DESIGN SOLUTIONS FOR SEEPAGE END-AROUND-EFFECTS AT CUTOFF WALL DEPTH TRANSITIONS

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Cutoff walls are commonly used to mitigate underseepage problems for levee remediation projects. At the transition between shallow and deep seepage cutoff walls there is a potential for water to flow around the back of the deeper cutoff wall leading to elevated seepage pressures on the landside that could result in exit gradients exceeding design criteria. This condition is referred to as end-around-effects and is a complex 3-D problem that requires detailed and potentially time consuming analysis. This paper presents a simplified approach for assessing end-around-effects using the results of 2-D seepage analysis to determine if lateral extension of the deeper portion of the cutoff wall is required. This simplified approach provides a pragmatic solution to a complex 3-D problem.

INTRODUCTION

As the lead geotechnical consultant for the Feather River West Levee Project, URS were responsible for designing levee remediation works for approximately 35 miles of levee protecting the area around Yuba City, California, and communities to the north and south. Due to land use constraints, seepage cutoff walls were the main remediation alternative selected to address underseepage issues for the project.

As part of the design review process, the California Department of Water Resources (DWR) requested URS to look at 26 locations along the levee alignment where the depth of cutoff wall transitioned from shallow to deep, or vice versa. At these locations there was the potential for seepage pressures to pass behind the deeper section of cutoff wall and stress the blanket layer landward of the cutoff wall. A condition referred to as end-around-effects.

In discussions with DWR, URS developed a simplified approach to provide a more objective assessment of potential end-around-effects and whether the location of cutoff wall transition at a particular location was appropriate or whether extension of the deeper section of cutoff wall were necessary.

UNDERSEEPAGE AND EXIT GRADIENT

As seepage pressures beneath a levee increase due to rising flood waters, boils and subsurface piping can develop landward of the levee that can induce subsidence, loss of freeboard and lead to a levee breach. This failure mechanism is the result of underseepage and develops when a levee is founded on a fine-grained layer, referred to as a blanket layer, overlying more pervious material, referred to as an aquifer (Figure 1). If the thickness of the blanket layer is not sufficient to resist uplift pressures generated by water flowing through the aquifer, cracks and/or boils can develop on the landside of the levee. As water flows up through a crack or boil, subsurface materials can be transported to the ground surface leading to the formation of a void or pipe beneath the levee, which may collapse over time and cause the levee to fail.

The potential for the formation of boils and transportation of subsurface material to the ground surface can be represented by the ratio of the uplift pressure generated by flow through the aquifer to the thickness of the blanket layer. This ratio is referred to as the exit gradient and can be calculated using the following equation.

$$\text{Exit gradient (i)} = \frac{\text{Underseepage Uplift Pressure}}{\text{Blanket thickness}}$$

Underseepage uplift pressure is measured at the bottom of the blanket layer and is measured in terms of feet of water.

Past experience shows that boils can initiate at exit gradients ranging from 0.3 to 0.8 depending on the nature of the materials present (Mansur and Kaufman, 1955). In accordance with Urban Levee Design Criteria (DWR, 2012), a calculated exit gradient at the landside levee toe of 0.5 or less is required for the design water surface elevation. If the exit gradient for a levee exceeds 0.5, then remediation is required.

