH SLOPES

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Abstract

Injection leaching can improve leach ore recovery by displacing retained solutions, enhancing ore wetting, and creating new flow paths for efficient solution collection. This paper presents a method to assess the feasibility of injection leaching in finer-grained, potentially contractive ores (from a geotechnical slope stability perspective) using limit-equilibrium (LE) slope stability analysis and static deformation modeling. LE models were carried out by assigning peak undrained strengths to the heap leach ore material, and modeling the excess pore pressure induced during the injection leaching process using spatial function in Slope/W. Static deformation modeling was completed using the software Fast Lagrangian Analysis of Continua (FLAC) to evaluate the potential for deformations due to the excess pore pressures induced during the injection leaching process. A constitutive model was used to represent the geomechanical behavior of the leached ore material, which enables the prediction of deformation and potential stability issues resulting from excess pore-pressure induced during injection leaching process. The two-pronged approach provides a practical method to assess geotechnical impacts and guide data-driven decisions in injection leaching operations.

INTRODUCTION

The relatively lower cost associated with heap leaching makes it a cornerstone of modern mining, but the stability of large, unconsolidated, sometimes fine-grained ore piles rely on a delicate balance of hydrological, mechanical, and chemical factors. Injection leaching along or near heap leach slopes refers to introducing solution directly into the heap's interior—typically via wells to re-wet under-irrigated or low-permeability zones and to enhance metal recovery. Any practice that elevates the pore pressure in soil reduces available shear resistance. In low-permeability or segregated zones where drainage cannot keep pace, injections can rapidly increase pore pressures thereby triggering undrained behaviors. Materials susceptible to strength loss or brittle behavior under such loading conditions could exhibit strain softening, and, in rapid loading conditions, can undergo static liquefaction.

Instability in heap leach facilities is often associated with excess pore pressure, perched saturation, and inadequate drainage—conditions that may be exacerbated by injection if pressures/flows are not matched to the heap's hydraulic capacity. Heterogeneity, fines migration, and chemical precipitation can create low-permeability barriers that trap solution; operational factors such as aggressive stacking, variable permeability, and clogging of internal drains or liners can raise the phreatic surface. Preferential flow paths can result in uneven wetting and bypass substantial ore volumes (Shlomo 2002). Although modern designs favor thinner lifts with full drainage, the industry trend of re-leaching older, deeper heaps via injection reintroduces pore-pressure–induced failure risks. Recent and historical case histories underscore these mechanisms: at Victoria Gold's Eagle Mine HLF, an independent review board reported that a rising water table within low-permeability ore generated excessive pore pressures culminating in a deep, static liquefaction event and catastrophic flow slide (Govt. of Yukon 2024); at Bellavista, Costa Rica (USGS 2009), heavy rainfall led to saturation and a landslide under a waste rock stockpile and adjacent heap leach pad, highlighting vulnerability to fluid loading and at Codelco's Chuquicamata (Ghorbani, Y et. al. 2015), inadequate basal drainage and poor ore consolidation contributed to saturation and slope failure. While injections were not identified as the trigger in these examples, the failures illustrate how localized high pore pressure and constrained drainage conditions can undermine heap stability.

During work led by Knight Piésold and Co. at a confidential heap leach facility, a localized, and thankfully, inconsequential slope failure was documented. The event was driven by the same mechanisms that injection can also trigger if not controlled (i.e., rapid pore-pressure build-up in low-permeability zones, undrained response, and potentially strength loss in contractive leach ore at or near saturation). Field signs included new seeps on benches and small face sloughs. Loose soils—such as uncompacted sands and normally consolidated silts and clays—tend to deform in a ductile manner under drained or unsaturated loading, but under undrained loading they can develop high excess pore pressures, lose effective stress, and fail in a brittle manner with a large drop in strength. The leached ore at the facility is run-of-mine (ROM) leach ore, which classifies as gravel with varying sand, clay and silt contents and fines content ranging from 5% to approximately 50% with an average fines content of 27%. The findings from cone penetration tests (CPT), resistivity, and Nuclear Magnetic Resonance (NMR) tests indicate the leach ore is at or near saturation, contractive and susceptible to undrained strength loss at large strains. Laboratory undrained shear tests confirmed low peak undrained strength ratios, strain softening toward steady state, and failure surfaces coinciding with fines-rich lenses. Currently, an injection leaching program is being evaluated at the same site to assess feasibility and safety before any large production level application. The feasibility framework includes stability analyses using total-stress (undrained) LE and static deformation analyses to reflect the response during active injection.

The geotechnical evaluations associated with a pilot program and field observations, together with gaps in published guidance on managing injection leaching specifically on heap slopes, and lessons learned from past bench scale slope failures, motivated this paper. To protect confidentiality, the study presented here is anonymized. The modeling framework, governing concepts, and analytical workflow used to define the problem, implement the models, generate predictions, and interpret stability outcomes are identical to those applied in practice. However, select identifying details—such as overall geometry, stratigraphic thicknesses, injection layout and rates, and certain hydraulic and strength parameters—have been adjusted within realistic, literature-supported ranges. These modifications were made both to avoid disclosure of proprietary information and to broaden sensitivity testing, to further corroborate the methodology. The adjustments do not alter the underlying physics, the modeling logic, or the conclusions, and no client- or site-specific identifiers are reported.

