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Lessons Learned from Hurricane Katrina – With Emphasis on Cost Effective Retrofitting Techniques

Abstract. *Hurricane Katrina brought unprecedented precipitation, causing widespread flooding in New Orleans and failure of its flood protection system in August 2005. The enormous destruction power of this tropical storm devastated the city causing 1,000+ casualties and $80 billion+ in property damage. Through the long recovery effort in the wake of this painful disaster, much research has been conducted and published regarding problems in administration, management, design, and construction. Engineers and researchers have applied these valuable lessons to design more resilient and sustainable flood protection systems. This paper presents new findings for cost effective but resilient retrofitting techniques. Some examples include placing a bentonite apron to prevent gap formation in the river side of the floodwall, erosion resistant materials at the levee crest, and reinforcing caps to prevent localized floodwall failure.*
Keywords: *hurricane, Katrina, levee, failure, retrofitting, gap.*

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Introduction. After the devastation from Hurricane Katrina, a quick recovery effort restored most of the flood protection system in a relatively short time. Sections of I-walls were replaced with T-walls which were supported by pile foundations. Electric pumps in rainwater pumping stations were replaced with larger sized diesel pumps. Sections of erosion resistant concrete pads were installed on the land side of levees. Even some sections of I-walls in other parts of the country (along the Missouri River) were removed and the height of the levees were increased. All these techniques are effective and logically sensible techniques. These techniques, however, may not be the most economic ones. The cost for replacing all I-walls in the New Orleans area with T-walls was rumored to be $6 billion dollars.

Thanks to the DHS-SERRI research program, the authors of this paper could conduct research which investigated cost effective but resilient retrofitting techniques for levees and dams. The authors' research was different from other research in such that it is focused on blocking the triggering mechanism of the failure of levees rather than completely redesigning the levees. The background idea was that the levee system in New Orleans which was composed of earthen levees, I-walls, and T-walls stood the test of time for decades. In fact, the water level in canals and rivers around the New Orleans area slightly exceeded the maximum design water level during Hurricane Katrina. Therefore, slight creative retrofitting techniques might make the existing flood protection system resilient enough to fight future critical conditions.

It is known that 17th St. Canal levee and London Ave. Canal levee failed due to the gap development along the floodwalls on the river side of the levees. Therefore, a gap stopping mechanism was developed. The IHNC (Inner Harbor Navigation Canal) levee was known to have failed due to water overtopping the I-walls. Therefore, a low-cost technique to tie floodwalls each other or erosion resistant treatment technique for levee soils was devised.

This paper presents test and analysis results of these three techniques.

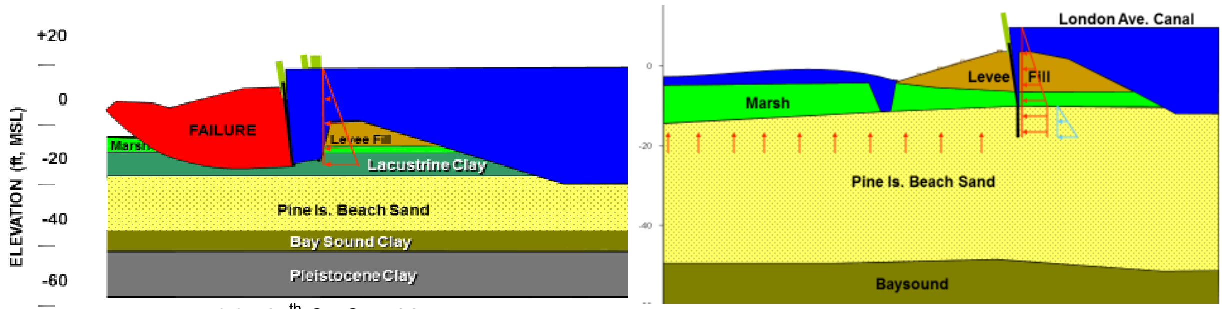
Retrofitting Techniques

Gap Development and Gap Sealing Technique

Figure 1 shows the failure mechanism of the 17th St. Canal levee and London Ave. Canal levee depicted by IPET [1]. Water which infiltrated through the gap into 17th St. Canal applied extra water pressure to the floodwall and reduced the strength of soil to reach failure [2]. For the case of London Ave. Canal levee, infiltrated water applied extra pore pressure to the sand layer underneath the levee and increased buoyancy force. It subsequently reduced the horizontal resistance the floodwall to the lateral force to reach failure.