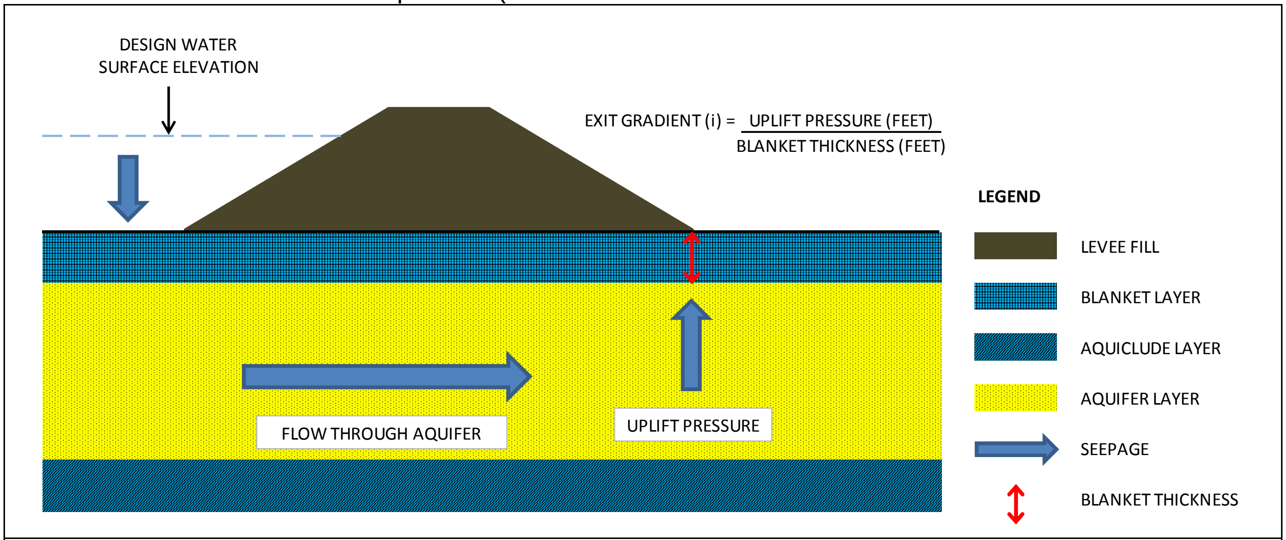

Figure 1 – Typical Levee Cross Section

Remediation alternatives include:

- Installation of a seepage cutoff wall to form a seepage barrier
- Installation of relief wells to reduce the uplift pressure on the bottom of the blanket layer
- Construction of a seepage berm

In the case of the cutoff wall option, the wall must penetrate deep enough to either cutoff the seepage path completely (Figure 2a) or create enough of a thickened blanket by "stitching" together intermediate fine-grained layers (Figure 2b) to bring the exit gradient to 0.5 or less.

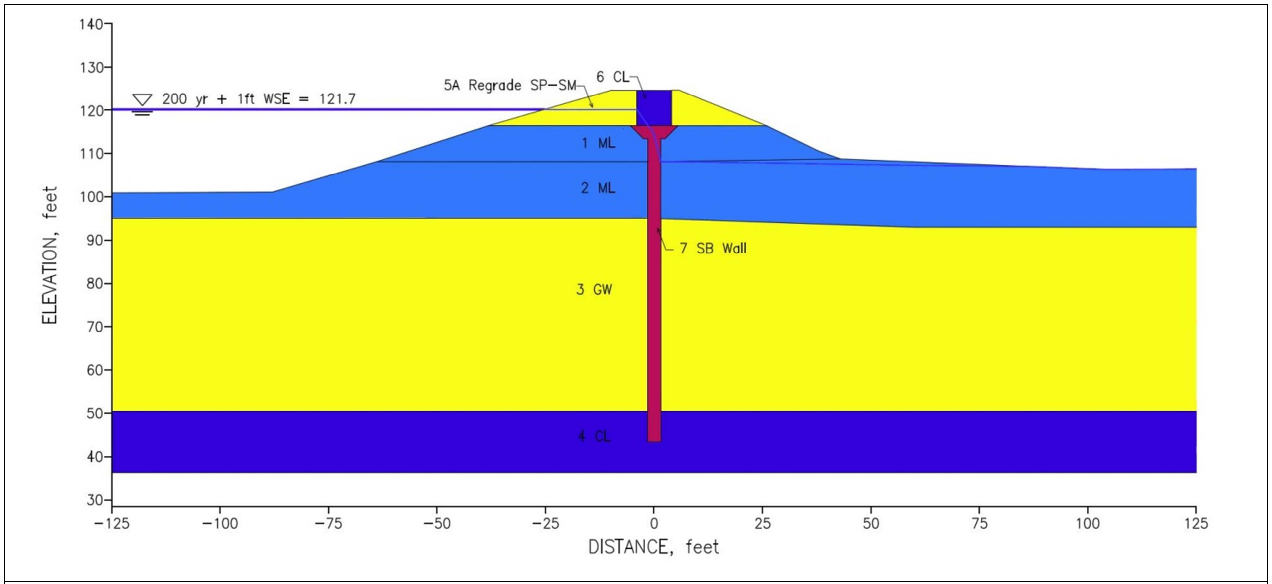

Figure 2a – Typical Cross Section of Fully Penetrating Cutoff Wall Forming a Seepage Barrier

