Analysis of Injection Wells for London Avenue Canal Test Section

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Two different analyses were performed to analyze the effectiveness of the injection wells, and to determine the required depth and spacing needed to approximate the condition where the sheet pile cofferdam is installed in the center line of the canal and there is a direct hydraulic connection between the bottom of the canal and the relic beach sand layer. One analysis was performed assuming that the sheet pile cofferdam penetrated into the bay sound clay (fully penetrating case). The second analysis was performed assuming that the sheet pile cofferdam is driven to an elevation of -31.5 ft NAVD88 (partially-penetrating case).

Fully-Penetrating Sheet Pile Cofferdam

Shown in Figure 1 is the general cross section used for the analysis incorporating a fully penetrating sheet pile cofferdam. The geometry used is based on the topographic survey and site exploration completed at the midsection of the test area. The hydraulic properties of the soil layers used in the analysis are the same as used in the IPET report for the London Avenue Canal.

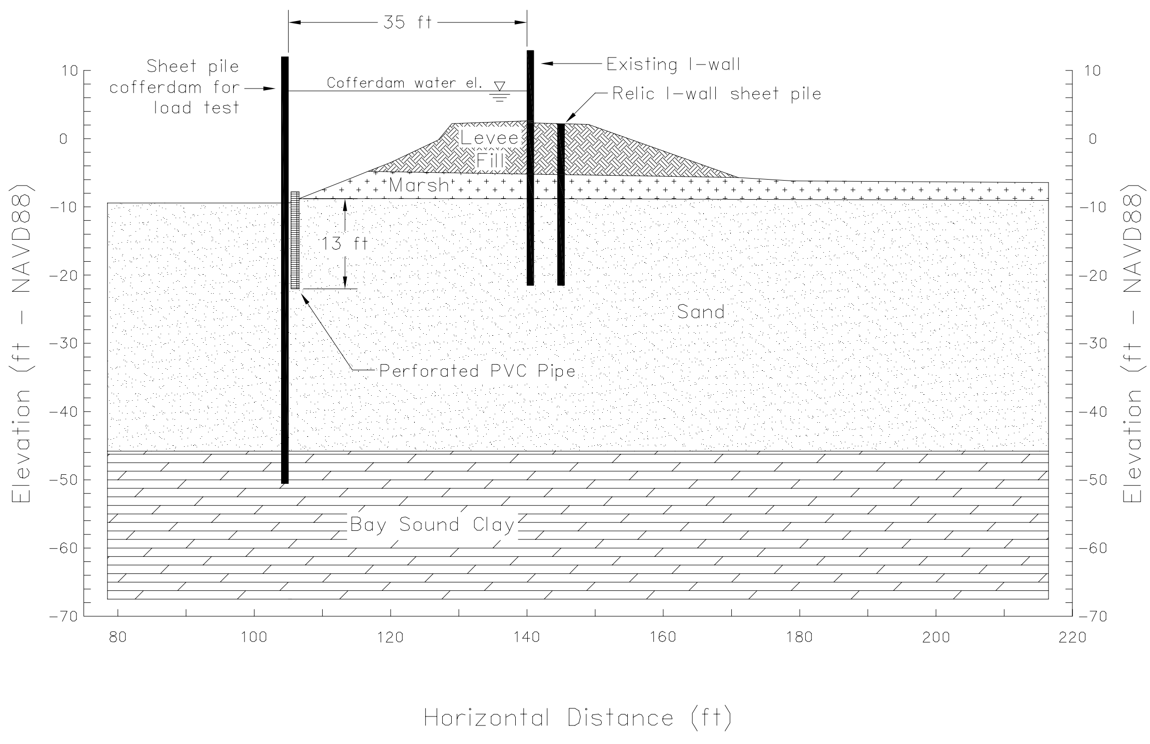


Figure 1 Cross section used for analysis of fully-penetrating sheet pile cofferdam.

Shown in Figure 2 is the finite element mesh used for the fully-penetrating case. The injection wells was modeled using constant head nodes, with the head assigned being equal to the cofferdam water level. The sheet pile cofferdam was modeled with zero flow nodes.