The objective of this study is to develop and demonstrate the efficiency of a framework for assessing the feasibility of injection leaching in heap leach pads, from a geotechnical slope-stability perspective, by LE slope stability analysis with continuum-based static deformation modeling. In the LE component (Seequent 2024), a constant peak undrained shear strength ratio is assigned to the heap-leach ore using SHANSEP (Ladd, CC. et. al. 1974) model and injection-induced excess pore pressures are represented via spatial pressure-head functions. In the static deformation component evaluated using FLAC, the leached ore is modeled using the PM4Silt constitutive model (Boulanger, R. W et. al. 2022) with coupled fluid-mechanical calculation turned on, enabling realistic representation of stress–strain development and pore-pressure response under monotonic loading and evaluation of deformations driven by the same excess pore-pressure fields. PM4Silt was selected for static deformation modeling because it is an effective stress critical state compatible plasticity model that can be calibrated directly to undrained shear strength. It reproduces shear-induced excess pore-pressure and strain-softening in silts and clays subject to undrained monotonic loading. In contrast, a simple Mohr–Coulomb model, even with dilation, uses constant strength parameters and cannot generate state-dependent pore pressures or the peak-to-steady (critical) strength drop that governs instability in contractive leach ore. Nonetheless, Mohr–Coulomb with SHANSEP has been used in LE analyses using undrained strength ratios since LE assessments are not triggering assessments. Alternative critical-state models such as NorSand and CASM can represent state dependence, but they require relatively rigorous calibration of numerous parameters (e.g., full critical-state line, state parameter mapping, hardening/softening laws) from extensive high-quality lab and/or CPT data, which are often not readily available. PM4Silt offers a balanced approach: it embeds the necessary physics to simulate contractive behavior, shear induced pore-pressure generation, and strain softening to a steady/critical state, yet relies on a tractable set of parameters. The constitutive model has been effectively implemented in FLAC, supporting stable analyses across multiple scenarios. Prior Knight Piésold applications have demonstrated that PM4Silt adequately reproduces undrained, monotonic responses in excavation modeling, providing additional confidence in its suitability for injection-related assessments where similar undrained behavior and failure mechanisms are anticipated.

By integrating factors of safety with predicted displacement patterns and potential failure mechanisms—and by explicitly accounting for the magnitude and spatial distribution of injection-induced pressures—the framework provides a practical, two-pronged tool to evaluate geotechnical implications of injection leaching and to support data-driven operational decisions.

MODEL SETUP

A simplified cross-section was built for this study using engineering judgement and experience with similar projects. The inter-bench slope of the heap leach pad is approximately 2.5H:1.0V and has an overall slope of 3.2H:1.0V with an approximate pad height of 155 m as shown in Figure 1 below. Injection wells are set up to be advanced up to a depth that remains 15-meters above the underlying liner system for each drilled well. Other controls include, but are not limited to, maintenance of minimum offset distances from the ground surface and adjacent heap slope, and prohibitions on injecting adjacent wells without adequate time for drain down.

The wells are perforated over a 1.5-meter interval every 6.0-meters. Starting from the bottom of the well, each perforated interval is isolated with a straddle packer, and barren solution from the gold mill is introduced under pressure generally until a target volume has been delivered over a period of about 8 hours. To prevent hydro-fracturing of the ore, injection pressures are limited such that they do not exceed the vertical confining stress at the interval under pressure. The field observations completed with downhole resistivity at the site indicated that these injection wells formed a pore-pressure bulb of approximately 35-meter diameter, which rapidly dissipates after cessation of injection leaching at the well. These control measures and findings from field observations formed the basis of modeling presented herein albeit these measures could vary from site to site and thus should be investigated and implemented accordingly.

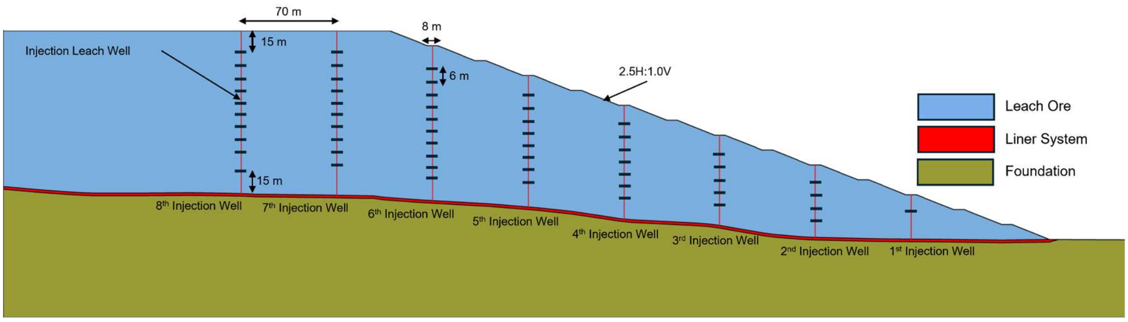

Figure 1: Model Setup and Slope Configuration

MODELING FRAMEWORK

LE slope stability analyses were completed in SLOPE/W using the Spencer (Spencer 1967) method to compute FoS for undrained loading conditions, with leach ore represented by constant peak undrained shear strength ratios using SHANSEP framework. To simulate the expected pore pressure conditions during active injection leaching, spatial functions were utilized to model the variation of injection-induced pore pressure in terms of pressure head. The spatial function defined pore pressure conditions at discrete points by employing Krigging techniques (Seequent 2024) to generate a smooth surface that interpolates through the specified data points. Using this surface, pore pressure values can be estimated at any other location within the vicinity of the defined data points. The pore pressures induced by injection leaching at a specific point within a well were implemented into the models based on the depth of the injection point relative to the top free surface of the leach ore and targets defined based on control measures. Sensitivity analyses considered slightly elevated pore-pressure, but these were capped at the total vertical stress at the location. Each calculated pressure was then distributed around the injection point using the spatial function to represent the pore pressure head variation within the leach ore due to the injection leaching. Based on estimated pressure bulb distributions, the pore pressures were distributed within a diameter of 35 m for each injection point considered.

