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THREE DIMENSIONAL SOIL-STRUCTURE-INTERACTION ANALYSIS OF A FLOOD WALL UNDER FULL-SCALE LOAD TEST

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ABSTRACT

The U.S. Army Corps of Engineers (Louisville District) conducted a number of full-scale tests to determine the behavior of continuous steel sheet pile flood walls when subjected to hydrostatic loads simulating actual flood conditions. Among these tests, Test Series III (sheet piling with concrete jacket) was conducted at the Tell City site in Indiana. The results of these full-scale load tests provide valuable data that could help verify geotechnical design procedures. In addition, numerical analyses simulating these tests could be useful in interpreting the foundation and structure behavior and in predicting the performance of similar I-wall-type levee systems subjected to flood loading conditions.

The full-scale load test was conducted on a portion (42 feet long) of the completed flood wall. Three-dimensional (3D) numerical finite difference (FLAC 3D) models for an I-wall that simulate full-scale load test conditions were developed to compute wall deflections and compare with the measured deflections from the full-scale test. This approach was used because it was recognized that using 2D analyses for the 3D load test conditions did not accurately simulate actual conditions. The analyses performed in this study provided quantitative estimates of wall displacements that reasonably simulate the 3D effects of the load tests on the levee wall.

INTRODUCTION

The U.S. Army Corps of Engineers (Corps), Louisville District, conducted a number of full-scale tests to determine the behavior of continuous steel sheet pile flood walls (I-shaped walls) when subjected to hydrostatic loads simulating actual flood conditions (U.S. Army Corps Final Report - Flood Wall Stability Investigation, 1941). These full-scale tests provide valuable data, such that geotechnical design procedures could be developed and verified based on the results of these tests. In addition, numerical analyses simulating these test results could be useful in interpreting the foundation and structure interaction and in predicting the performance of similar I-wall types subjected to flood loading conditions. Among these tests, Test Series III (sheet piling with concrete jacket) was conducted at the Tell City site in Indiana.

A photo of the as-built I-wall and the load test structure is presented in Fig. 1. The plan view and section view of the structure are shown in Fig. 2 and 3, respectively. As shown in these figures, a cofferdam approximately 11 feet by 42 feet in plan dimensions, and 16 feet high was erected on the riverside against a completed section of "I" type flood wall. Three sides of this cofferdam were composed of M-116 steel sheet piling, driven to a penetration of 15 feet below the ground surface, and incorporated tie rods and braces. Observation points were established on the landside of the completed I-wall above the ground surface only. Loads for the full-scale tests were applied by filling water inside the cofferdam. In test series III (at Tell City), four tests were conducted (Nos. 13 to 16). Among these tests, Test Nos. 13 and 14 developed leaks, and Test No.15 was only loaded up to a water height of 12 feet. In Test No.16, a water head of 13.3 feet was attained and sustained for 24 and 139 hours, until there was no further change in the deflection readings. The water head was then increased to 15.3 feet, which was the maximum water head possible on the test monolith, and was sustained for 24 and 192 hours. For Test No. 16, measured wall deflections for the water levels of 13.3 feet and 15.3 feet are available. Note that the wall was unloaded after each test series prior to the subsequent load tests.

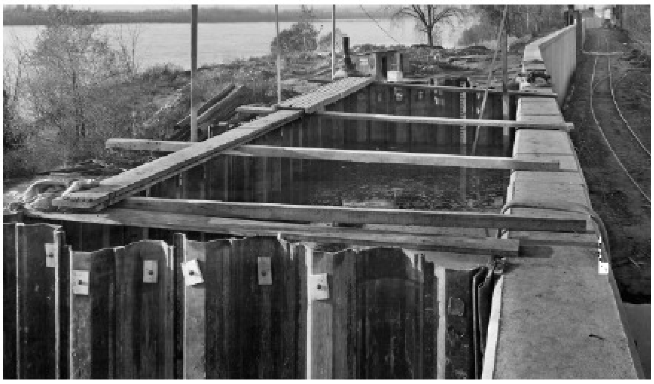

Fig. 1. Test Structure for Test Series No.III – Tell City, Indiana

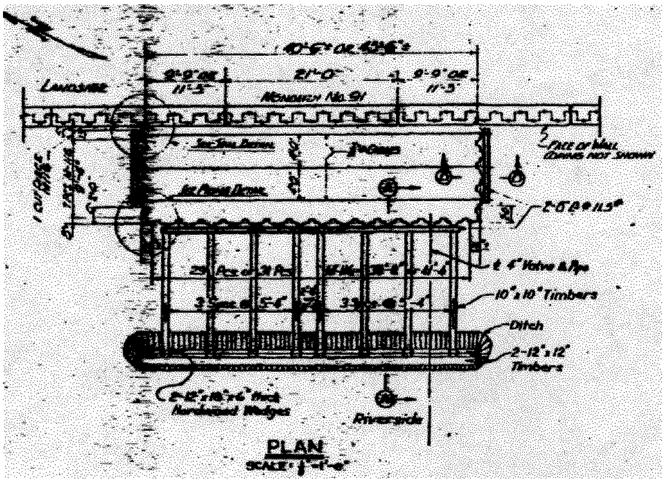

Fig. 2. Test Structure for Test Series No.III – Tell City, Indiana, Plan View

A two-dimensional (2D) numerical FLAC model for an I-wall that simulates a full-scale test condition was developed, and analyses were performed to compute wall deflections and compare with the measured deflections from the full-scale test. The section properties and subsurface stratigraphy were developed and approximately based on a section from the full-scale tests at Tell City, Indiana. The detailed Tell City I-wall evaluations and analyses, were documented in a report entitled "Numerical Models and Analysis of I-walls under Phase III Program", Tasks 4, 5 and 6 (AMEC Geomatrix 2010).