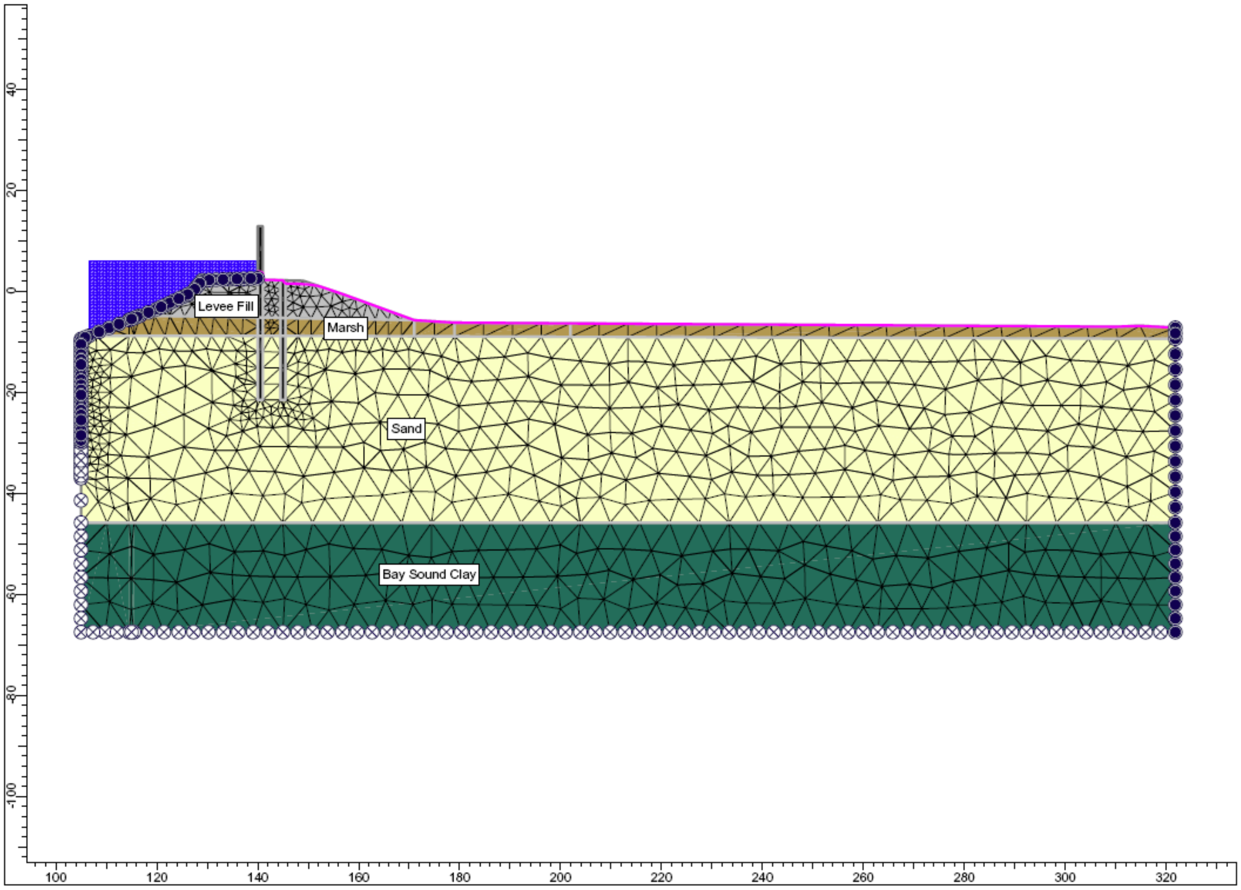


Figure 2 Finite element mesh used for fully-penetrating sheet pile cofferdam.

In order to assess the effectiveness of the injection wells, pore pressures were calculated at the tip of the I-wall sheet pile, and at the marsh/sand interface directly beneath the toe of the protected side levee embankment. It was assumed that if the pore pressures at these locations were the same as those calculated for a condition where the center of the canal was a no-flow boundary, then the injection wells could be deemed effective. These two locations were chosen because (1) the pore pressure values at these locations affect the I-wall performance for stability and erosion, and (2) piezometers are planned to be installed at these locations.

Analyses were performed varying the depth of the injection wells. Shown in Figure 3 are the pore pressures determined at the marsh/sand interface for injection well tip elevations ranging from -10 ft NAVD88 to -30 ft. This analysis was performed for a water level inside of the cofferdam equal to +4 ft NAVD88. The pore pressure at this location increases with increasing depth of the injection well. At a tip elevation of about -22 ft, the pore pressures at this location are equal to the “correct” pore pressures determined for the full-canal analysis. For injection well tip elevations below -22 ft, the pore pressures for the test section would exceed those expected for actual canal loading.

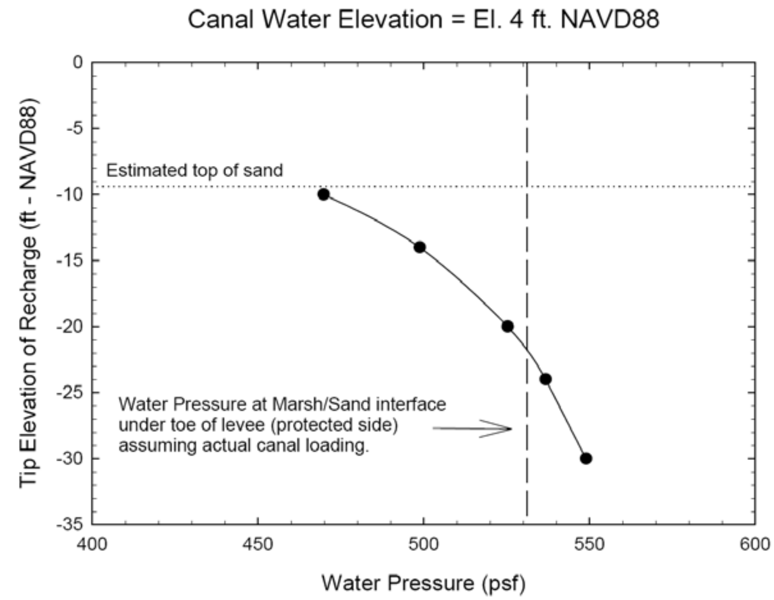


Figure 3 Pore pressures at marsh/sand interface for canal water elevation of +4 ft NAVD88 (fully-penetrating sheet pile cofferdam).

