

# Geo-mechanical and flow modeling for Paradox Valley Unit

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## 1 INTRODUCTION

The Paradox Valley Unit (PVU) is a water salinity control facility located along the banks of the Dolores river in the Colorado River basin. The Dolores runs across the valley instead of along it, giving the Paradox Valley its name. The valley was formed over geological times by the collapse of a salt fold present in the stratigraphy. The Paradox Valley facility uses shallow extraction wells to intercept saline groundwater (brine) before it discharges to the Dolores River. The brine is processed and reinjected in a deep well for disposal. The injection target is the Leadville formation located, more than 2.5 miles deep, below the Paradox Salt formation which serves as containment. The PVU has been operated by the United States Bureau of Reclamation for more than 25 years. Under normal operation, the PVU injects about 7.5 million gallons of brine per month, or about 95,000 tons of salt per year. The PVU is encountering serious challenges in the form of seismic activity caused by fluid injection into the underlying formation, and of a progressive increase in wellhead injection pressure towards the maximum allowed value to prevent formation damage (King et al. 2014). Operational changes, including shut down periods, and reduction of injection rate have addressed the challenges but also reduced the amount of salt removed each year. Reclamation is evaluating the siting of a second deep-injection well to develop a long-term replacement solution to the PVU injection well.

The objective of this project is to conduct an appraisal-level numerical analysis of five potential new disposal well sites in the paradox Valley area identified by Reclamation, as well as the existing PVU injection well, given an assumed injection history and initial stress state. The criteria for appraisal set by USBR are: 1) the potential for simulated wellhead pressure to reach a critical target pressure, 2) the risk of induced seismicity in the injection layer, measured by a Coulomb factor of safety index with respect to pore pressure, and 3) the potential for surface heave.

## 2 DESIGN AND ANALYSIS

The fluid injection simulations for this project are conducted using *FLAC3D* (Itasca 2017). The hydro-mechanical component of coupling allows prediction of the effect of pore pressure changes on deformation, and potential inelastic deformation (as controlled by Coulomb shear strength). The data provided by Reclamation for the analysis includes formation horizons (provided in the form of depth grids, and converted into surface meshes), interpreted faults, initial formation properties, as well as 25 years measurement history of brine injection rate and wellhead pressure.

The *FLAC3D* model is about 7.5 km deep, and covers an area of 40 km by 56 km. It is large enough to accommodate the existing and five additional potential disposal wells and simulate brine injection for up to 50 years without significant boundary effects. In addition to major faults and welds, the following formations are represented in the model, see Figure 1: Upper, Salt, Leadville, Sedimentary, Upper Precambrian, and Lower Precambrian. The model contains a total of about 616,000 zones.

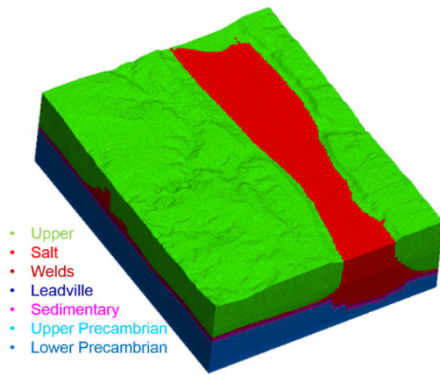


Figure 1. *FLAC3D* model showing the stratigraphy.

Brine injection is simulated in the Leadville at the PVU-1 location for a period about 25 years using the injection rate history provided by USBR. A preliminary calibration is performed by testing various combinations of permeable layers and fault sections in the model and looking for the best match between predicted and measured wellhead pressure data.

The calibrated model is used to simulate brine injection in the Leadville at a constant rate of  $0.0151 \text{ m}^3/\text{s}$  for a period of 50 years at the five potential well locations, taken individually. The criteria for appraisal are then quantified for each site.

### 3 RESULTS AND DISCUSSION

The numerical prediction of wellhead pressure at PVU-1 for the permeability scenarios investigated suggests that a) the existing permeability of the Upper has little influence on the results, b) the presence of the welds has also little impact, c) major faults are probably not all permeable, and d) the use of impermeable major fault sections with large offsets ( $>500 \text{ ft}$ ) in the model reproduce the trend of an overall pressure increase in the data.

A comparison between the predicted wellhead pressure at PVU-1 and the recorded values for the calibrated model is plotted versus time in Figure 2. The Salt and Lower Precambrian are assumed to be impermeable in this scenario. Also, fault sections with offset larger than 500 ft are considered impermeable.

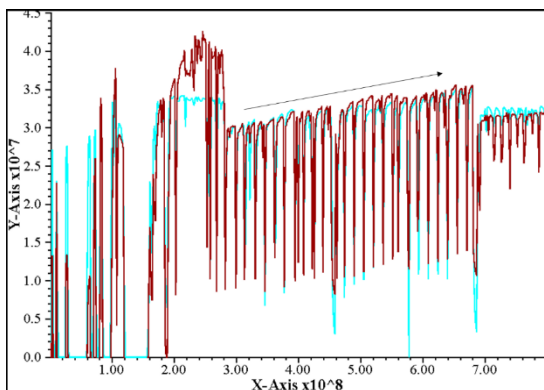


Figure 2. Wellhead pressure [Pa] vs time [sec] – comparison between data (blue) and prediction (red).

A partial view of the model stratigraphy at the location of the existing well is shown to the left in Figure 3. Fluid pressure contours in the Leadville formation induced by 50 years of injection in PVU-1 are plotted to the right on the same figure.

