

6 Summary and Conclusions

An earth retaining structure such as a lock wall may be subjected to a significant downdrag force generated during placement of the backfill. This downdrag force has a stabilizing effect that could produce a substantially more economical design if accounted for in the design of the wall. Accurate estimation of the downdrag force requires use of an appropriate model for the interface between the backfill and the wall. The model must provide accurate predictions of the interface response to the type of loading applied during placement of the backfill, inundation of the lock, and subsequent operational stages.

The hyperbolic formulation developed by Clough and Duncan (1971) has been used extensively in Soil-Structure Interaction (SSI) analyses for modeling the interface response under monotonic loading. However, it is not applicable to cases where the interface undergoes unloading-reloading or simultaneous changes in shear and normal stresses such as in the backfill-to-structure interface in lock walls. An extended hyperbolic model was developed during this investigation that can predict the interface response to simultaneous changes in shear and normal stresses as well as unloading-reloading and staged shear.

The accuracy of the model was evaluated against the results of interface tests performed for this investigation. In addition, the model was implemented in the finite element program SOILSTRUCT-ALPHA. A pilot-scale test was performed at the Instrumented Retaining Wall (IRW) at Virginia Tech to simulate backfilling, application and removal of surcharge, and changes in the elevation of the water table behind a lock wall. Finite element analyses of all the stages of the test were performed using SOILSTRUCT-ALPHA. Comparisons between the test measurements and the results of the finite element analyses indicate that the extended hyperbolic model provides accurate approximations of the interface response.

This chapter summarizes the activities performed and the conclusions from this investigation. The advantages and limitations of the extended hyperbolic model are presented, as well as recommendations regarding future work on interface modeling for lock wall analyses.

6.1 Summary of Activities

This section summarizes all the activities completed for this investigation: literature review, laboratory testing, the extended hyperbolic model, and lock wall simulation.

6.1.1 Literature review

The literature review focused on interface testing, interface modeling, and SSI analyses of retaining walls.

In the experimental work reviewed, the direct shear box (DSB) and the direct simple shear (DSS) are the devices most frequently used for testing sand-to-concrete and sand-to-steel interfaces. Most of the previous work on interfaces investigated monotonic shear of the interface under constant normal stress. Some investigations have been published concerning cyclic shear of interfaces under conditions of constant normal stress or constant normal stiffness. No previous studies of interface response under staged shear were found in the literature.

All of the interface testing devices described in the literature present limitations. The interface sizes are limited and do not allow the determination of the residual interface strength in all cases. In addition, end effects may be present, inducing errors in the measurement of the pre-peak and peak interface response. The Large Direct Shear Box (LDSB) at Virginia Tech allows testing of interfaces as large as 711 by 406 mm under monotonic or cyclic shear. The size of the interface minimizes end effects and permits maximum interface displacements of 305 mm, allowing the determination of the residual interface strength. The large displacement capabilities of the LDSB also make possible shearing of the interface in several stages with changing normal stress.

Two types of elements are commonly implemented for modeling interfaces: the joint element and the thin layer element. The joint element, developed by Goodman, Taylor, and Brekke (1968), appears to be used most frequently due to the simplicity of its formulation.

Several models of interface response under shearing have been described in the literature. The hyperbolic formulation by Clough and Duncan (1971) was described in detail in Chapter 2. It has been widely used for modeling the interface response to monotonic shear under constant normal stress. It is a simple model that incorporates the most important aspects of interface behavior using parameters that have physical meaning. However, the Clough and Duncan (1971) hyperbolic formulation was not developed to model interface response under cyclic loading or staged shear. None of the other interface models found in this literature review accounts for simultaneous changes in shear and normal stresses.

Several studies have been published concerning SSI analyses of retaining structures. From these studies, it may be concluded that the downdrag force acting on the back of a retaining wall can contribute significantly to the stability of the structure. In typical lock walls, the downdrag develops during fill placement. During this stage, the shear and normal stresses acting on the backfill-to-structure interface are changing simultaneously. During submergence and operation of the lock, the shear stresses may be reduced or even reversed. Hence, it is important to model accurately the interface response under staged shear, unloading-reloading, and shear reversals.