Figure 4 shows the results of a similar analysis for the pore pressures at the tip of the I-wall sheet pile for the same conditions as described above. As shown by the figure, an injection well tip elevation of -22 ft would create the same pore pressures as for full canal loading. Analyses were also performed for cofferdam water levels of +6 ft and +8 ft. As might be expected from the geometry, the optimal well tip elevation was not dependent on the cofferdam water elevation, and an elevation of -22 ft was obtained for these cofferdam water elevations as well. These analyses are shown in Figures 5 through 8.

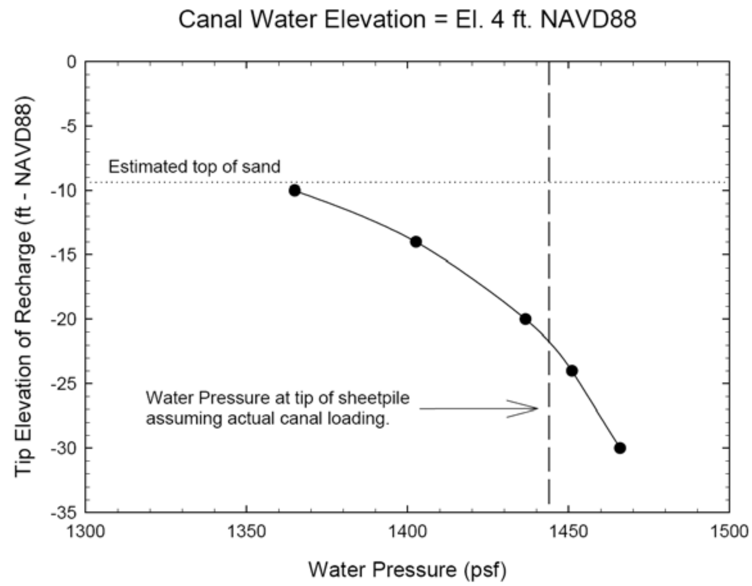


Figure 4 Pore pressures tip of I-wall sheet pile for canal water elevation of +4 ft NAVD88 (fully-penetrating sheet pile cofferdam).

In summary, an injection well tip elevation of -22 ft NAVD88, corresponding to about 13 ft of penetration into the sand layer, would create pore pressures approximately the same as for full canal loading for the case of a fully-penetrating sheet pile cofferdam.

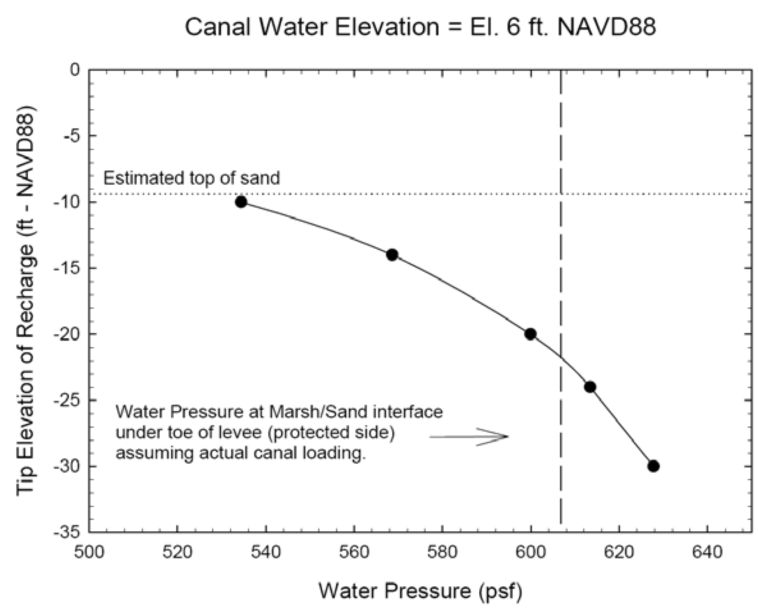


Figure 5 Pore pressures at marsh/sand interface for canal water elevation of +6 ft NAVD88 (fully-penetrating sheet pile cofferdam).

