Sheetpile Cell Filling: Finite Element Model Verification for Two Case Histories

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Cellular sheetpile structures are used as temporary cofferdams to keep construction activities dry and as permanent bulkheads. Successful design ensures that allowable sheetpile interlock tensions are not exceeded during cell filling operations. For two cellular cofferdam case histories, axisymmetric finite element analyses were performed to estimate main and arc cell fill pressures and arc cell tensions. Results of the analyses are compared with field strain gage data and conventional predictions of main and common wall interlock tensions.

Cellular sheetpile structures have been used both as temporary cofferdams to keep construction activities dry and as permanent bulkheads. Cells are composed of interlocking steel sheetpiles, which are commonly arranged in a circular configuration and usually filled with sand or gravel. Cellular structures are built by joining individual main cells with connecting arc cells to form a continuous retaining system. Successful design ensures that allowable sheetpile interlock tensions are not exceeded during cell filling operations and that the system is stable under applied external loads. Conventional methods for estimating sheetpile interlock tensions and stability under external loads are based largely on procedures developed by Terzaghi in the 1930s and 1940s (*1*). These methods generally do not consider soil-structure interaction effects and are thought to be conservative (*2*). The advent of the finite element technique and the instrumentation of constructed cells over the past 20 years have led to important new insights that can be used to develop improved design procedures for these structures.

This article describes the cell filling behavior of sheetpile structures constructed for the Lock and Dam 26 [Replacement (R)] and Trident Drydock case histories. For both projects, the results of axisymmetric finite element analyses are compared with project instrumentation data and predictions of interlock tensions from conventional methods.

This work is of particular significance because it introduces a new approach for predicting common wall behavior and confirms the importance of soil-structure interaction effects on cell filling behavior. Additionally, this work presents the first finite element analyses for the Trident Drydock cells known to the writers.

BACKGROUND

Cellular structures are constructed by first driving a series of interlocking steel sheetpiles around a circular template to form individual cells. Sheetpile penetration depths generally range from no penetration for cells constructed on hard materials to significant penetration for cells constructed on relatively loose deposits. Cell construction is completed by initially filling each of the main cells, and then subsequently filling the adjacent connecting arc cells (Figure 1).

During main cell filling, main cell sheetpiles bulge radially outward in response to cell fill pressures. These radial deflections are characterized in part by the reduction of slack in the initially loose sheetpile assemblage and also by elastic tensioning of the sheetpiles. Near the dredgeline, outward sheetpile deflections are reduced by the passive resistance of the foundation soils. The combination of increasing cell fill pressure with depth and the constraining influence of the foundation soils results in a pattern of radial deflections that increase with depth from the top of the cell to some point near the dredgeline. Based on field observations, the point of maximum radial deflection is typically between one-fourth and one-third the cell free height above the dredgeline (*3*). Because tensions increase with increasing radial deflection, the point of maximum bulging corresponds to the point of maximum sheetpile interlock tension.

Main and arc cell maximum tensions (t_{max}) are commonly estimated using the hoop stress equation:

$$t_{max} = p_{max} \cdot \text{radius}, \quad (1)$$

where p_{max} is the maximum lateral pressure acting against the sheetpile wall. The maximum lateral pressure is assumed to occur at the point of maximum bulging (*4*). Design for main and arc cell interlock tensions therefore requires that cell radius, soil unit weight, the coefficient of lateral earth pressure, and the point of maximum bulging be known. The coefficient of lateral earth pressure depends on both the sheetpile movements and on the amount of arching that occurs within the cell. Arc cell tensions are less than main cell tensions because arc cell radii are smaller than main cell radii, and because arching within the arc cells reduces the horizontal earth pressures acting against the sheetpiles to a greater extent than it does for the main cells.

Sheetpiles installed along the main/arc cell common wall (Figure 1) are loaded by several mechanisms. During main cell filling, common wall piles bulge radially outward in a manner similar to the other main cell piles. Then, during arc cell filling, the common wall is pushed back toward the main cell interior, causing a reduction in interlock tension. At the same time, tensions that occur in the arc cell piles because of filling are transmitted through the wye pile and increase common wall interlock tensions. The effect of these two mechanisms generally results in a net increase in common wall interlock tensions following arc cell loading (*5*).

PROJECT DESCRIPTIONS

In the following, important aspects of the Trident Drydock and Lock and Dam 26 (R) projects are briefly summarized. Complete

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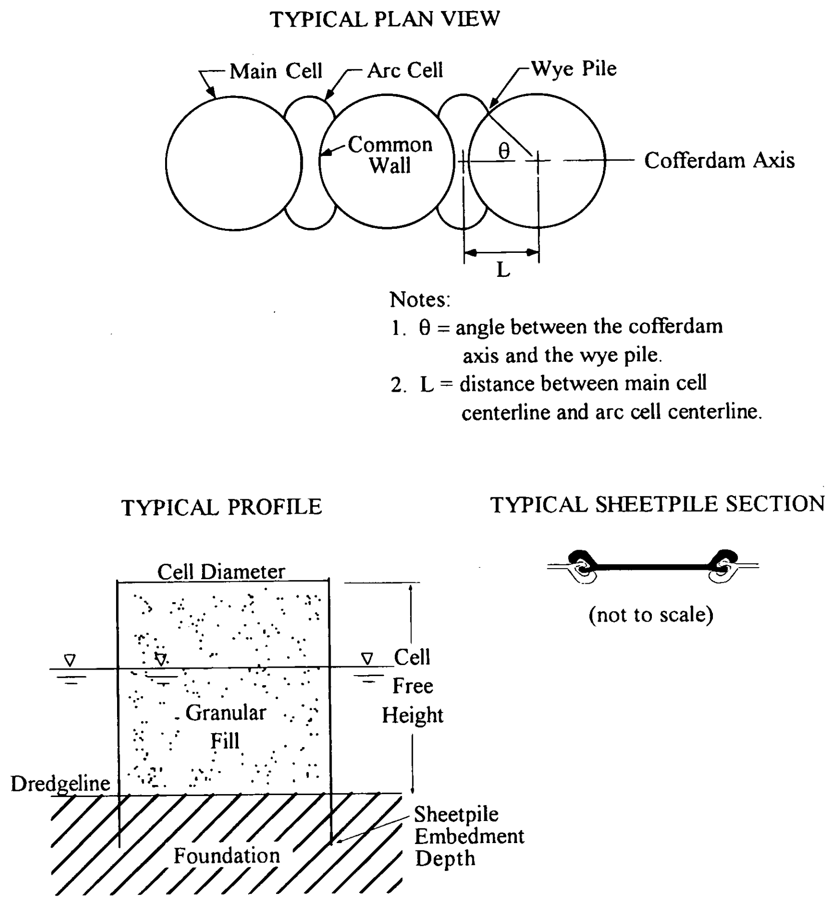


FIGURE 1 Cellular structure description.

project descriptions are provided by Sorota and Kinner (*6*), Sorota et al. (*7*), and Shannon and Wilson, Inc. (*8,9*).

