Stress-induced pore water pressures in the vadose zone beneath a composite-lined landfill
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ABSTRACT

A finite-element model was developed to evaluate mechanisms contributing to positive pore pressures measured with sealed pressure transducers in the geological buffer beneath the Environmental Management Waste Management Facility (EMWMF), a composite-lined mixed waste disposal facility operated by the US Department of Energy. The geological buffer is a 3-m-thick engineered fine-textured layer directly beneath the EMWMF’s composite liner, and above the groundwater table. The model accounts for changes in pore water pressure resulting from (i) moistening of the geological buffer due to equilibration with the underlying geological materials, (ii) loading imposed by waste placed on the overlying liner, and (iii) fluctuations in the elevation of the underlying groundwater table. Pore water pressures predicted by the model are in good agreement with pore water pressures measured in the field. The predictions confirm that positive pore water pressures recorded by the sealed pressure transducers in the geological buffer are excess pore water pressures induced by the vertical normal stress imposed by waste placed on the liner, and are not due to a rise in the groundwater table. Simulations also showed that two additional years of filling would further increase the pore water pressure without any change in elevation of the groundwater table. The geological buffer remained unsaturated during the simulation, with a Bw-coefficient similar to that computed from the field-measured pore water pressures and waste filling records. Larger increases in pore water pressure were observed when the geological buffer was assumed to have higher initial saturation, as was observed in the field data. Incorporating seasonal fluctuations in the groundwater table beneath the geological buffer in the model resulted in predictions of small seasonal oscillation in the pore water pressure predicted at the measurement location, similar to seasonal oscillations observed in the field. Predictions made with the model indicate that the dissipation of the excess pore water pressures will occur over decades due to the low hydraulic conductivity of the geological buffer material.

Keywords: composite liner, excess pore water pressure, groundwater, landfill, piezometer, radioactive waste, numerical modeling

1 INTRODUCTION

The Environmental Management Waste Management Facility (EMWMF) is a double-lined landfill comprised of six contiguous cells that are used for disposal of radioactive and non-radioactive debris from decommissioning at the US Department of Energy’s (DOE) Oak Ridge Reservation in Tennessee, USA. Regulatory agreements for the EMWMF require that the base of the liner be no less than 3 m above the groundwater table. Eight pneumatic pressure transducers are buried in sand packs in the vadose zone beneath the liner in Cells 3 through 6 of EMWMF to monitor pore water pressures that could be indicative of a rising groundwater table beneath the landfill. The expectation is that the pressure transducers will register a positive pressure if the groundwater table reaches the location of the transducer, in a manner similar to detecting a rise in the groundwater table using a standpipe piezometer. Other mechanisms, however, can also contribute to changes in pore water pressure at the transducer location.

After filling of Cell 3 commenced, positive pressures were recorded by two of the transducers. Pressures recorded by the transducers climbed as the cell was filled, raising concerns that the groundwater table was encroaching on the base of the liner. However, flows in an underdrain located beneath the landfill and near the groundwater table remained unchanged during this period, suggesting no change in groundwater elevation beneath the landfill. The pore water pressures ceased increasing once filling was complete, and did not increase significantly after seasons with high precipitation, suggesting that other mechanisms might be contributing to the pore water pressures. Monitoring wells outside the periphery of EMWMF are too distant to draw specific inferences regarding the elevation of the groundwater table beneath EMWMF, further confounding interpretation of the pore water pressure data.

Excess pore water pressure induced by total stress from the waste was hypothesized as contributing to the measured porewater pressures (Benson and Tian 2019). However, the transducers are in the vadose zone, and stress-induced pore water pressures due to the placement of fill are not commonly reported for unsaturated soils.
Excess pore water pressures are normally associated with loading saturated fine-textured soils below the groundwater table (e.g., when an embankment is constructed on soft clay).

This paper describes how a coupled hydro-geomechanical model was used to evaluate the relative contributions of loading and changes in elevation of the groundwater table on pore water pressures at the transducer locations. Predictions from the model are used to illustrate the mechanisms responsible for the rise in pore water pressure in the vadose zone beneath the liner. Comparisons are made between predictions and field data to study the impact of groundwater fluctuations and waste loading on pore pressures in materials beneath the liner, as well as initial conditions.

