SERRI
Southeast Region Research Initiative

SERRI Report 70015-000

Summary Report for SERRI Project Titled Increasing Community Disaster Resilience Through Targeted Strengthening of Critical Infrastructure

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"An Industry, Agency & University Partnership"

This material is based upon work supported by the U.S. Department of Homeland Security under U.S. Department of Energy Interagency Agreement 43WT10301. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

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SUMMARY REPORT FOR SERRI PROJECT TITLED INCREASING COMMUNITY DISASTER RESILIENCE THROUGH TARGETED STRENGTHENING OF CRITICAL INFRASTRUCTURE

Performing Organization Report No. CMRC-12-02

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Date Published:

September 2012

Prepared for
U.S. Department of Homeland Security
Under U.S. Department of Energy Interagency Agreement 43WT10301

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The authors are especially grateful for the financial support provided by the *SERRI* program. In addition, due gratitude is extended to everyone employed at *DHS* and *ORNL* who worked diligently with the authors to make this project a success. A great deal of the success of this research can be attributed to the efforts of *DHS* and *ORNL* personnel.

Multiple people and entities supported the research activities summarized in this report alongside *DHS*, *ORNL*, and *SERRI*. These individuals have been mentioned in the individual research reports that are summarized by this report. The support of these individuals and entities were essential to the success of this project.

Special thanks are also due to all authors of the eleven research reports summarized in this report. These twenty-seven individuals provided the dedication and expertise necessary to perform this multi-year and multi-part research program. Without an exceptional team of researchers willing to work tirelessly on this project, it would not have been successful.

SYMBOLS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
CEE	Civil and Environmental Engineering
DHS	Department of Homeland Security
MSU	Mississippi State University
ORNL	Oak Ridge National Laboratory
SERRI	Southeast Region Research Initiative
USACE	United States Army Corps of Engineers
WLS	Wave Load Software
AdH	Adaptive hydraulics simulations
DLEMM	double layer elastic membrane model
FEM	Finite element modeling
F_x/W	Force in x-direction divided by bridge weight
F_y/W	Force in y-direction divided by bridge weight
GGBFS	Ground-granulated blast furnace slag
H_1	Levee height
H_2	Berm height
RDAS	Rapidly Deployable Armoring System
$R_{y\text{-}G1}/W$	Y-direction reaction force divided by bridge weight predicted by AASHTO
$R_{y\text{-}max}/W$	Y-direction reaction force divided by bridge weight predicted by WLS
SLEMM	Single-layer elastic membrane model
STAPs	Short term aging protocols
S_x’	Anchor spacing in wave overtopping direction along landward levee slope
S_z’	Anchor spacing in *z-direction* along levee
T	Depth of anchor trench
t_{Load}	Time from when mix was loaded into truck from silo
%AIR	Factor in AASHTO equation accounting for entrapped air
T_{STAP}	Short term aging protocol temperature
T_{Post}	Post-haul temperature
T_{Screed}	Mix temperature behind the paving screed
Diefenderfer Est.	Temperature extrapolated from research project

CHAPTER 1 - INTRODUCTION

1.1 Overview of SERRI Project 70015

This document summarizes all work performed within Task Order 4000064719 sponsored by the *Department of Homeland Security (DHS)* through its *Southeast Region Research Initiative (SERRI)* program administered by *UT-Battelle* at the *Oak Ridge National Laboratory (ORNL)* in Oak Ridge, Tennessee. The research was proposed by members of the *Department of Civil and Environmental Engineering (CEE)* at *Mississippi State University (MSU)* to *SERRI* in a document dated 1 June 2007. The proposed research was authorized by *UT-Battelle* in its task order dated 10 December 2007. Work on the project was initiated on 1 January 2008 and ended 31 August 2012 (total project duration of 57 months). During the 57 month duration, the project was modified three times (September 2008, June 2010, and April 2011), with one of the modifications adding a phase 2 to the research effort.

Task Order 4000064719 was performed under SERRI project number 70015. The project research results were presented in eleven reports numbered 70015-001 to 70015-011. This 12^{th} project report summarizes the findings of the other eleven documents.

1.2 Research Areas Covered

The scope of work associated with Task Order 4000064719 included several related components. Civil infrastructure was the focus of all research performed. For summary purposes, the research can be categorized into four areas: levees, bridges, pavements, and emergency construction materials with accompanying construction methods.