Trident Drydock

A cellular cofferdam was constructed for the Trident Drydock (Bremerton, Washington) to keep construction activities dry and to function as a permanent laydown area for dry-dock operations. Main cells are 23.2 m (76 ft) in diameter and extend 24.4 to 26.5 m (80 to 87 ft) above the dredgeline (Figure 2). Forty-degree wye piles were used to connect the main cells to the 4.9 m (16 ft) radius connecting arcs.

Cell construction started with sheetpiles being driven up to 1.21 m (4 ft) into the hard glacial till foundation soils. High strength PSX32 sheetpiles were used for all main cell, arc cell, and common wall sections. Cell fill consisted of gravelly sands placed with a clamshell bucket. Cells were filled to an elevation of 5.2 m (17 ft) before dewatering operations. Two cells were instrumented with strain gages, located on both main and common wall piles.

Lock and Dam 26 (R)

Lock and Dam 26 (R) was constructed in three separate stages to replace existing Lock and Dam 26 on the Mississippi River near Alton, Ill. Stage 1 main cells were 19.2 m (63 ft) in diameter and extended 18.3 m (60 ft) above the river bottom (Figure 2). Thirty-degree wye piles were used to connect main cells with 4.9 m (16 ft) radius connecting arcs.

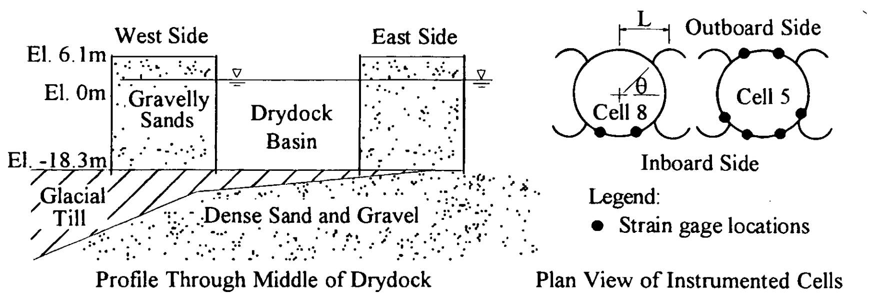
Construction activities started with sheetpiles driven 10.7 m (35 ft) into the medium-dense to dense alluvial foundation sands. Standard Penetration Test blowcounts in the sand indicated a fairly uniform relative density of about 70 percent (*10*). High strength PSX32 sheetpiles were used for the common walls; mild steel PS32 sheetpiles were used for the remaining main and arc cell sections. After pile driving, cells were filled with dredged sand placed with a clamshell bucket. Instrumentation installed to observe cell filling behavior consisted of strain gages and inclinoms (Figure 2).

NUMERICAL MODELING

Main Cell-Filling Analyses

The finite element modeling of main cell filling was performed with an axisymmetric formulation because of the inherent axisymmetric nature of the physical problem. In order to provide a realistic representation of the soil response, a nonlinear (hyperbolic), confining pressure-dependent model was used (*11*). Soil element stiffnesses (E_t) are given by

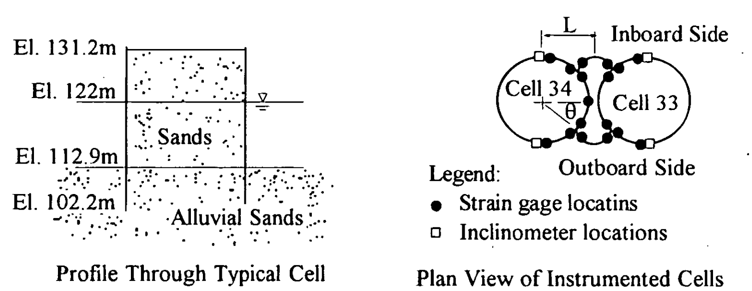
TRIDENT DRYDOCK CELL GEOMETRY



Notes:

1. Main cell diam. = 23.2m.	5. Wye pile angle = 40 degr.
2. Arc cell radius = 4.9m.	6. θ = 36.5 degr.
3. Pile embedment = 0 to 1.2m.	7. L = 14.3m.
4. Cell height = 24.4m.	8. 1 meter = 3.28 ft.

LOCK AND DAM 26 (R) CELL GEOMETRY



Notes:

1. Main cell diam. = 19.2m.	5. Wye pile angle = 30 degr.
2. Arc cell radius = 4.9m.	6. θ = 30 degr.
3. Pile embedment = 10.7m.	7. L = 13.2m.
4. Cell height = 18.3m.	8. 1 meter = 3.28 ft.

FIGURE 2 Project descriptions.

$$E_t = K_m P_a \left(\frac{\sigma_3'}{P_a} \right)^n (1 - R_f SL)^2, \quad (2)$$

where K_m, n, and R_f are values developed from laboratory testing, P_a is the atmospheric pressure, σ_3' is the effective confining pressure, and SL is the soil element stress level. Soil element volume changes depend on the bulk modulus (B), which is given by Duncan et al. (*12*):

$$B = K_b P_a \left(\frac{\sigma_3'}{P_a} \right)^m, \quad (3)$$

where K_b and m are values developed from laboratory testing and P_a and σ_3' are defined above. Interface elements were used to allow for the relatively large movements that can occur between the soil and sheetpile walls. Cell filling was modeled by establishing the initial stresses in the foundation soils, adding shell elements to represent the sheetpiles, and incrementally filling the cell interior with soil fill. Incremental loading is necessary because the response of the soil and interface elements is dependent on the magnitude and history of stresses in the system (Equation 2). For these analyses, a minimum of 120 load steps were used to model filling operations. The water level within the cell fill was assumed to be the same as the exterior water level because clamshell bucket filling is sufficiently slow to allow dissipation of excess pore water pressures in the fill.