A detailed description of a simplified method (Appendix F of Engineer Manual 1110-2-2100 (HQUSACE, in preparation)) to estimate the downdrag force was presented in Chapter 2. It is based on a number of SSI analyses of typical lock structures. The simplified method is useful to illustrate the importance of an adequate estimation of the downdrag force in design.

6.1.2 Laboratory testing

The following laboratory and field activities were performed for this investigation:

- a.* Modifications to the Large Displacement Shear Box (LDSB).
- b.* Selection of sand specimens for interface testing.
- c.* Grain size distribution, minimum/maximum density, specific gravity, consolidation testing, and triaxial testing on the Density Sand and Light Castle Sand.
- d.* Field survey of existing concrete retaining walls to determine a range of representative surface textures for the concrete specimen.
- e.* Design and construction of a soil box and concrete slab.
- f.* Development of appropriate testing procedures.
- g.* Interface tests following a variety of laboratory stress paths to investigate the constitutive behavior of interfaces and to determine the interface response under field conditions for lock walls.

The LDSB was modified specifically to accommodate soil-to-concrete interface testing for this investigation. A special aluminum soil box was designed

and constructed that allows compaction of the sand sample directly onto the concrete specimen and minimizes the disturbance of the interface during test setup operations.

A field survey of concrete walls was performed. A concrete specimen was prepared with surface features similar to those observed in the field. The concrete specimen was contained in a frame, which was designed and constructed to act as an external reinforcement for the concrete and to minimize its deformations during interface shear.

A fine, rounded, silica sand (Density Sand), and a fine, angular sand (Light Castle Sand) were selected for interface testing. A series of basic laboratory tests, such as minimum/maximum density and grain size analyses, were performed on these sands. Consolidation and CD triaxial tests were also performed to determine sets of hyperbolic parameter values for these soils for a range of relative densities representative of the backfill in lock walls.

An interface testing program was carried out that included initial loading tests, staged shear tests, unload-reload tests, and multi-directional stress path tests. Three types of interfaces were tested: dense Density Sand against concrete, medium-dense Density Sand against concrete, and dense Light Castle Sand against concrete.

From the results of the interface tests, it was found that the average ratio between the values of interface friction angle and internal friction angle of the soil was 0.8. Displacement softening was observed in all tests. The displacements required for the development of the residual condition were as large as 20 mm.

Staged shear tests were performed by increasing the normal pressure in steps during shear. The staged shear tests provided important information about the behavior of sand-to-concrete interfaces and were used to define the yield surfaces implemented in the extended hyperbolic model. It was found that it is possible to determine a complete residual strength envelope from staged shear tests, as long as the displacement capability of the equipment is enough for the development of the residual condition.

Several unload-reload tests were performed during which a complete loading cycle was applied between two predetermined stress levels. These tests follow stress paths similar to field stress paths in which the shear stresses may decrease as a consequence of a rise of the water table behind a lock wall. A substantial increase in the interface shear stiffness was observed during unloading and reloading. It was observed that compression takes place during unloading, followed by dilation during subsequent reloading of the interface. In some tests, one or more cycles of shear were performed upon mobilization of the residual

strength. Similar shear stress-displacement response and residual strength values were obtained for both directions of shear in all tests.

Multi-directional stress path tests were performed on all three types of interfaces. The purpose of these tests was to provide a basis for a performance evaluation of the extended hyperbolic model under complicated loading paths. They also modeled certain aspects of the type of loading expected at the backfill-structure interface during backfill placement and operation of a lock wall. The extended hyperbolic model was validated against the results of these tests.

6.1.3 Extended hyperbolic model

An extended hyperbolic model for interfaces was developed during this investigation. The model captures important aspects of interface response under the type of loading expected to occur in a wall-backfill interface. The material parameters required for implementation of the model are the same as those introduced by Clough and Duncan (1971).