Static deformation analyses were performed in FLAC v8.1 (Itasca. 2017) using the PM4Silt model to capture contractive undrained response, potential post-peak softening and strain localization. Meshes were developed using scripts provided by ZG-Geo (ZG-Geo Ltd. 2022) under an MIT license. The method used avoids triangular zones to improve numerical stability and run time. However, this method produces jagged exterior slopes, for which a small nominal cohesion was applied at outer zones to prevent numerical issues. Bottom boundaries were fixed, and side boundaries were roller supported, with boundaries placed far from the area of interest. The existing pore pressure within the leach ore were assumed to be sufficiently small such that it was not needed to implement positive pore pressures because the measured pore pressures were not large enough to materially impact effective stress; however, the pore pressures induced by the injection leaching at each defined injection location was implemented in the model by applying the calculated target pore pressures on the nodes of the identified zone, manually. The pressure to be applied was calculated based on the target pressure with respect to depth from the free surface based on injection leaching control specifications. For pore-pressure sensitivity models, these applied target pore-pressures were increased such that these were still less than total stress at the location to prevent hydraulic fracturing. Finally, the leach ore zones were assumed to be fully saturated during the computation. These static deformation models were completed using coupled fluid-mechanical calculation approach in FLAC. As such the leach ore was assigned a typical permeability value to facilitate the fluid flow.

A series of analyses were conducted in both LE and FLAC. First, LE analyses were conducted on selected well locations and depths under baseline injection conditions, applying spatially distributed pore-pressure loads to compute the FoS. Next, the critical configurations resulting from LE modeling were carried into FLAC for the static deformation modeling. The base case analyses are as follows:

LE base case

The LE base case used a peak undrained strength ratio of 0.35 for leach ore and applied normal target injection heads as 35 m–diameter pressure bulbs around each injection point at each well. The pressures were limited to avoid hydraulic fracturing.

FLAC base case

The FLAC base case modeled the LE-identified critical configurations under the same baseline heads, treating leach ore as fully saturated. PM4Silt was calibrated to produce a peak undrained strength ratio near 0.35 with softening toward ~0.25 under monotonic shear at larger strains. Outputs focused on displacement, pore-pressure buildup, and shear-strain concentration.

LE and FLAC sensitivity analyses

LE sensitivities were carried out by:

1) Reducing peak undrained strength ratio to 0.30
2) Varying pore pressure to elevated pore pressure case, and
3) Activating single injection points at multiple wells simultaneously along the section.

FLAC sensitivities mirrored LE analyses by:

1) Adjusting PM4Silt inputs to achieve a more contractive response,
2) Running elevated pore pressure and no pore pressure cases on the critical configuration, and
3) Modeling single injection points at multiple wells simultaneously along the section.

MATERIAL PROPERTIES AND CALIBRATION

Material properties were assumed based on field data, laboratory testing, engineering judgment and experience with similar projects and are tabulated below. The values listed inside parentheses that assume weaker leach ore behavior were used during sensitivity analyses. Tables 1 shows the material properties adopted for the numerical modeling for leach ore, liner system, and foundation and Table 2 shows the interface strength of the liner system.

Table 1: Material Properties used for numerical modeling

Property	Values		
	Leach Ore	Liner System	Foundation

Dry Density γ_{dry} (kg/m^3)	1857	1704	2345
Porosity (n)	0.29	0.31	0.01
Total Unit Weight γ_t (kN/m^3)	21.1	18.7	-
Effective Stress Friction Angle Φ'	41	Non-Linear	-
Peak Undrained Strength Ratio $(S_u/p')_{peak}$	0.35 (0.3)	-	-
Residual Undrained Strength Ratio $(Su/p')_{residual}$	0.25 (0.2)	-	-
Poisson Ratio ν	0.26	0.25	0.24
Large Strain Shear Modulus G_{max} @1atm (Pa)	9.00E+05	6.00E+06	-
Large Strain Bulk Modulus B @1atm (Pa)	1.54E+06	1.00E+07	-
Small Strain Shear Modulus Coefficient $K_{2,max}$	126	-	-
Small Strain Shear Modulus G_{max} @1atm (Pa)	2.81E+08	6.00E+07	1.35E+09
Small Strain Bulk Modulus B @1atm (Pa)	4.82E+08	1.00E+08	2.35E+09
Hydraulic Conductivity k_{sat} (cm/sec)	1.57E-02	-	-

Note: The values in the parenthesis are the material parameters for the reduced strength leach ore.

Table 2: Liner system interface strength values

Liner System		
Normal Stress (kPa)	Shear Stress (kPa)	Secant Friction Angle (deg)
0	0	--
200	140	35.1
400	234	30.3
600	315	27.7
1,400	588	22.8
2,800	979	19.3
3,000	1,029	18.9

PM4Silt Calibration

The PM4Silt constitutive model was utilized to capture the potential for undrained behavior within the loose-dumped leach ore upon application of the target pore-pressures during the injection leaching process. This constitutive model was selected due to its ability to exhibit undrained behavior within an effective stress framework and because of the ability to easily input the desired undrained strength ratio directly into the model. The calibration was performed by using the PM4Silt calibration files provided on the Itasca website and running single element simulations of DSS tests in FLAC with parameters calibrated at an effective confining stress of 1 atmosphere.

Relevant parameters of the PM4Silt constitutive model are presented in Table 3 with corresponding calibrated parameters for the leach ore material.