The authors found that the levee soils in New Orleans might experience substantial strength reduction when exposed to a prolonged precipitation and gap development and some sections of levee developed gaps between the levee and floodwalls [3]. Therefore, the levee, whether the soil was strong enough or not, gap development could be a critical mechanism.

A retrofitting technique to prevent the gap development was devised using a Bentonite apron. It was found that a 40%:60% mix of Thiele commercial Bentonite and ASTM C-109 sand provided an adequate swelling amount, swelling pressure and swelling time through 2/3 scale test results for the floodwall [4]. Numerical analysis also showed that the mixture of bentonite and sand provided the proper swelling pressure to fill the gap without applying adverse lateral pressure while swelling quick enough to prevent the crack development. 1/64th scale centrifuge tests by USACE confirmed that the above Bentonite and sand mix filled the gap and prevented failure in comparison to the same test for a specimen without the bentonite and sand mix, in which the apron failed as shown in Figure 2.



(a) 17th St. Canal Levee

Figure 1. Failure Mechanism of 17th St. Canal Levee and London Ave. Canal Levee (IPET, 2007)

(a) Floodwall without Bentonite and Sand Apron

(b) Deformed but Intact Floodwall Retrofitted with Bentonite and Sand Apron

Figure 2. Levee Condition after Centrifuge Test for 1/64 Scaled Model [5]

Erosion of Levee Materials and Erosion Resistant Levee Materials

Levees along IHNC(Inner Harbor Navigation Canal) were known to have been failed by the erosion of levee materials on the land side due to overtopping water, as depicted in Figure 3. Materials used for levee construction were essentially scrapped local materials available at the time of construction. Use of these materials, however, should not be blamed due to the lack of a proper source of quality local soils.

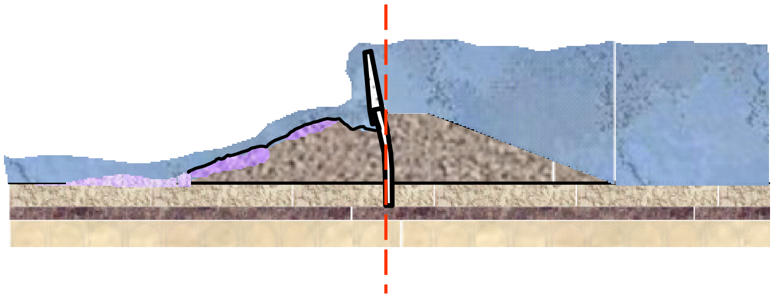


Figure 3. Failure of IHNC Levee Caused by Overtopping Water [1]

Based on Song et al. [6], the time needed for failure of the levee by the erosion mechanism could be less than one hour considering the water level in the canal during flooding and erosion characteristics of soils on the IHNC levee. It is obvious that this type of failure could be prevented if levee materials were erosion resistant. Kidd et al. [7] researched an erosion resistant soil treatment and obtained a promising result showing that POSS (Polyhedral Oligomeric Silsesquioxane) treated soils may substantially enhance the erosion resistance of levee soils as shown in Figure 4.

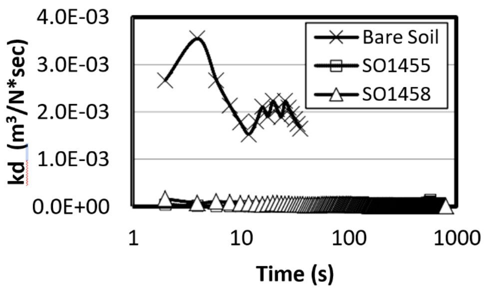


Figure 4. Erosion Coefficient of Modified Soil Compared to Bare Soil [7]

Localized Failure of I-walls and Structural Cap

Major failures of levees such as the ones at IHNC, 17th St. Canal, and London Canal Ave. were reported and received attention. A number of small scale local failures of I-walls as shown in Figure 5 were also reported.

Figure 5. Local (Isolated) Failure of I-walls [1]

These localized failures were of a much smaller scale compared to the previously mentioned major failures. Considering that a section of floodwall was approximately 24ft, the failure of one section of I-walls might easily flood the whole city quickly – these local failures were as important as major failures. These localized failures could be caused by several different factors such as a non-homogeneous soil condition, non-homogeneous concrete quality, defect in sheet pile wall, and many others. Soils usually show more severe non-homogeneity compared to concrete and steel. To overcome the effect of non-homogeneity of soils, structural caps as shown in Figure 6 were devised.