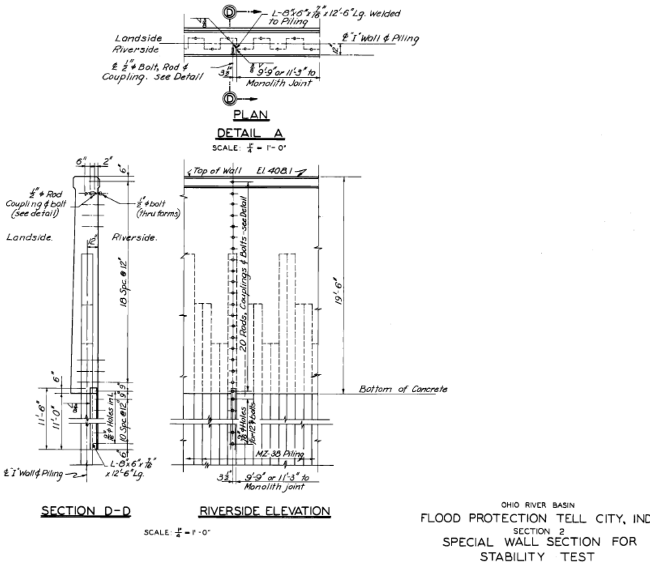

Fig. 3. Test Structure for Test Series No.III – Tell City, Indiana, Wall Section Views

Using the best estimated soil strength and modulus parameters derived from lab testing and literature review, the computed wall displacements, using the 2D numerical simulation, were about twice as high as the measured values. It was judged that the computed displacements will be significantly improved if the actual 3D load test conditions were properly simulated in a full 3D numerical model. Note that the full-scale load test was conducted on a section (42 feet long) of the completed flood wall.

In the study described in this paper, models in FLAC and FLAC 3D were developed to simulate the full-scale load test at Tell City. It was noted that removing/adding the cofferdam structure in the 2D model did not have significant impact on the analysis results. Therefore, the cofferdam, which is composed of M-116 steel sheet piling, tie rods and braces, was not modeled in the current study.

MODEL DIMENSIONS

The full-scale load test at Tell City has a three-dimensional configuration. The cofferdam (water tank) is 11 feet by 42 feet in plan dimensions, by 16 feet in height. A sketch of 2D I-wall system representing a vertical cross section perpendicular to the I-wall is shown in Fig. 4. Some of the key dimensions are provided below:

- Cofferdam and concrete wall are about 16 feet high and 11.5 feet apart. Note that the cofferdam structure was not modeled in the analysis model.
- Ground surface was at elevation 392.7 ft.
- Concrete wall (with a total height of 19.8 ft and a width of 2.3 ft) extended from elevation 388.2 ft to elevation 408 ft (i.e. 15.3 ft above, and 4.5 ft below the ground surface).

- Sheet pile extended from elevation 371.7 ft to elevation 400.7 ft (i.e. embedded 12.5 ft into the concrete wall, and extending 16.5 ft below the base of the wall).
- Except for a few feet below the ground surface, foundation soils are silty clay (CL and ML) to elevation 366.7 ft. Below elevation 366.7 ft, stiff shale material was encountered in the boring logs; accordingly the base of the numerical model is located at the top of shale. Near the ground surface, the soil consists of silty sand with gravel.

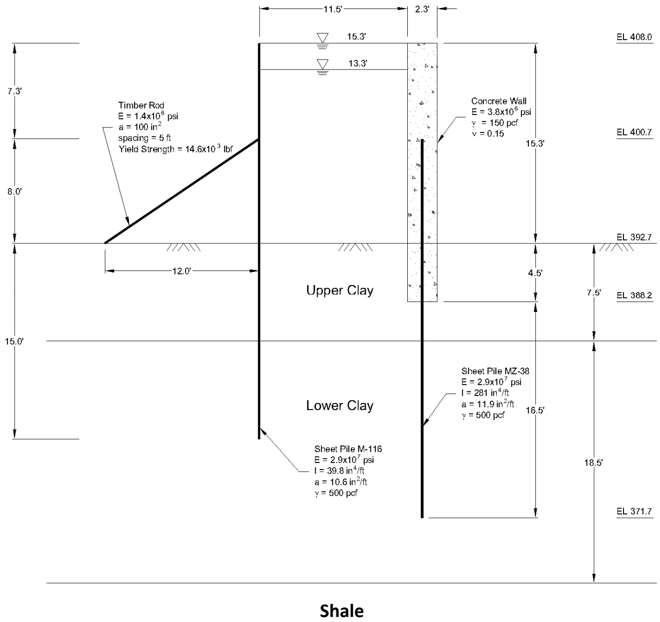

Fig. 4. Sketch of Two Dimensional Model for the Simulation of Full Scale Tests at Tell City, Indiana,

STRUCTURE PROPERTIES

The sheet pile types were provided by the Corps in the 1941 final report. The type of steel sheet piles in the I-wall system is MZ-38 (or PZ38). The cofferdam was constructed with steel sheet pile type M-116 (or PDA27). As mentioned earlier, the cofferdam was not modeled in the current study. The moment of inertia and cross-section area of the sheet pile and concrete wall (modeled by solid zones) are listed in Table 1 below.

