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Cost-effective method for reducing local failure of floodwalls verified by centrifuge tests

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Abstract. Hurricane Katrina swept New Orleans, Louisiana, USA, in 2005, causing more than 1,000 fatalities and severe damage to the flood protection system. Recovery activities are complete, however, clarifying failure mechanisms and devising resilient and cost-effective retrofitting techniques for the flood protection system are still of utmost importance to enhance the general structural integrity of water retaining structures. This study presents extensive centrifuge test results to find various failure mechanisms and effective retrofitting techniques for a levee system. The result confirmed the rotational failure and translational failure mechanisms for the London Ave. Canal levee and 17th St. Canal levee, respectively. In addition, it found that the floodwalls with fresh waterstop in their joints perform better than those with old/weathered waterstop by decreasing pore water pressure build-up in the levee. Structural caps placed on the top of the joints between I-walls could also prevent local failure by spreading the load to surrounding walls. At the same time, the self-sealing bentonite-sand mixture installed along the riverside of floodwalls could mitigate the failure of floodwalls by blocking the infiltration of seepage water into the gap formed between levee soils and floodwalls.

Keywords: centrifuge test; floodwall; levee; retrofitting technique; self-sealing

1. Introduction

Hurricanes and tropical storms bring much-needed precipitation to sustain modern civilization; however, they also bring occasional but severely destructive power, causing life loss and property damage. Records of recent tropical storms and major hurricanes show that Hurricane Irma (Cangialosi *et al.* 2018), Harvey (Blake and Zelinsky 2018), Isaac (Berg 2013), Gustav (Beven and Kimberlain 2009), and Katrina (Knabb *et al.* 2005) caused human life loss as high as 84, 82, 34, 112 and 1833, respectively. One noticeable fact from this record is that Hurricane Katrina caused a far higher number of lost lives than the sum of the other four. A unique difference in the flooding mechanism of Hurricane Katrina from the others is the large-scale failure of levees and floodwalls and the associated rapid overnight flooding of the highly populated city of New Orleans

With the advent of more reliable modern science to track and predict the path and category rating of hurricanes and tropical storms, more time is available than ever for citizens to evacuate from their residences. However, as in the case of Hurricane Katrina, the failure of levees and floodwalls and associated rapid flooding challenge the capability of this modern prediction techniques. Therefore, obtaining a more resilient but economically viable flood protection system is imperative through a thorough study of the failure mechanisms of levees and floodwalls.

Not long after the incident of massive damage by Hurricane Katrina, centrifuge tests jointly conducted by USACE-ERDC and RPI (United States Army Corps of Engineers - Engineering Research and Development Center and Rensselaer Polytechnic Institute) demonstrated the accurate failure mechanisms of the floodwalls at the 17th Ave. Canal and London Ave. Canal (IPET 2007, IPET: Interagency Performance Evaluation Task Force). Further independent studies by Duncan *et al.* (2008), Brandon *et al.* (2008), Seed *et al.* (2008), and other dedicated authors in J. Geotech. Geoenviron. Eng. Vol. 134 showed that the failure mechanism obtained from the centrifuge model tests was reliable.

The current study, motivated by previous centrifuge test results by IPET and other centrifuge based studies such as Priya *et al.* (2020) for soil replacement, Stefano (2020) for lateral piles, Wang *et al.* (2021) for preloading and Medi *et al.* (2021) for model piles, conducted various cases of centrifuge tests and reported the detailed behavior of floodwalls and levees so that engineers may have better understanding of the failure mechanisms.

Previous centrifuge model conducted by USACE-ERDC and RPI (IPET 2007) was a 50g model with a single solid aluminum plate acting as a floodwall and another solid aluminum plate acting as a sheet pile. The test results

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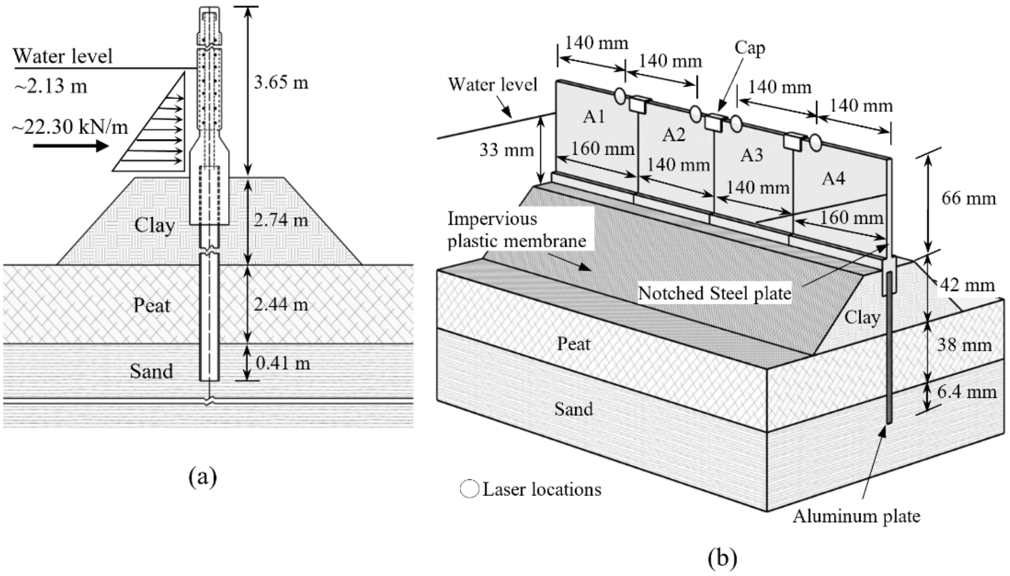