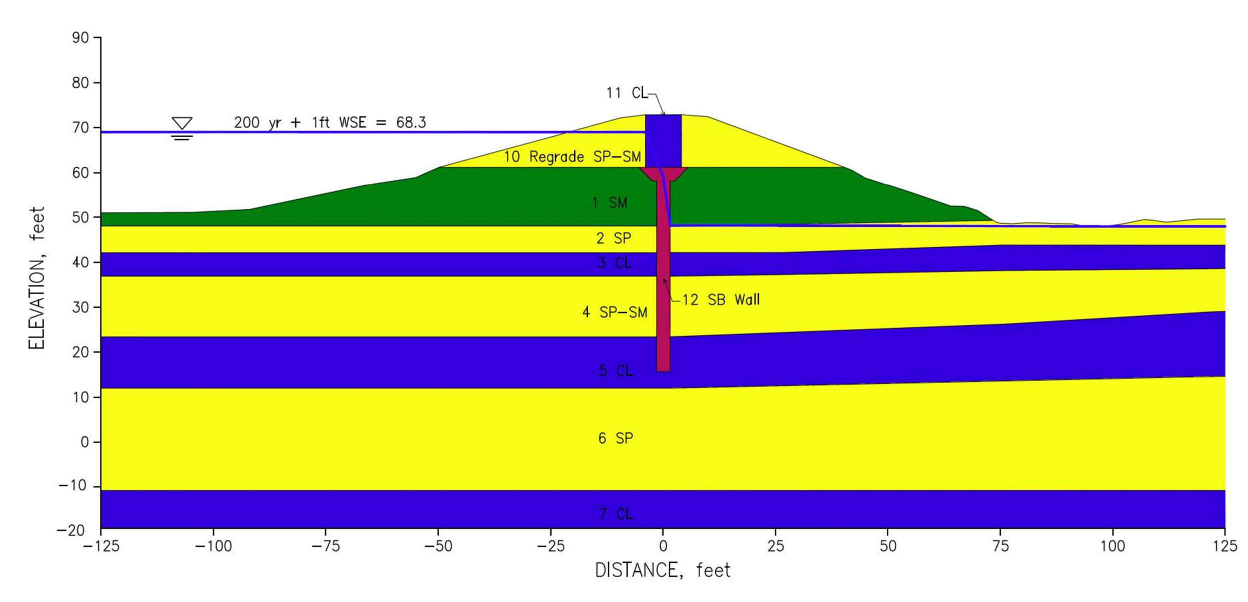

Figure 2b – Typical Cross Section of Stitching Cutoff Wall Creating a Thickened Blanket

END-AROUND-EFFECTS

Due to changing subsurface conditions along the alignment of a levee, the depth to which a cutoff wall needs to be installed can change abruptly. Consider the longitudinal profile shown in Figure 3. On the left hand side of the profile there are several interbedded fine grained layers where a shallow cutoff wall can stitch together these layers to create a thickened blanket condition sufficient to reduce the exit gradient to less than 0.5. However, on the right hand side, there are no such intermediate fine grained layers and a deep cutoff wall is required to completely cutoff the aquifer.