Table 1. Structure Members (from the Corps report, 1941)

	Unit Weight, pcf	Young's Modulus, ksi	Poisson's Ratio	Thickness, ft
Concrete	150	3,830	0.15	2.3
	Unit Weight, pcf	Young's Modulus, ksi	Moment of inertia, in^4/ft	Area, in^2/ft
Sheet pile	500	29,000	281	11.91

As-built drawing 727-12.3/15 (Fig. 3) shows that the portions of the sheet piles embedded in the concrete wall varied in length along the alignment of the I-wall. One third of the piles had a length of 12.5 feet, one third had a length of 8.5 feet, and the remaining third had a length of 4.5 feet. The sheet piles were all treated as embedded 12.5 feet into the concrete wall, but their effective properties at a given elevation in the numerical model were in proportion to the number of sheet piles present in the concrete wall. This means that the lower 4.5 feet of the 12.5-foot pile will have the full section area and moment of inertia of a continuous sheet pile wall, the middle 4-foot section of the pile (from 4.5 to 8.5 feet above the bottom of the concrete wall) has 2/3 of the area and moment of inertia of the full wall, and the top 4-foot section of the pile has 1/3 the section area and moment of inertia of the full wall.

In the numerical models in this study, the sheet piles were modeled by FLAC's liner elements. Liner elements in FLAC are used to model thin liners for which both normal-directed compressive/tensile interaction and shear-directed frictional interaction with the host medium occurs. The equivalent thickness of the liner element was calculated (assuming a rectangular cross-section) from the given section area and moment of inertia of the sheet piles. The density was scaled, so the total unit weight of the liner element is the same as the real structure element. Also, because the portions of the sheet piles embedded in the concrete wall varied in length along the alignment of the I-wall as discussed above, the liner elements were divided into three portions and the corresponding parameters are listed in Table 2.

Table 2. Input Parameters for Liner Element

Elevation, ft	Thickness, ft	Unit Weight, pcf	Young's Modulus, ksi	Poisson's Ratio
371.7-392.7	0.55	75.5	29,000	0.2
392.7-396.7	0.48	57.4	29,000	0.2
396.7-400.7	0.38	36.5	29,000	0.2

SOIL PROPERTY AND MODEL PARAMETERS

Recent field investigations and laboratory testing performed by the Corps of Engineers, Louisville District (USACE, 2008) were utilized to develop soil properties and model parameters for the FLAC analyses. The soil properties and model parameters are discussed in detail in AMEC Geomatrix (2010) report and are summarized herein.

The soil underlying the Tell City test site generally consists of low plasticity clay (CL) and silt (ML). It was observed that the upper 7.5- foot layer in general has higher soil strength than the layer below. Based on the undrained tri-axial test data, mean strengths of 1.57 ksf and 0.65 ksf, and Young's modulus of 360 ksf and 150 ksf (also referred as best estimated parameters) were obtained for the upper 7.5-foot layer and the lower layer, respectively. Table 3 summarizes the soil undrained strength, Young's modulus, Poisson's ratio and density selected.

Table 3. Undrained Soil Strength S_u, Young's Modulus E, Poisson's Ratio ν, and Density

Soil Layer	S_u, ksf	E, ksf	ν	Density, pcf
Upper Layer	1.57	360	0.3	120
Lower Layer	0.65	150	0.3	115

The Mohr-Coulomb constitutive model was used in this study, and the shear and bulk modulus values (G and K) were derived from Young's modulus E and Poisson's ratio ν using elasticity relations. The undrained shear strength, S_u, is treated as cohesion in the model.

The concrete I-Wall and the steel sheet pile beneath the I-wall are in contact with the surrounding soil. The shear resistance at the contact surface (i.e., interface between sheet pile and soil, and between concrete wall and soil) is normally smaller than that of the soil. In the FLAC model, this behavior was simulated using the so-called interface element. For cohesive soil, the interface shear resistance, F, is estimated using $F= \alpha S_u$, where a value of 0.5 is used for coefficient α. The steel sheet pile is also partially embedded in the concrete wall. Interface elements were assigned at the contact surface between the sheet pile (liner element) and the concrete zones. The shear resistance (in terms of cohesion and friction angle), shear stiffness K_s, normal stiffness K_n, and tension limit selected for the interface elements are shown in Table 4 below.

Table 4. Input Parameters for Interfaces

Interface Location	Cohesion, psf	Friction Angle, degree	K_s, pcf	K_n, pcf	Tension Limit, psf
Concrete Wall / Soil	0.5*1570=785	0	3.8e4	1.2e6	0
Steel Sheet Pile / Soil	0.5*1570=785 (upper soil layer) 0.5*650=325 (lower soil layer)	0	2.5e5	3.0e6	0
Steel Sheet Pile / Concrete	5,000	50	2.5e5	3.0e6	1,000

In the FLAC 3D model, for the liner element, the interface behavior is represented numerically at each liner node by a linear spring with finite tensile strength in the normal direction, and a spring-slider in the tangent plane to the liner surface. Assigning interface elements between liner elements and surrounding soil or concrete zones is not necessary. The coupling spring properties of the liner elements are defined as part of the liner element properties, and selected to be the same as the properties of interface elements used in FLAC 2D model (Table 4).

FLAC (2D) MODEL

The 2D finite difference grid was developed in FLAC to model the system described earlier. For efficiency of numerical computation, the following sub-zones are constructed:

a) The concrete I-wall is simulated with solid zones that consist of 6 columns and 20 rows (about one foot thick for each row). The total width of the I-wall is 2.3 feet, and is founded 4.5 ft below the ground surface.
b) The sheet pile is simulated by liner elements embedded 12.5 feet from the bottom of the concrete wall.
c) On the left and right sides of the concrete I-wall (below the ground surface) and the pile liner elements, the soil adjacent to the structural elements is subdivided into two finer grid zones.
d) Around the I-wall pile tip location, a 'local' fine zone is developed for better numerical accuracy of pile response near the pile tip.
e) The two "finer" and the "local" zones are attached to both sides of the concrete wall and sheet pile through interface elements.
f) The finer zones are attached together with the grid below the sheet pile tip elevation.
g) The finer zones are attached to the outer coarser zones of the soil.