Fig. 1 (a) Prototype floodwall and (b) schematic of the 64 g scaled centrifuge model

Table 1 Description and purpose of different centrifuge tests conducted in this study

Test Designation	Description	Main Purpose of the test
Test 1 & 2	London Ave. Canal levee without retrofit. Test 1: Fresh water stop condition. Test 2: Weathered water stop. condition.	To compare failure mechanism obtained from this research and IPET(2007) results. And to evaluate the effect of weathering condition of water stops.
Test 3 & 4	London Ave. Canal with composite caps. Test 3: With cap sample 1. Test 4: Repeatability check for Test 3.	To evaluate the influence of composite caps on the performance of floodwalls.
Test 5 & 6	17th St. Canal levee. Test 5: Without composite cap. Test 6: With composite cap.	To evaluate the effect of composite caps on the performance of floodwalls.
Test 7	London Ave. Canal levee with self-sealing apron.	To evaluate the performance of self-sealing bentonite-sand mixture in mitigating gap formation.

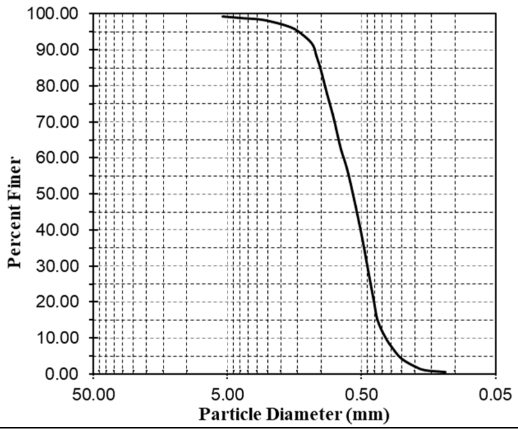
showed that the London Ave. Canal levee experienced rotational failure of the floodwall system, while the 17^{th} St. Canal levee experienced translational failure. The model floodwall of the Orleans Canal did not fail, matching the field behavior of the field floodwalls during Hurricane Katrina.

Motivated by the findings in IPET (2007) research, engineers conducted several model tests to verify the previously found failure mechanisms and develop new techniques developed through small-scale laboratory tests (Jackson 2013) and numerical analyses (Adhikari 2012). Jackson (2013) showed that properly designed composite caps (similar to the one in Fig. 1) installed on the top of the $1/7^{\text{th}}$ scaled floodwalls could prevent the localized overturning failure of floodwalls. Along with Jackson's findings, Adhikari's numerical results (2012) found that an E-glass (also known as Electrical glass) fiber composite cap with EI(Flexural Rigidity) = 62.6 kN-m^2/m , length = 0.60 m, thickness = 0.03 m, and depth = 0.60 m would provide the equivalent performance as the mini composite cap used in Jackson (2013).

The role of preventing localized failure by installing composite caps at the top of the junction point between floodwall sections is to redistribute the lateral stresses from weak zones to strong zones so that floodwalls in weak zones may survive critical incidents. In addition, Jackson (2013) noted that the failure of one section of the floodwall and that of five sections of the floodwall might not make a practical difference in terms of flooding time and severity. Both cases may flood the whole city quickly because the length of one section of the floodwall in the field is longer than 7 m. The idea of the cap is valid only when the overall factor of safety of the floodwall and levee structures is proven to be higher than unity. And this requirement has been implicitly verified because the remaining floodwall and levee structures were tested and passed Mother Nature's full power. For example, Hurricane Gustav and Hurricane Isaac topped off the floodwalls in New Orleans in 2008 and 2012, respectively, and floodwall and levees survived. However, this result does not necessarily guarantee that the factor of safety of floodwalls in the New Orleans area is safely higher than unity everywhere. It could mean that the

Table 2 Properties of McCoy's Playground Sand

Property	Value or Symbol
Lab moisture content	4%
Saturated moisture content	21%
Loose dry unit weight	14.4 kN/m^3
Loose saturated unit weight	14.6 kN/m^3
Dense dry unit weight	17.7 kN/m^3
Dense saturated unit weight	18.1 kN/m^3
$C_u = 2.3$	2.3
$C_c = 1.01$	1.0
USCS Classification	SP
D_{50}	0.54 mm
Consistency	Non-Plastic



global factor of safety of floodwalls in New Orleans is slightly higher than unity. Therefore, providing an additional low-cost but resilient retrofitting technique that offers extra support to hidden critical sections may elevate the minimum factor of safety across the lines.

