Design of a geosynthetic drainage system for soil-cement slope protection subjected to drawdown conditions

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ABSTRACT: A geosynthetic drainage system was designed to relieve excess pore water pressure behind soil-cement slope protection generated during drawdown. The drainage system includes geosynthetic strip drains located mid-slope with outlets extending through the soil-cement and a continuous drain (geonet/geocomposite) extending below the toe of the soil-cement. Design considerations included the number of strip drains placed behind the soil-cement, the location of the drains and the orientation of the outlet (perpendicular vs. horizontal). Three modes of failure were evaluated: i) uplift of the soil-cement due to the excess pore pressures, ii) local, or shallow, slope stability, and iii) global slope stability. Each mode of failure was evaluated for two drawdown conditions. Transient finite-element analysis was used to simulate the drawdown conditions and obtain the pore pressures acting on the soil-cement. Limit equilibrium analysis was used to evaluate the stability of the slope during drawdown. Analysis results were used to develop the final design of a drainage system that produced desired performance for uplift and slope stability. Final design used combination of strip drains and fill placement; however, the alternative system using strip drains and the geocomposite also met minimum design criteria.

1 INTRODUCTION

The slope of an embankment can be protected from erosion due to fluctuating water levels and wave action through the placement of layered soil-cement (Adaska 1985). However, pore water pressure can build up behind the soil-cement during a drawdown event unless drainage is provided to relieve the excess pressure (Huzjack et al. 2008). The excess water pressure can cause the soil-cement to crack and could potentially affect the global stability of the slope being protected by the soil-cement. A geosynthetic drainage system is one possible solution to reduce the pressure build-up be-hind the soil-cement due to fluctuating water levels.

The design of the geosynthetic drainage system, which included multiple geosynthetic strip drains and a geocomposite (geotextile/geonet), involved finite-element and limit equilibrium analyses to evaluate the effectiveness of the drainage system and the stability of the slope. Specifically, the number of strip drains, the orientation of the strip drain outlets and the placement of the geocomposite were the variables considered in the analysis. The results of the analyses were used to select the most effective system configuration, including the drainage features, of those evaluated as part of this study.

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2 DESIGN ALTERNATIVES

Three embankment and drainage system configurations were evaluated to identify the most effective alternative design. For all three configurations, the geosynthetic strip drains run parallel to the crest of the embankment between elevations 13 m and 17 m. Each strip drain has outlets that extend up through the soil-cement, daylighting in the impoundment.

2.1 *Alternative A*

A 0.46-m thick layer of soil-cement covers the 3H:1V slope from elevation 19.7 m to 13.0 m. A 0.23-m thick layer of soil-cement covers the slope from elevation 13.0 m to 11.0 m. A 1.2-m thick layer of backfill lies at the toe of the soil-cement. A continuous drain (geonet) runs along the 0.23-m thick soil-cement, between embankment fill and the soil-cement, and extends beneath the backfill into the impoundment.

2.2 *Alternative B*

A 0.46-m thick layer of soil-cement covers the 3H:1V slope from elevation 19.7 m to 11.0 m. The toe of the lower 0.6 m of the soil-cement is embedded into a 1.2-m thick layer of backfill. A continuous drain (geonet) runs along the soil-cement, between embankment fill and the soil-cement, from elevation 13.0 m to 10.4 m. The geonet extends beneath the backfill into the impoundment.

2.3 *Alternative C*

A 0.46-m thick layer of soil-cement covers the 3H:1V slope from elevation 19.7 m to 13.0 m. A berm, with a crest width of 3 m at an elevation of 13.9 m and a 6H:1V slope, of embankment fill material provides a buttress the soil-cement. The toe of the soil-cement is embedded 0.6 m in the berm. The geonet is not included in this design alternative removed from the design.