Table 3: PM4Silt model parameters

PM4Silt Parameter	**Description**	**Calibrated PM4Silt Parameters**
$S_{u,cs}/\sigma'_{vc}$	Undrained strength ratio at critical state	0.25 (0.20)
G_o	Shear modulus coefficient	165

h_{po}	Contraction rate parameter	6.0
$n_{b\text{-}wet}$	Bounding surface parameter	0.20 (0.35)
A_{do}	Dilatancy parameter	0.8
φ'_{cv}	Critical state friction angle	38.4

Note: The values in the parenthesis are the calibrated parameters for the reduced strength leach ore.

Figure 2 presents the results of the calibrated PM4Silt model to the peak and residual strengths of 0.35 and 0.25, respectively, at an effective confining stress of 100 kPa and Figure 3 presents the results of the calibrated PM4Silt model to the peak and residual strengths of 0.30 and 0.20 for the same confining stress.

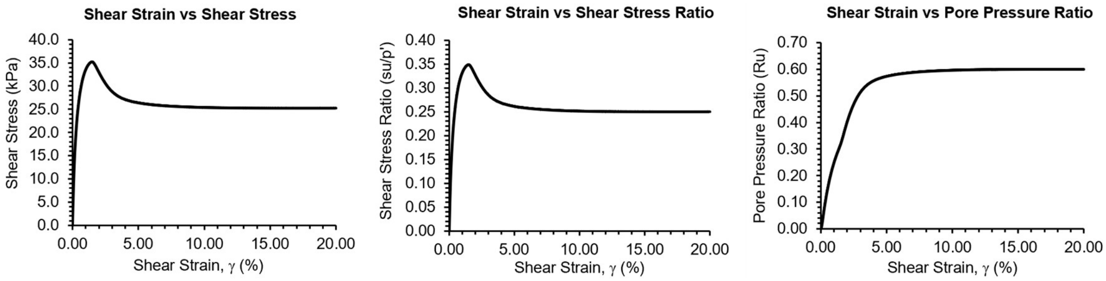

Figure 2: PM4Silt Calibration - Leach Ore - Peak Undrained (σ'_v = 100 kPa)

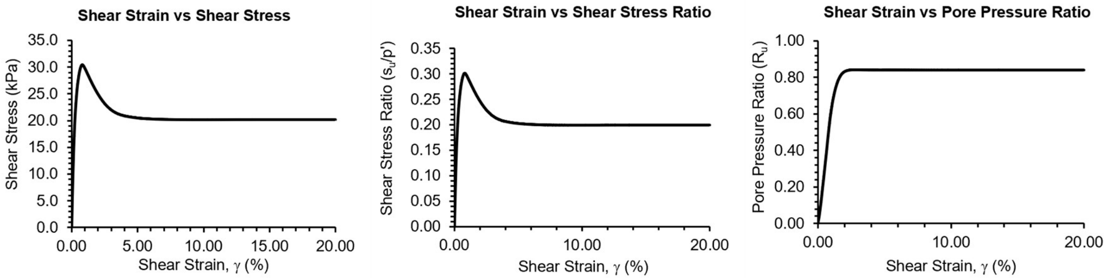

Figure 3: PM4Silt Calibration - Leach Ore Reduced Strength- Peak Undrained ($\sigma'v$ = 100 kPa)

RESULTS

LE Base Case

As shown in Figure 1 in the model setup, eight wells were included in the analysis. For each of the eight wells, multiple injection points were selected in accordance with the criteria outlined in the model setup. Without injection leaching, the LE analysis result indicates a FoS of 1.25. With injection leaching, LE base-case results indicate minimum FoS values between 1.18 and 1.25 across all injection wells and depths. The lowest FoS occurs at Injection Well 5 at 21 m (FoS 1.18), followed by Injection Well 4 at 21 m (FoS 1.19) and several shallow cases (15–21 m) at Injection Wells 3 and 4 (FoS ≈ 1.20). Stability generally improves with increasing injection depth and toward Injection Wells 6 through 8, where FoS values are consistently 1.25 for all depths evaluated as shown in Figure 4. Injection Wells 1 and 2 return intermediate values of about 1.21 and1.23. These results indicate that shallow injections and injections beneath the sloping face are more likely to result in larger reduction in FoS and thus could result in localized heap failures than injections that are fairly deep-seated and/or away from the downstream slope. This is because the combination of free-boundary kinematics and downslope seepage forces make shallow injections produce larger and faster slope movements than deep-seated injections. The results also indicate that FoS values tend to reduce by lower amount for injection wells near the toe and the reductions become significant for injections that approach the area near the mid-slope. Finally, the FoS has only marginally reduced for injection point beneath the slope near the crest and has remained unchanged from pre-injection values for wells sufficiently behind the crest. This is because the driving shear stresses are larger near the mid-slope versus locations near the toe or sufficiently behind the crest.

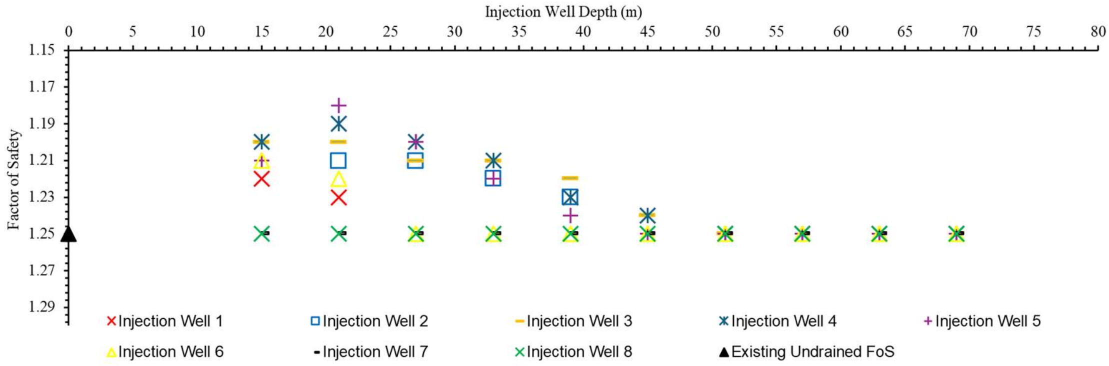

Figure 4: Variation of FoS for each well with injection well depth for Base Case.