Common Wall Analyses

The response of the common wall to filling of the main and arc cells is a complex three-dimensional problem. Hardin (*5*) gained insight into the common wall problem by performing two-dimensional finite element analyses on a horizontal slice extending through the Lock and Dam 26 main and arc cells. Analyses were performed by applying out-of-plane loads (vertical "fill" loads) on the elements of the horizontal slice and examining the displacements and stresses generated in the sheetpile walls. Hardin's results indicated that although high localized stresses were induced at the wye pile, tensions along all other common wall piles were approximately the same. The results suggest that the combination of arc fill lateral loading and the additional arc cell tensions transmitted through the wye pile result in a uniform common wall tension at any elevation. Mosher (*10*) performed three-dimensional finite element analyses for the Lock and Dam 26 cells. The three-dimensional analyses confirmed the predictions made by the horizontal slice analyses. Even though useful information can be obtained from the horizontal slice model and from three-dimensional analyses, there are important disadvantages to these approaches. The horizontal slice model provides information only at the elevation of the slice. Additional analyses must be performed at each elevation at which common tensions are desired. Additionally, when the horizontal slice model is used above the dredgeline, it does not include the effects of lateral restraint provided by the foundation materials. For this reason, the horizontal slice model does not work well near the dredgeline. In principal, three-dimensional analyses could provide a good model of cofferdam behavior. The major difficulty with three-dimensional analyses is that the engineering cost for performing analyses and interpreting the results is prohibitive.

For this research, we attempted to model the key mechanisms of common wall behavior while avoiding the disadvantages of the horizontal slice and three-dimensional approaches. The common wall problem was therefore modeled using the three step approach shown in Figure 3. Step 1 consists of an axisymmetric finite element analysis of main cell filling, as described previously. In Step 2, the axisymmetric analysis of main cell filling is carried further by simulating fill placement in an annular space around the outside of the main cell. The effect of this fill placement is to push the sheetpiles back toward the center of the main cell and to reduce main cell sheetpile tensions. In Step 3, the component of the arc cell tension (obtained from axisymmetric finite element analyses of arc cell filling), in the direction of the common wall at the wye, is added to the main cell tensions from Step 2. The proposed procedure is advantageous because it is believed to effectively simulate the actual loadings on the common wall during cell filling. Additionally, this procedure produces a uniform tension in the common wall at any elevation, in agreement with the results of Hardin's horizontal slice

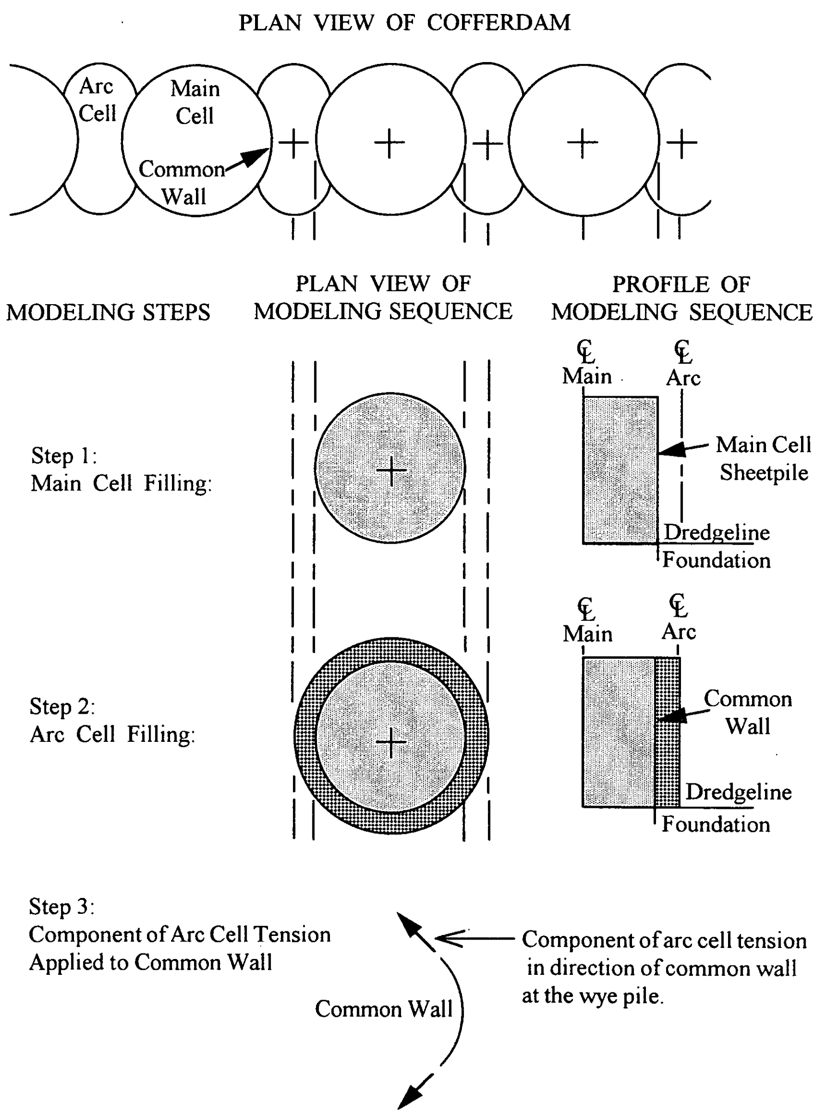
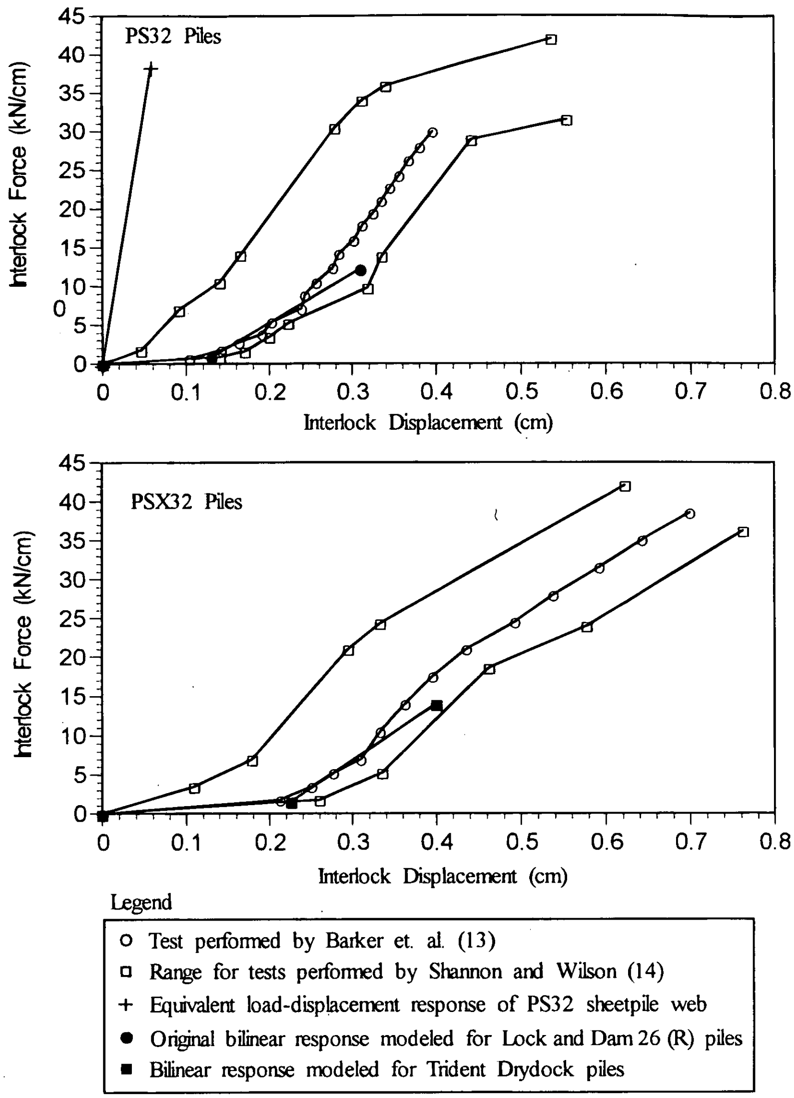