Meanwhile, Adhikari's (2012) computational result showed that a bentonite apron with a 0.3 m×0.3 m cross-sectional area installed along the riverside of the I-walls might prevent the gap formation during high water situations. Song *et al.* (2014) reported that a properly designed bentonite and sand mixture apron (40% bentonite and 60% sand) provided the expected self-sealing performance based on 2/3 scale laboratory tests.

Jackson (2013), Adhikari (2012), and Song *et al.* (2014), focused on the effectiveness of the retrofitting technique for a single panel or a single joint of the floodwall system. However, the behavior of a continuous floodwall system with a linkage of multiple panels was not yet verified, though floodwalls in the field were continuously connected at the bottom by sharing the sheet pile.

In this study, four-panel floodwall systems sharing a sheet pile were designed, and centrifuge tested to verify the performance of multi-panel floodwall system.

2. Centrifuge test

2.1 Design and fabrication of centrifuge model

The materials and testing models are similar to those used in the USACE-ERDC and RPI tests (IPET 2007). However, essential features of this research are readdressed as follows.

The proposed centrifuge model for the London Ave. Canal is illustrated in Figs. 1(a) and 1(b). The I-wall is composed of segmented steel plates resting on top of an aluminum sheet as shown in Fig. 1(b), to mimic realistic representation of the floodwalls. The bottom of the steel plates is notched and locked on the top of the aluminum plate, representing jointed concrete wall sections cast-in-placed over existing steel sheet piles. The model is scaled to 1/64th to fit the size of the centrifuge model box in USACE, Vicksburg office, while the models from the USACE-ERDC and RPI tests were 1/50th scale.

In addition, the boundary condition was similar to but slightly different from the previous IPET research. IPET used sliding boundary at both ends representing plane strain condition. In this research, the hinge boundary condition was used at the left and right ends of the wall when mobilizing the bending moment with respect to the vertical axis of the floodwall system. This condition created the more critical condition when testing structural members resisting inter-floodwall bending. However, the boundary condition was additionally controlled by cutting or connecting a part or all four sections of steel floodwalls. For example, Test 7 used the sliding boundary condition at the left and right ends of the wall when mobilizing the maximum bending moment with respect to the horizontal axis of the floodwall system. Description and purpose of each test are shown in Table 1.

The soil condition for centrifuge tests was similar to that of the London Ave. Canal and 17th St. Canal, as shown in USACE-ERDC and RPI (IPET 2007). However, it turned out to be slightly different from the previous one due to the availability of materials and working condition as follows.

2.2 Sand layer for London Ave. Canal

The bottom of the levees along the London Ave. Canal contains a sandy material called "Beach Sand." To comply with the properties of this sand, sandy materials with the brand name "McCoy's Playground Sand" were used. The material properties for this poorly-graded sand (USCS classification SP, USCS: Unified Soil Classification System) turned out to be similar to Nevada sand (which was used in the IPET(2007)), with the exception that D_{50} was slightly coarser (0.5 mm) than that for Nevada sand (0.2 mm) as shown in Table 2. In addition, a different procedure from that in IPET (2007) was utilized for placing the 0.2 m thick sand layer into the model box to accelerate the saturation time. Instead of pluviating the dry sand into the model box and subsequently saturating it from the bottom up, the dry sand was pluviated directly into the water. Total saturation of the sand was thus achieved in a much shorter time frame, and measurements showed an in-place saturated density of 15.2 kN/m^3. The in-place saturated density was intended to be low, mimicking

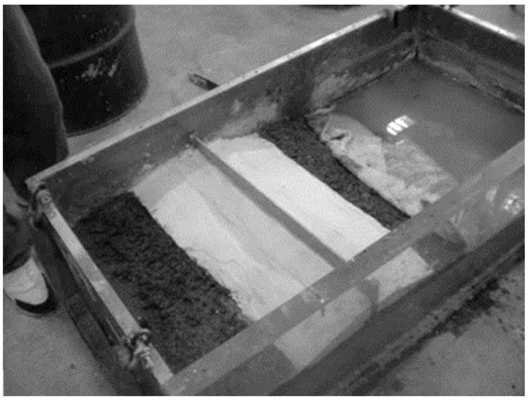


Fig. 2 Layer system for Centrifuge Test. (Note: The white colored layer is the kaolin clay levee and black colored layer is the peat)

loose sand and a poor foundation under the I-wall sections.

After the 0.2 m thick sand layer was placed, the excess surface water was drained out, completing the saturated loose sand layer. Pore pressure transducers were vacuum-saturated with water and placed in top of the sand layer, and customized brackets were installed over the floodwalls for contactless laser deformation measurement.

