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Fundamental examination of scaled cantilever pile walls

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ABSTRACT: Approximately 10% of the levee systems in the US Army Corps of Engineers (USACE) portfolio include cantilever pile walls, known as I-Walls. Following the catastrophic I-Wall failures during Hurricane Katrina, there is continued concern about the safe use of I-walls as a flood retention system, its longevity, and its response to major flood events. Over 70 pre-existing I-Wall segments are still in use in the New Orleans area and evaluations are proving challenging due to the limited catalogue of case histories and diversity of failure mechanisms. Recent numerical studies have established that soil properties and embedment length are key to establishing performance indicators for inspectors before, during, and after significant flood events. Validation of these results using systematic, physical models are underway at the Engineering Research and Development Center (ERDC) Centrifuge Research Complex (CRC). In the experiment a scaled sheet pile wall is embedded at different depths into different soil foundation profiles. Water height in the model is raised for a set period to replicate typical sustained flood loading. A combination of instrumentation and measurement techniques were used during the experiments capturing a variety of key parameters including soil/structure movement and rotation, net soil stress distribution against the wall, bending moment, and general soil behaviour which were then related to system response.

1 INTRODUCTION

This paper will go over the test plan development to conduct an upcoming series of scaled centrifuge tests of cantilever walls. Cantilever sheet pile flood walls, referred to as I-Walls in this report, are steel sheet piles driven into the foundation. I-walls rely on the adjacent soil to provide passive resistance during flood loading. I-Walls can be placed on flat ground or are commonly added to the top of existing levees to raise the height without increasing the levee footprint.

The goal of this series of centrifuge tests are to further investigate the failure mechanisms for I-Walls with a specific focus on the soil stiffnesses. First, the background summarizes the motivation for this series of tests. Second, a series of previous I-Wall studies is summarized. Then the experiment design section explains the proposed test matrix, the instrumentation plan, materials, and model geometry. Finally, there is a placeholder in this draft for experimental results to be added once initial tests are complete.

2 BACKGROUND

Approximately 10% of the levee systems in the US Army Corps of Engineers (USACE) portfolio include cantilever pile walls, known as I-Walls. Following the multiple failures of I-Walls during Hurricane Katrina, there remain uncertainties about the performance of I-walls during future flood events. Over 70 pre-existing I-Wall systems are still in use in the New Orleans area and numerical evaluations are proving challenging due to the limited catalogue of case histories, the complex failure mechanisms, and the sensitivity of numerical models to small changes of input material parameters.

Recent numerical modeling has shown small changes in soil properties, especially stiffness, and embedment length are key to evaluating the I-wall response during flood loading. The uncertainty around those paramaters is critical to understanding the complex soil structure interaction problem. The numerical models show changes in failure mechanisms especially the ratio of the strengths and stiffnesses in layered systems, including cross sections on flat ground or with a levee. This series of centrifuge experiments and corresponding numerical results will help develop analysis procedures by selecting the stiffness models and material parameters.

Validation of these numerical results using systematic, physical models are underway at the Engineering Research and Development Center (ERDC) Centrifuge Research Complex (CRC). In the experiment a scaled sheet pile wall is embedded at different depths into level ground or on top of a levee. Water height in the model is raised for a set period to replicate typical sustained flood loading. A combination of instrumentation and measurement techniques are used during the experiments capturing a variety of key parameters including soil/structure movement and rotation, net soil stress distribution against the wall, bending moment, and general soil behaviour which are then related to system response.

3 PAST STUDIES OF I-WALLS

There have been a series of studies on I-wall performance in the last 40 years. The tests have included both full scale and centrifuge test accompanied by analytical and/or numerical analysis.

In 1985, the USACE conducted a full-scale load test on the E99 I-Wall in the Atchafalaya Basin near Morgan City (Jackson 1988). The experiment was conducted to investigate whether to use drained or undrained strength parameters during design. The measurements from the field test compared favourably to force balance analytical solutions for displacements. However, the E99 full-scale load test did not capture the effects of the riverside gap formation found in subsequent testing and field case histories. The E99 full scale load test only considered one foundation condition and the I-Wall was not installed on the crest of an embankment.