FIGURE 3 Common wall construction sequence modeling.



1 cm = 0.394 in.
1 kN/cm = 0.571 kips/in.

FIGURE 4 Lock and Dam 26 (R): sheetpile load-displacement curves.

analysis. The main drawbacks of this procedure are that not all of the three-dimensional effects are explicitly modeled and that loads are superpositioned although the system is nonlinear. The error associated with superposition in this case, however, is thought to be minimal because the load increment associated with the application of the arc cell tension is small and because the soil elements are at relatively low stress levels, corresponding to portions of the stress-strain curves that are not highly nonlinear.

Sheetpile Response Modeling

In an effort to quantify sheetpile interlock load-displacement behavior at Lock and Dam 26 (R), two sets of sheetpile interlock pull tests were performed (*13,14*). The test results show that the interlock load-displacement responses for both PS32 and PSX32 piles are considerably softer than the elastic stiffness of the sheetpile web (Figure 4). This anisotropic system behavior is primarily attributed to the imperfect and initially slack fit between the thumb-and-forefinger interlocks that connect adjacent sheet-piles (Figure 1).

Sheetpile behavior is modeled within the code by assigning an orthotropic stiffness reduction factor, E-ratio, to the shell elements (E-ratio = circumferential stiffness divided by axial stiffness). Because of the predominantly bilinear response of the pull tests, bilinear E-ratio reduction factors were used to model stiffnesses for sheetpiles installed at both Lock and Dam 26 (R) and Trident Drydock.

TABLE 1 Hyperbolic Soil Parameter Values Used in Analyses

Project	Material	Unit Weight (kg/m^3)	Friction Angle (degrees)	K_m*	n*	R_f*
Trident Drydock	Moist Fill	2064	35	800	0.65	0.82
	Buoyant Fill	1162	35	800	0.65	0.82
	Foundation	**	**	**	**	**
Lock & Dam 26(R)	Moist Fill	1968	35	800	0.65	0.82
	Buoyant Fill	1130	35	800	0.65	0.82
	Foundation	1130	41	1600	0.50	0.85

* Elastic Modulus = $E_t = K_m P_a \left(\frac{\sigma_3'}{P_a}\right)^n (1 - R_f SL)^2$,

where Pa = atmospheric pressure, and

SL = soil element stress level

** Linear elastic parameters used for Trident Drydock foundation materials.

Soil Parameter Values

Laboratory tests were previously performed to select input parameters for earlier Lock and Dam 26 (R) finite element studies. Because of the similarities in the descriptions of the fill materials and placement methods at Lock and Dam 26 (R) and at Trident Drydock, similar fill parameter values were used in both analyses (Table 1). Because the Trident Drydock was founded on hard glacial tills, linear elastic parameter values, similar to those appropriate for lean concrete, were used for the foundation materials.

ANALYSES RESULTS

Trident Drydock

Calculated deflections and interlock tensions for Trident Drydock are presented on Figure 5. As expected, calculated cell deflections and interlock tensions increase from low values at the top of the cells to maximum values just above the dredgeline. The range and average measured interlock tensions are also shown in Figure 5. The location of maximum interlock tension shown in Figure 5 was interpreted using data from longer piles where strain gages were located at the point of maximum tension. It can be seen that there was good agreement between the calculated and measured tensions. Unfortunately, measured deflections are not available for Trident Drydock cell filling.

Lock and Dam 26 (R)

Calculated and measured deflections for Lock and Dam 26 (R) are presented in Figure 6. The calculated deflections were significantly lower than the measured deflections, and the calculated tensions were significantly higher than the measured tensions.

One possible reason for these differences is that the sheetpile response at Lock and Dam 26 (R) may have been softer than the laboratory tests indicated. This possibility was investigated (*8*) by converting the average radial deflections from the inclinom data to tangential displacements per interlock with the relationship

$$u = \frac{dr \cdot L}{R}, \tag{4}$$

where u is the interlock displacement, dr is the sheetpile radial deflection, L is the sheetpile width, and R is the cell radius. The displacement per interlock is plotted versus the interlock tension from the average of the strain gage data on Figure 7. It can be seen that sheetpiles installed for the Lock and Dam 26 (R) cells were much looser than the laboratory pull tests indicate. The reasons for this softer response were not obvious, but may have been because of more interlock slack left in the pile assemblage during construction than during the laboratory tests.

Revised analyses for Lock and Dam 26 (see Figure 8) were performed with revised E-ratios obtained from the inclinom and strain gage data. It can be seen that the calculated deflections and tensions were in better agreement with the measured values when the E-ratios from the field data (Figure 7) were used. The agreement between calculated and measured values for the main cell and the common wall was good. For the arc cell, the calculated tensions were larger than most of the averages of the measured tension data. Some of this difference is thought to have been because of localized cell fill arching effects occurring near the wye piles.

