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3D GROUNDWATER SEEPAGE ANALYSIS OF A LEVEE INTERSECTION

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ABSTRACT:
This paper investigates the modeling of seepage through a levee in two and three dimensions. The use of three dimensional analysis facilitates the simulation of under and through seepage and the resulting exit gradients at a complex junction in a levee system. These complexities include a 90 degree bend in the levee alignment, as well as a box culvert through the levee. Such analysis are typically only performed on 2D cross-sections. Therefore the impact of various operational flow scenarios on designs is largely unknown in the industry. It is shown that such factors can only be modeled in three dimensions and can lead to changes in the final conclusions. The issues related to the formation of critical gradients under 3D scenarios are examined. The impact of typical operational scenarios is examined in light of the 3D nature of the structure.

RÉSUMÉ:
Cet article étudie la modélisation de l'infiltration à travers une digue en deux et trois dimensions. L'utilisation de trois dimensions d'analyse facilite la simulation d'infiltration sous et à travers et les gradients de sortie résultant à un carrefour complexe dans un système de digues. Ces complexités inclure un angle de 90 degrés dans l'alignement levée, ainsi que un dalot à travers la digue. Une telle analyse ne sont normalement effectuées sur des sections 2D. Par conséquent l'impact de différents scénarios de flux de fonctionnement sur les dessins est largement ignorée dans l'industrie. Il est démontré que ces facteurs ne peut être modélisée en trois dimensions et peut conduire à des changements dans les conclusions finales. Les questions liées à la formation de gradients critiques dans les scénarios 3D sont examinées. L'impact de scénarios opérationnels typiques est examinée à la lumière de la nature 3D de la structure.

1 INTRODUCTION

Two dimensional numerical modeling of earth structures is a common practice in geotechnical engineering. State-of-the-practice for levee design considers seepage and stability analysis at cross-sections spaced at 1000-ft intervals perpendicular to the levee alignment. Analysis performed in three dimensions benefit from the increased spatial accuracy and consideration of more variables in cases where there are irregular features,

This paper presents modeling of seepage through and under an earthen levee along the Rio Grande in arid northern New Mexico. The levee is intended to protect residential and agricultural land from flooding. At the project's termination point, there is a bend in the levee alignment to accommodate the cut-off point to a highway embankment. Due to the presence of a groundwater ditch on the landside of the levee, a box culvert and weir is required to allow water passage. During flood events a weir at the riverside of the box culvert is closed to prevent backflow. The culmination of these factors is a scenario that can only be effectively simulated in three dimensions. The SVFlux 3D finite element groundwater flux package was used to perform this modeling.

2 BACKGROUND

The levee separates the flood plains of the Rio Grande (upstream) from surrounding agricultural land and residences. A open, trapezoidal channel which functions as a groundwater drain and has been labelled the Clear Ditch, runs parallel to the levee alignment and is located between approximately 20 and 50 feet of landside of the levee toe. The levee was tied into a bridge abutment at the Interstate 25 crossing of the Rio Grande to provide a suitable termination point. This intersection required a box culvert to allow flow from the Clear Ditch to be passed through the levee. A weir was installed to control the ditch water level and to prevent backflow through the culvert in the event of a flood. Effective design of the combination of these elements in the levee system requires three dimensional modeling. Two-dimensional modeling does not account for either the funnel effects at the inside corner of the 90-degree bend in the levee or transition of the landside levee face and foundation at the box culvert and Clear Ditch.

3 MODELING APPROACH

The SVFlux finite element groundwater modeling software was selected to model the levee in two and three dimensions. Flooding scenarios, as well as material properties were based upon existing work performed by AMEC Earth and Environmental. Based upon design drawings, idealized geometry was developed and material layering interpolated.

3.1. Flood Scenarios

There are two different flood-wave events that required design. The first is the scenario where flood waters reach the top of the levee. Such a scenario is expected to occur over a very short time period. Post Hurricane Katrina, levee designers acknowledged the need for levees to withstand flood wave forces (under-seepage and stability) to the levee top, without the consideration of a freeboard. This realization has been reflected in recent levee design guidance published by the United States Army Corps of Engineers. The second scenario is for the mean annual snowmelt flood, which occurs over approximately 100 days in the spring. The associated flood wave for this snowmelt scenario is considerably lower in elevation. Steady state models were created for both of these scenarios. Steady state models are highly conservative for the top of levee flood, due to the short time interval over which these water elevations will be observed.

A more realistic scenario considers the maximum flood wave as transient subsequent to the steady-state saturation generated by the snowmelt flood wave. Using the steady state mean annual flood as a starting point in terms of groundwater flux conditions, the water level was raised over the course of half a day. The fall of the water level is also modelled to determine the effect over time. The distribution over time is shown in Figure 1.