3 SEEPAGE ANALYSIS

Differential pressures, or the change in pressure acting on the soil-cement from hydrostatic conditions, are generated as the drawdown occurs when excess pore pressure does not dissipate as quickly as the water level is drawn down. The strip drains and the continuous drain (geocomposite/geonet) enhance the dissipation of the differential pressures at the base of the soil-cement during drawdown. However, even with the drains, there could be a potential for uplift of the soil-cement due to the differential pressures. The differential pressures from the seepage analyses were compared with the weight of the soil-cement to evaluate the potential for uplift of the upstream slope protection layer during drawdown.

3.1 *Model*

A transient, two-dimensional finite-element seepage analysis was conducted to model the differential pressures acting on the soil-cement during two drawdown events: i) operational drawdown (approximately 0.1 m/day), and ii) extreme drawdown (approximately 0.23 m/day). The total change in water level from the beginning to the end of drawdown is approximately 8.5 m.

To evaluate the effect of the two drawdown events on the pore pressures beneath the soil-cement, each drawdown condition was modeled by applying a time-dependent head boundary condition along the face of the soil-cement. The geosynthetic drains (strip drains and geocomposite) were modeled using a variable head boundary condition equivalent to the change in water level during drawdown. A single node represented an outlet for the strip drain, with each node placed at the location of the strip drain at the interface of the soil-cement and the embankment fill.

3.2 *Strip Drain Outlets*

A critical transition phase was identified in the calculated pressure imbalance that could occur as the water level is drawn down from the drain outlet elevation to the bottom of the soil-cement at the drain location (i.e. the thickness of the soil-cement layer at the drain outlet) (Figure 1). One of the primary simplifying assumptions for the initial analysis was that the boundary condition applied at the drain would be equal to the water level in the impoundment since losses through the outlet pipe are small for the flows expected. This condition is valid for any orientation of the drain under submerged conditions. However, this assumption does not model a transition interval in potential differential head that could occur as the strip drain outlet pipe transitions from a submerged condition unless the pipe is horizontal or sloped downward. The application of this simplifying boundary condition to the analysis effectively models a drain outlet situated horizontally, but does not model changes in drainage condition for a pipe outlet higher than the strip drain (i.e. a perpendicular drain outlet configuration) as the water level passes below the pipe outlet invert. Therefore, the factor of safety (FoS) would be lower with the drain outlet extending up through the soil-cement perpendicular to the strip drain, versus a horizontal outlet.

Pre-fabricated drains with outlets that extend horizontally from the drain for the 3H:1V slope are not readily available. Installation of drain outlets extending horizontally from the drain through the flat plate soil-cement would be difficult to construct. Therefore, additional seepage analysis was performed to model the outlets for the drains at an elevation 0.46 m higher than the elevation of the bottom of the drain.

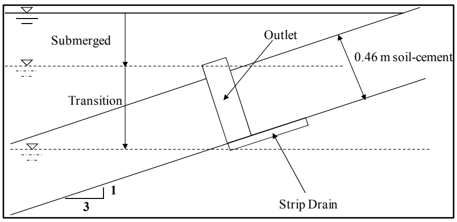

Figure 1. Illustration of the strip drain and outlet with respect to the water level during drawdown.

3.3 *Uplift of the Soil-Cement*

The FoS against uplift of the soil-cement was calculated considering the dead weight of the soil-cement

(W_{sc}) divided by the pressure differential (Δh) acting on the soil-cement, as expressed by the following equation:

$$FOS = \frac{W_{sc}}{\Delta h}$$

When the water level, $h_t >$ [elevation of a given point (h_e) – vertical projection of the thickness of the soil-cement ($t_{sc,vp}$)],

$$\Delta h = h_{p,drawdown} - \left(h_{p,hydrostatic} - t_{sc,vp}\right)$$

where:

$$h_{p,hydrostatic} = h_t - h_e$$

When $h_t \leq (h_e - t_{sc,vp})$,

$$\Delta h = h_{p,drawdown}$$

where $h_{p,drawdown}$ is the pressure head obtained at a point along the base of the soil-cement from the seepage analysis, and $h_{p,hydrostatic}$ is the hydrostatic pressure head at the same point.