COMPARISONS WITH CONVENTIONAL PREDICTIONS

Main Cell Interlock Tension

Conventional cellular design methods use the hoop stress approach to predict main cell interlock tensions. With the hoop stress equation, the maximum interlock tension is calculated by simply multiplying the maximum lateral cell fill pressure (which occurs at the point of maximum cell bulge) times the cell radius (Equation 1).

Three recognized design methods, Terzaghi (*1*), Tennessee Valley Authority (TVA) (*3*), and Schroeder and Maitland (*15*) provide alternate recommendations for the lateral earth pressure coefficient, *K*, (see Table 2) and for finding the point of maximum bulge. For finding the location of maximum tension, Terzaghi (*1*) recommended that the maximum lateral cell fill pressures be computed at the dredgeline where the overburden stresses within the cell are largest. Alternatively, the TVA procedure (*3*) suggests that the point of maximum tension occurs at one-fourth of the free cell height above the dredgeline. Schroeder and Maitland (*15*) recommend that the point of maximum tension is most likely to occur at one-third

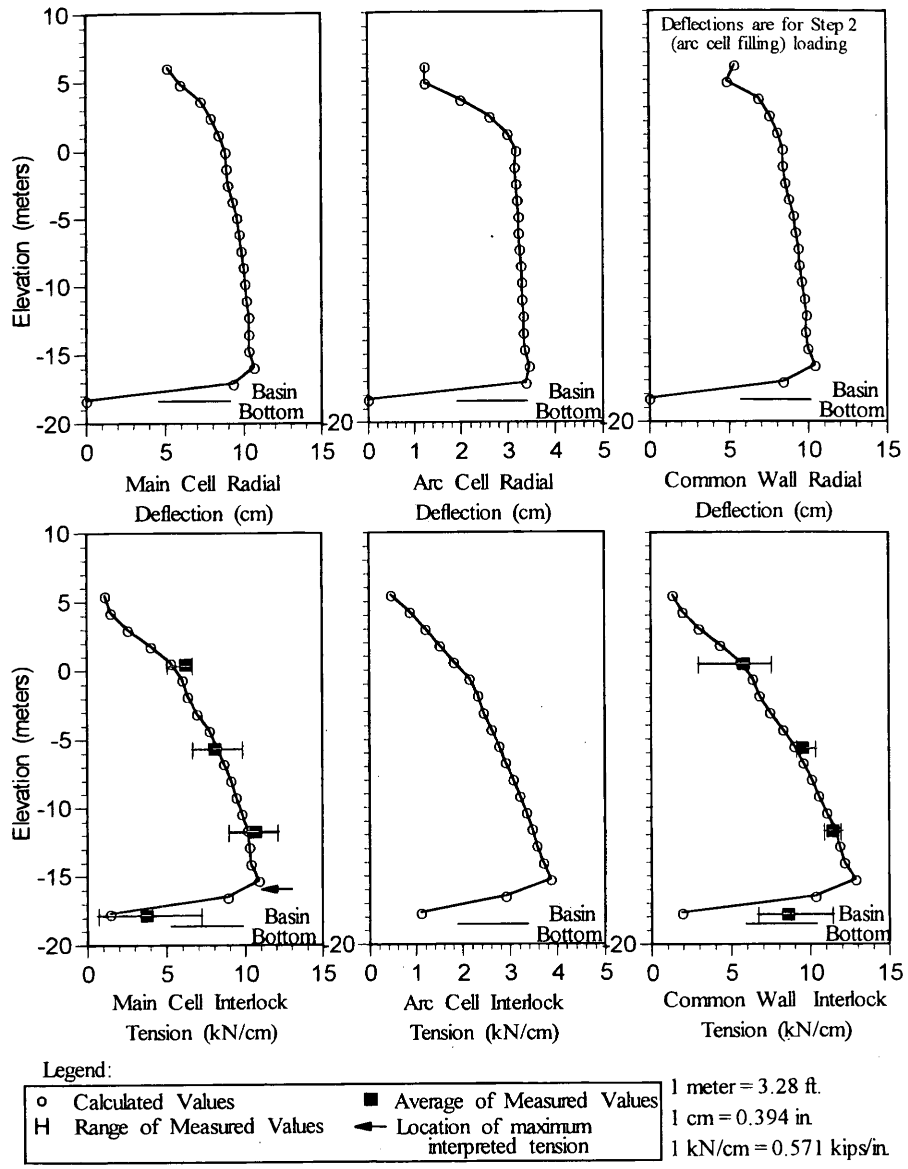


FIGURE 5 Trident Drydock: sheetpile deflections and interlock tensions.

the distance between the point of pile fixity within the foundation material and the top of the cell.

Main cell interlock tensions predicted with the three conventional procedures are compared with finite element results and strain gage data in Figure 9. For both the Trident Drydock and the Lock and Dam 26 (R) projects, the Terzaghi method overestimates the maximum interlock tensions by at least 40 percent because no provisions for tension reductions above the dredgeline are made. Maximum tensions calculated using the TVA method are less than the maximum tension at the Trident Drydock and approximately equal to the maximum measured tension at Lock and Dam 26 (R). Maximum tensions calculated using the Schroeder and Maitland method are approximately equal to the maximum measured tension at Trident Drydock and are greater than the maximum measured tension at Lock and Dam 26 (R). For both the TVA method and the Schroeder and Maitland method, the location of maximum tension is higher than the observed location for Trident Drydock and approximately at the observed location for Lock and Dam 26 (R).

Common Wall Interlock Tensions

The TVA secant method (*3*) and the Swatek method (*4*) are commonly used to predict interlock tensions in the common wall. These methods are illustrated in Figure 10. The maximum lateral earth pressure (p_{max}) value used in both methods is evaluated by the procedures described above for the main cells.