The overall research objective was to investigate means for rapidly using on-site materials and methods in ways that would most effectively enable local communities to rebuild in the wake of a flooding disaster. A key component of this research was to develop solutions which may be rapidly deployed to achieve maximum benefit to the community, typically through use of on-site materials, pre-engineered components, and innovative construction materials and techniques. This research aimed to develop solutions for protecting and/or expeditiously reconstituting critical civil infrastructure components. In this context, the specific objective of the total effort of Task Order 4000064719 was to develop specialty materials and design and construction procedures which may be rapidly deployed to protect and restore selected key civil infrastructure components.

1.3 Scope of Research

A variety of research efforts were performed within project 70015, with tasks ranging from assembling current knowledge that could be useful for disaster recovery, to performing research that is a modest extension of current knowledge, to performing research that is a considerable extension of current knowledge. A natural extension of the research scope is varying levels of implementation ready products. Some of the end products were intended to be ready for implementation, while others were exploratory efforts aimed at advancing the knowledge base for use by other researchers. A discussion of the implementation readiness of each area of the four overall research areas is provided in this report. The remainder of this report summarizes the findings by subject area and references the other eleven reports.

CHAPTER 2 - RESEARCH RELATED TO LEVEES

2.1 Levee Research Reports

Three of the eleven reports are related to levees. They are cited below. Saucier et al. (2009) focused on levee breach closure simulation, while Hughes et al. (2011) and Bilberry et al. (2012) focused on preventing earthen levee breaches from storm surge and wave overtopping events. Levee breach closure simulation research is summarized in Section 2.2, while research to prevent earthen levee breaches is presented in Section 2.3.

Saucier, C.L., Howard, I.L., Tom, J.G. (2009). *Levee Breach Geometries and Algorithms to Simulate Breach Closure.* SERRI Report 70015-001, US Department of Homeland Security Science and Technology Directorate, pp. 154.

Hughes, S.A., Sharp, J.A., Shaw, J.M., Howard, I.L., McAnally, W.H. (2011). *Physical Testing and Hydraulic Simulation of Wave Overtopping of Earthen Levees.* SERRI Report 70015-009, US Dept. of Homeland Security Science and Technology Directorate, pp. 144.

Bilberry, A.C., Howard, I.L., Gullett, P.M. (2012). *Temporary Earthen Levee Protection from Overtopping Using a Rapidly Deployable Armoring System.* SERRI Report 70015-010, US Dept. of Homeland Security Science and Technology Directorate, pp. 88.

2.2 Levee Breach Closure Simulation

Levee breach research examined the common conditions in which levee breaches may exist and the various means by which the typical size of a levee breach may be estimated. A set of computational algorithms were developed to simulate the motion of solid particles entrained within a fluid flow. The algorithms were developed for specific application to the problem of achieving levee breach closure via entraining large solid masses into the breach discharge. The proposed techniques, though, are general in nature and may be useful in applications beyond levee breach closure.

Fluid motions in the vicinity of the particle are independently generated from a hydrodynamic simulation. The resulting fluid velocity field is maintained constant over a small increment of time corresponding to that required for a single particle to be entrained and subsequently come to rest. An entire simulation of breach closure may be created through successive cycles alternating between the hydrodynamic model and the particle trajectory model. The computational algorithms are centered upon modeling the trajectory of the solid masses under the influence of interactions with a flowing fluid, local boundaries, and other particles.

The algorithms presented in this report appear to be sufficiently flexible to accommodate modeling of levee breach closure. However, several questions remain regarding the level of sophistication required of the various model parameters (and the appropriate set of values themselves) to properly reproduce full scale problems. These problems may be greatly resolved by the results of experiments. The algorithms should be compared against competing breach closure models for representative prototype levee breach closure problems. This benchmarking would permit modelers to identify the strengths and weaknesses associated with various computational modeling approaches. At present, the levee breach work performed should be considered only a tool (or work for others to build upon). The results are not implementable into an actual disaster environment at present.

This report focused upon breach closure simulation via computational techniques, but during this process the work identified a significant void in the set of physical experiments needed to calibrate all computational models of levee breach closure. Physical experiments involving the effects of several levee variables are needed. If properly calibrated with experimental data, models of the sort proposed herein offer immediate value to the levee breach closure problem in evaluating various proposed techniques for achieving breach closure. These evaluations would permit proper staging and placement of equipment and supply lines during the breach closure process to achieve the most rapid solution in a manner that reduces the risks associated with loss of life or property.

Including higher fidelity models in numerical approximation is desirable, though in some instances little value may be added to a closure effort if the numerical process simulated cannot be performed in a time span that would help the community affected by the breach. Advances in model sophistication may be greatly tempered by the results of ongoing research efforts to establish the window of time in which breach closure must be achieved and the availability of material and labor resources within that window. The severe constraints imposed by the limited time available to achieve breach closure may also shift the emphasis of preparedness and response measures away from breach mitigation and toward breach prevention. The remaining levee work performed for project 70015 is related to levee breach prevention by way of levee protection, and is provided in Section 2.3.