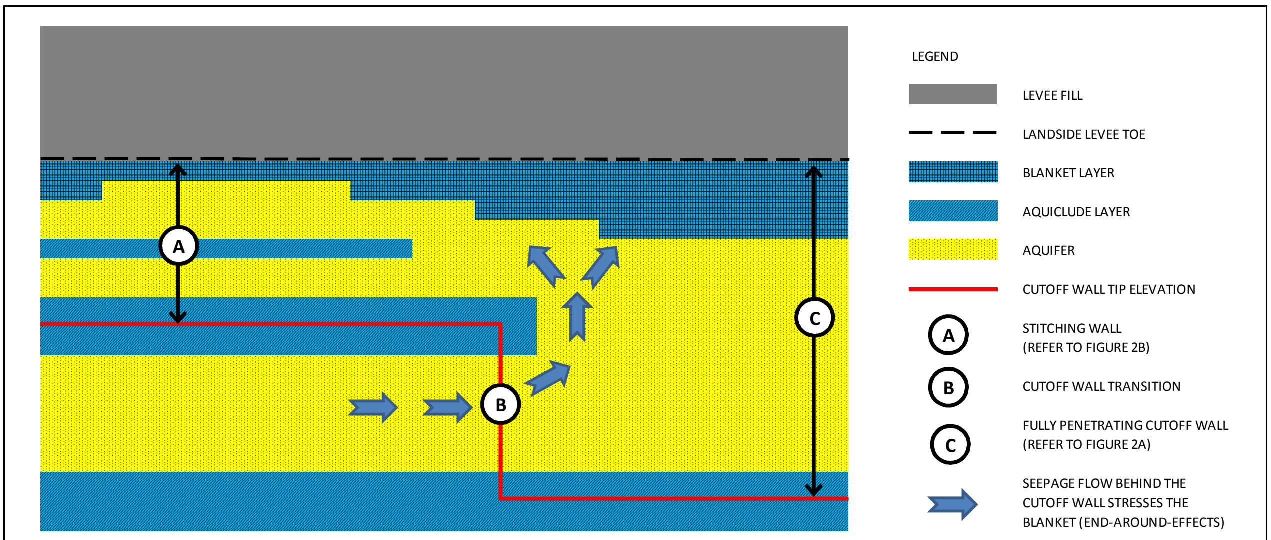

Figure 3 – Typical Longitudinal Profile Through Levee Crown

At the edge of the deeper portion of cutoff wall (labeled B in Figure 3), seepage pressures can pass through the aquifer layer adjacent to the edge of the deeper cutoff wall and stress the blanket landward of the cutoff wall. This condition is referred to as end-around-effects. As the water seeps behind the wall there is a drop in hydraulic head due to friction losses. If the seepage path from the edge of the deep cutoff wall to a potentially critical blanket location (For example location A, B, or C in Figure 4) is not long enough, there might not have been sufficient dissipation of excess head to prevent the exit gradient from exceeding 0.5.

To address the potential for end-around-effects, the standard of practice in the industry has been to laterally extend the deeper cutoff wall an arbitrary distance based on engineering judgment without quantifying whether such an extension is sufficient or whether it is needed at all. The implication of this is that a levee maintaining agency might be paying more than necessary for a levee remediation project, or might still have a weak point in their levee system after completion of levee remediation works. For this reason a more objective assessment of end-around-effects is needed in the industry.

SIMPLIFIED APPROACH FOR ASSESSING END-AROUND-EFFECTS

The simplified approach developed by URS in consultation with DWR uses steady state seepage results from two-dimensional SEEP/W analyses to identify the rate of head loss through the aquifer layer and uses this to check whether end-around-effects are a concern. The procedure uses the following steps:

1. Using engineering judgment, identify locations relative to the transition point between the deeper and shallower sections of cutoff wall where the blanket layer thins and could be critical in terms of exit gradient. Determine the distance between the potentially critical blanket condition locations and the transition point between deeper and shallower sections of cutoff wall.
2. For each of the potentially critical blanket condition locations identified in Step 1, identify the excess pressure head relative to the calculated existing conditions exit gradient at each location, i.e. with no cutoff wall present. For example, if the blanket layer at the critical location was 10 feet thick and the calculated exit gradient across the blanket was 0.65 at the design water surface elevation, the excess gradient equals 0.65 – 0.5 = 0.15. For a 10 feet thick blanket layer an excess gradient of 0.15 represents 1.5 feet of excess pressure head (10 x 0.15).
3. From the existing conditions SEEP/W analysis, i.e. without the cutoff wall present, identify the length of flow path through the aquifer layer required to provide a 1-foot drop in pressure head.
4. Multiply the length of flow path required to provide a 1-foot drop in pressure head calculated in Step 3 with the excess pressure head calculated in Step 2 to identify the length of flow path required to achieve an exit gradient that meets criteria, i.e. 0.5 at the design water surface elevation.
5. Compare the length of flow path required to achieve an exit gradient of 0.5 calculated in Step 4 with the actual distance between the critical blanket condition location relative to the transition point between the deeper and shallower sections of cutoff wall identified in Step 1. If the actual distance is greater than the calculated required distance then no wall extension is required. If not, the deeper section of cutoff wall needs to be extended to achieve a total flow path distance equal to that calculated in Step 4.

Consider the example shown in Figure 4. Three potentially critical blanket locations have been selected, labeled “A”, “B”, and “C”.