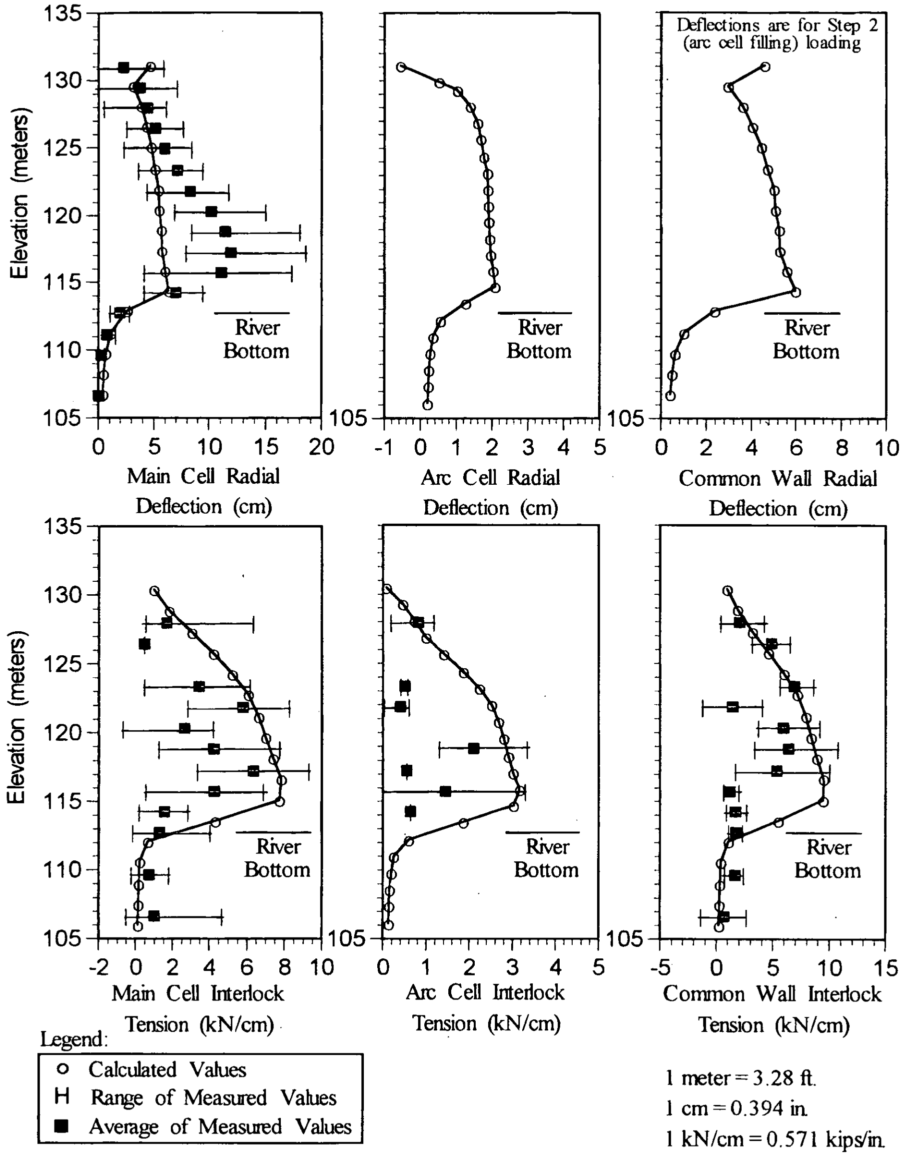


FIGURE 6 Lock and Dam 26 (R): sheetpile deflections and interlock tensions for bilinear sheetpile response from laboratory tests.

Common wall interlock tensions predicted by the TVA secant and Swatek methods are compared with three-step finite element analyses and average strain gage results in Figure 11. For simplicity, the TVA main cell procedures for the coefficient of lateral earth pressure and point of maximum tension were used to find the maximum lateral earth pressure. For the upper portion of the Trident cells, it can be seen that the TVA method generally provides relatively good predictions, whereas the Swatek method modestly underestimates common wall tensions in comparison with the trend in strain gage data. Both methods, however, provide locations of maximum common wall tension that are too high in comparison with the trend in Trident cell strain gage data. This is because both methods rely on main cell tension prediction procedures to find the point of maximum tension. For the upper portion of the Lock and Dam 26 (R) cells, it can be seen that the Swatek method provides a reasonable prediction of common wall tension in comparison with the strain gage data. The TVA method slightly overpredicts maximum tension. Both methods provide locations of maximum common wall tension that are relatively close to that indicated by the strain gage data.

CONCLUSIONS

Finite element analyses of cellular structures are advantageous because soil-structure interactions are modeled and insight into con-

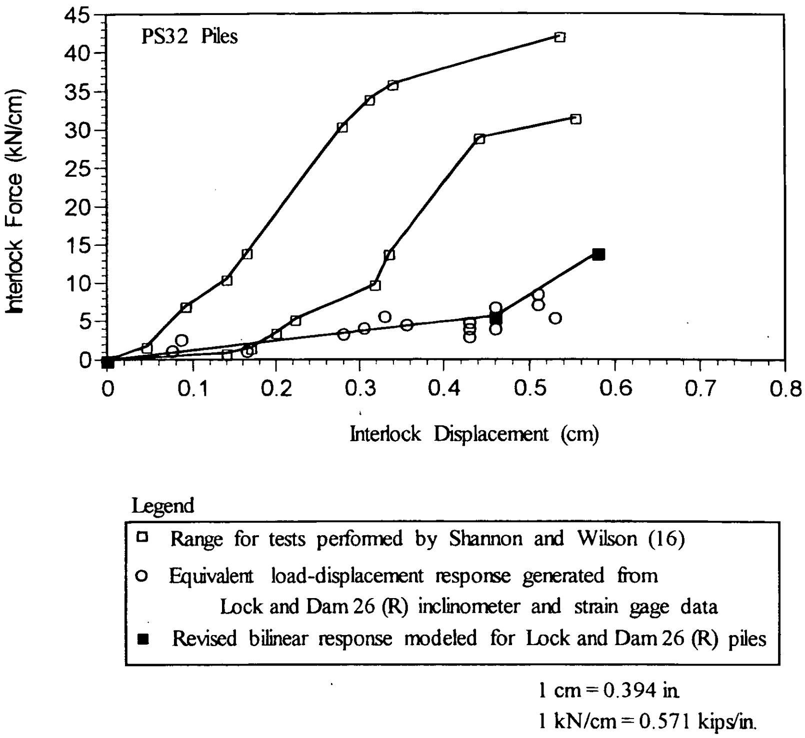


FIGURE 7 Lock and Dam 26 (R): revised sheetpile load-displacement curves.

trolling mechanisms is gained. Conclusions based on the results of studies performed for two case histories can be summarized as follows:

1. Calculations of main and arc cell sheetpile displacements and interlock stresses that are in good agreement with measured values can be obtained from axisymmetric finite element analyses.

2. Computed sheetpile deflections and interlock tensions from the finite element model are sensitive to the sheetpile circumferential stiffness (E-ratio), which may be difficult to determine a priori.