2.3 Clay (Peat) layer and levee for the London Ave. Canal

The swamp clay (peat) layer, scaled to a 1/64th prototype thickness, was placed into the model box. The materials for swamp clay layer were obtained from a Mississippi River backwater alluvial deposit. In the lab, the material was manually screened to remove roots and detritus. It was then placed into shallow pans and manually compressed to obtain horizontal layers approximately 38 mm thick. Moisture content averaged 51%, close to the field water content. Strength measurements of the in-place clay layers were taken using a pocket penetrometer and a hand-held torsion vane shear tester. Both instruments yielded shear strengths ranging from 7.7 to 9.6 kN/m^2. Average in-place bulk density was 17.3 kN/m^3. Average Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) were 63%, 30%, and 33%, respectively. The swamp clayey soils were a fat clay, therefore this research tried to make the kaolin clay as impermeable as possible rather than adhering to 1/64th scale factor.

The kaolin clay levee was subsequently placed on top of the swamp clay layer as shown in Fig. 2. A heavy-duty cellophane wrap was placed on top of the exposed soil to minimize moisture evaporation prior to the centrifuge flight as shown in Fig. 2.

The average moisture content of the kaolin clay was 51%. The average wet bulk density equaled 16.5 kN/m^3. The pocket penetrometer and torsion vane shear tester yielded shear strengths of 12.0 kN/m^2 and 23.9 kN/m^2, respectively. Then, a 6.35 mm water supply tube was installed to provide in-flight filling of the canal side. Gravel was placed on the top of the canal side sand layer to prevent sand or clay erosion during the in-flight water filling.

Prior to construction of the model, the box had been hydrostatically leak tested by being filled with water and flown at a 100 g load, though the actual target acceleration was 64 g. Immediately prior to its first flight, water was added via the water supply pipe to verify proper operation and to detect any preferential seepage paths in the soil layers as the water height was increased to the top of the I-wall.

Then the following flight procedure was followed: (1) spin up to 10 g and check the balance of the machine, (2) at 50 g, introduce water into the model container, (3) spin up to the desired gravity level of 64 g, (4) check instruments readings and turn on video, (5) raise water to desired level, (6) maintain gravity level till desired model behavior is reached, (7) shut down all systems and slow the boom. The reason why the water was introduced from 50g, not from the very beginning, was aimed to recreate the heavy rain condition or quick river level rise. However, no attempt was made to correlate the water supply inflow rate to the prototype hurricane storm surge rise as previously addressed. For some tests that did not show any noticeable sign of failure, acceleration was increased up to 100g or even higher until the model shows a sign of failure.

3. Test results

3.1 Tests 1 & 2

These tests were conducted to confirm whether the results and failure mechanisms are comparable to previous USACE and RPI (IPET 2007) test results as well as to see the difference between floodwalls of fresh waterstops and old weathered waterstops. Test 1 was configured with floodwalls with fresh waterstop applying silicone caulk between each of the four I-wall panels. Test 2 was configured with weathered waterstop represented by cut panel joint from the adjacent plates.

Fig. 3 shows the measured displacements for the top-of-I-wall segments A1 through A4 in Fig. 1(b), for the first flight – the one with fresh waterstop. It is noted that the negative displacements shown by A2 and A4 occurred

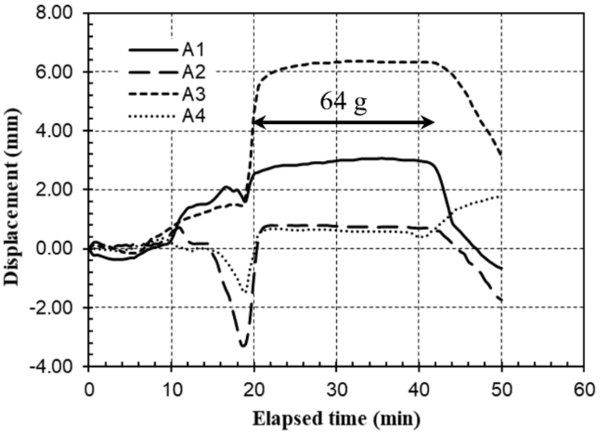


Fig. 3 Test 1 laser displacement results. (Note 1: Positive displacement is toward the land side)

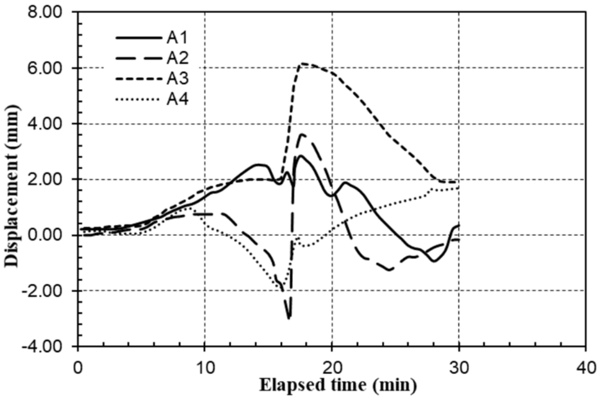


Fig. 4 Test 2 laser displacement results (Note 1: Positive displacement is toward the land side)

during initial impoundment prior to reach 64 g. After reaching full height water level (approximately 25 mm below of top of I-walls), the 64 g acceleration was maintained. The displacements for extended period of time for A1, A2, A3, and A4, after compensating these initial negative or positive displacements, were approximately 1.7 mm, 4.4 mm, 5.0 mm, and 1.7 mm, respectively. Considering that A1 and A4 had the same boundary condition, while A2 and A3 had the same boundary condition, the measured deformation is consistent. In addition, displacement data showed that they did not return to their initial points exactly, meaning that the levee soils experienced a slight plastic deformation. However, the sustained level of displacement at 64 g loading sustained with constant deformation even at 64 g condition, and it is regarded as the stable condition of the floodwall-levee system. On the other the walls with the composite caps did not sustain the loading properly, but quickly failed one it hit the 64 g." Post-test model tear-down provided no evidence of any vertical I-wall displacement as well for test 1.