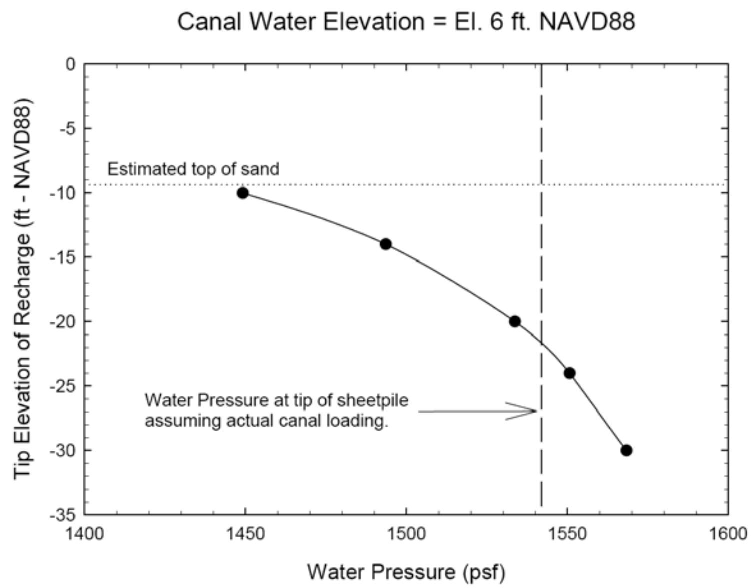


Figure 6 Pore pressures tip of I-wall sheet pile for canal water elevation of +6 ft NAVD88 (fully-penetrating sheet pile cofferdam).

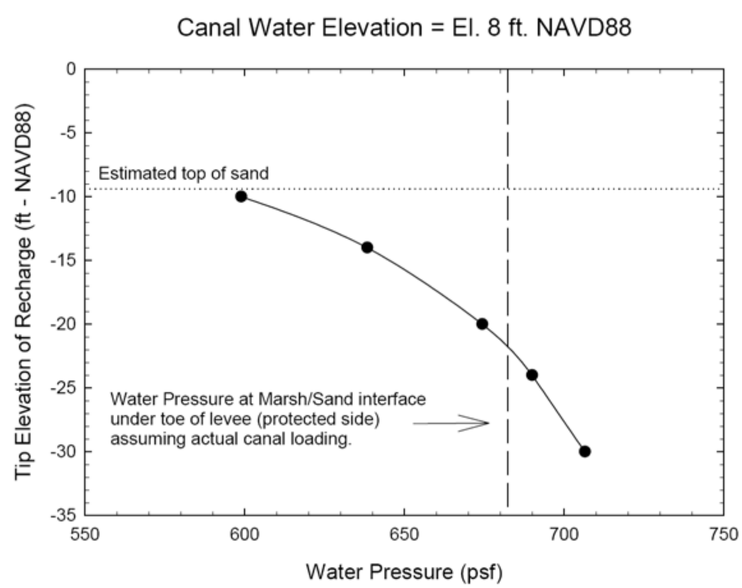


Figure 7 Pore pressures at marsh/sand interface for canal water elevation of +8 ft NAVD88 (fully-penetrating sheet pile cofferdam).

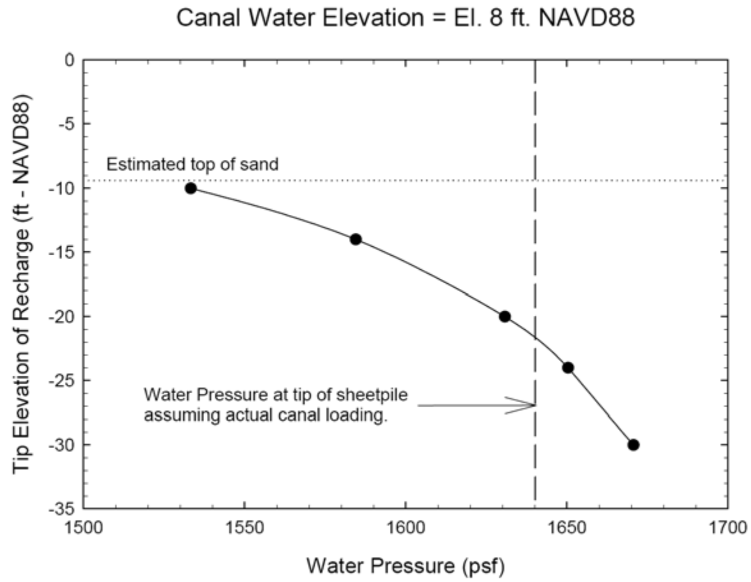


Figure 8 Pore pressures tip of I-wall sheet pile for canal water elevation of +8 ft NAVD88 (fully-penetrating sheet pile cofferdam).

Partially Penetrating Sheet Pile Cofferdam

Shown in Figure 9 is the general cross section used for the analysis of the partially-penetrating cofferdam. It was assumed that the sheet piles are driven to a tip elevation of -31.5 ft NAVD88. Figure 10 shows the finite element mesh used for the analysis. The injection well was modeled as constant head nodes along the sheet pile cofferdam. This analysis required that the sand layer on the canal side of the cofferdam, as well as the canal water level, be incorporated into the model as well. The canal-side geometric boundary was set at about 75 feet from the I-wall.