After the failure of I-Walls along the 17th Street and London Ave canals during Hurricane Katrina in 2005, the USACE established the Interagency Performance Evaluation Task Force (IPET, 2007). The IPET investigated the performance of the levee systems during Hurricane Katrina. The performance of I-Walls was summarized in Volume V, Appendix V of the IPET report. The report included Spencer's Method Limit Equilibrium analyses and physical modelling in centrifuges at the ERDC in Vicksburg, MS, and Rensselaer Polytechnic Institute (RPI) in Troy, NY. The main findings from the modelling included understanding the formation of a waterside gap formed between the I-Wall and the adjacent soil. The physical and numerical models showed a decrease in factor of safety caused by the added driving force of the water filling the gap. Both the physical and limit equilibrium slope stability modelling focused on ultimate strength at failure and cross sections specific to the I-Walls which failed.

There were two additional centrifuge efforts undertaken by ERDC c. 2008. The first was to continue understanding the mechanisms of failure to compare with numerical models to inform USACE design guidance. Unfortunately, this effort was poorly documented and there were no published findings. The second effort, (Vanadit-Ellis, et. al. 2012) was a partnership between ERDC and the University of Mississippi focused on evaluating two methods to remediate I-walls. The first remediation method tested in the centrifuge were clips added to the joints in the I-Wall concrete caps to limit differential movement during loading. The second remediation tested was a bentonite apron designed to fill the waterside gap as the I-wall deflected. The report concluded both methods showed moderate success with both remediation methods in the centrifuge model but alluded to potential issues transitioning the methods to full scale field conditions.

The current series of centrifuge models is motivated by ongoing analysis to evaluate I-walls throughout the USACE portfolio. Currently, numerical modelers are using FLAC and OptumG2 to analyse the I-walls. The numerical analysis identified the need to reduce the uncertainty of the soil stiffness which has yet to be addressed in experiments and the supporting analysis methods.

4 EXPERIMENT DESIGN

The centrifuge used is at the Engineer Research and Development Center's (ERDC) Centrifuge Research Complex (CRC) in Vicksburg, MS. The 1200 gton centrifuge was recently rennovated and has a 6.5 m radius (Bowman et al., 2022). The centrifuge is large enough to minimize the effects of water curvature on the loading profile.

The tests are conducted in recently fabricated window box for the ERDC CRC. The interior model space in the large window box is 1.2 m long, 0.4 m wide, and 0.5 m tall. This results in a 90 m by 30 m by 38 m working area in prototype scale at 75g as shown in Figure 1. These dimensions allow testing of I-walls up to 10.7 m in tall with a burial depth of 6.5 m and a stickup height of 4.2 m. The total foundation depth can be up to 18 m deep. In model scale, the I-wall model is placed 200 mm from the flood side end of the box to limit the amount of water pumping required and to allow room for the passive side failure zone to develop.

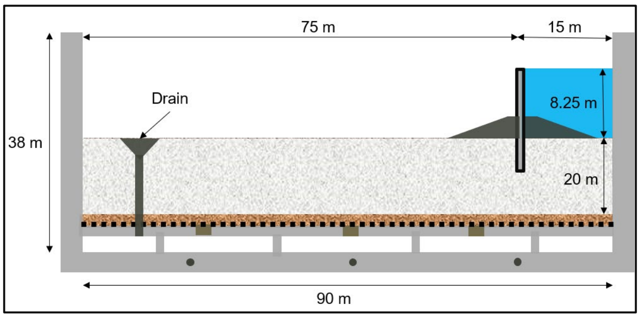

Figure 1: Planned Configuration of I-wall in the Centrifuge Box with Prototype Scale Dimensions. This figure shows the levee on top of kaolin clay foundation configuration.