Fig. 4 shows the displacement data for floodwalls with cut silicone caulk simulating weathered waterstop between the floodwall sections. Compensated peak displacements for A1, A2, A3, and A4 are 1.0 mm, 6.3 mm, 4.0 mm, and 3.5 mm, respectively. These numbers are not substantially different from those in Fig. 3. The main difference is that the wall yielded much faster than the previous case, and the system lost the water from the river side quickly.

Pore pressure plot Fig. 5 for piezometers installed at the top of the sand layer showed 6.7 m water head for Test 2 (the one with the weathered waterstop), which is close to the full static water head (7.3 m) at the piezometer location in the prototype model while the matching piezometer reading for Test 1 (the one with the fresh waterstop) is only 70% that of Test 2. The result implied that the river water seeped through the joints between floodwalls for Test 2, opened the gap between the levee soil and the aluminum plate, started to pressurize the underlain sand layer and decreased the effective stress until the floodwall system to fail. This logic may explain the sudden peak and drop in floodwall displacement in Fig. 4 and similar behavior in pore pressure in Fig. 5. After the test, a failure section with clean rotational failure pattern is observed as shown in Fig. 6, indicating the development of the destructive seepage path to the sand layer. It is noted that I-walls in New Orleans had old and weathered water stop, therefore, the

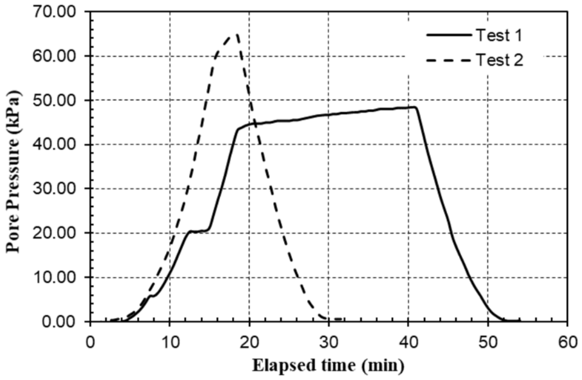


Fig. 5 Pore pressure transducer data. (Note: The pore pressure was higher during Test 2, indicative of elevated water pressure caused by water leaking through the unsealed floodwalls joint)

Table 3 Property of composite cap materials (Jackson 2013)

Cap No.	Layout (°)	Thickness (mm)	E_{flx}[a] GPa	E_{fly}[b] GPa	E_x[c] GPa	E_y[d] GPa	ν_{xy}[e]	ν_{yx}[f]	G_{xy}[g] GPa
1	0/+45/-45	3.4	8.7	20.2	10.5	18.1	0.22	0.38	6.9
2	0/+45/-45	3.4	9.0	20.9	10.9	18.5	0.22	0.37	7.2

Note:
[a]: Flexual Modulus along x direction
[b]: Flexual Modulus along y direction
[c]: Tensile Modulus along x direction
[d]: Tensile Modulus along y direction
[e]: Poisson ratio
[f]: Poisson ratio
[g]: Shear Modulus

Fig. 6 Rotational failure for I-walls occurred for London Ave. Canal for test 2

field behavior is close to Test 2 than to Test 1.

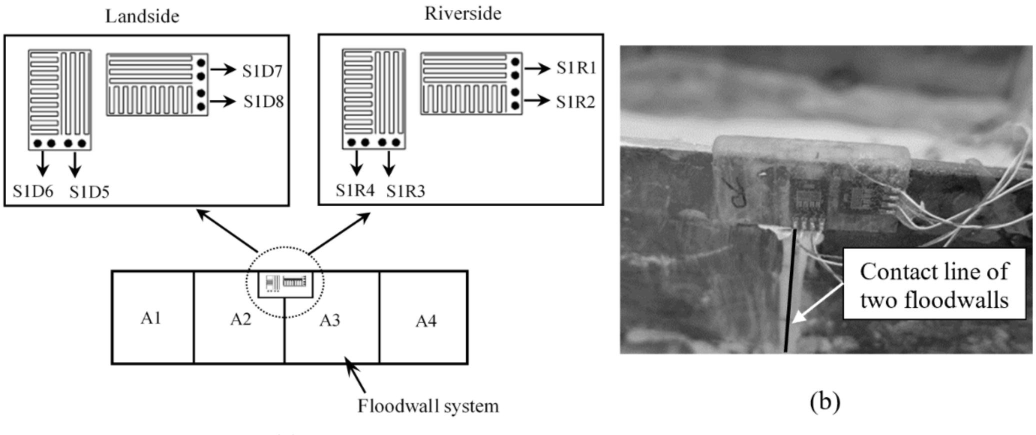
In addition, a post-test model teardown provided no evidence of any permanent steel I-wall deformation or bending, indicating that the model I-wall 'failure' was primarily due to water pressure pushing the steel plates not due to the yielding of either the steel plates or the aluminum sheet composing the model I-wall.