The complete grid system including the "finer" zones and the 'local' fine zone are presented in Fig. 5 and Fig. 6.

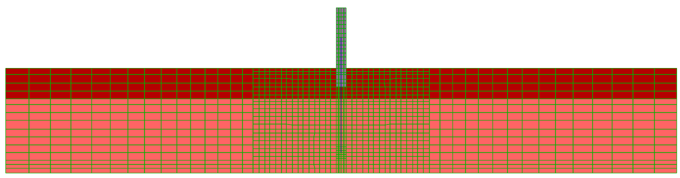

Fig. 5. Complete FLAC Grid for Tell City Full Scale Test Simulation

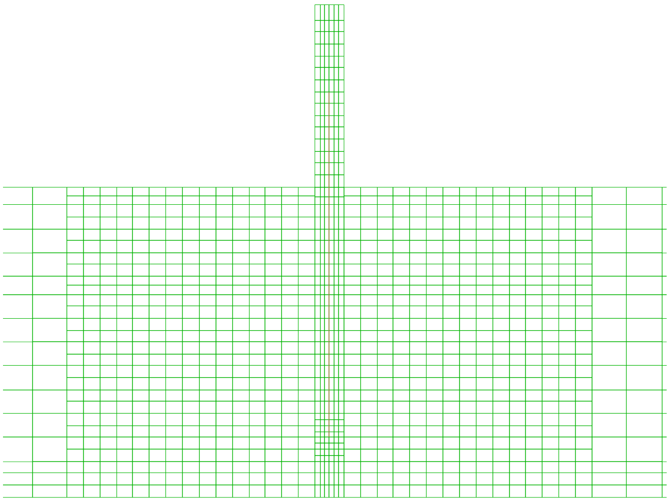

Fig. 6. FLAC Finer and Local Fine Grid for Tell City Full Scale Test Simulation

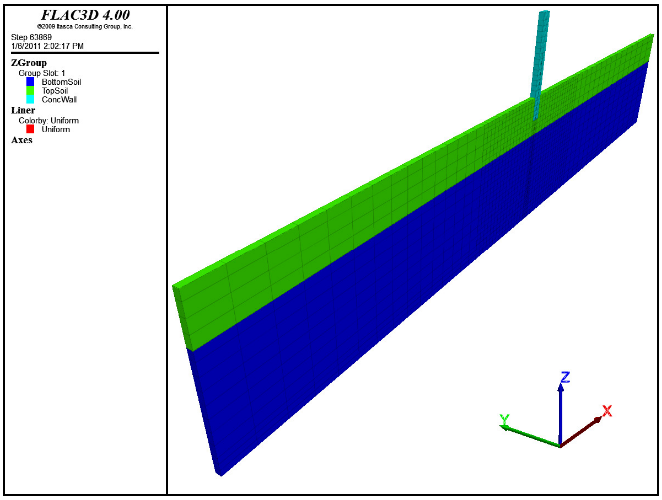

Fig. 7. One-Row-Element (ORE) FLAC 3D Grid for Tell City I-Wall System

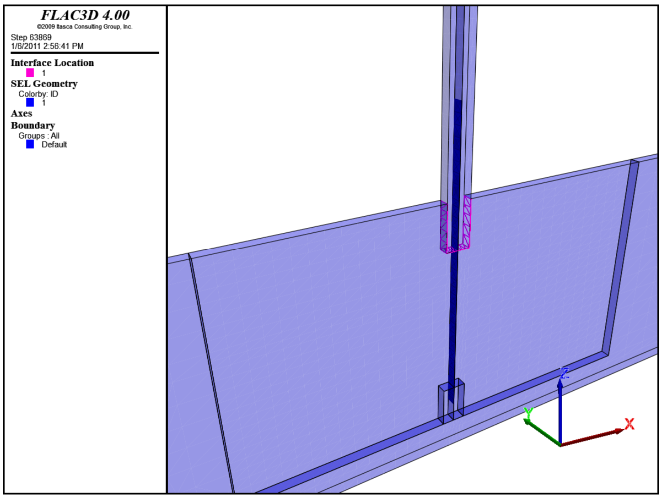

Fig. 8. Liner Element and Interfaces in ORE FLAC 3D Model, Tell City I-Wall System

FLAC 3D MODELS

Note that since the water load in the full scale test was applied only on the 42-foot long section of the wall, the two-dimensional FLAC model was considered a simplified approximation of the actual three-dimensional test loading conditions. In the 2D analysis, the water load is modeled in a plane strain condition, and is applied on the entire length of the wall. In the actual load test, the floodwall beyond the 42-foot-long loaded section was not subjected to the water loads, and thus is expected to provide additional support to the loaded section of the wall. This effect is modeled in the 3D FLAC analyses described below.

<u>One-Row-Element (ORE) FLAC 3D Model</u>

Before developing a full FLAC 3D model, a one-row-element (ORE) FLAC 3D model with plane strain condition was developed to compare with the results of the 2D FLAC analysis and provide verification for the full FLAC 3D model. The running time of such model is comparable to 2D FLAC analysis and much less than full 3D FLAC 3D analysis.