An approach similar to that described for the fully-penetrating sheet pile cofferdam was used to determine the required depth of the injection well such that similar pore pressures were achieved at the tip of the I-wall sheet pile and at the marsh/sand interface beneath the protected side levee toe. Analyses showed that the tip of the injection well must be located at approximately the same elevation as the tip of the sheet piles comprising the cofferdam to provide pore pressures that approximate full canal loading. However, the analysis revealed certain influences not present in the previous analysis.

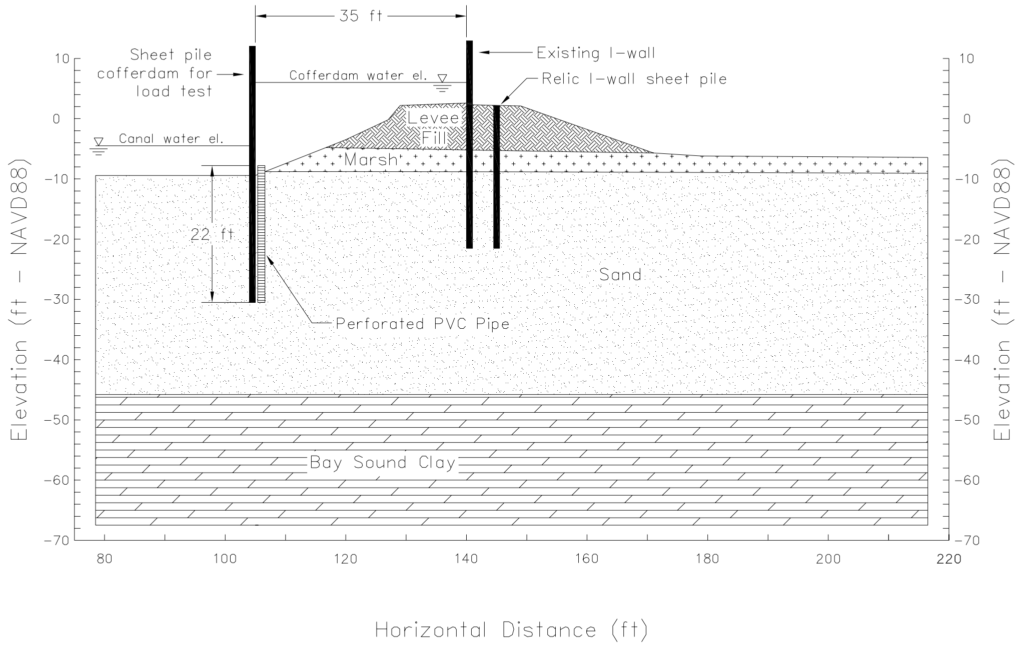


Figure 9 Cross section used for analysis of partially-penetrating sheet pile cofferdam.