2.3 Earthen Levee Breach Protection from Storm Surge and Wave Overtopping

Earthen levee breach protection research was divided into four parts. All parts were ultimately intended to facilitate design and development of a Rapidly Deployable Armoring System (*RDAS*) used to temporarily protect the landward side of critical portions of earthen levee systems against storm surge and overtopping events. Shallow anchors and geotextiles were the primary materials used for the *RDAS*. An *RDAS* could improve resilience of the current US levee system. Overall, the research performed was favorable to using an *RDAS*. Note that some of the research presented has other uses in addition to its usefulness for design and development of an *RDAS*.

The first part was obtaining levee face shear stress profiles during overtopping via flume testing to determine expected conditions during overtopping events. Small-scale physical experiments were performed that simulated combined wave overtopping and storm surge overflow of an earthen levee having a trapezoidal cross section. These physical experiments were complimented with numerical modeling using adaptive hydraulics (AdH) simulations. In the physical model, time series of irregular and unsteady instantaneous flow thickness were obtained at two locations on the levee crest and at five locations on the levee landward-side slope. Time series values of unsteady overtopping flow velocity were obtained at two locations coincident with flow thickness measurements. The data acquisition and instrumentation program used in this research is a defining characteristic not common to previous research efforts attempting to characterize overtopping of earthen levees. Figure 1 is an example levee setup where laser velocity measurements were made at positions P4 and P7. Figure 2 is an example view of the levee section during overtopping.