2 FIELD CONDITIONS

The footprint for EMWMF is shown in plan view in Fig. 1a, along with locations of the eight pressure transducers. The landfill is segregated into six cells, with waste placed sequentially from Cell 1 to Cell 6. Cells 3 and 4 were being filled when the data described herein were collected. A cross-section of the landfill in the vicinity of Cells 3 and 4 is shown in Fig. 1b, along with the subsurface directly beneath the landfill.

All of the cells are lined with a double liner separated by a geocomposite drainage layer functioning as a leak detection layer. The upper liner is a 1.5-mm-thick textured high-density polyethylene (HDPE) geomembrane (GM). The lower liner is a composite liner consisting of a 1.5-mm-thick textured HDPE GM overlying a 0.9-m-thick compacted clay liner having a saturated hydraulic conductivity no greater than 1x10⁻⁹ m/s (Benson et al. 2008). The lower composite liner is directly on top of a 3-m-thick “geological buffer,” an engineered fine-textured layer intended to provide separation between the bottom of the liner and the groundwater table. The geological buffer is comprised of compacted and natural clayey soil over an existing natural layer of “residuum” - a moderately plastic residual soil ranging from silty to sandy clay. The residuum overlies fractured shale bedrock (Ogden 1993).

Before the landfill was constructed, a tributary flowed along the surface in a depression in the residuum near the center of Cell 3. To manage water in this area, an underdrain was constructed beneath Cell 3 to intercept any groundwater in the area (BJC 2005). Flows in the underdrain are measured at the discharge point with a weir. When preparing the surface grade on the residuum, the soil was reported as noticeably wetter near the underdrain relative to distances farther from the centerline of the underdrain (BJC 2005).

3 HYDRO-GEOMECHANICAL MODEL

A coupled hydro-geomechanical model accounting for groundwater fluctuations and waste loading was developed using the Sigma/W module in GeoStudio 2019, a software package employing the finite-element method (GeoSlope Inc., Calgary, Alberta Canada). Two-dimensional models were constructed that permit 2-D seepage in groundwater and the overlying unsaturated zone, providing an understanding of the relationship between groundwater elevation beneath the liner and water levels measured around the periphery with monitoring wells and piezometers.

Site-specific information from EMWMF was used to develop and parameterize the model, including groundwater elevations, seasonal groundwater periodicity, overburden stress by waste loading, and geomechanical and hydraulic properties of the geological buffer, residuum, and bedrock (i.e., fractured shale and sandstone). A schematic of the domain of the Sigma/W model is shown in Fig. 2. The domain includes the geological buffer, residuum, and fractured shale/sandstone present at EMWMF.

Hydraulic properties were assumed to be uniform in each domain and to follow the van Genuchten formulation for the soil-water characteristic curve (SWCC):

\[
\Theta = \frac{\theta_s - \theta_r}{\theta_s - \theta_t} = \left[ \frac{1}{1 + (\alpha \psi)^n} \right]^m
\]

(1)
and the van Genuchten-Mualem formulation for the hydraulic conductivity function (van Genuchten 1980):

\[ K_s = K_\theta \left[ 1 - \left( \frac{1 - \theta}{1 - \theta_s} \right)^m \right]^{2/n} \]  

(2)

In Eqs. 1 and 2, \( \theta \) is the saturated water content, \( \theta_i \) is the residual water content, \( \Theta \) is the effective saturation, \( I \) is the pore interaction term, \( K_s \) is the saturated hydraulic conductivity, \( K_\theta \) is the unsaturated hydraulic conductivity at water content \( \theta \), and \( a, m, \) and \( n \) are shape parameters defining the SWCC. Eqs. 1 and 2 were used assuming \( m = 1 - 1/n \) (van Genuchten 1980) and \( I = -2 \). Physical, mechanical, and hydrological parameters of the geological buffer, residuum, and bedrock are summarized in Table 1. Pore water pressure was “measured” at the bottom of the geological buffer (i.e., see red circle in Fig. 2) using an observation node in the model. An underdrain (150 mm diameter) was constructed at the depth of the average groundwater table (1.8 m below the bottom of the geological buffer, see black circle) with a boundary condition as the potential seepage face (i.e., 0 kPa pore water pressure). The underdrain nodes were only active when evaluating underdrain flow, and were not used during analysis of coupling between groundwater elevation and waste loading on pore water pressures.