The series of tests is designed to test both clay, sand, and layered sand/clay soil profiles. The soil profile is built on a false floor. The false floor was added allow drainage during consolidation while spinning. The false floor has 12 holes 12.7mm in diameter evenly distributed drain into the 10 cm tall reservoir below the model. This, combined with a vertical drain allows for the double drainage consolidation condition.

4.1 I-Wall Scaling and Design

While previous numerical analysis showed that the stiffness of the sheet pile wall has a negligible effect on the soil structure interaction, the wall stiffness in the centrifuge model was approximately matched for consistency. The wall stiffness, EI, is scaled by $1/N^3$ consistent with the method discussed in Bolton and Powrie, 1988 and ERDC, 2012. Where E is the Modulus of Elasticity and I is the moment of inertia for the section along the bending axis. The stiffness was scaled using an aluminium plate with a lower stiffness and reducing the dimensions of the plate.

The typical steel sheet pile section is a PZ-27 with a Young's modulus of 200 GPa and a moment of inertia of 2.52e-4. The model scale I-wall is made from an aluminium plate 4.75 mm thick with a Young's modulus of 69 GPa and a moment of inertia of 2.52e-4. Rubber C-channel gaskets are installed on both edges of the I-wall to prevent water from leaking between the wall and the side of the box.

4.2 Materials

The soils used were a Specwhite Kaolin Clay to represent soft foundation clays. The Specwhite clay was mixed at twice the liquid limit. The sand foundations and base drainage layer is OK85 or a poorly graded fine sand depending on the needs of the tests. Non-hardening oil-based modelling clay is used to construct the levee sections on either side of the I-wall. The soils are undergoing testing to classify the materials. In addition, a series of triaxial tests will measure the strength and stiffness properties.

4.3 Instrumentation

A suite of instrumentation methods are used to monitor the I-wall and foundation during the experiments. The methods include pore pressure transducers, tactile pressure sensors, distributed fibre optic strain & temperature sensing, stereo camera, Linear Variable Differential Transformer (LVDT), and Particle Image Velocimetry (PIV) as shown in Figure 2.

Two models of pore pressure transducers (PPT) are used. The models are Druck PDCR-81 and TE Connectivity MS5407-AM housed in a custom 3D printed enclosure and porous stone case. The PPTs are used to monitor the degree of consolidation in clay layers during spin up, the water level on the waterside reservoir, and water pressures developed during loading. In the sand layers, the PPTs are used to monitor the development of seepage flows.

The Tekscan I-scan™ tactile pressure system are used to monitor the net pressure distributions on the surfaces of the I-wall along the interface between the soil and structure.

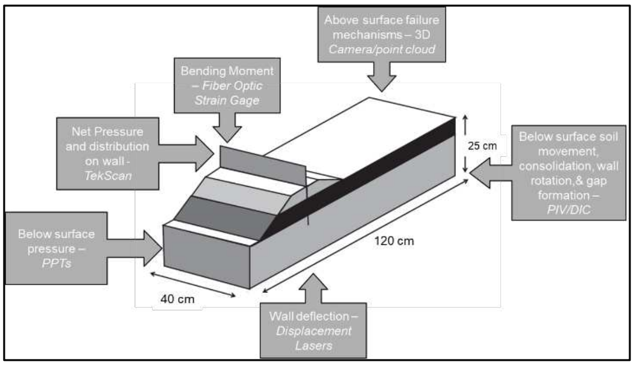

Figure 2: Schematic of Instrumentation Methods Planned for the I-wall Centrifuge Model.

The LUNA ODiSI 7100 distributed fiber optic strain and temperature system are used to measure the axial strains in the I-wall. The strains in the I-walls are used to calculated the bending moments and compared to numerical models.

A RealSense™ D455 depth camera records video and can generate dynamic 3D point clouds to monitor displacements of the soil surface and the I-wall during consolidation, flood side water loading level, and downstream displacements.

The LVDTs are used to measure displacements of the I-wall during loading and the ground surface during clay consolidation.

Finally, Raspberry Pi V2 cameras are used to record top and side views of the mode. The video, combined with static anchor points and tracer particles, is used by PIV software to track displacements during the experiments.