3.2 Tests 3 & 4

For tests 3 and 4, the model floodwalls are structurally connected at the top with the custom designed "cap" connectors. These caps are fabricated from folded sheets of reinforced polymers by Dutta Technologies, Inc. The samples were folded into a u-shape to applied on the top of the connection joints of the floodwalls.

The strength ranged from 125 MPa for compression to 1,044 MPa for tension. However, actual strength may differ by the direction of loading and fibers orientation. Other material properties are as shown in Table 3. Dimension of caps are L x H x W (Length x Hight x Width) = 31.8 mm x 19.1 mm x 4.8 mm with thickness 1 mm.

Fig. 7(a) shows a typical instrumentation plan for the caps. Strain gages in two measurement directions were attached to capture the two-dimensional strains caused by bending moment with respect to vertical axis (major bending) and longitudinal axis (minor bending). In addition, a duplicated set of strain gages were also attached on both sides of the floodwall (Landside and Riverside) as a backup system. Fig. 7(b) shows a cap in place over two I-wall sections without using adhesives because the caps were designed to be applied in the field without adhesives.



(a)

(b)

Fig. 7 (a) Typical schematic for strain gages on a cap connector and (b) picture of an instrumented cap

Test 3 was conducted using cap sample 1, while Test 4 was conducted using cap sample 2 to check repeatability. The London Ave. Canal in Test 3 levee model did not fail. Since the I-wall did not fail at 64 g, the gravity level was increased to 100 g to induce failure. Strain gages showed slight wall movement at 100 g, but no obvious failure occurred as shown in Fig. 8. However, it is noted that the test result with 100 g should not be interpreted as a true 100 g test result, because the physical sizes of the model and material properties were not scaled to 100 g model.

From locations of strain gages in Fig. 7, it is expected that strain gage S1D6 (Landside, Tension-side) and S1R4 (Riverside, Compression-side) might be subjected to highest bending moment. The measured strain in Fig. 8 agrees with this expectation by showing that S1D6 (the uppermost line) experienced highest tensile strain while S1R4 (the lowermost line) experienced highest compressive strain. The magnitude, however, is not exactly symmetrical. The authors believe that it is because the caps are not structurally bonded to the floodwall, but they were compression fitted. Then, S1D7 (Landside, Tension-side) and S1R1 (Riverside, Compression-side) show similar but lower magnitude of strain than S1D6 and S1R4 do.

This behavior is rational considering that location of S1D7 and S1R1 are not exactly symmetrical. S1R2 and S1R3 are installed in the riverside, and they could not be compared to their counterpart in the landside. However, non-zero strain magnitude of S1R2 and S1R3 may indicate the tendency for caps to slide out of the location at high bending moment. All these readings, however, showed clear break points at time 1420 sec. where the acceleration is even higher than 100 g, indicating a general failure of the cap system.

For Test 4, the London Ave. Canal levee model with polymer cap 2 was tested to check the repeatability. The flood wall did not fail as well. The gravity level was also raised to 100 g as in test 3, but there was no wall failure, indicating that the provision of hinge support and proper caps may improve the stability of the levee and floodwall system against localized failure. The hinge support in the field could be provided by naturally existing hard soils next to the weak zone. This hinge support in the field may not be a perfect hinge but allowing some amount of lateral deformation, conforming the lateral deformation occurred in the weak section, and reducing the stress concentration in caps. The laboratory testing condition in this study is, therefore, conducted under the more ideal condition than a possible condition in the field condition. As far as the overall factor of safety of the floodwall system is higher than unity, composite polymer caps will redistribute the lateral stress and reduce the magnitude of lateral stress acting on the weak zone.

3.3 Tests 5 & 6

Fig. 9 shows the schematic test condition of the 17th St. levee. The I-wall in Test 5 tested without composite caps failed in the rotational mode, which was different from previous USACE-ERDC/RPI test results that showed translational failure. Review of test condition showed that the foundation clay in this test turned out to have somewhat higher strength (28.7 kN/m^2) than the target strength (19.2 kN/m^2), restraining the translational failure of the wall in the foundation clay but allowing rotational failure.

With this finding of possible rotational failure in this study and observed translational failure in USACE-ERDC/RPI, it is anticipated that the failure mechanism of the 17th St. Canal levee could be either a rotational failure at a zone of higher strength subsoils, or a translational failure at a zone of lower strength subsoils. In addition, considering that the depth of the sheet piles of the levees in New Orleans could be shorter than the optimum needed depth providing the cantilever action as reported by Woolley and Shabman (2007) and USACE (1988), the possibility of rotational failure seems to be possible due to minor changes in the length of sheet piles.