Fig. 2. Schematic of domain used in Sigma/W model. Gray = geological buffer (3 m thickness), white = residuum (0.5 m thickness), light blue = bedrock (> 8.5 m thickness). Blue dashed line indicates groundwater table at initial condition (1.8 m below bottom of geological buffer). Waste shown as black dashed lines and not drawn to scale.

Sigma/W was used to predict the pore water pressure in the geological buffer caused by each of the following mechanisms: (i) moistening by the surrounding environment (i.e., pore water pressure equilibrium post construction), (ii) waste loading, and (iii) seasonal groundwater periodicity. These mechanisms were considered in insolation and in a fully coupled model. A no-flow hydraulic boundary and a variable stress boundary were applied at the surface of the geological buffer to simulate the no-flow condition imposed by the liner and the stress applied by the overlying waste. Variable hydraulic head boundaries and no deformation boundaries were applied on the sides to account for variations in groundwater elevations outside the perimeter of the disposal facility and constraint imposed by lateral earth pressures. A unit hydraulic gradient boundary and no deformation boundary were used along the bottom.

Table 1. Physical, mechanical, and hydrological parameters of geological buffer, residuum, and bedrock used in model.

| Parameters                        | Geological Buffer | Residuum | Fractured Shale |
|-----------------------------------|-------------------|----------|-----------------|
| \( a \) (kPa\(^{-1}\))           | 0.014             | 0.014    | 0.08            |
| \( n \)                           | 1.12              | 1.12     | 2.24            |
| Sat. Hydraulic Conductivity \( (K_s, \text{ m/s}) \) | \( 1.0 \times 10^{-10} \) | \( 2.0 \times 10^{-10} \) | \( 1.0 \times 10^{-5} \) |
| Volumetric Water Content \( (\theta_i) \) | 0.3               | 0.3      | 0.3             |
| Effective Young’s Modulus \( (E’, \text{ MPa}) \) | 2                 | 2        | 1000            |
| Poisson’s Ratio \( (\nu) \)       | 0.4               | 0.4      | 0.3             |
| Unit Weight \( (\gamma, \text{ kN/m}^3) \) | 20                | 20       | 20              |

Notes: \( a \) and \( n \) from Tinium et al. (1997) for geological buffer and residuum and Benson et al. (2014) for fractured shale. Saturated hydraulic conductivity from Benson and Trast (1995) for geological buffer and residuum and Benson et al. (1997) for fractured shale. Effective Young’s modulus and Poisson’s ratio from Bowles (1996).

4 RESULTS AND DISCUSSION

4.1 Equilibration with surrounding environment

The geological buffer is unsaturated and in significant disequilibrium with the surrounding material immediately after placement (e.g., compaction near optimum water content, 90-100% of maximum dry unit weight). The geological buffer equilibrates with the surrounding environment by imbibing or releasing moisture. An initial degree of saturation \( (S_i) \) of 70, 80, 90, and 95% was assumed for the geological buffer, corresponding to suctions of 50, 120, 400, and 1000 kPa (from SWCC of geological buffer). The adjacent residuum and bedrock were set at hydrostatic equilibrium with the groundwater table 1.8 m below the bottom of the geological buffer as the initial condition.

To evaluate the effect of moistening independent of other variables, the model was run for 10 years assuming no fluctuation in the groundwater table and no loading. Predictions of pore water pressure at the piezometer during this period are shown in Fig. 3. The equilibration process can continue for years, confounding an assessment of groundwater levels based on pore water pressure data. For the wettest initial condition \( (S_i = 0.95, \text{ orange line, Fig. 3}) \), pore water pressure equilibration in the geological buffer occurs for at least one year after placement. For the driest condition \( (S_i = 0.7, \text{ blue line, Fig. 3}) \), equilibration occurs over more than 10 yr.

Construction of a liner and leachate collection system
(prior to waste disposal) typically requires about one year. After the 1-year construction period, pore water pressure in the geological buffer at the piezometer ranges from -29 kPa (wetter initial condition, $S_i = 0.95$) to -273 kPa (drier initial condition, $S_i = 0.7$).

Pore water pressure was due to the load imposed by the waste. That is, the pore water response from loading appears like a rise in the groundwater table when viewed from the perspective of a piezometer, but is unrelated to and independent of the location of the groundwater table.