FLAC Base Case

Three configurations for the base case were analyzed for static deformation modeling—near the crest, mid-slope, and near the toe as shown in Figure 5—to evaluate deformations (shown in Figure 7) and to capture the pore-pressure (shown in Figure 6) response.

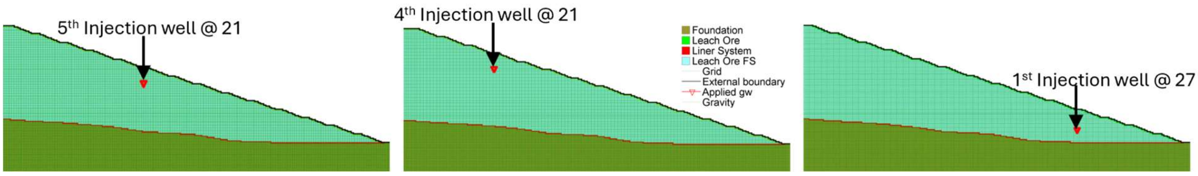

Figure 5: Model setup for base case

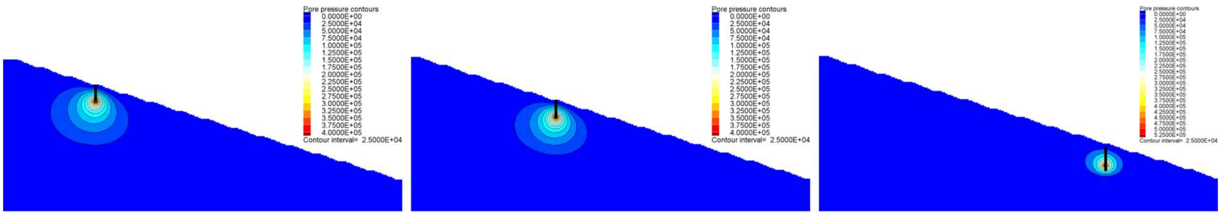

Figure 6: Pore pressure contours for base case (in Pascals)

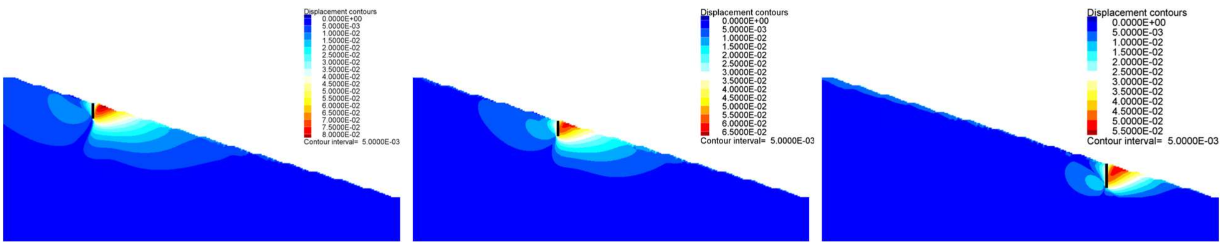

Figure 7: Total displacement contours for base case (in meters)

Near-crest and mid-slope injections reached the target excess pore pressure (about 40 kPa) and produced identical maximum deformations of approximately 8 cm. The LE results at these locations predicted FoS values of 1.18 and 1.19, respectively. This indicates that reducing effective stress high on the slope triggers larger outward movements and lower stability due to the reasons discussed previously. In contrast, the toe injection generated a higher excess pore pressure (≈50 kPa) yet produced smaller deformation (≈5.5 cm) and a slightly higher FoS (1.22). This response indicates that combination of driving shear stresses, free-field kinematics, and seepage force effects govern stability and deformation during injection leaching. The shallower injection locations therefore result in larger movement versus deep-seated ones because the resulting effects from these sources are more adverse near the sloping free face as opposed to deep-seated locations.

LE Sensitivity Cases

Reducing peak undrained strength ratio to 0.30 case

For this case, the minimum FoS values reduced to ranges from 1.01 to 1.07 across identical wells and injection depths analyzed during base case modeling. The governing condition occurs at Well 5 at 21 m depth (FoS = 1.01), closely followed by Well 4 at 21 m (FoS = 1.02). Shallow to mid-depth injections (15–27 m) are consistently the most critical, returning FoS values of about 1.01–1.04. A mild depth dependence is evident: FoS values generally increase with depth and plateau at approximately 1.07 for injections at depths ≥39 m depth. Wells 7 and 8 are the least sensitive to injection with reduced strengths, remaining at a FoS of 1.07 for all modeled depths. These predicted FoS values are lower but still adhere to the trends established during base case modeling.

Varying pore pressure to elevated pore pressure cases on the critical configuration

Elevated pore pressure sensitivity was applied to the lowest FoS LE base configuration by increasing the baseline injection pore pressures by 20%. This increase was selected to keep effective stresses positive around the injectors and below hydraulic-fracture limits. The controlling configuration, Injection Well 5 at 21 m depth, was evaluated under both strength assumptions. The resulting FoS were 1.15 for the base undrained strength ratio case and 0.99 for the reduced undrained strength ratio case, indicating a marginal condition in the former and near-failure in the latter.