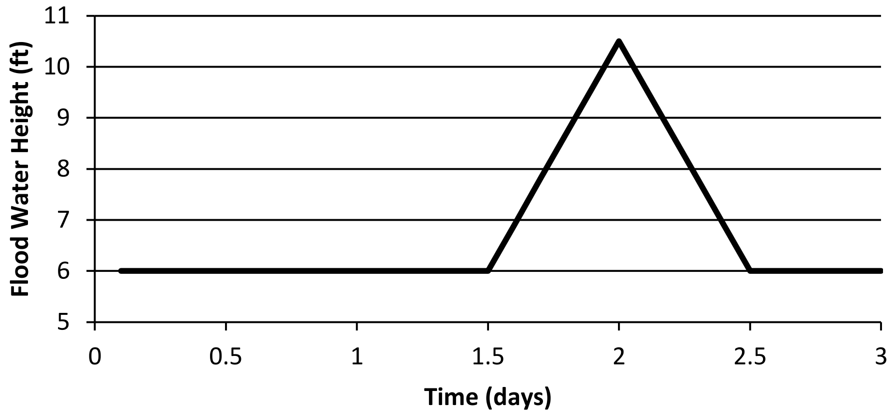

Figure 1: Flood water distribution over time.
Note: Datum is set at the assumed water table elevation equal to the depth of water in the Clear Ditch

3.2. Material Parameters

Material parameters were defined based upon field and laboratory testing performed and provided by AMEC Earth and Environmental. The parameters required include porosity, saturated hydraulic conductivity and specific gravity, as well as unsaturated data. The van Genuchten method was used to represent the soil water characteristic curve (SWCC) and allowed for unsaturated conditions to be considered. A summary of the material parameters is presented in Table 1.

Table 1: Unsaturated material parameters assigned to the different layers

Material	***Specific Gravity***	***Porosity***	***Ksat (ft/d)***	***van Genuchten SWCC Parameters***		
				Alpha (1/psf)	***Beta***	***Residual Saturation (%)***
SP1	2.75	0.383	61.7	0.0061	3.903	11.2
SM1	2.75	0.379	18.8	0.0033	4.685	3.6
C1	2.62	0.333	0.833	0.0053	1.554	5.9
SPSM	2.5	0.383	39.7	0.001	12.07	12.3
CL1	2.65	0.44	0.002	0.0041	2.278	14.9

3.3. Model Geometry

Both two and three dimensional models of the levee were created and analyzed. The presence of a 90 degree bend in the levee and the culvert to allow flow from the Clear Ditch passage through the levee could only be suitably modeled in three dimensions.

3.3.1. Two Dimensional Geometry

Figure 2 depicts the cross section of the levee and Clear Ditch in the east-west direction. Note that the Clear Ditch runs parallel to the Rio Grande and levee alignment from north to south.

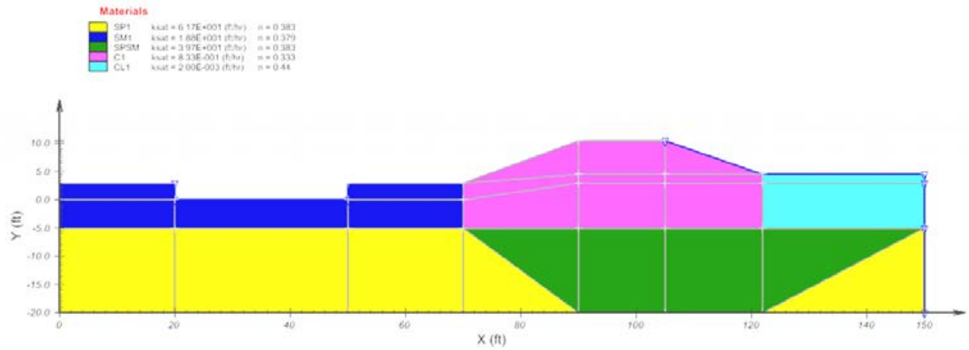

Figure 2: East-West 2D Cross Section. See cross-section A-A1 location in Figure 5.

A cross section of the levee running along the centerline of the Clear Ditch is shown in Figure 3. Zero flux boundaries are placed at the upstream and downstream vertical faces of the levee to simulate the presence of the concrete entrance structures of the culvert. The void of the actual box culvert cannot be modeled in 2D because it creates an unrealistic scenario where the upper part of the levee is discontinuous with the lower. The culvert is not considered in the 2D example as a three dimensional analysis is required to adequately model the presence of the culvert.

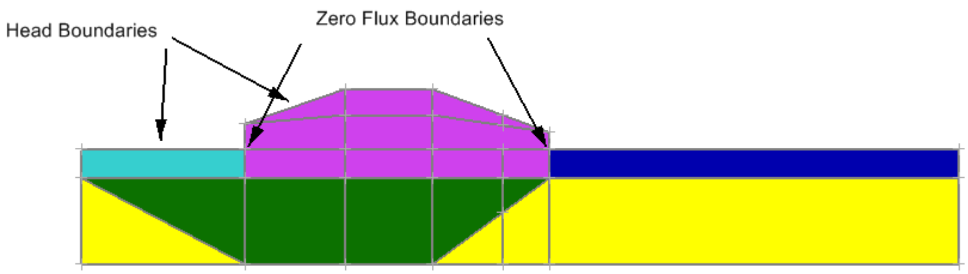

Figure 3: North-South Culvert Geometry (along Clear Ditch centerline). See cross-section B-B1 location in Figure 5.

3.3.2. Three Dimensional Model Geometry

Figure 4 shows the geometry of the three-dimensional model. The layering of the materials can be clearly visualized. The cut-outs for the ditch and culvert are not shown in this figure.