The vertical projection of the soil-cement is calculated by the following:

$$t_{sc,vp} = t_{sc} \cos\beta$$

where β is the embankment slope angle. The vertical projection for the 0.46-m soil-cement is about 0.43 m and the vertical projection of the 0.23-m soil-cement is about 0.21 m. A free body diagram of the pressure heads acting on the soil-cement is shown in Figure 2.

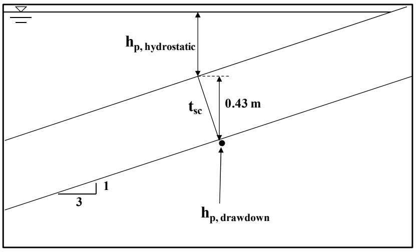

Figure 2. Free body diagram for pressure heads acting on a discrete point of the soil-cement

The weight of the soil-cement W_{sc} is the normal component of the load and is calculated as follows:

$$W_{sc} = \frac{\gamma_{sc}}{\gamma_w} z \cos\beta = \frac{\gamma_{sc}}{\gamma_w} \frac{t_{sc}}{\cos\beta} \cos\beta = \frac{\gamma_{sc}}{\gamma_w} t_{sc}$$

where γ_{sc} is the unit weight of the soil-cement, γ_w is the unit weight of water, and z is the vertical height of the soil-cement. A free body diagram for the calculation of forces acting on the system is shown on Figure 3. The weight of the berm at the toe of the soil-cement for Alternative C also contributes to the resisting forces in the system. The pressure head acting along the interface of the soil-cement and the embankment during each drawdown event were obtained from seepage analysis for each design alternative. The effectiveness of the geocomposite drain and the strip drains in reducing the uplift pressures acting on the soil-cement during each drawdown condition was evaluated based on the calculated FoS.

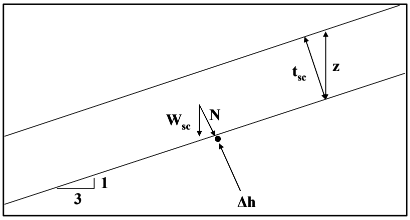

Figure 3. Free body diagram for calculation of factor of safety against uplift of soil-cement

The equations for calculating the FoS against uplift of the soil-cement are for discrete points along the soil-cement. However, the soil-cement will act as a structural element with 3 dimensions. The pressure imbalance, which is continually changing as the water level is drawn-down and drainage occurs, would have a varying pressure imbalance beneath any structural element. In addition to the weight of the soil-cement over 3 dimensions, significant frictional resistance would also occur along the irregular cracks that would form along the edges of a structural element. Therefore, the FoS for each structural composite element would be the weight of the soil-cement element resisting the composite pressure imbalance acting at the base of the element, plus the side shear also resisting uplift. The composite FoS was calculated assuming only the weight of the soil cement for resistance (i.e. no side shear resistance) and assuming tensile cracking occurs in the soil-cement about every 3 m, with the weight of a 3-m long portion of the soil-cement centered over the point being considered to resist uplift.

3.4 *Results*

The minimum design FoS for operational drawdown conditions is 1.3 and 1.2 for the extreme drawdown event. The calculated composite FoS against uplift of the soil-cement for the configurations evaluated are summarized in Table 1 and Table 2.

As discussed in Section 3.2, the strip drains modeled with horizontal outlets resulted in a higher FoS against uplift of the soil-cement than for the same configuration (i.e. Alternative A with 4 strip drains) with perpendicular outlets (Table 1). As the FoS for the 4-drain configuration with perpendicular drains for both drawdown conditions was less than the minimum recommended values, seepage analysis also included analysis with the addition of a fifth strip drain.

As expected, the FoS increased with the addition of a fifth drain. The composite FoS of 3-dimensional elements for each case analyzed were greater than or equal to the minimum design value (Table 2). However, the Alternative C configuration provided the highest FoS against uplift of the soil-cement.