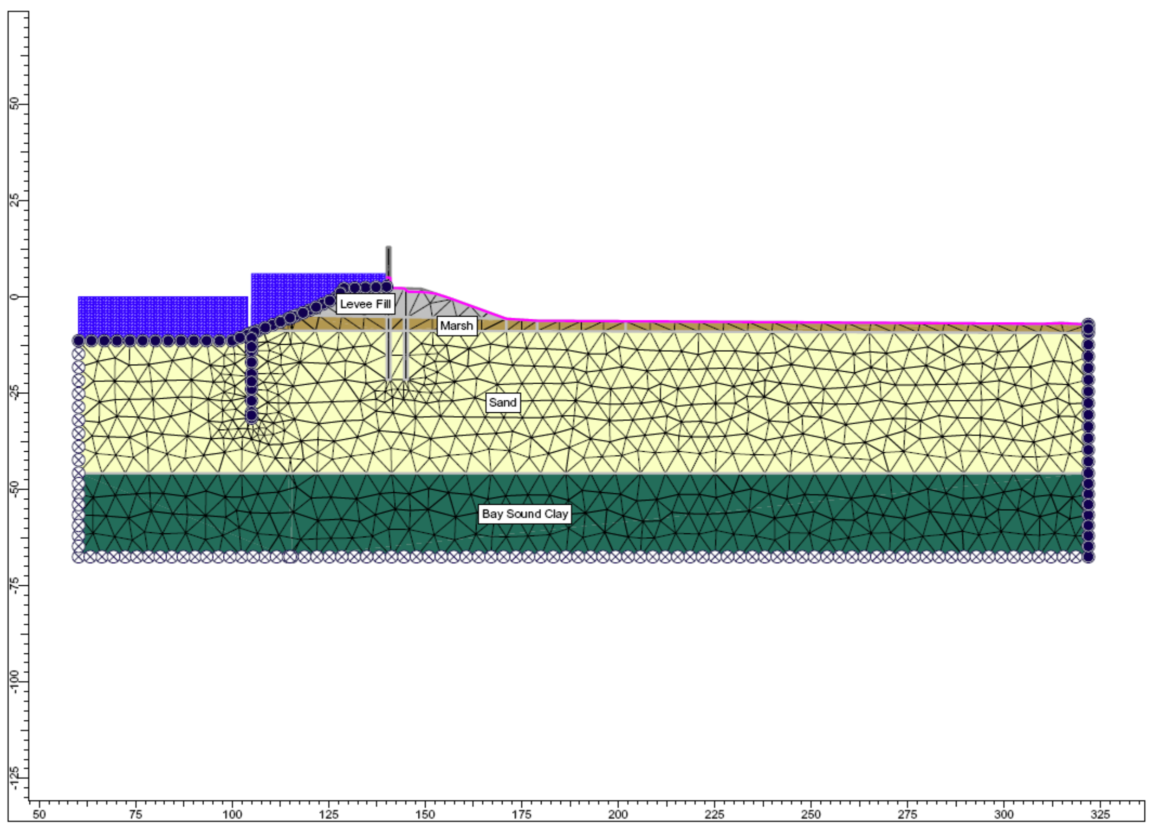


Figure 10 Finite element mesh used for modeling the partially-penetrating sheet pile cofferdam.

First, the pore pressures beneath the levee depend not only on the depth of the injection well and cofferdam water level, but also on the canal water level. Analyses were performed for canal water elevations of 0 ft and -1 ft NAVD88. Shown in Figure 11 are the pore pressures at the marsh/sand interface for these canal water elevations, along with the pore pressures calculated for full canal loading for cofferdam water elevations of +4, +6, and +8 ft NAVD88. As indicated by the figure, the pore pressures show some sensitivity to the water elevation outside of the cofferdam. However, the variations in pore pressure appear to be insignificant.

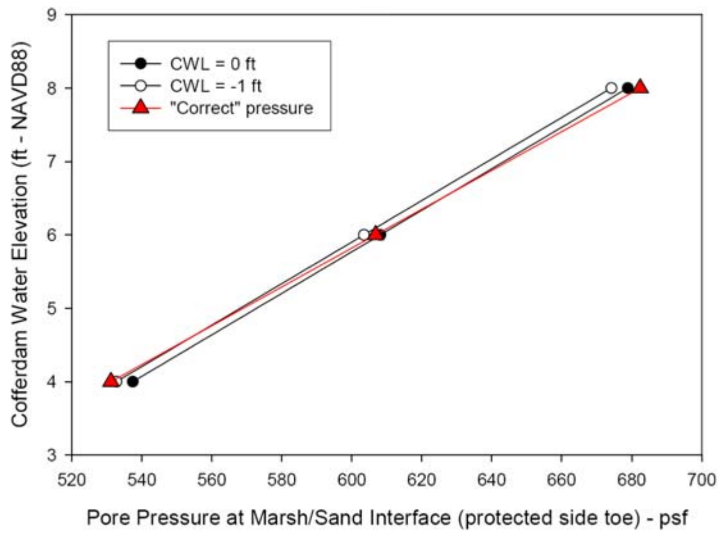


Figure 11 Pore pressures as a function of canal water elevation for different canal water elevations at the marsh/sand interface (partially-penetrating sheet pile cofferdam).

Second, there is some sensitivity of the pore pressures, for a given depth of injection well, for cofferdam water elevations. For a water level in the cofferdam of +4 ft, the pore pressures at the marsh/sand interface are greater than the "correct" value. At cofferdam water elevations of +8 ft, the pore pressures predicted for the test section are lower than the "correct" value. Again, this variation in pore pressure does not appear to be significant.

Third, as can be expected, the flow rate required to be handled by the injection wells increases. For the case of a cofferdam water elevation of +8 ft and a canal water elevation of +0 ft, the flow rate from the interior of the cofferdam is about 10 cfm for the case of the fully penetrating cofferdam, and about 25 cfm for the partially penetrating cofferdam. More flow will occur toward the canal than toward the protected side. However, these flow rates are still modest, and can be easily accommodated by the injection wells.

Shown in Figure 12 are the pore pressures at the tip of the I-wall sheet pile for different canal water elevations and different cofferdam water elevations. The same trends exhibited in the previous figure are also evident for the tip pore pressures as well.