A procedure for normalization of interface test data was developed that facilitated the study of interface response under a variety of experimental stress paths. Based on this study, the concepts of yield surfaces and loading regions were introduced. Two yield surfaces are defined by the past maximum and past minimum stress levels during shear. Two transition surfaces are defined by the past maximum and past minimum shear stresses on the interface.

Three types of loading are considered in the extended hyperbolic model: yield-inducing shear, unloading-reloading, and transition loading (Table 4-1). Yield-inducing shear occurs if the stress path reaches one of the yield surfaces. Transition loading in the first quadrant of the τ - σ_n plane occurs if the stress level is lower than the past maximum stress level and the shear stress is equal to or greater than the past maximum shear stress. Conversely, transition loading in the fourth quadrant occurs if the stress level is greater than the past minimum stress level and the shear stress is equal to or lower than the past minimum shear stress. Unloading-reloading takes place if the stress level is lower than the past maximum stress level and greater than the past minimum stress level, and if the shear stress is lower than the past maximum shear stress and greater than the past minimum shear stress.

A formulation for yield-inducing shear was developed in which the interface stiffness is determined by the normal stress, the stress level, and the rate of change of the normal stresses during shear, i.e., the inclination of the stress path. The formulation was found to predict the interface response accurately under a variety of experimental, yield-inducing stress paths.

For unloading-reloading or transition loading, one of three versions of the model can be applied, depending on the accuracy required for the analysis. In Version I, a linear, normal stress-dependent response of the interface is assumed both for unloading-reloading and for transition loading. This version does not model the hysteretic response of the interface under unloading-reloading. Comparisons of the calculated interface response with test data showed that this version may provide reasonable predictions of the interface response for unloading-reloading cycles that are not too large. It is inaccurate for modeling the response of interfaces to large unload-reload loops or interfaces subjected predominantly to transition loading. Version I is the simplest to implement and use in SSI analyses.

In Version II, a nonlinear, hyperbolic response is assumed for unloading-reloading and transition loading that accurately models the hysteretic behavior of interfaces subjected to large unload-reload loops. It provides accurate or reasonable estimates of interface response for most of the experimental stress paths considered in this investigation. However, it does not provide accurate estimates for cases in which the interface is subjected predominantly to transition loading. Although the formulation of Version II introduces some additional state variables, it is simple to implement in SSI analyses of retaining walls.

In Version III, the interface stiffness for unloading-reloading is determined in the same way as in Version II. For transition loading, on the other hand, the interface stiffness is determined by interpolation from the normalized stiffness diagram. Two normalized stiffness values are used for the interpolation: the normalized stiffness of the interface at the onset of transition loading and the normalized stiffness at yield. This version provides the most accurate estimates of interface response for all the experimental stress paths considered. It is particularly useful for cases where the interface is subjected predominantly to staged shear. Version III is the most difficult to implement in SSI analyses because it introduces several additional state variables with respect to the other two versions.

The principal advantages of the extended hyperbolic model are as follows:

- a. It has a simple mathematical formulation.
- b. Hyperbolic parameter values for different types of interfaces are available in the literature.
- c. It captures the main features of the interface response under simultaneous changes in shear and normal stress and unloading-reloading.

- d. It provides accurate estimates of the interface response for the experimental stress paths considered in this investigation.
- e. It is relatively easy to implement in SSI analyses.
- f. It establishes a framework for future work on plasticity-based interface models.

The formulations for yield-inducing shear and for unloading-reloading Version II of the extended hyperbolic model were implemented in the finite element program SOILSTRUCT-ALPHA, which is commonly used by the U.S. Army Corps of Engineers for analyses of lock walls. Finite element analyses of the IRW lock wall simulation suggest that these formulations are effective for prediction of vertical shear forces in retaining structures.

