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Evaluation of the Maximum Bending Moment of an Embedded Cantilever Flood Wall Measured by Distributed Strain Sensing Fibers

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ABSTRACT: This paper details an experimental study that uses centrifuge modeling and distributed fiber-optic strain sensing to evaluate the maximum bending moment on an embedded cantilever flood wall. The primary objectives were to demonstrate the successful instrumentation of a model wall with high-resolution fiber optic sensors and to validate the structural bending response of a flexible "I-wall" during gap formation at its base. The experiment, conducted at 50g, subjected to a scaled, instrumented aluminum wall embedded in a clay model to simulate flood conditions. The results show that fiber-optic sensing provides detailed, continuous strain measurements that are difficult to obtain with conventional methods. The study confirmed that as the gap between the wall and the soil widens, the peak bending moment increases, which is consistent with previous numerical modeling and field tests. The paper concludes that distributed fiber-optic sensing is a highly effective and robust tool for physical modeling, improving the understanding of complex soil-structure interactions and advancing flood wall design methodologies.

1 INTRODUCTION

The design and maintenance of flood retaining walls is critical for ensuring safety against catastrophic failure while maintaining serviceability limits state (SLS) to protect adjacent infrastructure. Driven sheet pile flood walls (generally referred to as 'I-Walls' in US Army Corps of Engineers' documentation) made of steel are one such flood defence used widely for coastal and inland flood barriers and are commonly deployed along the crest of earthen embankments or levees. The structural response of these systems to environmental loads is inherently complex, governed by multiple factors including the sheet pile and soil material strengths as well as soil-structure interactions (Bourne-Webb et al, 2007).

An Interagency Performance Evaluation Taskforce (IPET) assembled in the aftermath of Hurricane Katrina and the failure of the levees in New Orleans concluded that the formation of gaps between I-walls and adjacent embankment material was a major contributing factor to strucutural failure (IPET, 2007). Sills et al (2007) for example, noted that the design factor of safety for the 17th Street Canal breach was reduced to near unity partly attributed to the gap formation. As part of the IPET, a series of scaled centrifuge experiments were performed on behalf of the United States Army Corps of Engineers. As reported in Steedman and Sharp (2008), these experiments showed that the development of a water filled gap on the floodside of the I-wall could induce either wall rotation with uplift and sliding or a horizontal translational failure.

Subsequent numerical analyses by Pace et al (2012) by Adhikari et al (2014) showed that gap formation can also have significant impacts on the structural bending moment of non-ridgid (i.e., flexible) I-walls, an additional failure mechanism not previously considered by IPET. The formation of a gap changes the position of the neutral point of the bending moment of the I-wall, shifting it from somewhere near the middle of the wall to near its bottom. This subsequently changes the fundamental behavior of the wall from that of a cantilevered structure to a spring-supported beam. To date, the impacts of gap formation on an I-wall's bending moment has not been explicitly validated experimentally. This is due in part to the difficulty of conducting full-scale experiments (Jackson, 1988; Batool and Brandon, 2012) or instrumentation/technology limitations in earlier centrifuge tests.

This centrifuge modelling study has two primary objectives: first, to detail the successful instrumentation of a model cantilever wall with fiber optic strain sensors for high spatial resolution continuous strain measurement in-flight; and second, to validate the structural bending response of a non-rigid I-wall in response to gap formation.

2 EXPERIMENT DESIGN

Centrifuge modelling of the structure was conducted at 50g for a wall section experiencing variable heights of water inundation. Scaled physical modelling is particularly useful for flood inundation of retaining wall structures owing to the extreme environmental loading required and scarcity of well instrumented test sites. Traditional instrumentation methods to capture structural response, particularly foil strain gauges, provide only discrete data points that may miss critical areas of strain concentration. This study addresses these limitations by implementing fiber optic strain sensing inside the centrifuge using Optical Frequency Domain Reflectometry (OFDR) based on Rayleigh backscatter. This technology provides continuous, high-definition strain measurements along the entire fiber length, making it ideal for capturing complex bending profiles in retaining structures (Eichhorn & Haigh, 2024).

2.1 Model Cantilever Flood Wall

The sheet pile design for this centrifuge modeling study was inspired by the field-scale E99 Sheet Pile Wall Field Load Test, conducted on a sheet pile wall in Louisiana's East Atchafalaya Basin Protection Levee (Jackson, 1988). The resulting experiment design consisted of a model cantilever wall comprised of a 4.75 mm thick aluminium plate spanning the width of the centrifuge container embedded in a consolidated soil model. The wall had a prototype length of 20 m and height of 8.5 m; the embedment depth was 3.75 m shown in Figure 1.