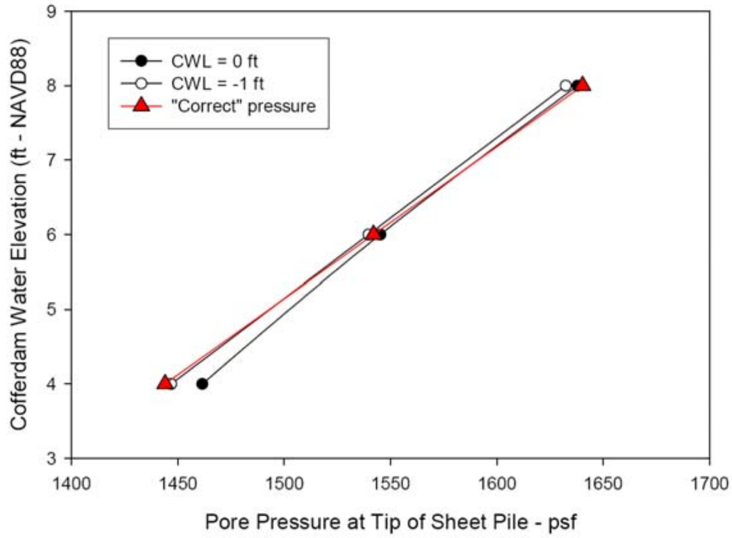


Figure 12 Pore pressures as a function of canal water elevation for different canal water elevations at the tip of the I-wall sheet pile (partially-penetrating sheet pile cofferdam).

Calculation of Well Spacing

The 2-D FE seepage analysis shown above determined that for a fully penetrating sheet pile cofferdam a required depth of penetration is 13 feet and for a partially penetrating sheet pile cofferdam a required depth of penetration is 22 feet. In the seepage analysis, the wells were analyzed as a continuous slot. However, in order to determine the size of the wells and well spacing needed to represent this, continuous slot equations from the NAVFAC Manual, "Dewatering and Groundwater Control for Deep Excavations," (April 1971) were used.

The equations for drawdown of a partially penetrating continuous slot (Eq. 1) and for a partially penetrating infinite line of wells (Eq. 2) are shown below.

$$H - h_e = \frac{L + E_a}{kDx} \bullet (Q) \qquad \text{(Eq. 1)}$$

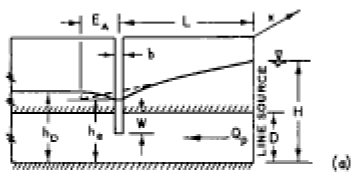
$$H - h_e = \frac{\frac{L}{a} + \theta_a - \theta_m}{kD} \bullet (Q) \qquad \text{(Eq. 2)}$$

with the variables defined in Figures 13 and 14.

The next step is to determine the well spacing such that the line of wells will produce the same drawdown as the continuous slot. Setting both equations (Eq. 1 and Eq. 2) equal to each other and solving for the well spacing gives equation 3.

$$a = \frac{-E_a}{\theta_m - \theta_a} \qquad \text{(Eq. 3)}$$

Using this simplistic approach, one can determine that the well spacing is dependent on the depth of penetration, thickness of substratum, and radius of each well. Using the sand thickness of 35 feet and well diameter of 6”, the required well spacing is approximately 5 ft for the 22 ft penetration and approximately 15 ft for the 13 ft penetration. Given the assumptions made, it would be best to install 6” diameter wells at 5-foot spacing for both sheet pile cofferdam penetrations analyzed. Again, it’s probably best to be conservative on the well spacing since time constraints did not allow for a 3-D seepage analysis and approximations were performed using simplistic equations from the NAVFA manual. A 3-D finite element seepage analysis has been commenced on the current configuration and preliminary results should be available by the tentative test date of August 15, 2007.



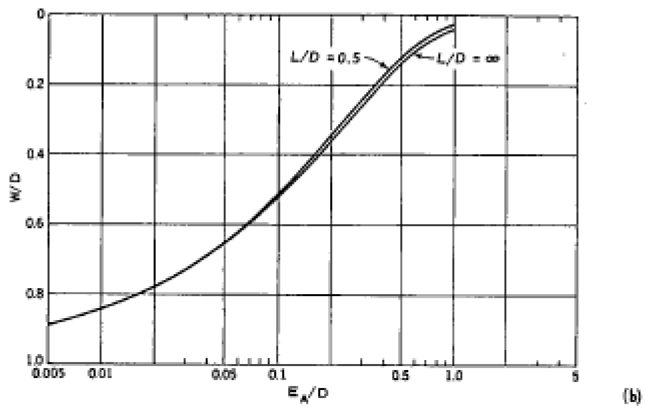
FLOW

$$Q_p = \frac{kDx(H - h_e)}{L + E_A} \qquad \text{(IV-9)}$$

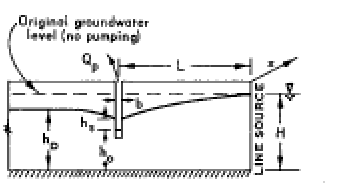
MAX RESIDUAL HEAD DOWNSTREAM OF SLOT

$$h_D = \frac{E_A(H - h_e)}{L + E_A} + h_e \qquad \text{(IV-10)}$$

WHERE E_A IS AN ADDITIONAL LENGTH FACTOR OBTAINED FROM THE FIGURE BELOW DEVELOPED BY BARRON [25]



ARTESIAN FLOW



h_s IS OBTAINED FROM FIG. IV-2 (c)