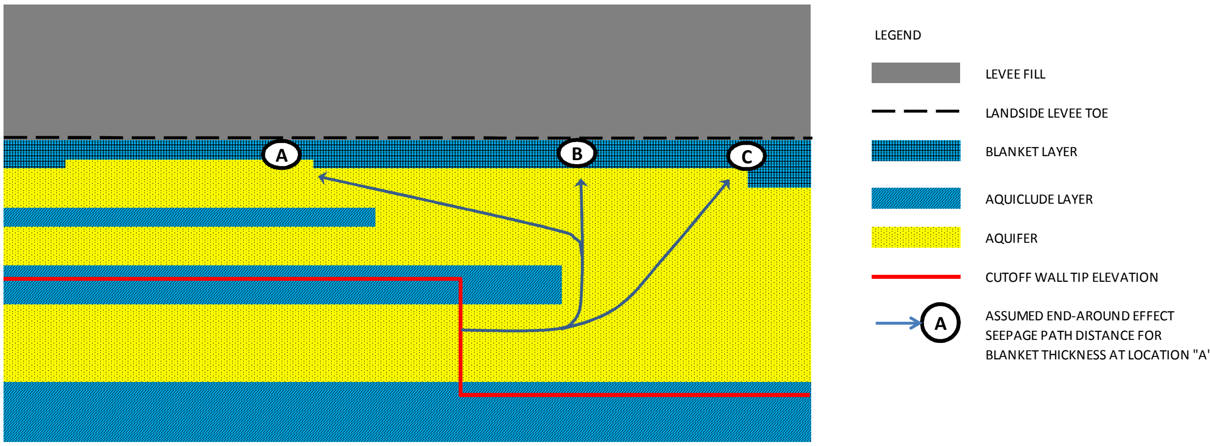

Figure 4 – End-Around-Effect Seepage Path Relative to Potentially Critical Blanket Thickness Locations

Assume that based on the SEEP\W results of the existing conditions analysis, the length of flow path through the aquifer layer to generate 1 foot of head loss is 75 feet. Running through the analysis steps:

Step 1 – identify the blanket thickness, length of the flow path and exit gradient at each location (Table1, Columns 2, 3, and 4 respectively)
Step 2 – identify the excess gradient relative to an allowable gradient of 0.5 or less (Table1, Columns 5)
Step 3 – identify excess head (Table 1, Column 6)
Step 4 – identify required length of flow path (Table 1, Column 7)
Step 5 – compare results of Column 7 with Column 2 to see if the existing length of flow path (Column 2) is greater than the required length of flow path (Column 7).

Based on the worked example presented in Table 1, the existing length of the flow path to location "C" relative to the blanket thickness at this location is sufficient to achieve an exit gradient of 0.5 or less. For locations "A" and "B", the existing length of flow path is not sufficient to achieve an exit gradient of 0.5 or less. Therefore, the transition point between the shallower and deeper cutoff wall needs to be moved to increase the length of the flow path around the end of the cutoff wall. Based on the calculated results the deeper cutoff wall needs to be moved 80 feet to the left in order to satisfy the exit gradient criteria at both "A" and "B".

Table 1 – Evaluation of End-Around-Effects for Different Blanket Thicknesses and Locations

Location	Blanket Thickness (feet)	Length of Flow Path to Blanket Location (feet)	Exit Gradient Across Blanket	Excess Gradient[1]	Excess Head (feet)[2]	Required Length of Flow Path (feet)	Length of Wall Extension Required (feet)
A	7	240	1.05	0.55	3.85	290	50
B	9	140	0.82	0.32	2.88	220	80
C	12	170	0.61	0.11	1.32	100	0

Notes:
[1] Assume allowable exit gradient of 0.5
[2] Equals Column 2 x Column 5
[3] Equals Column 6 x 75 (rounded to nearest 10 feet) – assuming 75 feet of flow for 1 foot of head drop.

CONCLUSIONS

The current standard of practice to address potential end around effects at the transition between shallow and deep seepage cutoff walls has been to adopt a standard cutoff wall extension distance based solely on engineering judgment. This paper presents an objective method using two-dimensional seepage results to assess exit gradients in the vicinity of shallow to deep cutoff wall transitions to determine the length of extension, if any, required to address end around effects.

URS used the presented approach to analyze end-around-effects at 26 cutoff wall transition locations on the FRWL project. The analyses showed that at 24 of the 26 locations the transition between shallow/deep cutoff walls was appropriate and end around effects were not an issue. At two locations the extent of the deep cutoff wall was increased in order to meet exit gradient criteria taking into account end around effects. If a standard cutoff wall extension had been applied in accordance with the current standard of practice, the length of wall extensions for the FRWL project would have been considerably greater and more costly to the Client.

The presented approach can also be used for the following cases:

- to assess end around effects at the start and end of a cutoff wall,
- to assess the required overlap distance between different levee remediation techniques, such as when a cutoff wall transitions into an area remediated using a seepage berm or relief wells.

In certain situations additional exploration data may be required to make an accurate determination of end around effects. In such cases, the cost of additional explorations should be weighed against the cost of an assumed wall extension based on engineering judgment to see if the additional expense is warranted.

REFERENCES

California Department of Water Resources, 2012. Urban Levee Design Criteria

Mansur C.I. and Kaufman R.I., 1955. Control of Underseepage, Mississippi River Levees. St Louis District, CE.