4.4 Drainage and Pumping

Moving water in flight is necessary to allow drainage during consolidation and to load the I-wall. During consolidation of the clay layers a 5 cm thick layer of sand is added above the false bottom. This has evenly spaced 1.3 cm diameter screened holes to allow water to drain from the sand into the reservoir created in the centrifuge box by the false bottom.

A Teknic, Inc. ClearPath-SDHP servo-controlled motor powers an impeller pump to move water from a reservoir on the centrifuge platform into the model box. The pump allows precise control of the floodwater loading during flight.

5 TEST SERIES

The test series begins with two demonstration models to prepare the methods for consolidation, loadings, and monitoring the experiments in a sand and a clay foundation.

After the preliminary experiments are completed, there are an additional 10 centrifuge tests planned to study sand, clay, and layered foundations. In addition, the penetration depth of the I-wall will be changed to investigate the influence of ratio of buried depth to stickup height. The test matrix is shown in Table 1.

Table 1. Text Matrix for the Planned I-Wall Centrifuge Experiments.

Soil Type	Model Geometry	Wall Length
Dense Sand	Flat	Short
	Levee	Short
	Flat	Long
	Levee	Long
NC Clay	Flat	Short
	Levee	Short
	Flat	Long
	Levee	Long
OC Clay	Flat	Long
	Levee	Long
Layered System	Flat	Long
	Levee	Long

The model geometry and wall lengths are still in development and final configurations will be decided based on the preliminary tests and informed by ongoing numerical modelling.

6 PRELIMINARY TEST

A preliminary test was run to develop construction techniques, consolidation methods, calibrate instrumentation, and validate the process of transitioning physical model results into numerical models. The first test was an I-wall on flat ground. Above the false bottom a fine woven metal screen was laid to drain and the soil layers above. Next, a fine to medium grained poorly graded sand was placed in a 25mm layer on the fine wire screen to provide adequate uniform drainage of the clay slurry above during consolidation. Informed by previous studies, Bolton and Prowrie (1988) and Cao et. al. (2002) and the needs of this experiment, the kaolin clay slurry was mixed at a volumetric moisture content of 120% or twice the liquid limit (LL = 60%) and placed above the sand drainage layer. A lean clay (CL) was added above the kaolin slurry.

Before the I-wall was added the model was spun at 50g for 2 hours to get approximately 20% consolidation the kaolin slurry. The centrifuge was stopped to add the I-wall, which was inserted by gently tapping the painted aluminium plate into the soil with a rubber hammer. Below are a series of photos showing the model in three different stages.