The mesh of the ORE FLAC 3D model was generated by "extruding" the 2D FLAC mesh in the out-of-plane direction. In the ORE model, the plane strain condition is in the x (horizontal) -z (vertical) plane. The width of the ORE model is 1 foot in y direction (out-of-plane direction, from y=0 to y=1). The y-displacement boundary condition for the y=0 and y=1 planes are set to be fixed. Figure 7 shows the ORE FLAC 3D model. The locations of the liner element and interfaces are shown in Fig. 8.

<u>200-foot-wide Monolith (100-foot Full FLAC 3D Model)</u>

In order to properly simulate the three dimensional effects of the field load test, the water load should be applied to a 42-foot-long section along the wall, and not over the entire length of the wall, as was modeled in the plane strain FLAC approximation, and the ORE FLAC 3D model.

The full 3D analysis was modeled for two assumed widths of the flood wall. In the first analysis, the wall was assumed as consisting of one solid monolith 200 feet wide. It is noted that the load test geometry is symmetrical around a plane passing through the center line of the 42-foot-loaded section. The symmetry of the problem is utilized here by only modeling half of the loaded portion of wall (i.e., from y=0 to y=21). The boundary condition on the plane of symmetry, y=0, is such that the out of plane displacement is zero. The extent or the width of the FLAC 3D model is selected at 100 feet in the out-of-plain direction (y direction, from y=0 to y=100). This is half continuous 200-foot-wide solid wall. The effect of the soil and wall beyond that 200-foot width is not considered. The mesh in y direction is generated in such a manner that it is finer toward y=0 and coarser toward y=100 with an average element size in the y direction of 2 feet (Fig. 9). The y-displacement boundary condition for the y=0 and y=100 planes are set to be fixed.

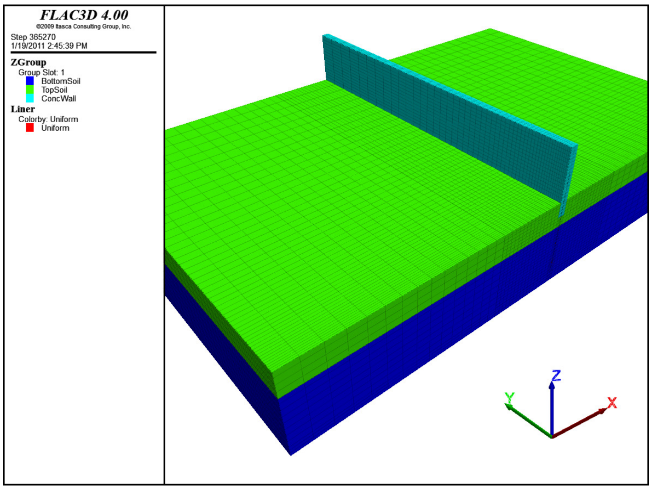

Fig. 9. 100-foot FLAC 3D Grid for Tell City I-Wall System (half of a 200-ft wide Monolith)

<u>66-foot-wide Monolith (33-foot Full FLAC 3D Model)</u>

It should be noted that in reality the I-wall consists of a series of monoliths. Each monolith is about 22 feet long. The information regarding the structural connection between the monoliths is not known. However, it is reasonable to conclude that the assumed 200-foot-wide wall described above (100-foot-wide symmetrical FLAC 3D model) could over-estimate the three dimensional effects by treating the 200-foot section of I-wall as a continuous solid wall, resulting in smaller displacements. If it is assumed that the joints between monoliths can move freely, then an alternative FLAC 3D model can be considered by assuming a 66-foot-wide solid wall monolith (or a 33-foot-wide symmetrical FLAC 3D model, where there is a monolith joint at y=33). Again in this case, the symmetry of the problem is utilized by only considering half of the wall being loaded (from y=0 to y=21). Figure 10 shows the grid of the 33-foot FLAC 3D model. The y-displacement boundary condition for the y=0 and y=33 planes are set to be fixed.

It is recognized that the analysis of this 33-foot FLAC 3D model could under-estimate the three dimensional effects, because most likely there is some restrain at the joints between the monoliths to keep them from separation, resulting in greater displacements. Nevertheless it is considered that the 33-foot and 100-foot FLAC 3D models would provide a range of the most-likely displacements under actual three dimensional loading effects.

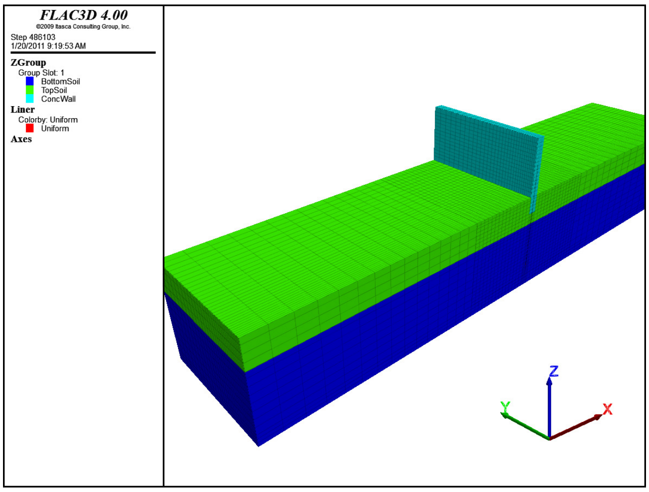

Fig. 10. 33-foot FLAC 3D Grid for Tell City I-Wall System (half of a 66-ft wide Monolith)

ANALYSES PROCEDURE

The analyses were performed in several stages, including the initialization of soil stress, the set-up of the I-wall and sheet pile, and the application of water loads. The “large deformation” option of the FLAC and FLAC 3D program was used.