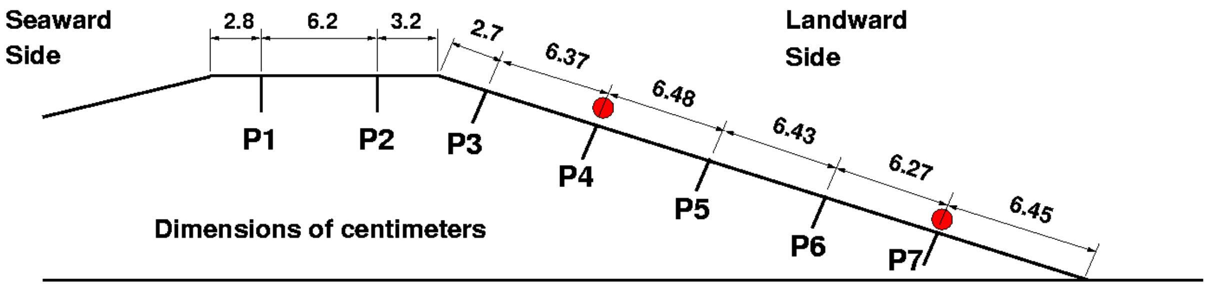


Figure 1. Example Test Layout of Earthen Levee Overtopping Experiment

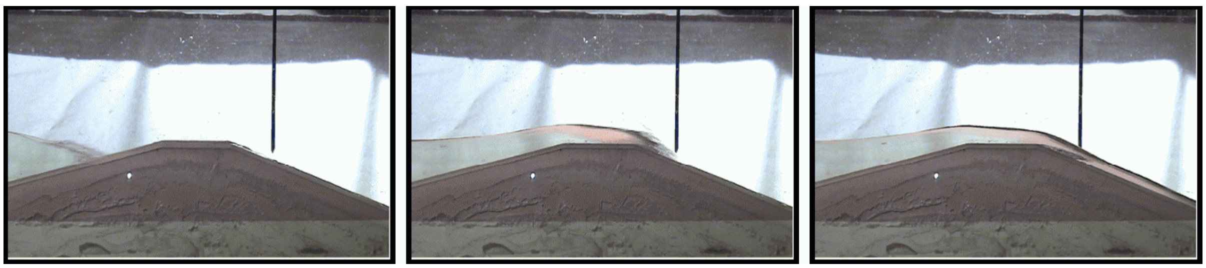


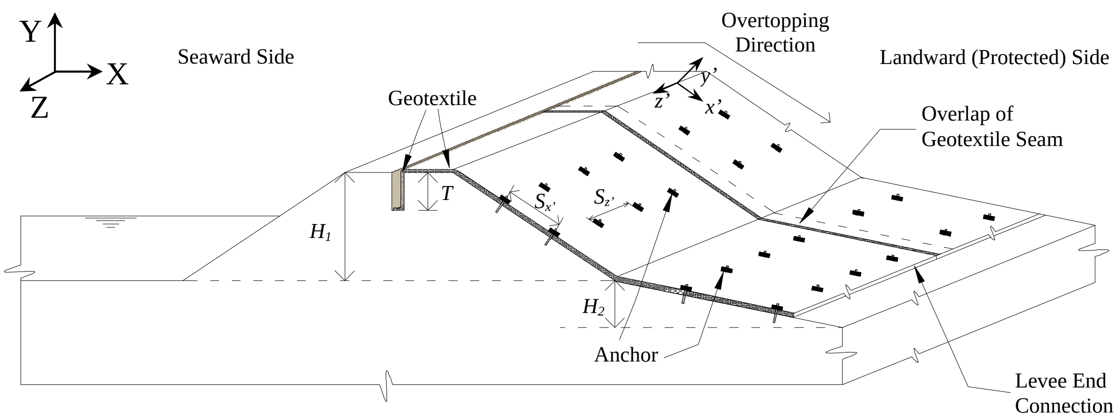
Figure 2. Example Test Condition of Earthen Levee During Overtopping

Data acquired were used to prove the time series of instantaneous overtopping discharge is conserved between locations on the levee landward-side slope with the only difference being a small time lag. Data acquired were also used to calculate the time series of instantaneous shear stress representing the average behavior over a 4.8-m-length of levee slope. Empirical relationships are presented for estimating the mean shear stress for steady overflow and for combined wave and surge overtopping. For the latter case, additional formulas are given to estimate representative parameters of the irregular shear stress peaks. While not directly measured, conservative estimates were developed of the shear stress conditions that could occur a considerable distance down the levee face where flows have reached terminal velocity.

Numerical model simulations successfully reproduced the hydrodynamics measured in the physical model for steady overflow. The model was then used to examine variations in shear stress due to levee surface roughness and the effect of slope transition between the steep levee slope and mild-sloped berm. Numerical hydraulic models calibrated with physical measurements can be valuable and used to perform parametric investigations of conditions beyond the scope or means of physical testing. The first part of the research effort was very successful and provided data that can be used in its present form.

The second part of the earthen levee protection research was to determine construction feasibility for an *RDAS* considering emergency field conditions alongside time and material constraints. This was partially accomplished using a case study on rapid levee armoring of the Yazoo Backwater Levee by the United States Army Corps of Engineers (USACE). Figure 3 is an example photo of the rapid levee armoring used on the Yazoo Backwater Levee. The remainder of the second part of the research effort used the aforementioned case study as a guide to extend the results to an anchored armoring system. Figure 4 is a summary of the concept incorporating anchors for additional stability that would likely be needed for hurricane level events. The overall assessment was *RDAS* construction is viable.

Figure 3. Example Photos of Yazoo Backwater Levee Armoring



Note: H_1 and H_2 are height parameters, T is the required trench depth, and $S_{x'}$ and $S_{z'}$ are anchor spacings.

Figure 4. RDAS Concept

The third part of the research effort was to perform full scale shallow anchor pullout testing to obtain anchor capacities in field conditions expected during wave overtopping. Figure 5 is an example anchor pullout test. Anchor capacities ranged from 145 to 155 kg for 0.3 m anchors and 280 to 360 kg for 0.6 m anchors. Maximum loads were consistent for all anchor types. Anchor test results were used to develop load-deflection curves for finite element modeling, which was performed in the fourth part of the research effort.