4.2 Effect of waste loading

Waste loading was simulated with a variable stress boundary applied as a strip load on the liner surface (Fig. 4a). The normal stress increases linearly from 0 to 320 kPa (19 m of waste, density = 19.5 kN/m³) over 4.7 years, mimicking actual waste filling between 1 January 2011 to 1 October 2015 (Fig. 4 black line). Pore water pressure in the geological buffer was assumed to be in equilibrium with the groundwater table 1.8 m below the bottom of the geological buffer (-18 kPa at the bottom of geological buffer).

The impact of waste loading on pore water pressure at the piezometer is shown in Fig. 4. Pore water pressure in the geological buffer transitions from the initial equilibrium condition (-18 kPa) to positive pore water pressure at 0.4 yr, and ultimately reaches 20 kPa after 4.7 years of filling. The increase in pore water pressure ($\Delta u_w$) due solely to waste loading is 38 kPa at 4.7 yr.

Pore water pressures 1 m and 2 m above and below the piezometer are also shown in Fig. 4. Waste loading has a greater impact on pore water pressure closer to the liner (i.e., further above the piezometer), with the increase in pore water pressure reaching 160 kPa at 2 m above the piezometer (Fig. 4 blue line). These pressures are higher because they are closer to the no-flow boundary imposed by the liner, which inhibits dissipation. In contrast, in the bedrock below the piezometer (1 m into fractured shale), the pore water pressure remained negative at -8 kPa during the entire filling period because porewater pressures dissipate very rapidly in the permeable shale. Moreover, there was no rise in the groundwater table – all of the change in pore water pressure was due to the load imposed by the waste.

Fig. 3. Temporal variation of pore water pressure at the piezometer (observation node in model) as geological buffer equilibrates with the surrounding environment.

Fig. 4. The effect of waste loading on the pore water pressure of the geological buffer at various depths.

B-coefficients are used to describe the pore water pressure response from loading. B-coefficients for unsaturated soil are defined in the same manner as for saturated soil, except separate B-coefficients are assigned the water phase ($B_w$) and the gas (air) phase ($B_a$) (Fredlund and Rahardjo 1993):

$$B_w = \frac{\Delta u_w}{\Delta \sigma} \quad B_a = \frac{\Delta u_a}{\Delta \sigma}$$

where $\Delta u_w$ is the increase in pore water pressure and $\Delta u_a$ is the increase in pore gas (air) pressure associated with an increase in total stress ($\Delta \sigma$). If the residuum were saturated by groundwater prior to the total stress being applied by the waste, $B_a$ would be undetermined (no gas phase) and $B_w$ would be approximately 1 in a manner similar to the increase in pore water pressure in saturated clay underlying an embankment under construction. Under unsaturated conditions, the compressibility of the gas phase renders $B_w < 1$, $B_a < 1$, and $B_w + B_a < 1$ (Fredlund and Rahardjo 1993).

$B_w$ computed from the applied normal stress and pore water pressures at the piezometer is less than 0.2 with an average of 0.08, which is similar to the $B_w$ computed from the field data collected from PP-01 (0.09) and indicates the geological buffer is unsaturated (Benson and Tian 2019). $B_w$ should also depend on the initial saturation of the geological buffer, with higher $S_i$ (wetter geological buffer) corresponding to higher $B_w$, as was observed in the field. This was confirmed by partitioning the geological buffer into five sections, each 12 m wide (labeled as S01 to S05, Fig. 5) with $S_i$ decreasing by 0.05
in each of the first four sections (i.e., 0.95 - S01, 0.90 - S02, 0.85 - S03, 0.80 - S04, 0.80 – S05) at 0.95 and 0.90. As shown in Fig. 5, higher $S_i$ (i.e., S01 and S02) yielded higher $B_{av}$, as observed in the field.

4.3 Effect of seasonal groundwater table periodicity

The effect of seasonal periodicity in the groundwater table on pore water pressure in the geological buffer was evaluated by applying a time-varying hydraulic head boundary on the right-hand side of the model representing seasonal fluctuations of the groundwater table. Data from monitoring well GW-946 (Fig. 1) were used to define the temporal variation in head (Fig. 6a, b black line). The average groundwater table elevation was set 1.8 m below the bottom of the geological buffer (same as constant head in other simulations). The initial condition was set assuming the pore water pressure in the geological buffer was in equilibrium with the surrounding environment and no waste loading.