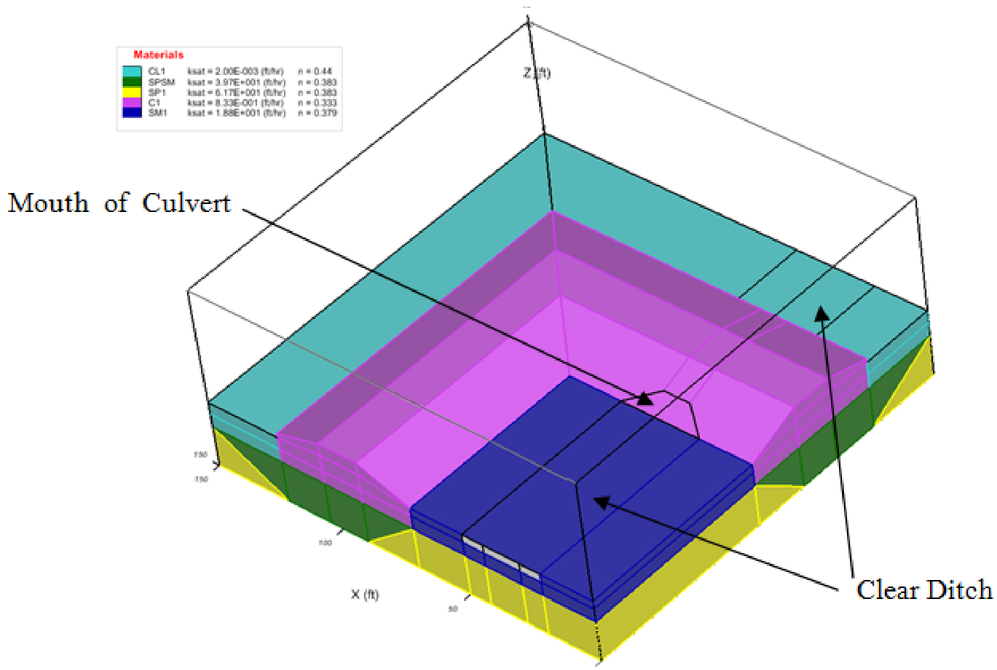

Figure 4: 3D Levee Intersection Geometry

The solution of the 3D model is seen in Figure 5. Here the 90 degree bend in the geometry and presence of the box culvert and wing walls can be visualized. Also shown are the locations of the cross-sections presented in Figures 1 and 2.

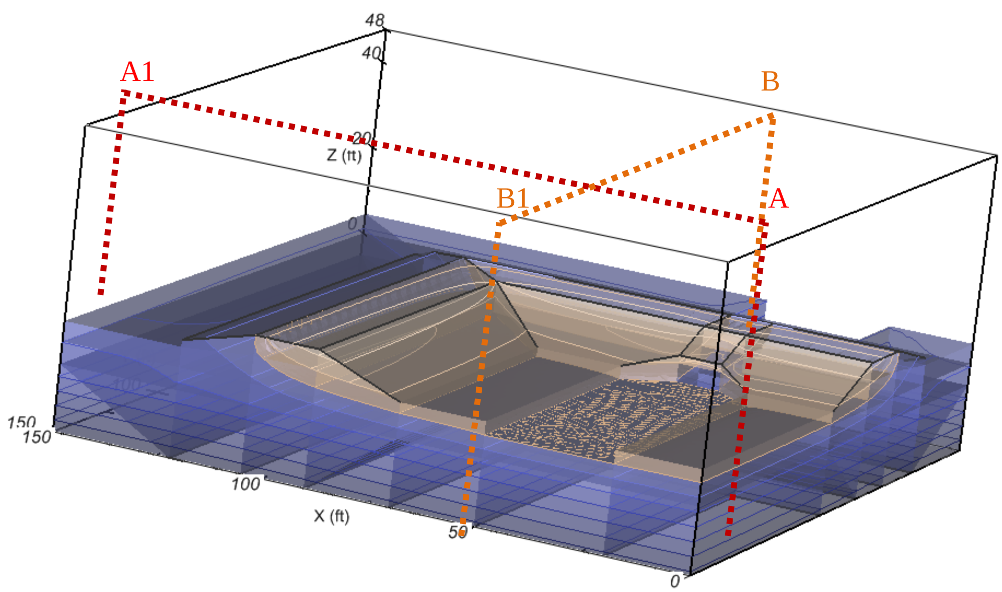

Figure 5: 3D Geometry Post-Analysis. Cross-Section A-A1 is shown in Figure 2, while cross-section B-B1 is shown in Figure 3.

3.4. Boundary Conditions

The system is assumed to be horizontally continuous in terms of the levee cross-section and material layers. Zero flux boundaries are placed upon the vertical edges and bottom boundaries. Variable head boundaries based upon the water level are applied to the levee sides and upstream ground surface. Head boundaries which change as a function of time are applied to the Clear Ditch bottom and side walls to simulate the filling conditions present within the ditch. As the primary purpose of the Clear Ditch is as a groundwater drain, it is assumed that during a flood event the ditch would be nearing capacity. For all scenarios, the 3 foot deep ditch is modeled as having a head of 2.5 feet. The datum for this model is set as the bottom of the Clear Ditch. This is expected to be the average groundwater elevation observed within the vicinity of the model.

4 RESULTS

4.1. Two Dimensional

The two dimensional results show that there will be no critical exit gradients developing in the Clear Ditch. There is not expected to be a seepage face developing on the downstream face of the levee. The following sections show the pore-water pressure contours and gradients of the two dimensional cross sections for each flood event.