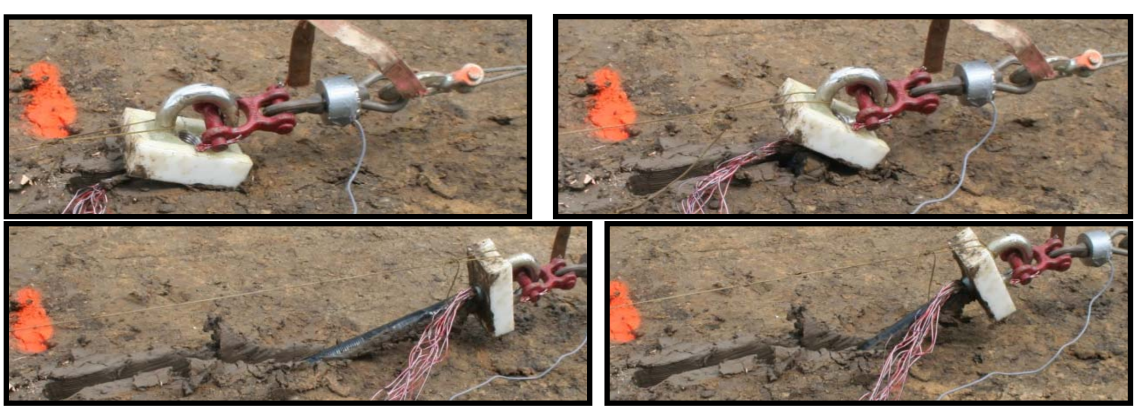


Figure 5. Example Anchor Pullout Test

Abaqus, Fortran, and Python programs were used to perform the finite element modeling of wave loads acting on the example *RDAS* shown in Figure 4 that was anchored with materials represented by Figure 5. Models were defined in general terms by the geotextile meshing method, levee configuration, and anchor rigidity. The modeling developed within this research increased computing efficiency, and could easily be applied to other modeling approaches. A single-layer elastic membrane model (*SLEMM*) was created that incorporated levee and geotextile contact interactions, flexible anchors, and wave loading. The *SLEMM* appears to perform the finite element calculations correctly, but does not appear to be adequate to provide physically meaningful results even though it is a more complicated model than normal. A double layer elastic membrane model (*DLEMM*) was also attempted, but it did not improve model quality. The current finite element model needs improvements before being used for design of an *RDAS*.

CHAPTER 3 - RESEARCH RELATED TO BRIDGES

3.1 Bridge Research Report

Research related to bridges was reported in a single document. It is cited below. The research focused on storm surge on coastal bridges. The research summary has been divided into: 1) modeling and retrofit findings; and 2) comparisons with existing design guides.

Gullett, P.M., Dickey, M-M., Howard, I.L. (2012). *Numerical Modeling of Bridges Subjected to Storm Surge for Mitigation of Hurricane Damage.* SERRI Report 70015-005, US Dept. of Homeland Security Science and Technology Directorate, pp. 82.

3.2 Finite Element Modeling of Storm Surge on Coastal Bridges

The primary objective of the research presented in this report was to perform finite element modeling to determine forces on coastal highway bridges as a result of storm surge and wave action and use these forces to investigate the feasibility of rapid retrofit techniques to prevent failure. Both objectives were met. The retrofit evaluation performed is a fairly traditional assessment that makes use of fundamental principles. The finite element modeling (FEM) approach, however, is fairly unique and has applications beyond those presented in this report. The FEM approach was calibrated using measured data from Oregon State University.

A three component FEM approach was developed and used in this research; the components are a structural model, a wave load model, and an element data transfer model (Figure 6). The structural model is comprehensive but is not unique and can be performed with a variety of commercially available FEM software packages (Abaqus was used in this project). The wave load model (named wave load software (WLS) by the authors) is much more unique and is a key component to this project. The WLS was written in Fortran (other languages could be used) and is a set of software routines that generates wave based surface and body forces based on a wave theory model that has core functionality that is independent of the FEM model. The element data transfer model was also written in Fortran (other languages could be used) to communicate problem specific information between the FEM structural model and the WLS. A third program (Python) was used to submit the multiple load cases and to extract numerical results in an automated manner.

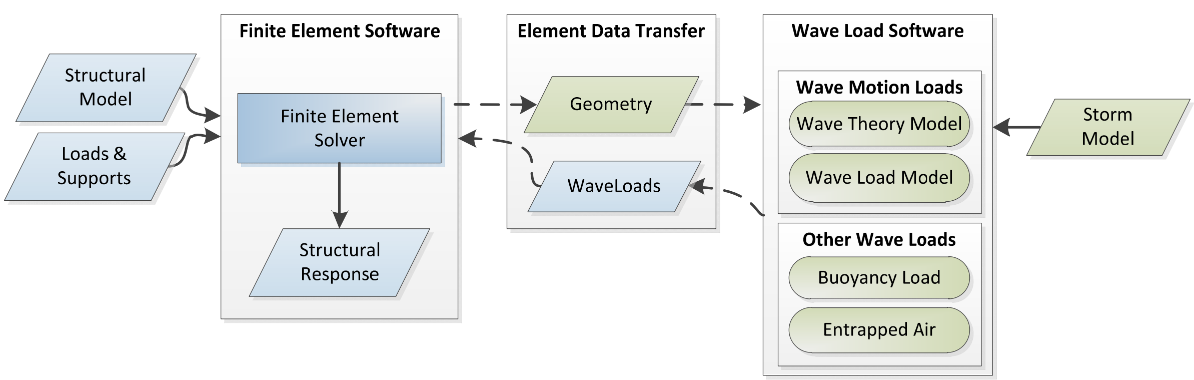


Figure 6. Finite Element Method Applied to Coastal Bridges

Research results using the Figure 6 model as a key component showed rapid retrofit of a highway bridge to resist uplift forces due to storm surge appears to be feasible for some storm events depending on the retrofit method employed. Venting the bridge deck to reduce forces due to entrapped air appears to be the most viable rapid retrofit approach. Anchoring the superstructure to the substructure in a rapid manner appears more useful for lower category storms than for higher category storms.