Test 6 was the last test in the cap mitigation series. Only one cap was used in this model. The cap was placed at the

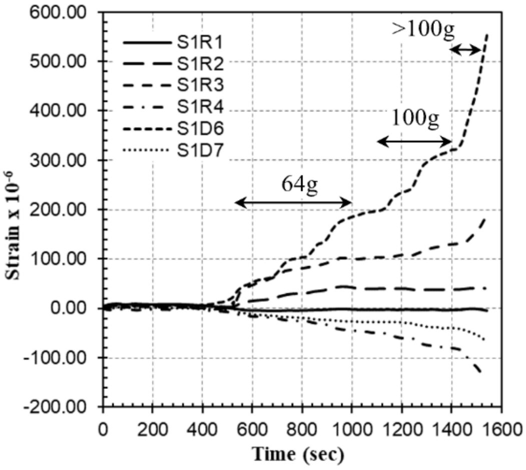


Fig. 8 Measured strain of the cap at different locations and acceleration levels. (Note 1: positive strain is tension while negative strain is compression. Note 2: S1D5 and S1D8 did not respond. Note 3: Legend of strain gauges is found in Fig. 7)

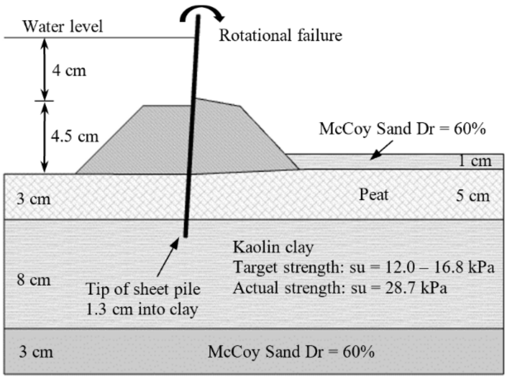


Fig. 9 Schematic of the 17th St. levee model for centrifuge testing

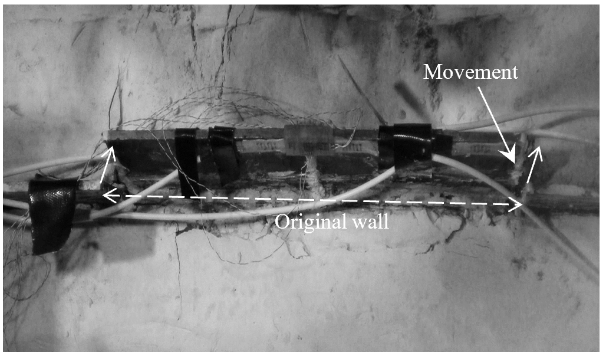


Fig. 10 Center sections of the I-wall with cap showing near zero differential movement. (Note: Both end sections without caps showed noticeable differential movement)

mid-joint; two outside joints were left unmitigated and allowed to move due to when water pressure is high or vice versa. The inner sections with the mitigation cap moved together, while outer two sections without mitigation caps did not move at all perhaps due to the friction resistance of the levee and the wall, creating large differential deformation at about 22 g as shown in Fig. 10. Fig. 11 shows a substantial displacement of the mid two sections, confirming that caps can effectively reduce the differential deformation of floodwalls and associated flooding.

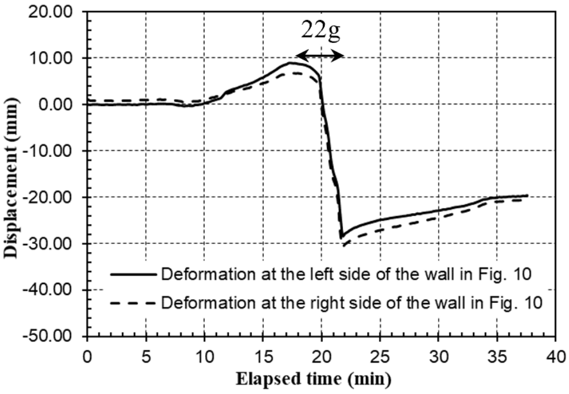
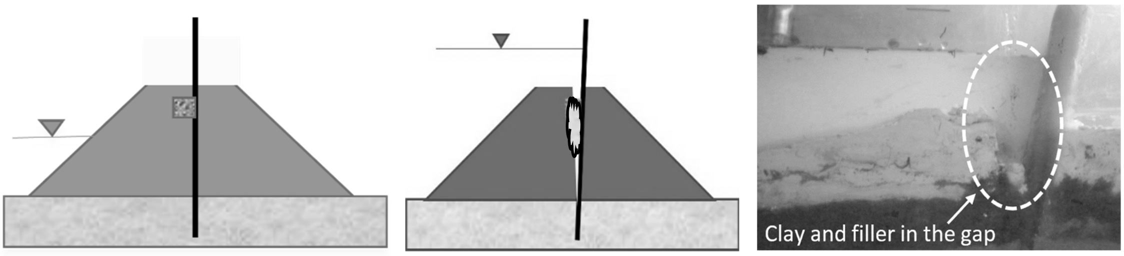