4.1.1. Snowmelt Flood Wave

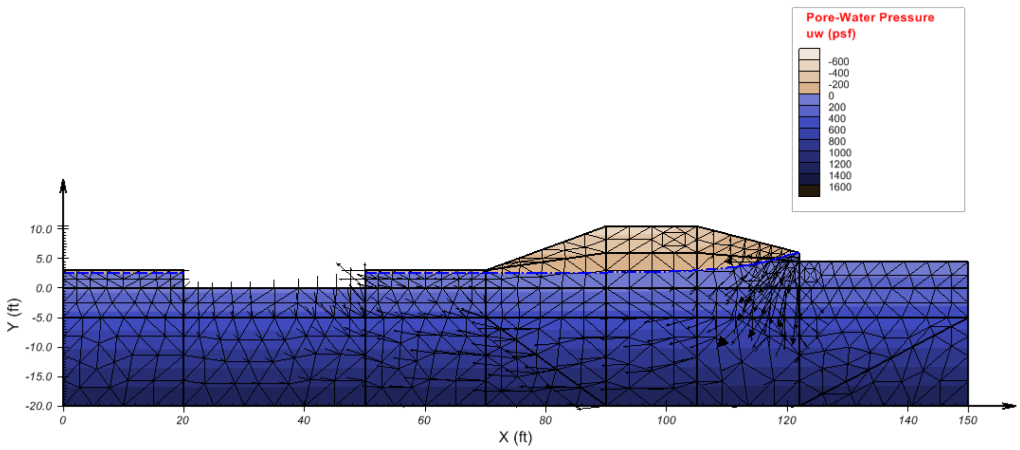

Figure 6: Pore-water pressure contours and flux vectors at the peak of the snowmelt flood wave

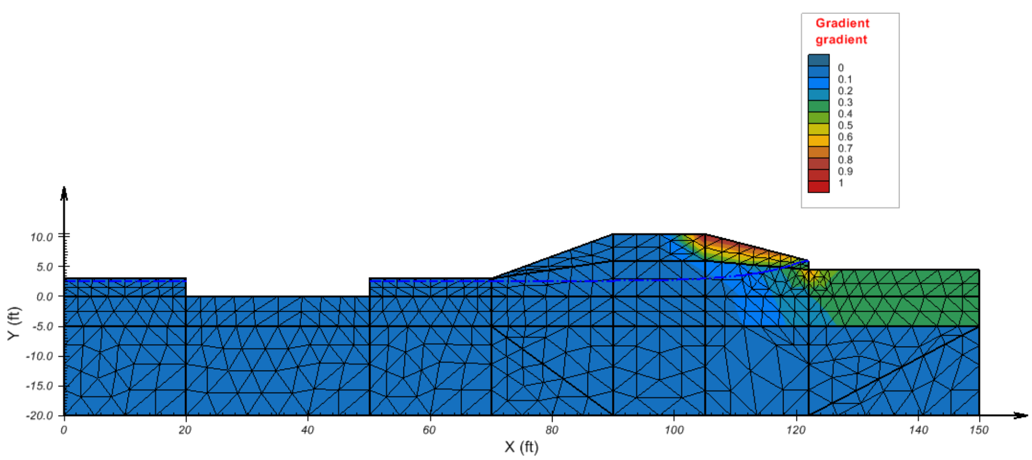

Figure 7: Gradients and flux vectors at the peak of the snowmelt flood wave

4.1.2. Steady-state Maximum Design Flood Wave

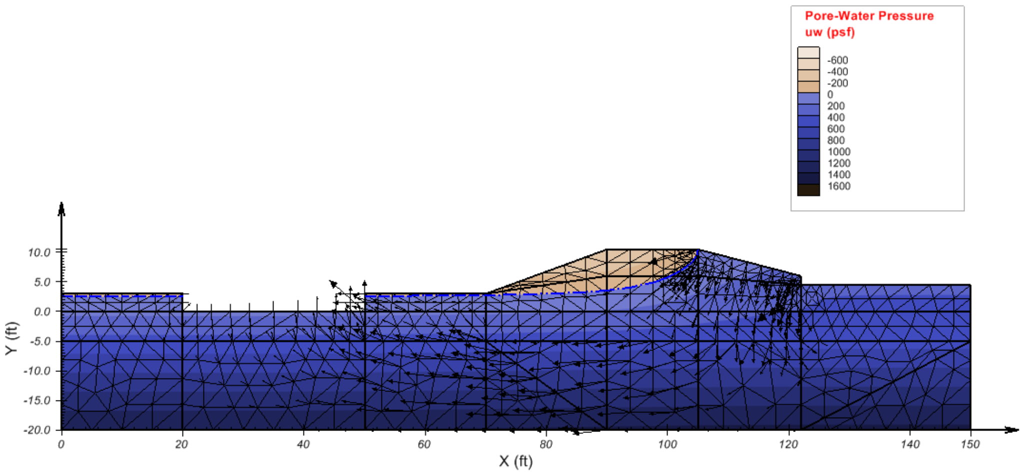

Figure 8: Pore-water pressure contours and flux vectors at the peak of the mean annual flood