3.3 Finite Element Modeling Findings Compared to Design Guides

The calibrated model was compared to a fairly recently released American Association of State Highway and Transportation Officials (AASHTO) document for storm surge on coastal highway bridges. The model compared well with the AASHTO document and has many appealing uses. An example comparison is shown in Figure 7. This comparison was performed with %AIR =20% (i.e. 20% entrapped air under the bridge), and shows that the two approaches give similar results under these conditions.

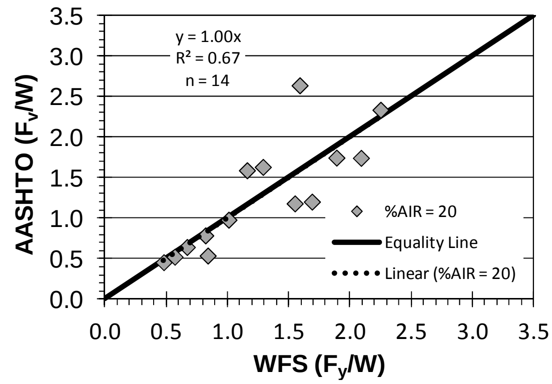


Figure 7. Comparison of FEM and AASHTO Guide Specifications Document

A second comparison is provided in Figure 8. A key point from Figure 8 is that as wave loads increase, the AASHTO loads become smaller than the WLS predicted values using FEM. This behavior may be an artifact of the rigid body assumption made by AASHTO, which would tend to break down as loading levels become large. This is significant as single girder loads may be being under predicted with current design approaches for larger storm events.

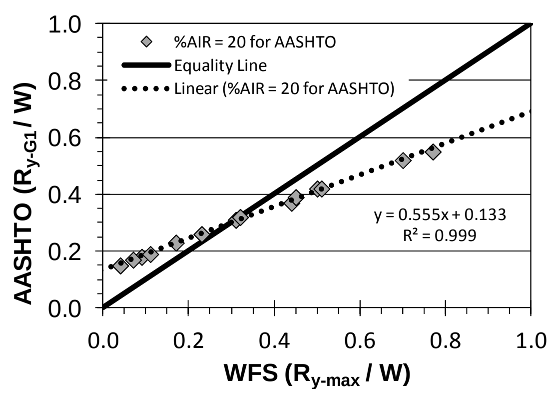


Figure 8. Comparison of FEM and AASHTO Single Girder Maximum Loads

CHAPTER 4 - RESEARCH RELATED TO PAVEMENTS

4.1 Pavement Research Reports

Two of the eleven reports are related to pavements. They are cited below. Howard et al. (2010) was phase 1 and Howard et al. (2012) was phase 2. Phase 1 can be broken into three categories: 1) develop a framework for performing emergency paving repairs; 2) provide general guidance for making emergency repairs, largely with existing technologies and methods; and 3) investigate use of hot-mixed warm-compacted asphalt in a laboratory setting. Phase 2 extended the hot-mixed warm-compacted research to full scale testing. All information related to hot-mixed warm-compacted asphalt is presented together, while the paving framework and repairs with existing technologies are presented separately. It is the assessment of the author that the work related to hot-mixed warm-compacted asphalt is ready for immediate implementation and is a very practical and useful finding from project 70015.

Howard, I.L., Cooley, L.A., Doyle, J.D., Hemsley, J.M., James, R.S., Baumgardner, G.L. (2010). *Rapid Pavement Repair Guidance in Response to Hurricane Damage.* SERRI Report 70015-004, US Dept. of Homeland Security Science and Technology Directorate, pp. 151.

Howard, I.L., Payne, B.A., Bogue, M., Glusenkamp, S., Baumgardner, G.L., Hemsley, J.M. (2012). *Full Scale Testing of Hot-Mixed Warm-Compacted Asphalt for Emergency Paving.* SERRI Report 70015-011, US Dept. of Homeland Security Science and Technology Directorate, pp. 125.