3. A good match between computed and measured tensions was obtained for the Trident Drydock when the results of the laboratory sheetpile pull tests were used to determine sheetpile E-ratios. For Lock and Dam 26 (R), axisymmetric analyses performed with E-ratios from laboratory pull tests resulted in smaller computed radial deflections and larger computed interlock tensions than measured in the field. A better match between computed and measured sheetpile deflections and tensions was obtained for Lock and Dam 26 (R) when inclinom and strain gage results were used to determine the effective sheetpile assemblage E-ratio.

4. A new approach for determining common wall interlock tensions was found to provide good agreement with measured field data. The approach developed for this study calculates common wall tensions by: (a) performing an axisymmetric finite element analysis for main cell filling, (b) modeling the effects of placing fill within the arc cell area, and (c) superimposing arc cell tensions on the common wall.

5. In each of the cases examined, the finite element analysis provided the best match between the predicted and measured interlock tensions. However, with the exception of the Terzaghi method, the predictive capability of the simplified methods was practically equal to that of our finite element analysis. Both the Schroeder and Maitland and TVA methods gave very good results for both cases, with the possible exception that the TVA method underpredicted the maximum main cell tensions at Trident by about 20 percent. The Terzaghi method however, was found to largely overpredict tensions near the dredgeline because the restraint provided by the foundation is not considered.

6. The finite element analyses used in this work provided insight into the behavioral mechanisms associated with cellular structures and confirmed the importance of soil-structure interaction effects. Of particular significance, our finite element approach agreed well with measured field data and suggests that this technique can be used to model complicated cases in which simplified methods may be limited, or develop new simplified methods to predict other aspects of cellular behavior such as lateral movements.

ACKNOWLEDGMENTS

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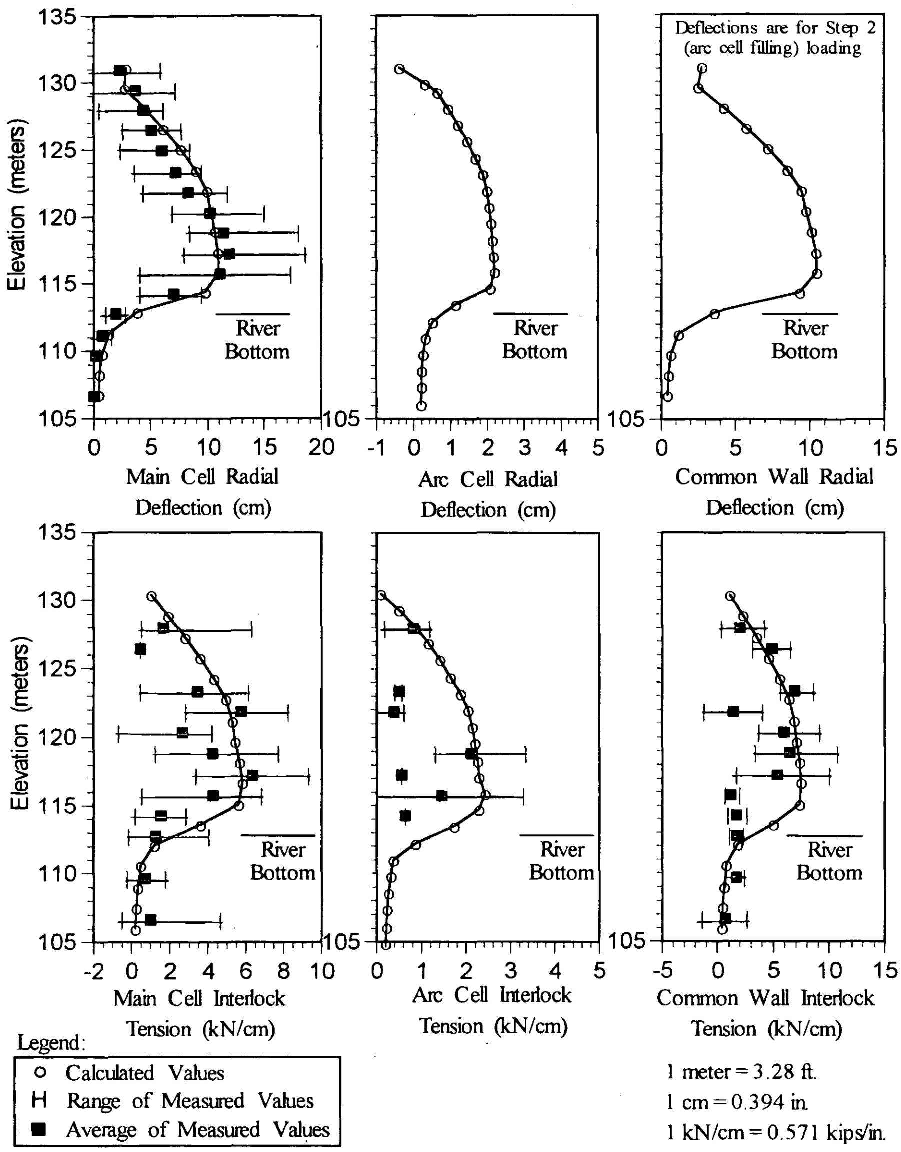

FIGURE 8 Lock and Dam 26 (R): sheetpile deflections and interlock tensions for revised sheetpile response.

TABLE 2 Conventional Recommendations for K-Values During Cell Filling

Source	Coefficient of Lateral Earth Pressure (K)
Terzaghi (1)	0.40
Tennessee Valley Authority (3)	$K_a = \tan^2(45 - \phi/2)$
Schroeder and Maitland (17)	1.2 to 1.6 Ka