The model has several limitations:

- a. It does not model displacements normal to the interface, and the interface thickness is implicitly assumed as zero. Consequently, in finite element analyses, a large normal stiffness must be assigned to interface elements to minimize overlapping of adjacent two-dimensional elements. In addition, it cannot model the generation of normal stresses due to restrained dilation of the interface during shear between two stiff, rough media. This may not be important for analyses of stiff retaining structures that have relatively compressible backfills.
- b. It does not model displacement softening of the interface. According to the experimental data collected during this investigation, displacement softening may take place in interfaces subjected to relative displacements of 6 to 20 mm. Therefore, in cases where larger magnitudes of interface displacement take place, the model cannot provide accurate predictions of the softening response.
- c. The model predicts interface stiffness values that are zero or negative for certain loading combinations. For implementation of the model in finite element programs, it is then necessary to use appropriate stiffness values and adequate numerical procedures to prevent numerical problems. It is believed that the model predictions for these cases are correct. However, if finite element analyses of lock walls show that these types of loading are common, it may be necessary to perform additional experimental work to verify the model predictions.

As discussed in Chapter 5, the model was used successfully for the estimation of vertical shear forces in the IRW lock wall simulation. However, it has not yet been used for routine analyses of actual lock walls.

6.1.4 Lock wall simulation

A pilot-scale test was performed in the IRW to simulate construction and operation of a lock wall. The test was carried out in three stages: backfilling, surcharge application, and backfill inundation. Light Castle Sand was used as backfill material for the test.

The IRW was not originally designed for surcharge application and inundation of the backfill. Consequently, preparations were necessary to accommodate the intended simulation. In order to allow full inundation of the backfill, a wooden bulkhead was designed and constructed at the bottom of the access ramp and all the gaps between the instrumented panels were sealed. Two perforated Polyvinyl Chloride (PVC) pipes were installed for inundation and drainage of the backfill. A soil box was prepared to contain the soil used as surcharge. Before the start of the test, all the instruments were calibrated in situ and a data acquisition system was installed in the IRW.

The test results show that a significant vertical shear force develops at the wall-backfill interface during placement and compaction of the backfill. This shear force increases significantly during surcharge application, and decreases during inundation of the backfill. However, it was observed that the final magnitude of the vertical shear force at the end of the test, after drainage of the backfill, was similar to the shear force at the end of backfilling. This suggests that there is not a significant degradation of the vertical shear force with cycles of surcharge application and backfill inundation.

The vertical shear force coefficient K_v was calculated from the vertical force measurements during backfilling. It was found to increase with increasing backfill height. The measured values of K_v are greater than the values predicted using the design line recommended in Appendix F of Engineer Manual 1110-2-2100 (HQUSACE, in preparation). This is a result of the conservatism employed in establishing the design line and the relatively large effect of compaction-induced stresses in short walls such as the IRW. It is not recommended here that the K_v values given by the design line be exceeded for design of lock walls.

The vertical shear force coefficient for surcharge $K_{v,q}$ was determined from the test measurements from the surcharge application stage. It was found that the design line in Appendix F of Engineer Manual 1110-2-2100 (HQUSACE, in preparation) provides a slightly conservative approximation of the measured $K_{v,q}$ value.

The correction factor C_{wt} for determination of the vertical shear force coefficient during inundation was determined from the vertical force measurements during inundation and drainage of the backfill. It was found that the design line in Appendix F of Engineer Manual 1110-2-2100 (HQUSACE, in preparation) provides a good approximation of the C_{wt} value for water-to-wall height ratios D_2/H less than 0.5. For larger ratios, the design values are conservative.

Compaction-induced stresses are significant in the IRW because of its short height. Because the influence of compaction on the stresses decreases with increasing wall heights, accurate finite element analyses of lock walls do not commonly require modeling the stresses applied during compaction. However, for the finite element analyses of the IRW, it is important to account for these compaction effects.