The following steps were performed in the FLAC analyses:

- The shear strength, model parameters and mass densities of the soil layers, and the concrete wall/sheet pile element properties are listed in Tables 1, 2 and 3.
- The Mohr-Coulomb (bi-linear) model was used in the analysis.
- Gravity was turned on to balance the stresses based on the specified moduli.
- Assuming no groundwater was present.
- Interfaces were connected between sheet pile liner elements (portions beneath the concrete wall) and soil, between sheet pile liner elements (portions embedded in the concrete wall) and concrete grid, and between concrete wall and soil on the two sides and bottom of the embedded 4.5 ft x 2.3 ft portion of the concrete wall. The interface properties are listed in Table 4. In FLAC 3D, interface behavior between the liner elements and surrounding media are included in the properties of the liner element.
- The top of the sheet pile was embedded 12.5 feet into the concrete wall, and the pile tip was modeled in a “free” condition (i.e. carries no moment and no shear).

- The weight of the pile and concrete wall was applied in 10 steps. The stress-strain conditions in the adjacent soil zones were re-balanced after each step.
- Initial displacement and velocity were set to zero before raising the water level in the cofferdam box on the flood side in order to separate the effects of the wall weight from that of the water load.
- The mechanical water load was increased incrementally from the ground surface to 15.3 feet. These loads were applied to the vertical faces of concrete wall and to the ground surface inside the cofferdam dimension.
- The permeability of the clayey soil underlying the test site is very low (in the range of 10^{-6} to 10^{-7} cm/second), such that the soils are treated as behaving in an undrained condition, i.e. no water flow or seepage flow into the soil was considered.

ANALYSES RESULTS

The stresses in the level ground prior to installing the structures were computed using the assigned soil properties (unit weight, modulus, and Poisson's ratio) and the gravity turn-on option of the program. It is noted that free-field horizontal stress is related to the vertical stress by the lateral earth pressure coefficient, K_o, where $\sigma_{xx}= K_o\ \sigma_{yy}$ (or σ_{zz} for 3D), and K_o is related to Poisson's ratio ν by $K_o=\nu/(1-\nu)$.

To better estimate the soil response, the wall and structure weights were added in ten increments. The weight of the I-wall altered the uniform distribution of initial soil stresses. The vertical stresses in the soil adjacent to the wall are higher than those in the zones away from the structure. The horizontal stress distribution was also altered due to the wall installation such that at both sides of the embedded concrete wall, the horizontal stresses are higher than those away from the concrete wall.

The mechanical water load was increased in one-foot increments from the ground surface to 14 feet above ground surface, and then increased to 15.3 feet (top of the wall) in last increment. These loads were applied to the vertical faces of concrete wall and to the ground surface inside the cofferdam area.

The computed top-of-wall displacement versus water load height is shown in Fig. 11. The computed top-of-wall displacement at a water height of 15.3 feet (full height water) form the FLAC analysis is about 0.25 ft. It can be seen that the horizontal displacement at the wall top from the ORE FLAC 3D analysis matches the FLAC analysis fairly reasonably. The horizontal displacement at the wall top from the 33-foot full FLAC 3D analysis (0.13 ft) is less than that from the FLAC analysis (0.25ft) and ORE FLAC 3D analysis (0.28 ft), but greater than that from the 100-foot FLAC 3D analysis (0.06 ft).

The computed entire wall deflections at a water height of 15.3 feet are shown in Fig. 12.

Note the wall displacement for 100-foot FLAC 3D analysis and 33-foot FLAC 3D analysis in Fig. 11 and Fig. 12 are from the symmetrical plane (y=0), where the wall displacements are expected to be maximum. The measured wall displacements after 24 hours of sustained load (short term) and after 139 or 192 hours of sustained load (long term) are also presented in Fig. 11 and Fig. 12 for reference.

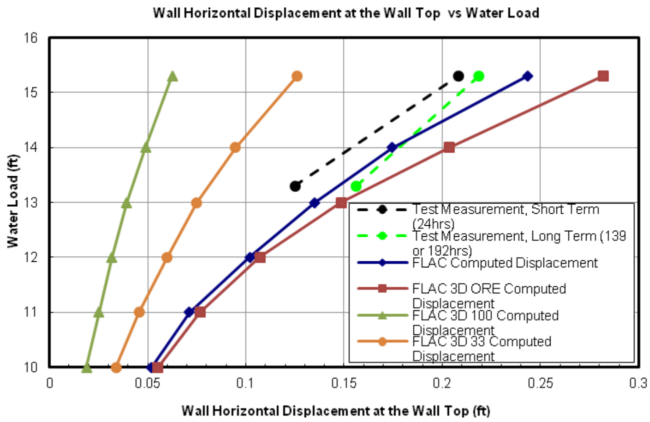

Fig. 11. Computed Top-of- Wall Displacement versus Water Level (feet)

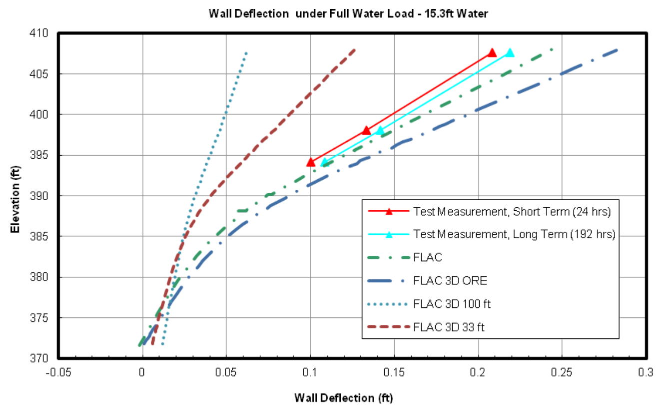

Fig. 12. Computed Wall Deflections under water height 15.3 ft

The mechanical responses of sheet pile, namely moments and shear forces, at a water height of 15.3 feet are calculated. The moments and shear forces in the sheet pile due to the water load are presented in Fig. 13 and Fig. 14 respectively. Note the wall responses for 100-foot FLAC 3D analysis and 33-foot FLAC 3D analysis in Fig. 13 and Fig. 14 are from the symmetrical plane (y=0), where the wall responses are expected to be maximum. It can be seen that the sheet pile responses from FLAC analysis and ORE FLAC 3D analysis are similar, and significantly greater than those from full

FLAC 3D analyses.