4.2 Framework for Performing Emergency Paving Repairs

To effectively utilize rapid-pavement-repair techniques, there must be a plan in place that allows on-site responders (i.e., Decision Makers) to achieve goals in an efficient manner. Figure 9 is an example scenario in which the primary objective is to reach pre-defined emergency shelters and, once they are reached, to connect shelters. The Figure 9 protocol is an example of the information provided in phase 1 to provide Decision Makers the required information to make informed decisions on which pavements to repair and which techniques to use. Figure 9 utilizes imagery from satellites or aerial vehicles coupled with ground reconnaissance to determine which routes to repair. Imagery can define large damage (e.g., bridges out and/or considerable sections of pavement totally destroyed), and then ground personnel can be deployed to rapidly repairable pavements to obtain additional information and make repair technique decisions.

Once a desired route is chosen, categories of pavement condition are developed. Repair techniques (Sections 4.2 and 4.3) are then selected. It should be noted the repair techniques are intended to facilitate response actions rather than to provide permanent solutions. A target performance timeline of 60 days has been established for emergency repairs, and as such, pavement quality does not have to meet permanent construction standards.

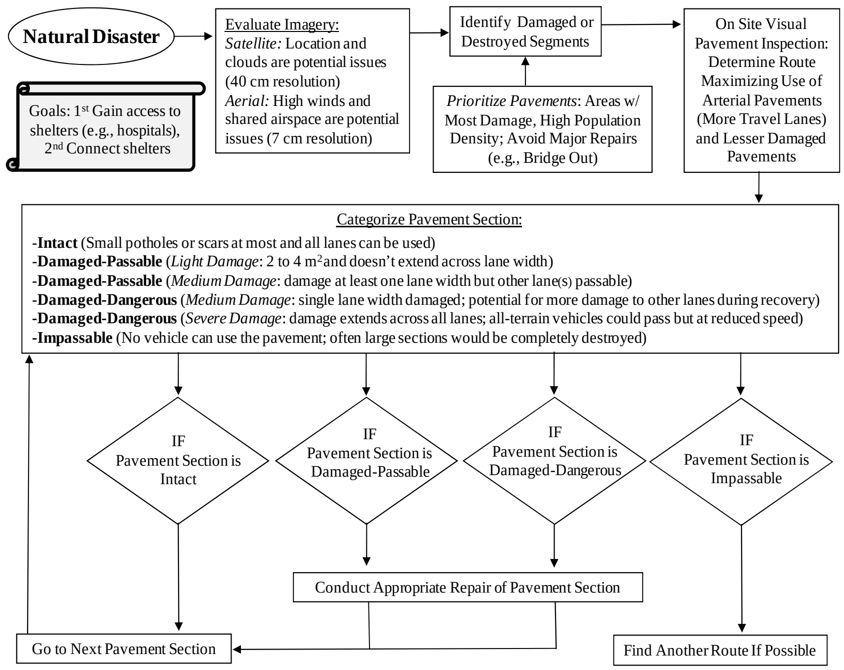


Figure 9. Example Flowchart for Emergency Pavement Repair

4.3 General Guidance for Emergency Paving Repairs

Even though pavements are an integral part of any recovery effort, emergency repair guidance is not readily available, especially in a central location. To this end, information was assembled on six relevant rapid repair techniques using established approaches (plant mixed asphalt concrete produced at various temperatures was also presented as an option, but this information is presented in full detail in Section 4.4). All techniques focused on the pavement and did not consider debris removal, though all techniques could enhance debris removal.

The six techniques investigated besides asphalt concrete are provided below in bullet form. Generally speaking, a flowchart highlighting usefulness of the technique was provided alongside references for additional information. Repairs that could be made with a given technique were also discussed.

- Geotextile and Aggregate Rapid Set Concrete Flowable Asphalt
- Paving Mats Cold Patch Asphalt Slab Jacking

4.4 Emergency Paving with Hot-Mixed Warm-Compacted Asphalt

The overall goal of the research was to determine how far asphalt concrete could be hauled incorporating warm mix technology and how it would perform once on site for a given application. A target service life was set at 60 days in a warm and wet environment. After disasters such as hurricanes, power is often out for large distances, which limits the use of conventional construction approaches. Use of hot-mixed and warm-compacted asphalt hauled from a considerable distance (i.e. a location with power and functioning infrastructure) should drastically reduce recovery time by increasing efficiency of all activities associated with response and recovery.

Phase 1 tested hot-mixed warm-compacted materials in the laboratory with generally favorable results. At the conclusion of phase 1, two primary questions remained: 1) can hot-mixed warm-compacted asphalt be delivered to the location of interest at a temperature at or in excess of 105 C; and 2) can the mixture delivered be compacted to 11 to 14% air voids? An additional question was the suitability of short term aging protocols (STAPs) developed in phase 1 to condition materials in the laboratory for very long haul distances. Phase 2 determined the answers to the two primary questions were yes, but that the STAPs did not fully represent very long haul distances (Figure 10 summarizes the STAP to full scale test comparison using data collected from probes inserted into the asphalt concrete and monitored in real time).