Fig. 11 Laser gauges showing I-wall displacement (Note: Positive deformation is towards river side and negative deformation is towards land side)



(a)Before gap opening (b) After gap opening (c) After gap opening (picture)

Fig. 12 Illustration of Gap filling mechanism and actual performance of sand/bentonite mixture

3.4 Test 7

This "gap" formation between the floodwall and levee materials was observed from this study and previous centrifuge studies of levee failures at USACE-ERDC and at RPI. The gap is formed as the flood water pushes the I-wall towards the land side. The gap then becomes a short path for seepage to reach the back side of the wall. Test 7 provided a gap filler mitigation method intended to provide a self-sealing bentonite strip embedded in the levee as the opening occurs and bentonite strip expands, as addressed by Song *et al.* (2014) and Kidd (2011).

The filler is a sand and bentonite mix (60:40) and has a dry-unit weight of 16.5 kN/m^3 with a moisture content of 4.66%. The proposed design is to fill a shallow, 0.5 cm x 0.5 cm (that is 0.3 m x0.3 m square trench in full scale) adjacent to the I-wall with this mixture. When the river water level becomes high, the hydrostatic water pressure opens the gap, self-sealing material absorbs water to swell, and finally seal the gap in pace with the leaning motion of the I-wall.

Model construction for Test 7 used a single continuous wall panel instead of multiple I-wall sections to clearly see the gap sealing performance through the observation window of the centrifuge box. The 0.5 cm x 0.5 cm trench was "grooved" into the river side of the levee at 0.5 cm below the crest. A thin plastic sheet (Saran wrap) was used to encase the filler, preventing in-place expansion and facilitating the filler's ability to fall into a gap which has formed. The model was spun, and the leaning deformation of the I-wall occurred shortly after that gravity level reached 64 g.

Fig. 12 is the illustration of the floodwall before and after the test, showing that the gap opening was filled with sand/bentonite mixture, similar to the result from 2/3 scale static model test by Song *et al.* (2016). The sand/bentonite mixture swelled and fill the gap. The sand/bentonite mixture allowed the rotation of the floodwall, but blocked the formation of a shortened seepage path, and the integrity of the floodwall was maintained. Sand/bentonite mixture technique, therefore, may serve as viable technique to prevent rotational failure of floodwall and levee system – where the gap is a part of the triggering mechanism of the failure. It is, however, noted that some gaps observed in some areas of New Orleans after Hurricane Katrina could be a result of floodwall/levee failure in the case of deep-seated translational failure as reported by Song *et al.* (2014, 2016, 2018). This self-sealing bentonite technique may not be a very useful technique in that case.

4. Conclusions

This study investigated the validity of new ideas for designing and retrofitting floodwall/levee system in the nation. Selected findings from previous numerical analysis, model tests, and observation of field behavior were tested through instrumented scaled model tests in the USACE-ERDC centrifuge test center. Test results agreed well with findings from prior research results, providing pathways for designing new floodwall/levee systems and retrofitting existing floodwall/levee systems without incurring high expense. The key findings of this study shown below could contribute to make the nation's critical levee and floodwall systems more sustainable and resilient.

- 64 g centrifuge test for London Ave. Canal levee with conditions equivalent to the fresh waterstop showed the same rotational failure pattern as shown in the previous 50 g centrifuge test by IPET (2007), confirming the repeatability of the testing technique.
- However, the results for floodwalls with weathered waterstop abruptly failed at 64 g. For this test, it turned out that the "gap" was formed all the way down to the sand layer and induced the full pore water pressure in the sand, while the previous case with fresh waterstop showed the shallower gap depth, lowering pore water pressure and no failure.
- London Ave. Canal levee retrofitted with composite caps did not fail even at 100 g acceleration, showing that interconnecting the floodwalls with structural caps so that week sections may obtain slight additional support from the neighboring stronger sections may effectively mitigate the local failure of the floodwalls.
- 17^{th} St. Canal levee with cap mitigation on middle sections (but not on end sections) showed that two center sections stayed together but failed in rotation due to the lack of support from uncapped end sections, addressing the importance of maintaining continuity of floodwalls along longitudinal direction.
- London Ave. Canal levee with a self-sealing strip showed that the self-sealing strip did not allow abrupt rotational failure. The gap formation was observed, but it was sealed with self-sealing materials and prohibited the gap from serving a shortened seepage channel.
- It is noted that the techniques found in this research are the means to make floodwall system more resilient by reducing the probability of potential localized failure when the global factor of safety of existing floodwalls are higher than unity. It is not intended to dramatically increase the factor of the safety of the floodwalls but to make the system more sustainable.

In addition, authors disclose that centrifuge tests in this research could not exactly control scaling effects related to the particle size of soils, strength of soils, hydraulic conductivity, and flooding rates. It is also noted that the centrifuge test is one of more reliable methods to predict the full-scale behavior, it is not the method to reproduce the full-scale behavior exactly.

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