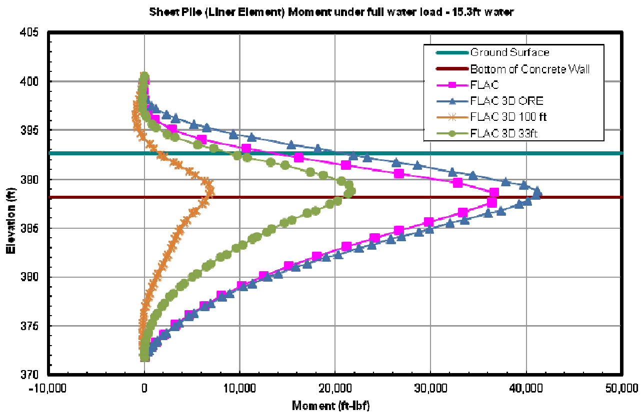

Fig. 13. Computed Moment of Sheet Pile under water height 15.3 ft

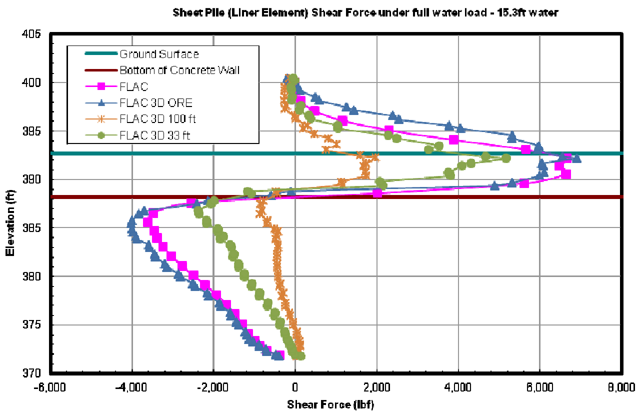

Fig. 14. Computed Shear Force of Sheet Pile under water height 15.3 ft

GAP FORMATION

The 3D effect was clearly illustrated above. However the field test measurements of wall deflection taken during the full scale load tests appear to be close to the 2 dimensional model results and greater than those computed from the full FLAC 3D models (Fig. 11 and 12).

For the clayey site at the Tell City load test, at the end of the full water load at a height of 15.3 feet, a gap was observed to have formed between the I-wall and soil on the water side (U.S. Army Corps Final Report - Flood Wall Stability Investigation, 1941). For such conditions, it is reasonable to assume that once the gap opens at the ground surface, water will flow into the gap and exert hydrostatic pressure on the I-wall, which consequently could cause the gap to propagate to greater depths.

The formation of the hydraulic gap was investigated and incorporated into the FLAC analysis. The detailed procedure used to assess the potential for gap formation and propagation due to the water load is described as follows:

- It is first assumed that no gap will form until the water level is above the level of the ground surface on the flood side of the wall;
- The water level is then raised in one-foot increment, and the horizontal stress, σ_{xx} at the center of the soil zone (element) just below the ground surface, adjacent to the flood side of the wall, is compared to the hydrostatic pressure at the same depth;
- If σ_{xx} is less than the hydrostatic pressure at that level, a gap is assumed to form between the soil and the wall (extending to the bottom of that zone). Then, the full hydrostatic load is applied to both the wall and the adjacent soil zone just below the ground surface.
- The calculation is then repeated to rebalance the stresses due to the gap formation, and to check for any further propagation of the gap to the second soil zone below the ground surface.
- If σ_{xx} in the second zone is found to be less than the hydrostatic pressure at that depth, the gap is extended to the bottom of the second zone; and the hydrostatic load is again applied to both the second soil zone and the wall. The system is rebalanced again, and the stresses are compared for the lower soil zone. This process is repeated until the σ_{xx} in the soil zone examined is greater than the hydrostatic pressure at that depth. This level defines the depth limit of the gap associated with the first water-level increment.
- The water level is then raised by the second one-foot increment and the sequence described above is repeated for all subsequent load increments.

For the analyses described above, it was found that when the water level exceeds a height of 5 feet, a gap would develop and propagate down to the pile tip. This gap development pattern was adopted in the FLAC 3D models by assuming a horizontally uniform gap that developed, within the cofferdam limits, down the pile tip. For this condition, the computed top-of-wall displacements versus water load height are shown in Fig. 15 for the various FLAC models analyzed.