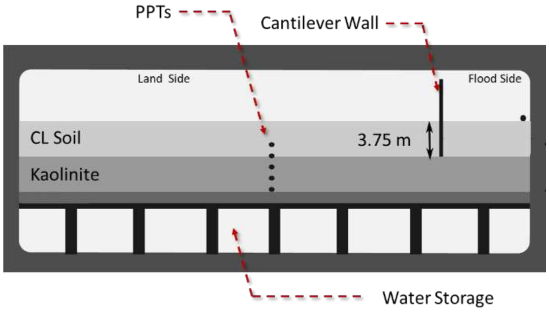

Figure 1. Model set-up for cantilever wall centrifuge tests.

Under g-loading, aluminum has a bending stiffness (EA) and area moment of inertia that were comparable to PZ-27 sheet piles used in the E99 Tests. Table 1 provides a summary of key properties of PZ-27 and the model, and prototype cantilever wall properties. Note that lengths are reported in this table following the per unit meter length designation used by sheet pile manufacturers.

Table 1. Cantilever Flood Wall Properties

Wall Property	PZ 27	Model	Prototype
Material	Steel	Aluminium	Aluminium
Modulus of Elasticity (Pa)	2×10^{11}	6.98×10^{10}	6.98×10^{10}
Thickness (m)	9.53×10^{-3}	4.75×10^{-3}	2.3×10^{-1}
Area Moment of Inertia (m^4 m^{-1})	2.52×10^{-4}	3.80×10^{-9}	4.74×10^{-4}
Bending Stiffness (N m^2 m^{-1})	5.04×10^{7}	2.65×10^{2}	3.31×10^{7}
Axial Stiffness (N)	1.79×10^{10}	5.64×10^{7}	1.41×10^{11}

2.2 Soil Model

The two layered soil model consisted of a kaolinite base overlain by a homogenous lean clay (CL) soil. The model was constructed in two stages. First a kaolinite slurry was consolidated under g followed by placement of the CL soil which was in turn, also consolidated under g. The model wall was driven into the final consolidated soil model as seen in Figure 1. The CL and kaolinite soils had an estimated unconfined compressive strength of 29.3 and 18.96 kPa, respectively.

2.3 Instrumentation

Shallow linear grooves were etched into the surface of the aluminum plate to designate one vertical and two horizontal sensing segments on each side of the plate where the fiber was to be installed. The vertical sensing segments were aligned along the center of the wall on both the tension and compression faces, enabling curvature and bending response to be computed from strain pair measurements. Etching helped improve bonding between the low-viscosity cyanoacrylate adhesive applied to the fiber and the aluminum plate. After gluing the bare fiber, a two-part epoxy was applied over the fiber to provide mechanical protection and ensure durability during centrifuge testing.

A single mode 9/125 telecom fiber with acrylate coating was used as the strain sensor. A 5 m length of fiber was placed into these grooves with gently curved redirects (Figure 2) to create a continuous series of linear sensing segments. The groove was primarily for alignment and gluing rather than protection. The length of fiberoptic was chosen to provide a 'flying lead' that ran from the model to an optical junction box affixed to the swing platform. the main optical interrogator was housed onboard the centrifuge near the center of rotation. A fifth horizontal strain segment was included on the flood side of the cantilever wall to monitor temperature change. This segment of fiber was placed within a clear furcation tube to mechanically isolate it from structural strains, allowing temperature measurements to be made.

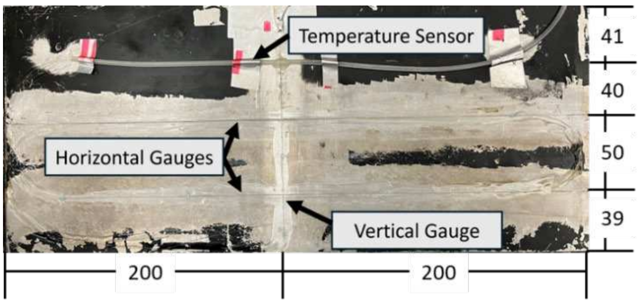

Figure 2. Installation of fiber on the floodside of wall. All dimensions shown are in millimetres (model scale).

A series of five pore pressure transducers (PPTs) were installed vertically in the CL and Kaolinite soil layers on the landside of the wall to monitor for flow beneath the wall. An additional sensor was installed on the floodside of the wall at the top surface of the CL soil layer to measure water height.

A Raspberry Pi Camera Module 3 was used to collect imagery through the side window of the centrifuge box during the flooding events. Imagery was used as a secondary approach for determining the water height on both sides of the wall as well as a way to monitor gap formation and growth on the floodside of the wall.