FLOW†

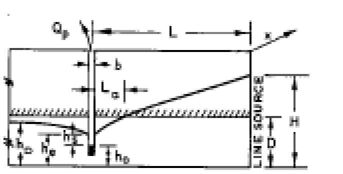
$$Q_p = \left(0.73 + 0.27\,\frac{H - h_o}{H}\right)\frac{kx}{2L}\left(H^2 - h_o^2\right) \qquad \text{(IV-11)}$$

MAX RESIDUAL HEAD DOWNSTREAM OF SLOT†

$$h_D = h_o\left[\frac{1.48}{L}(H - h_o) + 1\right] \qquad \text{(IV-12)}$$

WHERE $L \geqq 3H$

GRAVITY FLOW



h_s IS OBTAINED FROM FIG. IV-2 (d)

FLOW

$$Q_p = \frac{kDx(H - D)}{L - L_G} \qquad \text{(IV-13)}$$

MAX RESIDUAL HEAD DOWNSTREAM OF SLOT†

$$h_D = h_o\left[\frac{1.48}{L_G}(D - h_o) + 1\right] \qquad \text{(IV-14)}$$

PROVIDED $h_D \leqq D$; $L_G \geqq 3D$

$$\text{WHERE } L_G = \frac{L(D^2 - h_o^2)\left(0.73 + 0.27\,\frac{D - h_o}{D}\right)}{2D(H - D) + (D^2 - h_o^2)\left(0.73 + 0.27\,\frac{D - h_o}{D}\right)} \qquad \text{(IV-15)}$$

COMBINED ARTESIAN AND GRAVITY FLOWS

† DEVELOPED FROM MODEL STUDIES BY CHAPMAN [29,30].

(Courtesy of McGraw-Hill Book Co.)

Figure IV-3. Flow and drawdown for partially penetrating line slot; single-line source; artesian, gravity, and combined flows [modified from ref 45]

Figure 13 Equations for a partially penetrating slot. (From NAVFAC Manual)

PARTIALLY PENETRATING WELL

SEE DRAWINGS IN FIG. IV-6 AND FIGURES (a) AND (b) BELOW FOR DEFINITIONS OF TERMS IN EQUATIONS.

DRAWDOWN, $H - h_e$, PRODUCED BY PUMPING Q_w FROM AN EQUIVALENT CONTINUOUS SLOT IS COMPUTED FROM EQ IV-9.

HEAD LOSS DUE TO CONVERGING FLOW AT WELL

$$\Delta h_w = \frac{Q_w \theta_a}{kD} \qquad \text{(IV-80)}$$

TOTAL DRAWDOWN AT WELL (NEGLECTING H_w)

$$H - h_w = H - h_e + \Delta h_w = \frac{Q_w}{kD}\left(\frac{L}{a} + \theta_a\right) \qquad \text{(IV-81)}$$

HEAD INCREASE MIDWAY BETWEEN WELLS

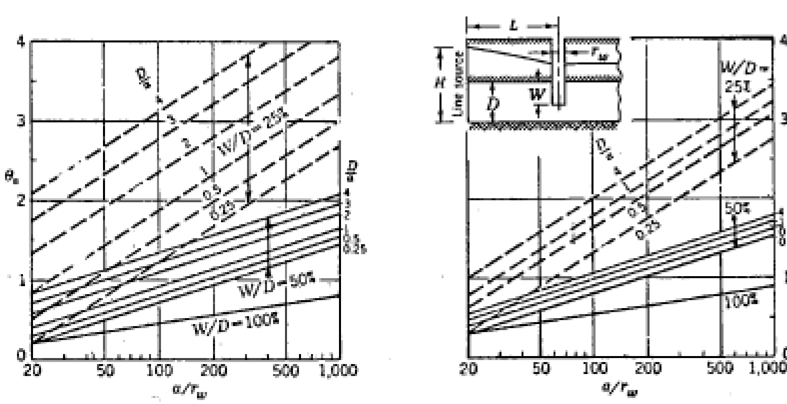
$$\Delta h_m = \frac{Q_w \theta_m}{kD} \qquad \text{(IV-82)}$$

DRAWDOWN MIDWAY BETWEEN WELLS

$$H - h_m = H - h_w - \Delta h_m = \frac{Q_w}{kD}\left(\frac{L}{a} + \theta_a - \theta_m\right) \qquad \text{(IV-83)}$$

HEAD INCREASE Δh_D DOWNSTREAM OF WELLS IS EQUAL TO Δh_w, EQ IV-80.

DRAWDOWN $H - h_D$ DOWNSTREAM OF WELLS IS EQUAL TO $H - h_w - \Delta h_w$ OR $H - h_e$ AND, CONSEQUENTLY, CAN BE COMPUTED FROM EQ IV-9.



(a) (b)

(Courtesy of McGraw-Hill Book Co.)

Figure IV-21. Flow and drawdown for partially penetrating infinite line of wells; line source; artesian flow [modified from ref 45]

Figure 14 Equations for a partially penetrating infinite line of wells. (From NAVFAC Manual)