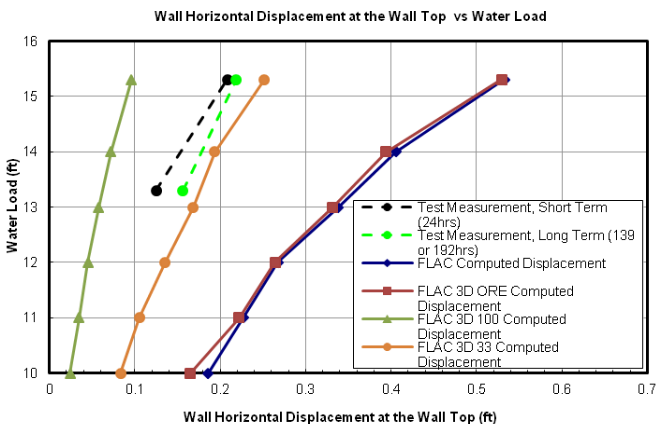

Fig. 15. Computed Top-of-Wall Displacement versus Water Level with Hydraulic Gap (feet)

It can be seen that the top-of-wall displacements vs. water load height from the FLAC analysis and ORE FLAC 3D analysis are similar, but significantly greater than those computed from full FLAC 3D analyses. The field test measurements of wall deflection taken during the full scale load tests fall in between the deflections computed from the 100-foot FLAC 3D analysis and the 33-foot FLAC 3D analysis. In other words, the 100-foot FLAC 3D model and the 33-foot FLAC 3D model provide the range of estimated deflections when properly accounting for the three dimensional loading effects.

CONCLUSION

This study investigates the three dimensional effects in full scale load tests on an I-shaped levee wall conducted at a site in Tell City, Indiana by United States Army Corps of Engineer (Corps). The purpose of the study is to quantitatively address the 3D effects in such a typical soil-structure interaction problem using the FLAC 3D program by comparing FLAC 3D analysis results with results from FLAC analysis.

A FLAC analysis was first performed. Based on this 2D FLAC model, 3D models were developed using FLAC 3D. The three FLAC 3D models that were developed are One-Row-Element (ORE) model, 100-foot model, and 33-foot model, respectively. The ORE FLAC 3D model simulates the plain strain condition of a 2D analysis, and the results, as expected, are similar to the FLAC analysis. The 100-foot model treats the 200 feet long wall as one monolith of solid wall. Using the model symmetry, the 200 feet long wall is represented by a 100-foot wide model. The 33-foot model considers the joint between the wall monoliths and assumes the joint can move freely. The latter two full FLAC 3D models provide a range of the expected performance for an appropriate modeling of the three dimensional effects.

Based on the displacements obtained from the analyses performed in this study, it can be concluded that after taking three dimensional effects into account, the wall displacements are approximately in the range of ¼ to ½ of that from the two dimensional analysis. The maximum sheet pile responses computed from three dimensional analyses are significantly less than those estimated from two dimensional analyses.

The hydraulic gap condition (which can develop in clayey soils when the hydrostatic water pressure exceeds the horizontal soil pressure) was examined. It was found that when the water level exceeds a height of 5 feet, a gap would develop and propagate to the pile tip. As a result of taking the gap formation into account, the computed wall deflections under high water levels increase significantly, and the field measurements of wall deflections taken during the full scale load tests fall within the range of defections computed from the 100-foot and the 33-foot FLAC 3D analyses.

REFERENCES

AMEC Geomatrix [2010]. "*Numerical Models and Analyses of I-walls under Phase III Program*", Task 1 through Task 6.

CECW-CE [2006]. "*Phase II Interim Guidance for Evaluating Existing I-Walls*".

Clough, G.W. and Duncan, J.M. [1969]. "*Finite Element Analyses of Port Allen and Old River Locks*", Contract Report S-69-6, Prepared for U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, College of Engineering, Office of Research Services, University of California, Berkeley, California.

Duncan, J.M. and Bursey, A. [2007]. "*Soil and Rock Modulus Correlations for Geotechnical Engineering*", Center for Geotechnical Practice and Research, Report No. CGPR #44, Virginia Tech.

Duncan, J.M and Chang, C.Y. [1970]. "*Nonlinear Analysis of Stress and Strain in Soils*," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol.96, No SM5, September 1970.

Duncan, J.M. and Wright, S.G. [2005]. "*Shear Strength and Slope Stability*", Hoboken, NJ Wiley.

Gomez, J.E., Filz, G.M. and Ebeling, R. [2000]. R.M., "*Development of an Improved Numerical Model for Concrete-to-Soil Interfaces in Soil-Structure Interaction Analyses*", Information Technology Laboratory, Technical Report ITL-99-1,US Army Corps of Engineers, Engineering Research and Development Center.

Itasca Consulting Group, Inc. [2005]. "*FLAC—Fast Lagrangian Analysis of Continua, Version 5.0 User's Manual*", Minneapolis, Minnesota: Itasca.

Ladd, C. C. and Foott, R. [1974]. "*New design procedures for* *stability of soft clays, Journal of the Geotechnical Engineering Division"*, ASCE, Vol. 100, No. 7, pp 763-786.e.

Peterson, M.S., Kulhawy, F.H., Nucci, L.R., and Wasil, B.A. [1976]. "*Stress-deformation Behavior of Soil-Concrete Interfaces*", Report B-49, Prepared for Niagara Mohawk Power Corporation, Department of Civil Engineering, Syracuse University, Syracuse, New York.

Potyondy, J.G. [1961]. "*Skin Friction between Various Soils and Construction Materials*", Geotechnique, Vol. 11, No. 4, December 1961, pp.339-353.

Reese L.C., Wang, S.T. and Arrellaga, J. [2004]. APILT Plus Version 4.0.

U.S. Engineer Office, Louisville, KY, [1941]. "*Final Report - Flood Wall Stability Investigation*".

U.S. Army Corps of Engineer, Louisville District, [2007]. "*Report of Phase II Evaluations Federally Constructed I-Walls*".

U.S. Army Corps of Engineer, [2007]. "*Analysis of the London Avenue Canal Load Test – Section 1*", Draft Report.

U.S. Army Corps of Engineer, [2009]. "*Gap Analysis of the London Avenue Canal Section 11b*", Draft Report.