2.4 Test sequence

Testing of the instrumented model was carried out at 50g in the centrifuge. The models were spun up with no water on the flood side. Flooding of the model was achieved in a three-stage sequence in which the water level was increased and lowered to observe the wall response. Figure 3 provides a summary of the water

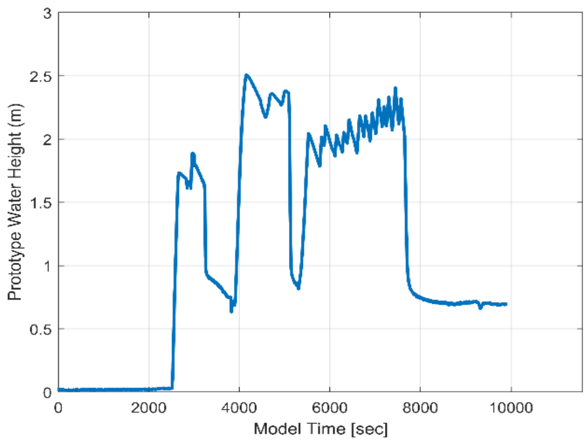

Figure 3. Water height measured during Test 4.

level as captured by the flood side PPT sensor. The fiber strain sensors were continuously monitored at a rate of 50 Hz.

3 BENDING MOMENT ANALYSIS

The fiber strain pairs were processed to account for temperature change caused by the flooding and other environmental factors in the centrifuge. Strain pair data along the vertical fiber section were converted to curvature and bending moment using a structural beam equation approach. Figure 4 presents the peak bending moment correlated with gap depth determined via digital image correlation performed on the Raspberry Pi camera imagery. These results are also compared in Figure 4 against physical measurements and FLAC numerical modeling results of the E99 tests (Jackson, 1988; Pace et al., 2012). Gap formation was normalized by the wall embedment depth to account for differences between the centrifuge and field-scale E99 wall which was embedded to a depth of 7 m but exposed to a similar flood water height.

Despite some differences in the overall size of the model and E99 walls, the magnitude of bending was similar. The peak bending moment was observed to increase with gap widening, in good agreement with the literature. The formation of the gap reduced the floodside resistive passive earth pressures that stabilize the wall. The larger maximum normalized gap observed in the centrifuge tests compared to that of the E99 can be attributed to the overall shorter embedment (i.e., 3.25 m difference). A deeper sheet pile embedment depth acts as a longer lever arm for passive resistance, reducing both the rotational and bending moment (Gilbert 1994; Amer, 2013).

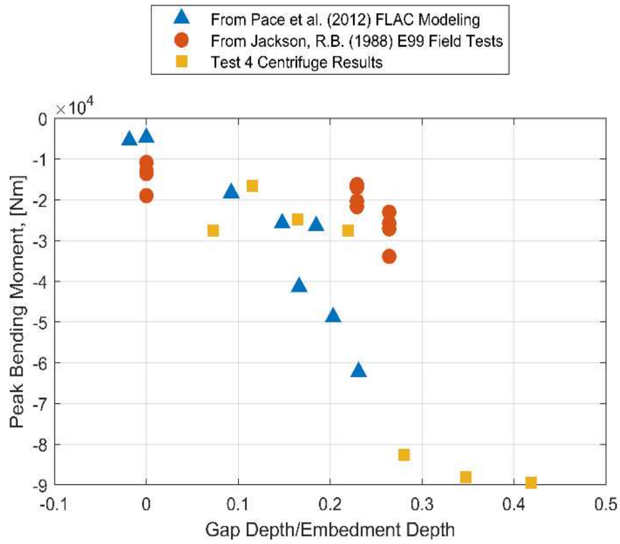

Figure 4. Comparison of peak bending moment as a function of normalized gap depth for centrifuge and E99 (full scale tests) and FLAC numerical model.

4 CONCLUSIONS

Fiber-optic distributed strain sensing provided valuable insight into the structural response of a cantelever flood wall subjected to hydraulic loading conditions and associated gap formation. The high spatial resolution of the measurements enabled detailed characterization of strain distribution and deformation patterns that are difficult to capture with conventional instrumentation in a centrifuge environment. These results demonstrate the effectiveness of fiber-optic sensing for evaluating structural performance and highlight its potential to improve understanding of soil–structure interaction mechanisms in earth-retaining systems. The findings support the use of distributed fiber-optic sensors as a robust tool for future physical modeling, validation of numerical analyses, and advancement flood wall design and assessment methodologies.

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