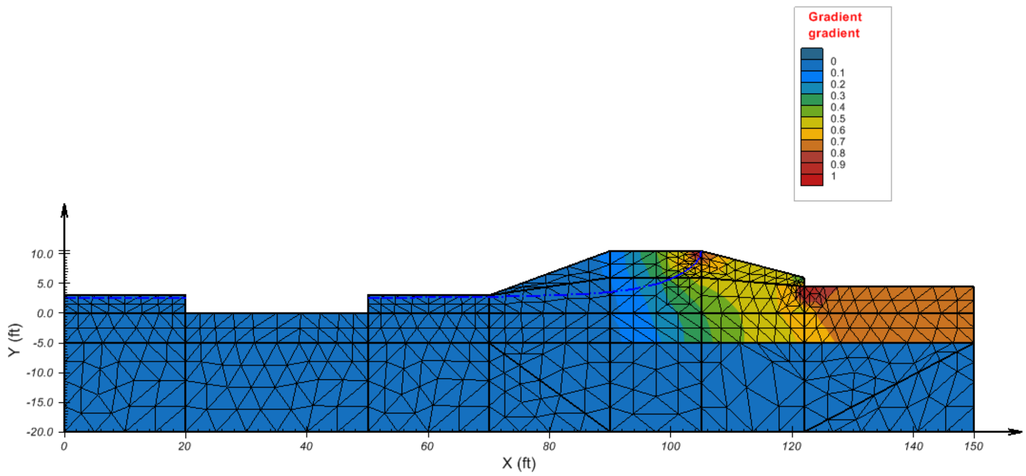

Figure 9: Gradients at the peak of the steady-state maximum design flood wave

4.1.3. Transient Maximum Design Flood Wave

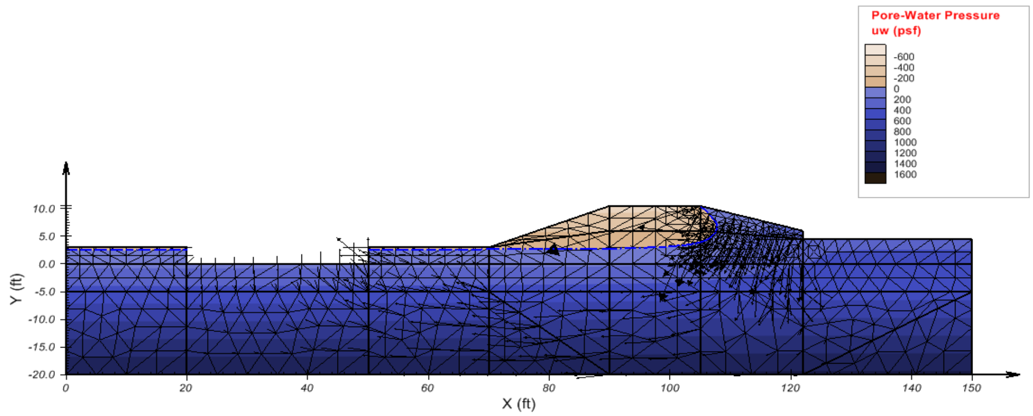

Figure 10: Pore-water pressure contours and flux vectors at the peak of the transient maximum design flood wave

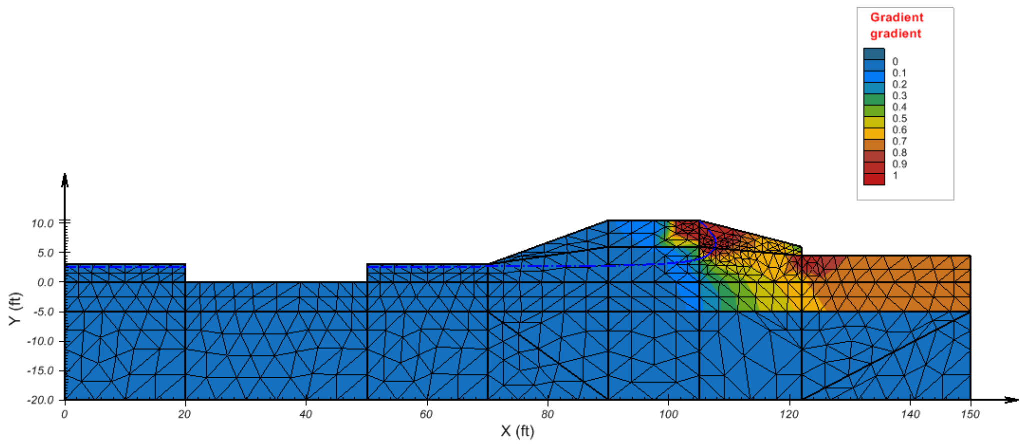

Figure 11: Critical gradients at the peak of the transient maximum design flood wave

4.2. Three Dimensional

The three dimensional scenarios differed from the 2D models when the culvert and 90 degree intersection are considered. The following sections summarize the results for each flood scenario.

4.2.1. Snowmelt Flood Wave

Figures 12 and 13 show the critical gradients and pore-water pressure for the snowmelt flooding scenario. It can be seen from this analysis the same conclusions can be drawn as for the 2D analyses. It can be seen that the majority of flow will be occurring near the entrance to the culvert in Figure 13.