A plot of calculated FoS values and total fluid pressure contours in the Leadville after about 21.5 years of injection is presented in Figure 4. A contour plot of predicted ground surface heave induced by fluid injection near the PVU-1 location is shown in Figure 5.

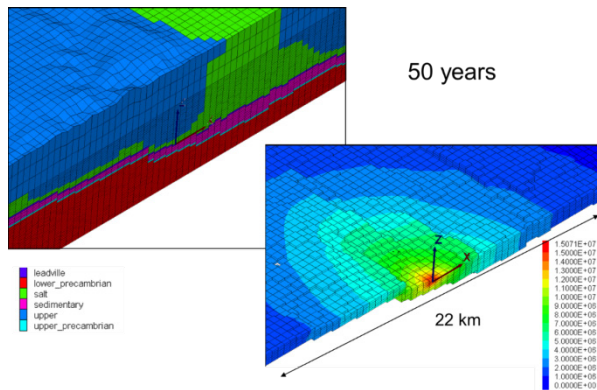


Figure 3. Stratigraphy and induced fluid pressure contours in the Leadville near PVU-1.

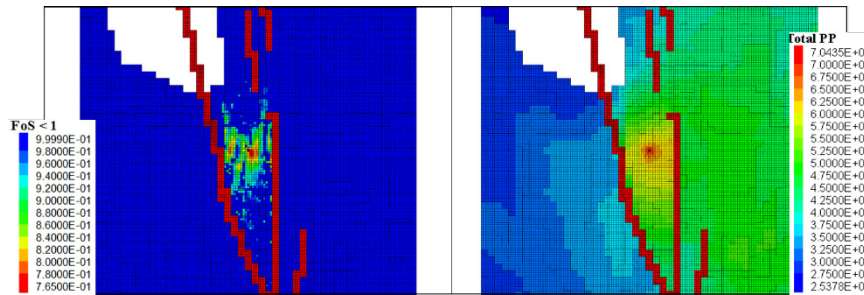


Figure 4. Predicted FoS values (left) and total fluid pressure contours (right) in the Leadville at 21.5 years of injection.

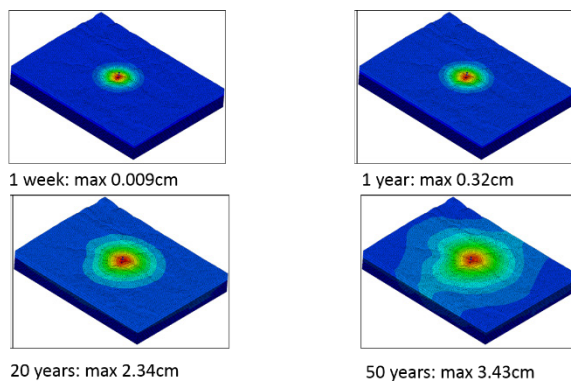


Figure 5. Ground surface vertical displacement contours predicted by the *FLAC3D* model.

*Well pressure predictions.* The simulations show that the wellhead pressure prediction would remain below the target pressure of 34.5 MPa at only two out of the five potential well locations after 50 years of injection at the assumed rate of 0.0151 m<sup>3</sup>/s.

*Predicted risk of induced seismicity.* The risk is quantified using a Factor of Safety (FOS) with respect to fluid pressure, based on a Coulomb criterion. A FOS less than 1 is taken as an indicator of possible yield in the model. The minimum FoS estimate in the Leadville decrease as injection increases, as expected.

*Heave predictions.* The maximum surface heave induced by injection is of the order of centimeters in the model. The numerical results indicate that the location of maximum predicted surface heave does not necessarily correspond to the location of maximum excess pressure at the well location. This is an interesting, but not surprising fact because the mechanical properties are not uniform in the model.

The results of injection scenarios at PVU in the calibrated *FLAC3D* Paradox Valley model, including computed stresses, pore pressures, and coulomb failure criteria, were provided to USBR for further processing and correlation with observed seismicity data.

#### 4 CONCLUSIONS

The numerical results obtained with the calibrated *FLAC3D* Paradox Valley model indicate that, with the model and properties used for the simulations, none of the six well locations meet simultaneously a minimum value for the three evaluation parameters considered in this work: 1) ratio of wellhead pressure to target pressure, 2) FoS index, and 3) surface heave.

The ratio of wellhead pressure to target pressure is used as an indicator of the risk of induced fracturing at the injection depth. The FoS index, based on an elastic stress state, quantifies the potential risk of slip-induced seismicity in the model. However, while the index is quite reliable to detect the onset of yield, the prediction of the extent of the yielding region in the model may be inaccurate because elasto-plastic readjustments would modify the stress-state in the model and make the indicator values unreliable over the whole region initially detected as yielding. The surface heave gives an indication of potential differential surface displacements that could affect the integrity of surface infrastructures. To improve the quality of the model predictions, it was recommended to refine the in-situ stress data and to run the simulations using an elasto-plastic mechanical framework instead of relying on elasticity for the prediction of potential slip induced by injection.

#### REFERENCES

- Itasca Consulting Group, Inc. 2017. *FLAC3D – Fast Lagrangian Analysis of Continua in 3 Dimensions, Ver. 6.0*. Minneapolis: Itasca.
- King, V.M., Block, L.V., Yeck, W.L., Wood, C.K. & Derouin, S.A. 2014. Geological structure of the Paradox Valley Region, Colorado, and relationship to seismicity induced by deep well injection. *J. Geophys. Res. Solid Earth*, 119(6), 4955-4978, doi:10.1002/2013JB010651.