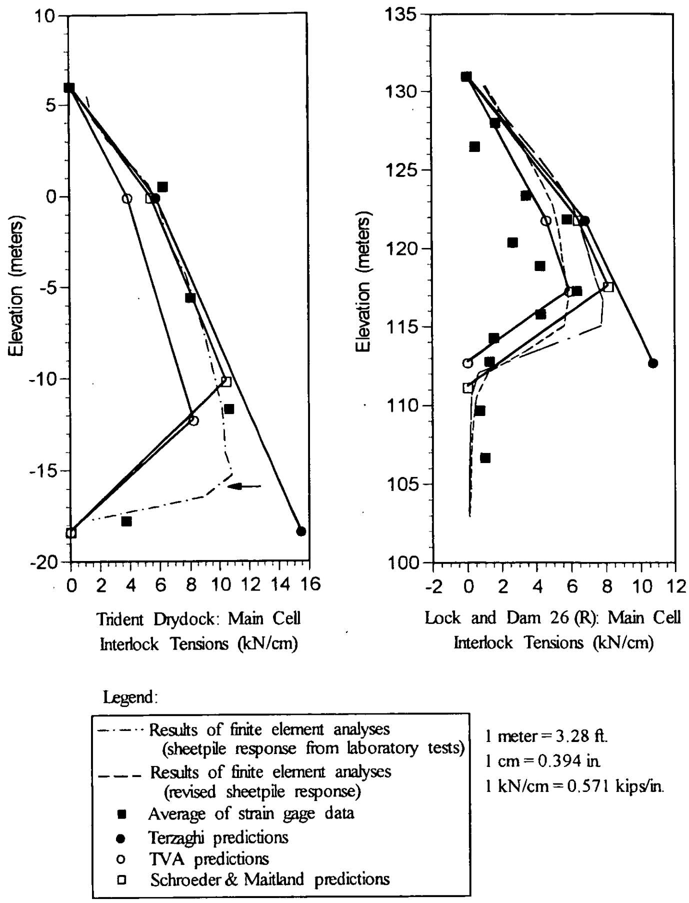

FIGURE 9 Methods for predicting main cell interlock tensions.

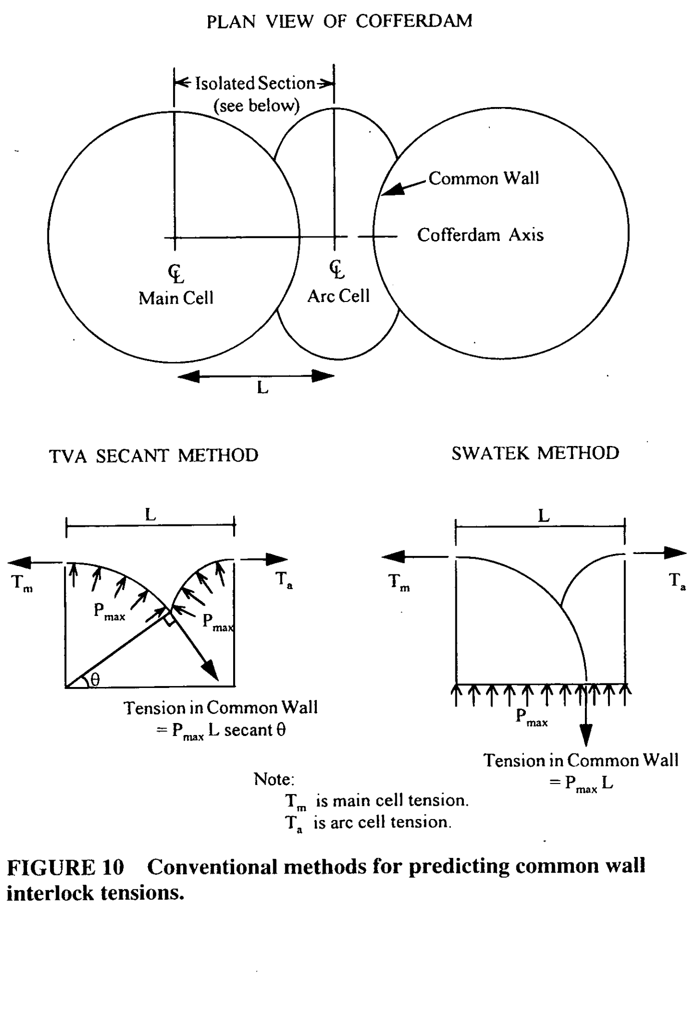

FIGURE 10 Conventional methods for predicting common wall interlock tensions.

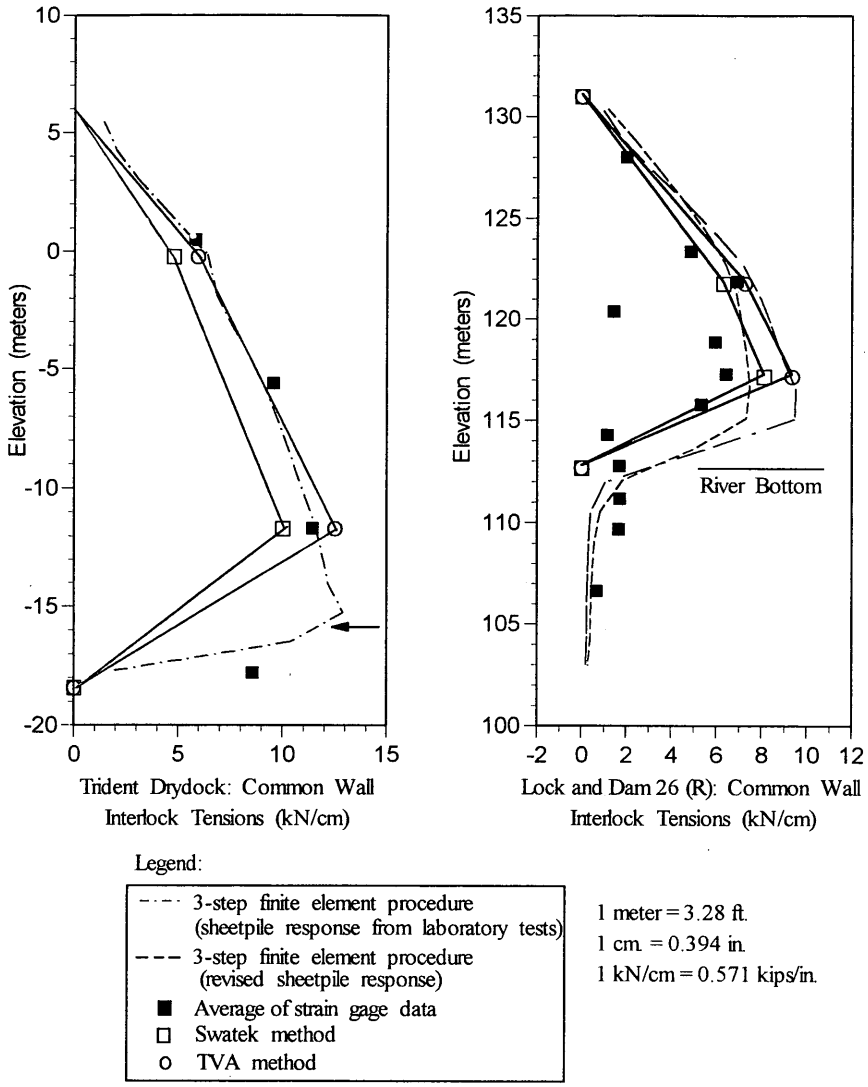

FIGURE 11 Methods for predicting common wall interlock tensions.

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