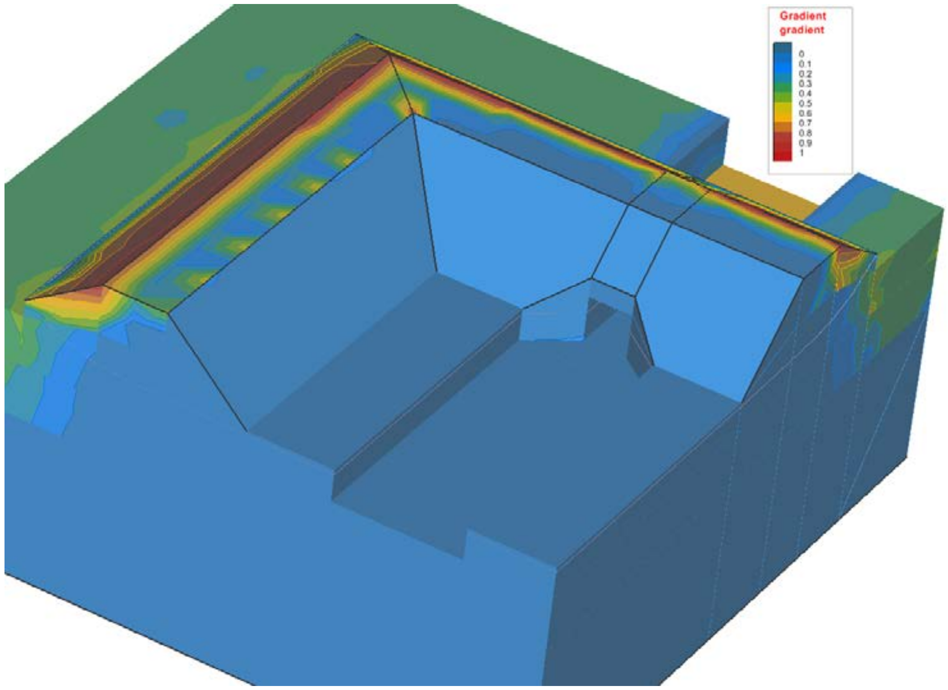

Figure 12 Critical gradients near the wing walls for the steady-state snowmelt flood wave

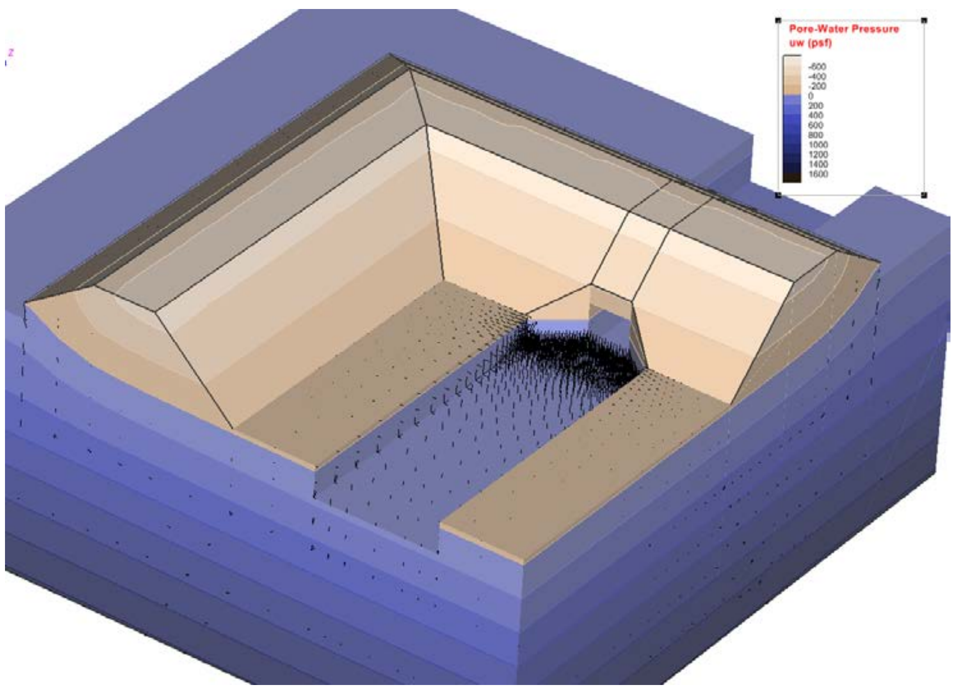

Figure 13: Pore-water pressure contours and flux vectors for the steady-state snowmelt flood wave, showing saturated (blue) and unsaturated zones (brown)

4.2.2. Steady-state Maximum Design Flood

Figures 14 and 15 show the gradient and pore-water pressure distributions for the steady-state maximum design flood. The pore-water pressure distribution shows that there is a seepage face developing at the intersection of the levees. There are also increased gradients of 0.3-0.4 occurring along the base of the wing walls at the culvert entrance. These gradients represent potential for piping and boiling resulting in levee instability.