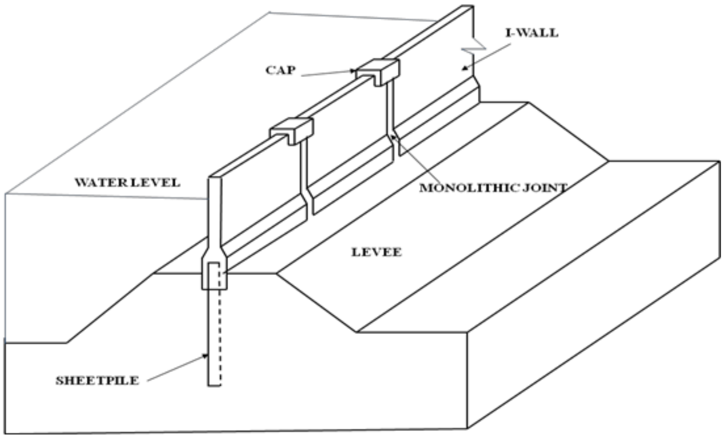


Figure 6. Fundamental Idea of Structural Cap

The bottom of the I-wall is resting on the top of the sheet pile walls. At the joint between two sections of I-walls, both walls share the same sheet pile, providing some degree of continuity along horizontal direction and bending resistance due to the flexural stiffness of the sheet pile. The top of the joint, however, is completely separated. There is no structural member that may provide restriction against the movement of a weak section of subsurface soils, which may lead to localized failure.

The structural cap was, therefore, conceptualized, analyzed, laboratory tested, and tested in a centrifuge chamber by USACE. To be prepared for the worst case scenario, the maximum probable variations of strength between weak soils and strong soils as reported in IPET [1] were used. Figure 7 shows the variation of soil strength between weak soil and hard soil.

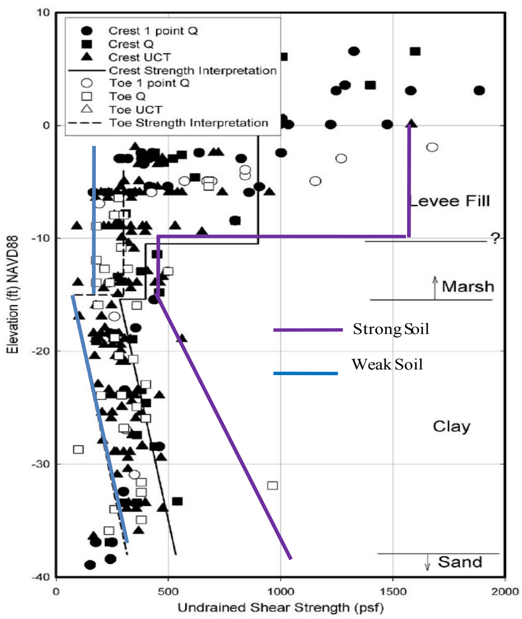


Figure 7. Strong Soil Condition and Weak Soil Condition [1]

Figure 8 shows the behavior of the floodwall system with structural cap applied. It is clearly seen that the floodwalls retrofitted with the structural cap did not fail while those without retrofitting failed as shown in Figure 2(a). The design of the cap is shown in Figure 9.

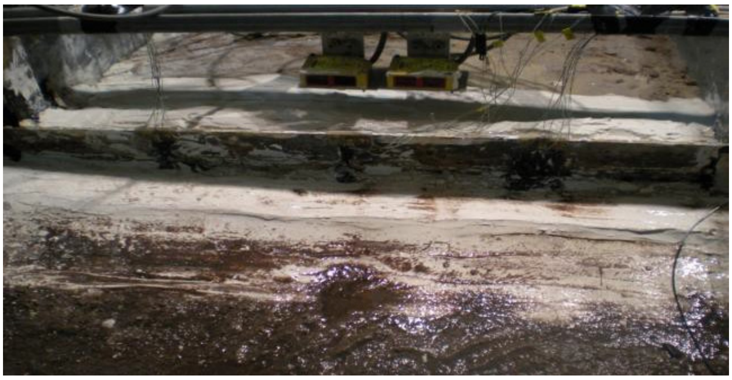


Figure 8. Comparison of Behavior of Floodwall System without Structural Cap
(Note: Gap was not observed and the wall did not fail.)