The finite element analyses of the IRW were performed using the updated version of SOILSTRUCT-ALPHA, which contains the extended hyperbolic model for interfaces. For finite element analyses of the IRW, different properties were assigned to the backfill during backfilling than were assigned during surcharge application. For the backfilling analysis, a lower modulus and larger Poisson's ratio than suggested by laboratory test data were assumed, which provided appropriate vertical and horizontal stresses at the wall-backfill interface. For the surcharge placement analysis, a stiffer backfill and a reduced Poisson's ratio were assumed. The properties of the backfill were adjusted by trial and error until the analysis results matched the target values of F_v and F'_x measured in the IRW at the end of compaction and surcharge application. It was found that once a match to the target F_v and F'_x values was obtained from the analyses, the analysis results for intermediate stages also matched the test data. This suggests that the procedures followed for the analyses are adequate, and that the models of the soil and interface provide reasonable approximations to their actual response.

A finite element analysis of backfill inundation was performed using the backfill properties determined from the calibration analysis of surcharge placement. The analysis provided a very good approximation to the values of F'_x and F_v measured during the test. It can be concluded that the implementation of the extended hyperbolic model in SOILSTRUCT-ALPHA was successful, and that the soil and interface models used in the analyses are accurate for inundation analyses of the IRW. It may be inferred that the model may be accurate for analyses of actual lock walls of greater height. Therefore, use of the model for lock wall analyses is recommended for further validation of its accuracy and usefulness.

6.2 Recommendations for Future Work

According to the findings from this investigation, the following recommendations are presented for future work on interface modeling and SSI analyses of lock walls:

- a. It is recommended that the updated version of the program SOILSTRUCT-ALPHA be used for analyses of lock walls to further verify the applicability of the extended hyperbolic model for interfaces. Such analyses would also serve to detect numerical problems, if any, arising from the implementation of the extended hyperbolic model in SOILSTRUCT-ALPHA.
- b. The relative significance of Versions I, II, and III of the formulation for unloading-reloading could be assessed by incorporating Versions I and III into SOILSTRUCT-ALPHA, and performing comparative analyses of typical lock wall configurations using the three versions of the model.
- c. The extended hyperbolic model does not account for displacement softening of interfaces. If peak strengths are used in cases where displacement softening takes place at the wall-backfill interface, SOILSTRUCT-ALPHA analyses may overestimate the magnitude of the downdrag force. It is therefore recommended to calculate the range of relative displacement magnitudes at the interface between backfill and interface from the results of SOILSTRUCT-ALPHA analyses of typical lock walls with varying foundation conditions. Such analyses may reveal the type of lock wall configurations where displacement-softening behavior of the wall-backfill interface needs to be modeled in order to obtain accurate estimates of downdrag forces. According to the results of the tests performed during this investigation, displacement softening may occur after relative interface displacements of 5 to 20 mm. Alternatively, residual interface strengths could be used to produce a conservative analysis.
- d. The extended hyperbolic formulation does not model displacements normal to the interface. According to the experimental results obtained during this investigation, dilation may take place in sand-to-concrete interfaces. Although the model provides accurate estimates of the interface response to simultaneous changes in normal and shear stresses, it cannot predict changes in normal stresses during shear induced by restrained dilation of the interface. Restrained dilation of interfaces is known to occur in rock joints, and rock joint models have been developed that allow the calculation of normal stress changes induced by this phenomenon. However, it is not known whether restrained dilation can occur at a wall-backfill interface. Relatively simple finite element

analyses can be performed using SOILSTRUCT-ALPHA to estimate the magnitude of changes in normal stress at the wall-backfill interface due to restrained dilation, and the results can be used to evaluate the importance of these normal stress changes for design of lock walls.

- e. If interface dilation is found to be an important issue for design of lock walls or other Corps of Engineers structures, it may be convenient to develop a new interface element formulation for use in finite element analyses. This new formulation could incorporate features of the extended hyperbolic model and account for coupled tangential and normal displacements. The formulation of the thin layer interface element developed by Desai et al. (1984) could be a convenient starting point for the development of such a coupled interface model.