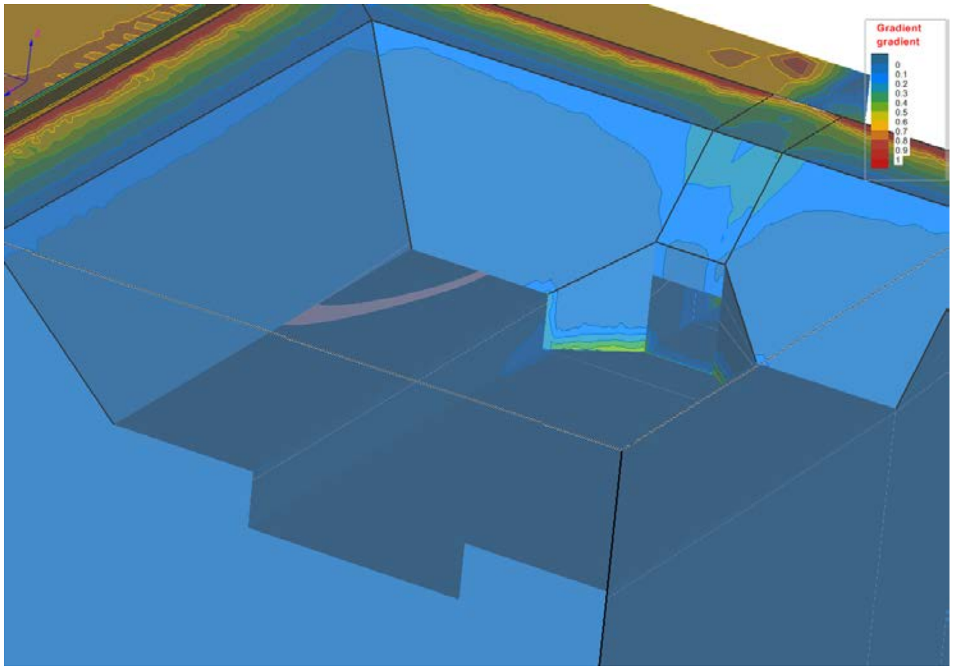

Figure 14: Critical gradients near the wing walls for the steady state maximum design flood

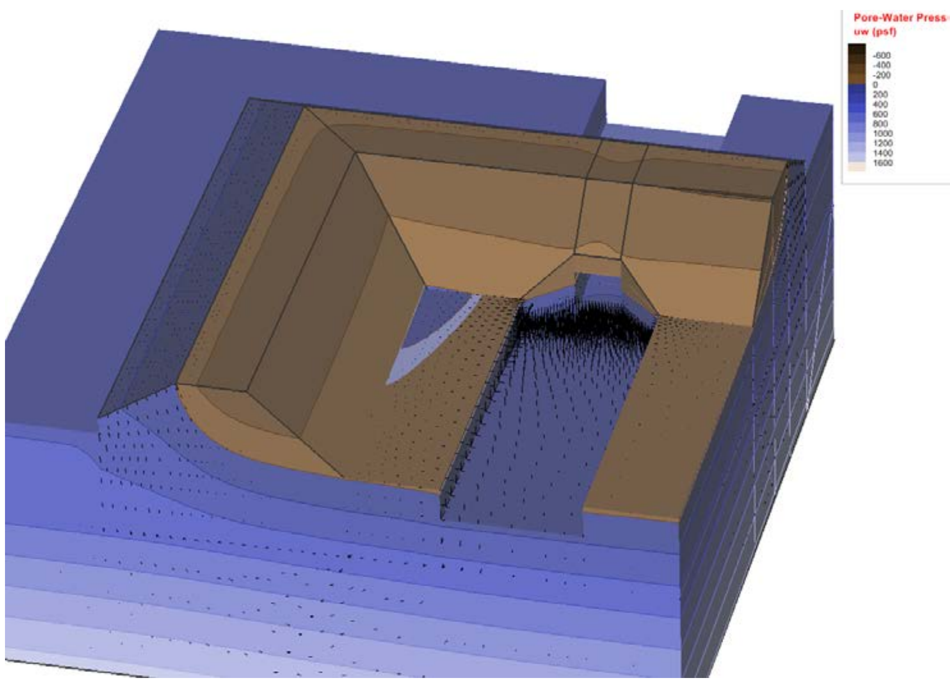

Figure 15: Pore-water pressure contours and flux vectors for the steady-state maximum design flood, showing saturated (blue) and unsaturated zones (brown)

4.2.3. Transient Maximum Design Flood

The gradient and pore-water pressure distribution for the transient maximum design flood are shown in Figures 16 and 17. When the transient conditions are assumed, no seepage face is found to develop on the downstream levee face. Similarly only small increases in the gradient along the wing walls are observed.

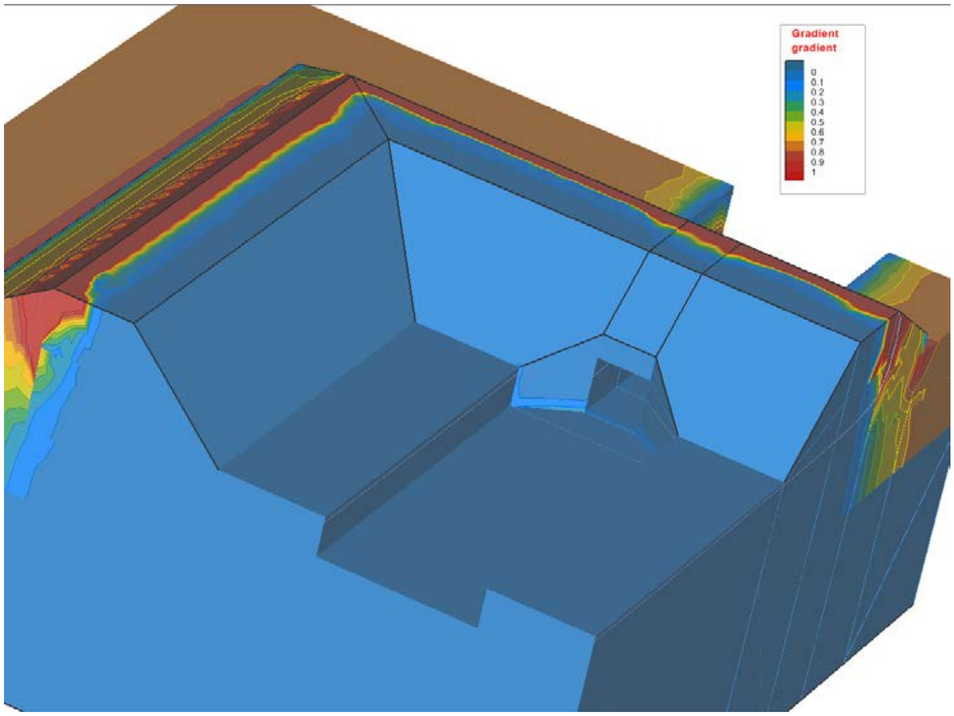

Figure 16 Critical gradients near the wing walls for the transient maximum design flood