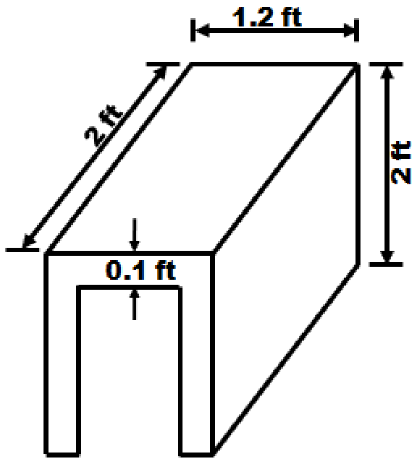


Figure 9. Specification of Full-Scale Structural Cap

It is notable that the required size of structural caps is not very big. The required stiffness, EI, of the cap material is 46.2 k-ft2/ft, which is not very high to achieve. Materials for structural caps were believed to be of a high strength and high stiffness composite, initially. However, the required stiffness of the material was adjusted so that the cap does not cause the failure of concrete floodwall at contact areas. The cap shown in Figure 9 does not induce failure in concrete floodwalls, but provides enough support to prevent localized failure.

Based on the manufacture's information, the cost of manufacturing and installation of these caps would be $40 to $50 per each as of 2011.

Summary and Conclusions

The flood protection system in New Orleans, particularly its levees, were tested by time for several decades. Although the existing design has several engineering imperfections, such as a short length of sheet piles, non-ideal levee materials, and lack of consistent height of floodwalls, the levee itself has passed the test of time until it was subjected to the enormous destructive power of Hurricane Katrina in 2005. After emergency retrofitting efforts were applied, the flood protection system was retested by Hurricane Issac in 2012 and Hurricane Gustavo in 2008. The system survived, even with incomplete application of reinforcing technique at the time of testing, indicating that the system might need just slight additional retrofitting such as caps or self sealing sand-bentonite aprons.

Through this research, the following conclusions are provided:

- A band of Bentonite and sand mix may self-seal the gap formation to prevent the occurrence of gap associated failure of I-walls.

- Erosion resistance of levee materials may be substantially improved by applying a proper polymer (POSS) treated soils.

- Localized failure of I-walls may be prevented by applying structural caps on the top joints of I-walls.

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«Катрина» дауылынан кейінгі жағдай салдарының экономикалық тиімді модернизация әдістеріне екпін беруі

Аңдатпа. «Катрина» дауылы бұрын-соңды болмаған жауын-шашынға ұласты. Бұл Жаңа Орлеанда кең көлемді су тасқынына және 2005 жылдың тамыз айында оның су тасқынынан қорғаныс жүйесінің бұзылуына әкеп соқтырды. Бұл тропикалық дауылдың орасан зор жойқын күші қаланы қиратып, 1000-нан астам адам қаза тапты және елге 80 миллиард доллардан астам материалдық шығын келтірді. Осы ауыр апаттан кейін қалпына келтіруге жұмсалған ұзақ күш-жігердің арқасында әкімшілік, басқару, жобалау және құрылыс мәселелеріне қатысты көптеген зерттеулер жүргізіліп, жарияланды. Инженерлер мен зерттеушілер бұл құнды сабақтарды су тасқынынан қорғаудың тұрақты жүйелерін жасау үшін қолданды. Бұл мақалада экономикалық тиімді, бірақ тұрақты модернизация әдістерінің жаңа нәтижелері келтірілген. Кейбір мысалдарға су тасқыны қабырғасының өзен жағында саңылаулардың пайда болуын болдырмау үшін бентонит алжапқышын орналастыру, су тасқыны қабырғасының жергілікті бұзылуын болдырмау үшін бөгеттің жотасындағы эрозияға төзімді материалдар және арматуралық қақпақтар жатады.

Түйін сөздер: дауыл, Катрина, бөгет, сәтсіздік, модернизация, үзіліс.

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Уроки, извлеченные из урагана «Катрина» – с акцентом на экономически эффективные методы модернизации

Аннотация. Ураган «Катрина» принес беспрецедентные осадки, вызвав широкомасштабное наводнение в Новом Орлеане и отказ его системы защиты от наводнений в августе 2005 года. Огромная разрушительная сила этого тропического шторма опустошила город, привела к более чем 1000 жертвам и более 80 миллиардов долларов материального ущерба. Благодаря длительным усилиям по восстановлению после этой масштабной катастрофы было проведено и опубликовано много исследований, касающихся проблем в области администрации, управления, проектирования и строительства. Инженеры и исследователи применили эти ценные уроки для разработки более устойчивых и устойчивых систем защиты от наводнений. В этой статье представлены новые результаты для экономически эффективных, но устойчивых методов модернизации. Некоторые примеры включают размещение бентонитового фартука для предотвращения образования зазоров на речной стороне паводковой стены, эрозионностойкие материалы на гребне дамбы и армирующие колпачки для предотвращения локального разрушения паводковой стены.

Ключевые слова: ураган, Катрина, дамба, провал, модернизация, разрыв.

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