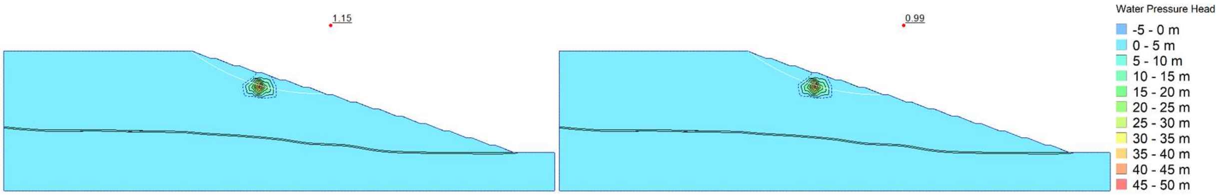

Figure 8: Base strength and reduced strength critical configuration with elevated head

Activating single injection points at multiple wells simultaneously

Simultaneous injections at multiple wells were assessed by activating single injection points at three wells located near the mid-slope sufficiently spaced from each other based on typical control specifications. Under baseline pore-pressure loading, the FoS decreased to 1.10 for the base strength case and to 0.93 for the reduced strength case, indicating a marginal to unstable condition as the pressure bulbs form simultaneously across the slope. When the same configuration was evaluated with a 20% increase in pore pressure, the FoS further declined to 1.07 (base strength) and 0.91 (reduced strength).

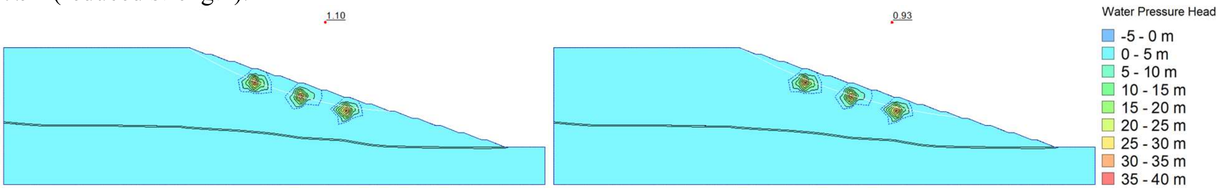

Figure 9: Single injection at multiple wells for base strength and reduced strength for base pore pressure case

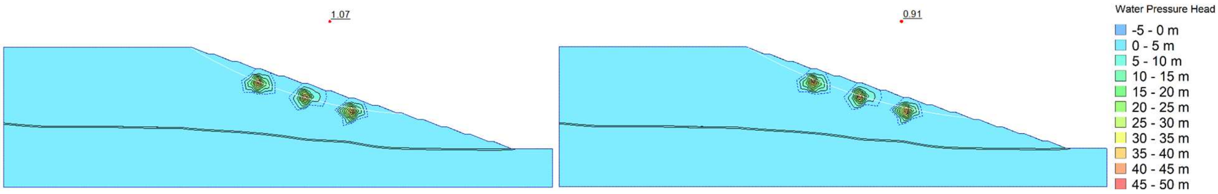

Figure 10: Single injection at multiple wells for base strength and reduced strength for elevated head case

FLAC Sensitivity Cases

Adjusting PM4Silt to a more contractive (brittle) response

The PM4Silt model was recalibrated to the leach ore peak to residual undrained strength values of 0.30 to 0.20 as described in PM4Silt calibration section and identical well configurations utilized during the base case analyses were evaluated with the reduced strength calibration to understand the resulting response. The results show a similar pore pressure response and higher deformations as compared to the base case FLAC results.

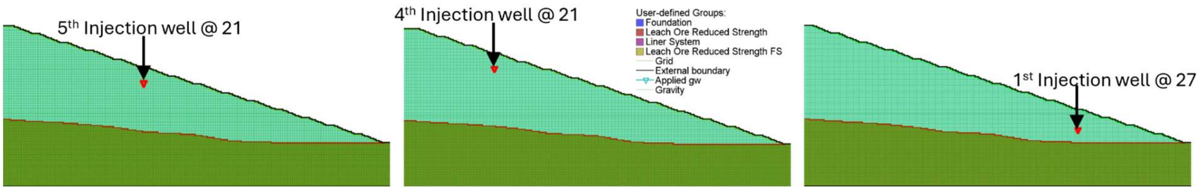

Figure 11: Model setup for reduced strength case

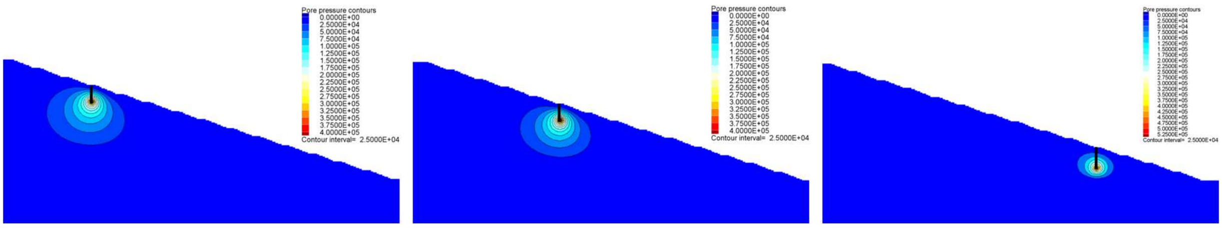

Figure 12: Pore pressure contours for reduced strength case (in Pascals)