5 DISCUSSION

5.1. Water Table

The 90-degree bend in the levee results in a decrease in the area through which flow can occur through the levee. This results in a higher water table than would be expected along a straight 2D continuous section of the levee. The 3D steady-state maximum flood wave simulation revealed a seepage face developing at the landside, inside corner of the levee 90-degree bend. The funnel effect at this inside corner is a result of the increased flux conveyed at this point. The 2D seepage analysis does not simulate this levee-geometry induced increase in flux. This focussing or funnel-effect occurs at any portion of a levee system which contains a horizontal alignment resulting in a riverside convex bend. Ignoring this effect could lead levee designers to underestimate the seepage under and through a levee. Considering this effect in design could yield insight into more effective means to control seepage (relief well and toe drain design) and strengthen or widen otherwise insufficient levee sections. Considering the converse case in which the levee alignment is concave relative to the flood waters levee designers utilizing only 2D analysis could be overestimating the required levee section width and required means to control seepage. In these cases 3D analysis would result in a cost savings. Three dimensional compared with 2D analysis will assist designers in generating a levee system which is more resilient and stable while minimizing costs associated with excess resource utilization and construction.

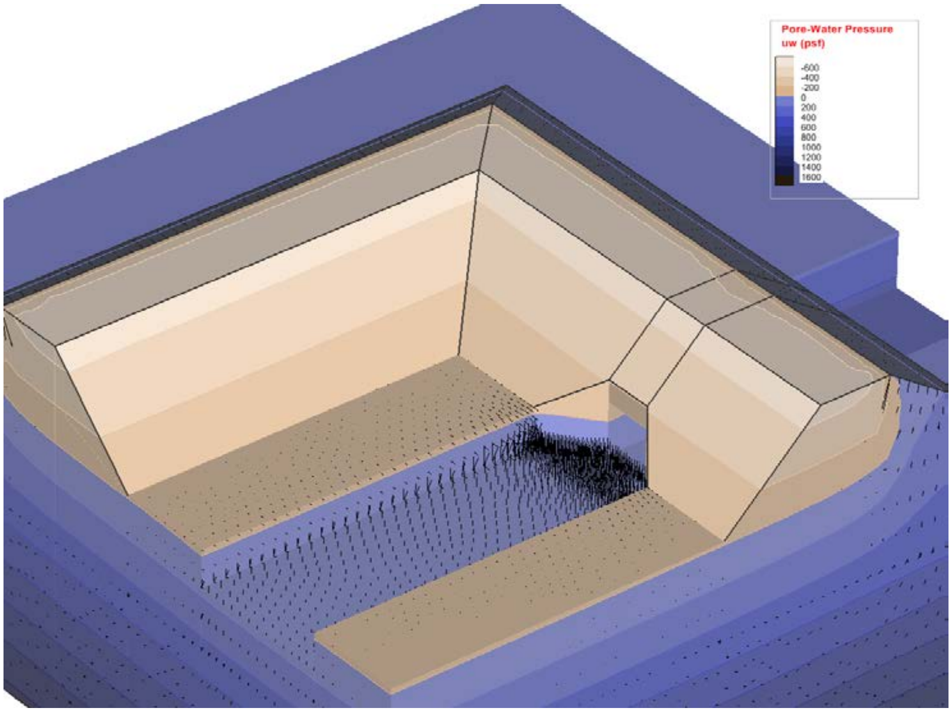

Figure 17: Pore-water pressure contours and flux vectors for the transient maximum design flood, showing saturated (blue) and unsaturated zones (brown)

5.2. Critical Gradients

While no critical gradients are observed on the downstream side of the 2D analysis, the 3D maximum design flood analyses show increased gradients around the wing wall leading into the culvert. This is indicative of potential erosion and piping underneath and around the wing walls. Most of the seepage through this area of the levee system will occur upwards at the floor of the Clear Ditch near the entrance of the culvert.

Critical gradients are observed on the riverside of the levee and are due to the dissipation of head as the fluid enters the system. Rapid drawdown on the riverside face of the levee can result in reduced slope stability associated with excess pore-pressure.

6 CONCLUSIONS

Based upon the results of 3D numerical modeling, the performance of irregular levee features can be effectively modeled to better depict the physical processes occurring. Sharp changes in levee alignments and intrusions, such as culverts, can only be effectively modeled in 3D. This also makes other advanced geotechnical analyses possible, such as 3D slope stability, with an overall improvement in the practitioner's understanding of the problem.

7 REFERENCES

AMEC Earth and Environmental, 2008. "*Albuquerque West Levee Project, Geotechnical and Seepage Analysis Report*": Albuquerque, New Mexico.

SoilVision Systems Ltd., 2011. "*SVFlux Theory Manual*": Saskatoon, Saskatchewan.