Table 1. FoS values for uplift of soil-cement for 4 strip drains

Drawdown Condition	4 Strip Drains (Horizontal Outlet)	4 Strip Drains (Perpendicular Outlet)		
	Alt A	Alt A	Alt B	Alt C
Operational	1.7	1.2	1.2	1.2
Extreme	1.6	1.0	1.0	1.1

Table 2. FoS values for uplift of soil-cement for 5 strip drains

Drawdown Condition	5 Strip Drains – Perpendicular Outlet		
	Alt A	Alt B	Alt C
Operational	1.3	1.3	1.4
Extreme	1.2	1.2	1.2

4 SLOPE STABILITY ANALYSIS

A limit-equilibrium stability analysis was performed using the Morgenstern and Price (1965) method to evaluate the effect of the differential pressures under drawdown conditions on the stability of the slope. The method satisfies both moment and force equilibrium. Two modes of failure were considered: i) failure surface that occur near the face of the soil-cement as a shallow failure, and ii) a deep-seated failure surface. Both types of failure surfaces coincide with the time step when the differential pressures are the most critical.

The minimum acceptable factor of safety against global slope failure is 1.3 for both drawdown conditions. Modeling was performed assuming a minimum failure surface depth of 1.2 m (i.e. shallow failure surfaces that could occur just below the soil-cement), that could damage the slope protection locally. For these shallow modes of failure that do not threaten global stability, the minimum acceptable factor of safety for the operational drawdown condition is 1.3 and 1.1 for the extreme drawdown condition.

The FoS against slope failure for the three alternative designs for each of the drawdown conditions are summarized in Table 3 and Table 4. As with the FoS against uplift of the soil-cement discussed in Section 3.4, the FoS values for the 4-drain configuration are below the minimum acceptable values. The addition of a fifth drain increased the FoS greater or equal to the minimum design value. Based on the results of the slope stability analysis, there does not appear to be a significant difference in the FoS with respect to the three alternative designs.

Table 3. Slope stability FoS values – Shallow slip surfaces

Drawdown Condition	4 drains (Perpendicular Outlet)			5 drains (Perpendicular Outlet)		
	Alt A	Alt B	Alt C	Alt A	Alt B	Alt C
Operational	1.3	1.3	1.3	1.4	1.4	1.4
Extreme	1.0	1.1	1.0	1.1	1.1	1.1

Table 4. Slope stability FoS values – Global stability

Drawdown Condition	4 drains (Perpendicular Outlet)			5 drains (Perpendicular Outlet)		
	Alt A	Alt B	Alt C	Alt A	Alt B	Alt C
Operational	1.3	1.3	1.3	1.4	1.4	1.4
Extreme	1.2	1.2	1.2	1.3	1.3	1.3

5 CONCLUSIONS

With a strip drain outlet oriented perpendicular to the slope, the pressure differential could temporarily increase as the drain outlet goes from a submerged condition (water level above the drain outlet) to atmospheric and result in a lower FoS than the original modeled drain outlet model. Four horizontal strip drain outlets would be equivalent to the 5-drain configuration with perpendicular outlets.

When considering the results of the analyses presented herein (resistance to uplift and slope stability) and the components of the drainage system, the Alternative C configuration is the most robust slope protection system because of the increase in mass and increase in available seepage paths in the berm to relieve pressure, in contrast to the geonet as a single drainage layer. However, the alternative systems using strip drains and the geocomposite also met the minimum design criteria.

REFERENCES

Adaska, W.S. (1985). "Soil-Cement Liners." *Hydraulic Barriers in Soil and Rock*, ASTM STP 874, Philadelphia, pp. 299-313.

Huzjak, R., Prochaska, A. and Olsen, J. (2008). "Transient Seepage Analysis of Soil-Cement Uplift Pressures during Reservoir Drawdown." *2008 GEO-velopment Seminar,* Colorado ASCE.

Morgenstern, N.R., and Price, V.E. (1965). "The Analysis of the Stability of General Slip Surfaces." *Geotechnique*, Vol. 15, pp. 79-93.