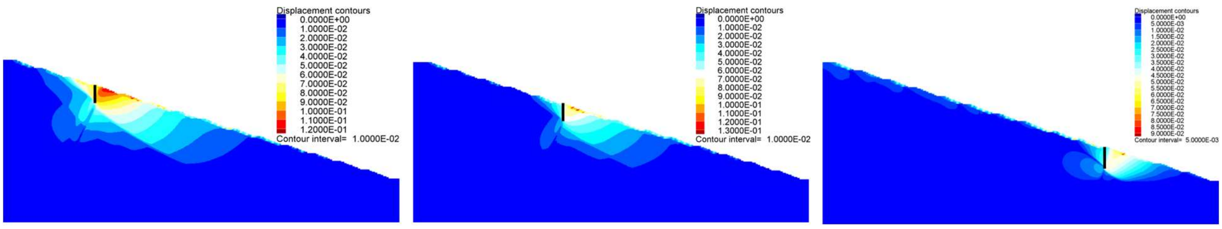

Figure 13: Total displacement contours for reduced strength case (in Pascals)

Under baseline heads, FLAC shows relatively larger displacement with the reduced-strength calibration (PM4Silt 0.30→0.20) consistent with the lower FoS trends. For the controlling configuration (Well 5 @ 21 m), maximum total displacement increases from 8 cm (base case, PM4Silt 0.35→0.25) to 12 cm (+50%), supporting the LE FoS drop from 1.18 to 1.01. At Well 4 @ 21 m, total displacement rises from 8 to 13 cm (+63%) as the LE FoS decreases from 1.19 to 1.02. For Well 1 @ 27 m, total displacement increases from 5.5 to 9 cm (+64%). Overall, the magnitude of displacement increases track with the LE FoS reduction: configurations with the FoS approaching unity (1.0) exhibit the largest movements, whereas mildly reduced FoS cases show smaller deformations.

Elevated pore pressure and no pore pressure cases on the critical configuration

Two bounding cases were evaluated for the critical configuration (Injection Well 5 @ 21 m). In the no-added-pore-pressure case, FLAC predicted negligible movements, confirming that injection-induced pore pressure is the dominant driver of the static deformation. In the elevated pore pressure case (i.e., 20% increase in applied pore-pressure), LE indicated near failure stability for the reduced-strength material (FoS 0.99), and the companion FLAC model produced a maximum total displacement of 20 cm—an increase of about 67% relative to the reduced-strength baseline-head result (12 cm) and about 150% relative to the base-strength baseline-head result (8 cm). Elevated heads applied to the base-strength material also increased displacements compared to baseline heads, consistent with the LE trend of reduced margin (FoS of 1.15 from 1.18). Overall, the results indicate that the magnitude of deformation increases as the FoS is reduced and the rate of increase in the magnitude of deformation increases as the FoS approaches to near-failure (FoS ~ 1.0) value.

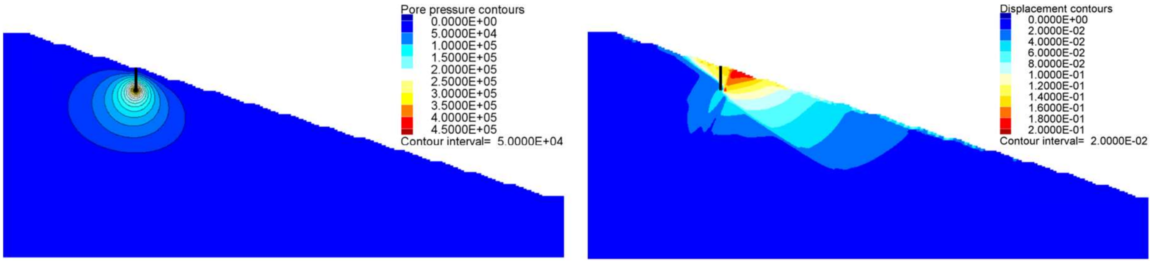

Figure 14: Total displacement and Pore pressure contours for elevated pore pressure case for reduced strength

Modeling single injection points at multiple wells simultaneously

Simultaneous single-point injections at multiple-wells along the section were modeled in FLAC as a companion to the LE multiple-well setup. Under baseline heads and base-strength properties, FLAC predicted substantially larger deformations than the single-well case, consistent with the significantly reduced FoS for the multi-well scenario (FoS value of 1.10 versus the mildly reduced FoS for single-well operation). For the reduced-strength condition, deformations increased further, validating the LE FoS of 0.93, which indicates a near-unstable condition. When the same multi-well configuration was run with elevated pore pressure (i.e., 20% increase in applied pore-pressure), LE yielded a FoS of 0.91 (Figure 10) and the FLAC model predicted very large displacements consistent with the failure shown in Figure 16. These outcomes reflect additive pressure-bulb effects under concurrent injections and highlight the heightened risk of instability and large deformations under simultaneous well operation along a given slope.

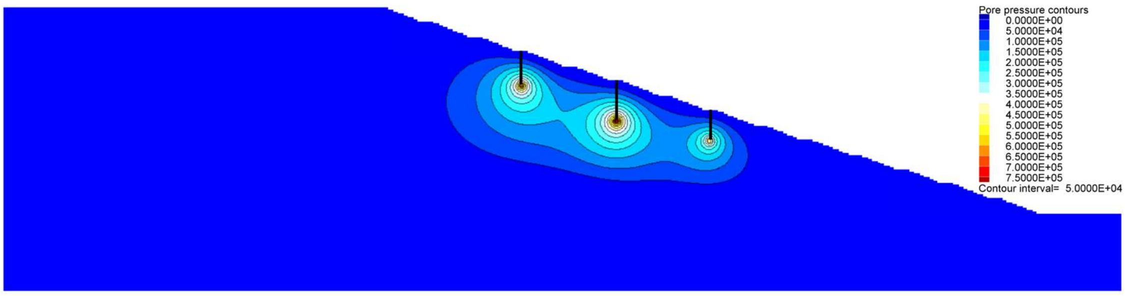

Figure 15: Pore pressure contours (in Pascals) for single injection at multiple wells for reduced strength for elevated pore pressure case