Impact of oscillations in the underlying groundwater table on pore water pressures in the residuum and geological buffer are shown in Fig. 6a. Oscillations in the groundwater table at depth propagate upward, as shown in the oscillation in porewater pressure at the piezometer and other locations in the overlying residuum and geological buffer. The oscillation in pore water pressures diminishes with increasing distance above the groundwater table, and lags behind that in groundwater. Greater lags are evident as the distance above the groundwater table increases (Fig. 6a).

Similar responses are evident in the underdrain. The underdrain flow oscillates with the variation in groundwater elevation, and remains less than 61 kL/day over the 7-yr simulation (assuming the length of the underdrain is 150 m, and half of the underdrain is wetted) (Fig. 6b). Absence of any systematic increase in underdrain flow is consistent with the absence of a rise in the groundwater table, as was observed in the field (Benson and Tian 2019).

4.4 Coupled mechanisms

The combined effects of equilibration with the surrounding environment, waste loading, and seasonal groundwater periodicity on pore water pressure in the geological buffer were evaluated by coupling the hydraulic and geomechanical models. The variable stress boundary (i.e., waste loading for 4.7 years) and the variable hydraulic head boundary (i.e., groundwater periodicity) were applied, with an initial pore water pressure of -122 kPa in the geological buffer to simulate the average matric suction after 1 yr of equilibration after the construction of the geological buffer and the liner. Predictions from the coupled model are shown in Fig. 7. Pore water pressure at the piezometer becomes positive after 1.6 yr of waste filling and reaches a maximum of 19.6 kPa (Fig. 7a), which is similar to the porewater pressure observed in the field (maximum of 18.7 kPa in PP-02) (Benson and Tian 2019). If filling had continued for another two years (i.e., 6.7 years), the maximum pore water pressure at the piezometer would have reached 27.1 kPa (Fig. 7b).
Moistening by the surrounding environment has a stronger impact on pore water pressure early in the record, with the pore water pressure increasing nearly linearly during the first 0.3 years (from -121.8 to -55.0 kPa). Subsequently, waste loading is the most significant contribution to the increase of pore water pressure in the geological buffer (shaded area in Fig. 7). The increase of pore water pressure due to waste loading can reach up to 45.1 kPa at 6.7 years (4.5 m of water), whereas the effect of seasonal periodicity of the groundwater table is at most 9.4 kPa (0.9 m of water). After loading ceases, the pore water pressure decreases, with complete dissipation requiring more than 20 years.

5 SUMMARY AND CONCLUSIONS

Predictions of pore water pressures in the geological buffer beneath the liner in the Environmental Management Waste Management Facility (EMWMF) have been presented that were made with a coupled hydraulic-geomechanical model. The model accounted for equilibration of the geological buffer with the surrounding environment, seasonal periodicity in the groundwater table, and waste loading on the liner. The predictions confirm previous observations and interpretations of pore water pressures measured by sealed piezometers beneath the EMWMF, and demonstrate that all three of the aforementioned mechanisms affect pore water pressure in the geological buffer.

The predictions demonstrate that waste loading induces increases in pore water pressure in the geological buffer without any rise in the groundwater table, and that pore water pressures induced by waste loading will require more than 20 years to dissipate. The predictions also demonstrate that oscillations in pore water pressure in groundwater induced by seasonal periodicity in the groundwater table propagate upward in the unsaturated zone, and are realized as smaller seasonal oscillations in porewater pressure in the geological buffer even though the geological buffer is above the groundwater table. Initial saturation of the geological buffer was shown to affect the rate of moistening by the surrounding environment and the magnitude of the increase in pore water pressure due to waste loading. Predictions of underdrain flow show that the flow rate is influenced by the seasonal periodicity in the groundwater table, and that the flow does not increase or decrease systematically without a systematic increase or decrease in the average elevation of the groundwater table.

These findings indicate that pressure monitoring points used to detect encroachment of the groundwater beneath landfills may respond to factors other than changes in groundwater table elevation. Other methods to monitor or predict the elevation of the groundwater table are needed to avoid incorrect inferences regarding encroachment of the groundwater table.

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