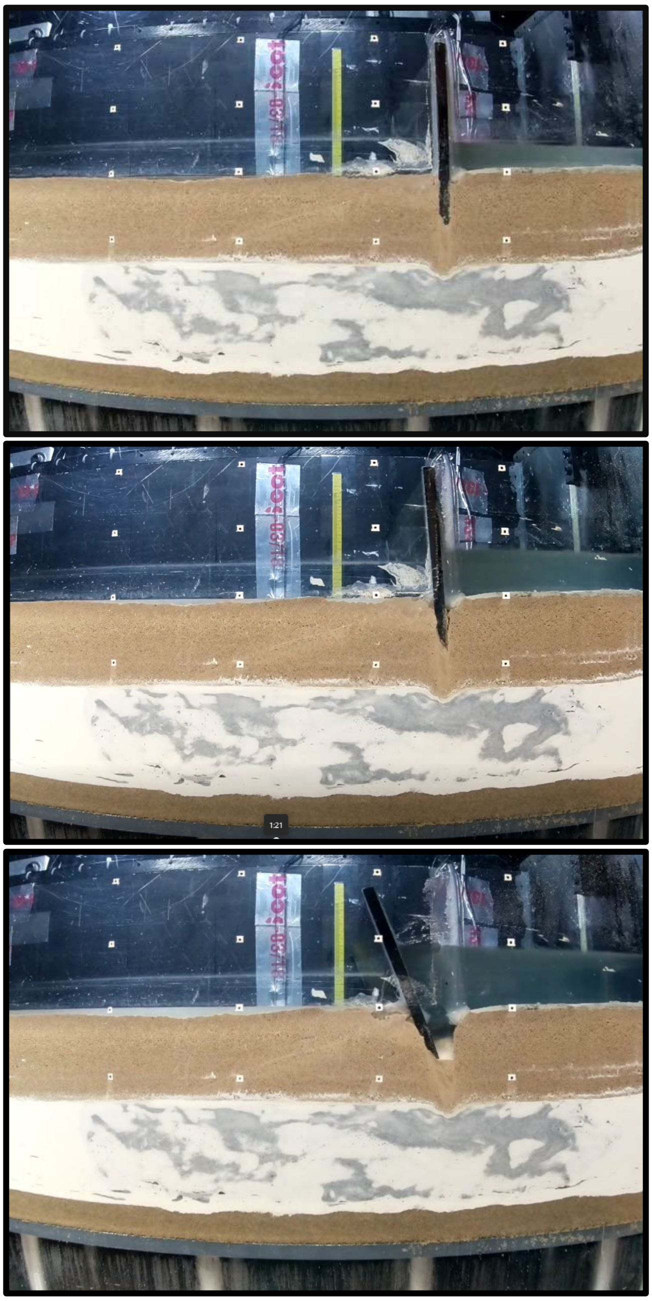

Figure 3: Series of three photographs showing the progression of the I-wall failure. (Top) Initial configuration and beginning of loading. (Middle) I-wall begins to lean and the floodside gap forms. (Bottom) End of test. The I-wall tipped over to a degree that side seals could no longer stop water.

The preliminary test was numerically modelled with OptumG2 a geotechnical finite element and limit analysis tool. The numerical model initially used estimated values for material properties based on the kaolin and lean clay layers. The numerical model was run in a strength reduction mode until failure occurred. There are significant refinements needed to both the physical model and the numerical model as the test series progresses and additional soil characterization is completed to understand how the soil stiffnesses effect the I-wall deformation. However, the passive wedge failure mechanism shown by the contours of shear strain shown in Figure 4 below is consistent with the I-wall rotated as observed in the images during the preliminary centrifuge model Figure 3. The wall rotated toward the landward side because the top clay layer was very soft. The rotation failure occurred before a deep-seated failure could occur in the partially consolidated weak kaolin clay layer.

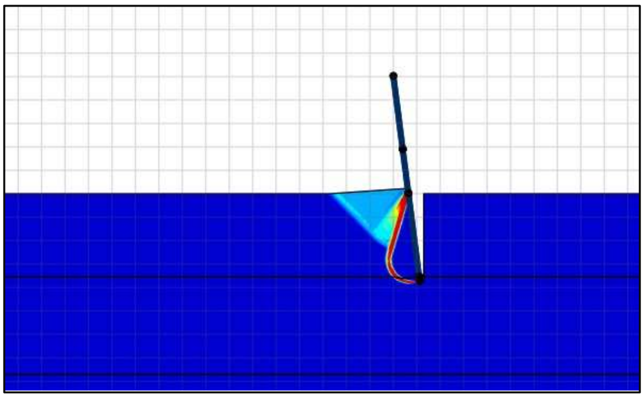

Figure 4: Numerical results of the preliminary test with OptumG2. The colour contours show the shear strain developed which highlight the failure mechanism.

7 CONCLUSIONS

There is a need for additional understanding of I-wall performance. Centrifuge tests have demonstrated the effectiveness investigating I-wall performance to inform and validate numerical modelling methods. While further refinement is needed of the preliminary physical models and numerical analyses, both have shown promise in capturing the failure mechanism. Further understanding the mechanism(s) observed by coupling the results of a suite of centrifuge and numerical models, can reduce the uncertainties the soil stiffness leading to improve the analyses of I-wall in the USACE portfolio.

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