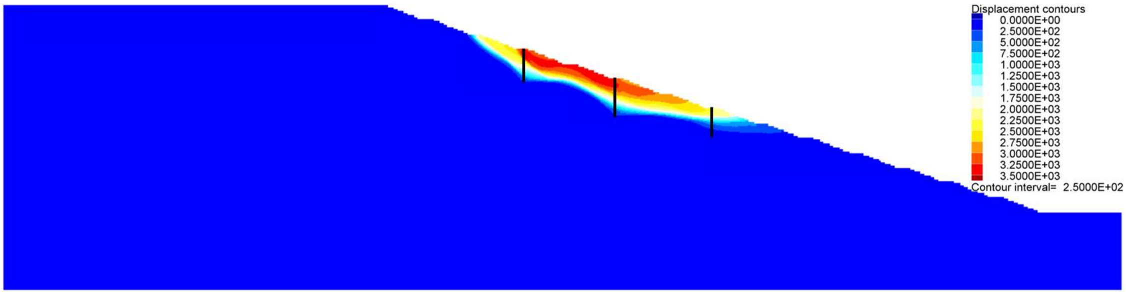

Figure 16: Total displacement contours (in meters) for single injection at multiple wells for reduced strength for elevated pore pressure case

CONCLUSION

This study implements a two-pronged approach that combines LE stability screening with FLAC static deformation modeling providing a practical and reliable method to assess the feasibility of injection leaching near slopes in finer-grained contractive leach ore. LE analysis facilitates rapid assessment of numerous injection configurations, predicts FoS values, and clearly ranks the risk. In this study, LE results identified shallow, near-face injections as most critical (for example, a shallow injection location near the mid-slope at Injection Well 5 at a depth of 21 m, which reduced to a FoS of 1.18 from a FoS of 1.25 in the base case). The results also illustrate that injections at locations with reduced available driving shear stress (i.e., near the toe, sufficiently behind the sloping free face) and/or in areas under greater confinement (i.e, at larger depths) only mildly reduce the FoS from the pre-injection level of 1.25. These LE analyses also captured the effect of reduced strength (lowering the critical FoS to 1.01-1.07) and elevated pore-pressures (further lowering the FoS to less than unity (1.0) in some cases), warranting tighter controls and/or deferral for configurations with significantly reduced FoS values that approach unity or the selected minimum required value based on acceptable risk.

FLAC modeling with PM4Silt complements LE by predicting deformations and shear induced pore pressure generation due to the onset of injection leaching. PM4Silt was chosen because it can approximate shear induced pore-pressures and contractive softening and is an effective stress model founded in critical state soil mechanics. In addition, the PM4Silt calibration process is more tractable, and the implementation is relatively straightforward, such that a user can implement the sought undrained behavior by specifying critical state undrained strength ratio. The deformation patterns aligned with the LE rankings, providing cross-validation: where LE FoS values decreased, FLAC displacements increased. For the controlling configuration (Well 5 @ 21 m), the base-strength case produced about 8 cm of maximum total displacement, while the reduced-strength calibration (PM4Silt 0.30→0.20) increased displacement to 12–13 cm, consistent with the FoS drop from 1.18 to 1.01–1.02. At a deeper location (e.g., Well 1 @ 27 m), displacements were smaller in the base case model (≈5.5 cm) and increased moderately under reduced strengths (≈9 cm), mirroring a higher FoS in LE. Multiple well configurations further demonstrated the approach's viability: concurrent injections produced additive pore-pressure effects, significantly reduced the LE FoS value (FoS ≈ 1.10 base strength; 0.93 reduced strength), and noticeably increased FLAC deformations more so than single-well cases.

Together, LE and FLAC with PM4Silt offer a coherent process to assess the feasibility of injection leaching with the use of LE to map safe operating envelopes (preferred depths and setbacks, allowable pore-pressure loading, and identification of critical configurations), coupled with the use of FLAC to confirm deformation acceptability. The combined results indicate that injection leaching feasibility improves with greater setback from the slope face, deeper targets, and single-well or staggered operation; feasibility decreases as undrained strength drops, multiple wells inject simultaneously, or pore-pressures rise. The method is readily transferable to other sites and can be updated appropriately to the desired undrained strengths and pore-pressure fields. It provides a balanced level of physics and practicality for safely pursuing injection leaching for enhanced metal recovery while maintaining geotechnical stability on heap leach slopes.

FUTURE WORK AND RECOMMENDATIONS

Based on the study completed herein, the future work and recommendations are listed below:

- One of the limitations of this work is the study ignores the 3-dimensional (3D) aspect of the injection leaching albeit a 2-dimensional representation of the problem is more conservative. Future work can be extended by assessing 3D hydro-mechanical models so that pressure-bulb shape, well spacing/interaction, benches and corners, and lateral drainage are represented more realistically. Pursuing such work may pose a challenge related to the availability of constitutive models that can simulate the desired behavior while being 3D compatible.
- A future comparative study can be performed using other state-dependent constitutive models such as NorSand, Clay and Soil Model (CASM) and/or other stress-strain sensitive models. Since controlled injection leaching exerts a loading condition that is localized, the effects of stress-strain behavior cannot be verified as effectively as desired. As such, a comparative study using other constitutive models could be beneficial for added confidence in the modeled results.
- Additional improvements could include targeted calibrations through step-injection/hold tests and piezometer time histories, expanded undrained monotonic lab testing to define peak-to-steady-state strength for key ore states and interfaces, and refinement of drain/liner conductance in the seepage model.

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