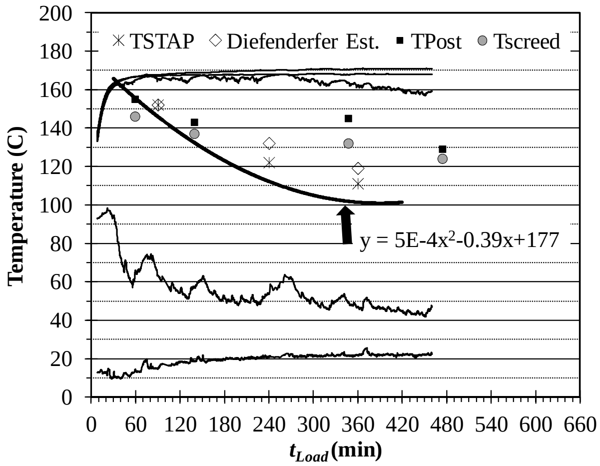


Figure 10. Comparison of Phase 1 STAP and Phase 2 Full Scale Data

Phase 2 consisted of producing asphalt concrete at a full-scale facility, loading the material into trucks (some trucks were instrumented to produce the data in Figure 10), hauling the material for different amounts of time, and compacting the material into test strips on a parking lot (Figure 11 is an aerial photo of the completed parking lot). The process was monitored from production, to transport, to paving, through compacted material properties.

Figure 11. Hot-Mixed and Warm Compacted Parking Lot Test Sections

Asphalt concrete could be hauled 1.0 to 10.5 hr and be placed with a paver. The mix was subsequently compacted to 6.8 to 11.6% air voids based on AASHTO T166. Testing including workability, binder grading, wheel tracking, and moisture damage revealed no formidable problems for emergency paving. An emergency pavement compacted to even modest levels should last at least a few thousand truck passes. For haul distances of 8 hr or less, there was no compelling case to use any mix type tested over another in terms of in place air voids. The overall recommendation from this research is to use hot-mixed and warm-compacted asphalt concrete as an emergency paving material for disaster recovery applications.

CHAPTER 5 - EMERGENCY CONSTRUCTION MATERIALS & METHODS

5.1 Emergency Construction Materials and Methods Research Reports

Five of the eleven reports are related to emergency construction materials and methods. They are cited below. These five reports can largely be sub-divided into three key components associated with emergency construction materials: 1) developing an emergency construction material for disaster recovery (Howard et al. 2010; Howard et al. 2012); 2) providing construction guidance for the emergency construction material developed (Howard 2012); and 3) using the emergency construction material with other materials (Howard et al. 2009; Howard and Trainer 2011). Each sub-category is evaluated individually in the remainder of this chapter.

Howard, I.L., Smith, M., Saucier, C.L., White, T.D. (2009). *2008 Geotextile Tubes Workshop.* SERRI Report 70015-002, US Department of Homeland Security Science and Technology Directorate, pp. 367.

Howard, I.L., Carruth, W.D., Rawlins, J.W., Ferguson, R. (2010). *Dewatering Soil for Use as an Emergency Construction Material for Disaster Recovery.* SERRI Report 70015-007, US Department of Homeland Security Science and Technology Directorate, pp. 69.

Howard, I.L., Trainer, E. (2011). *Use of Geotextile and Geomembrane Tubes to Construct Temporary Walls in a Flooded Area.* SERRI Report 70015-003, US Department of Homeland Security Science and Technology Directorate, pp. 99.

Howard, I.L. (2012). *Guidance for Using Cementitiously Stabilized Emergency Construction Materials.* SERRI Report 70015-008, US Dept. of Homeland Security Science and Technology Directorate, pp. 39.

Howard, I.L., Carruth, W.D., Sullivan, W.G., Bilberry, A.C., Cost, T., Badran, W.H., Jordan, B.D. (2012). *Development of an Emergency Construction Material for Disaster Recovery.* SERRI Report 70015-006, US Dept. of Homeland Security Science and Technology Directorate, pp. 300.

5.2 Development of Emergency Construction Materials

The majority of the effort presented in Chapter 5 was associated with developing an emergency construction material. The key element in the emergency construction material was very high moisture content fine grained soil since it will be abundant at almost any water based disaster such as a hurricane. The overall approach taken was to mix additives with the aforementioned on site materials in as small a quantity as possible to produce desirable short term properties. A variety of materials were used including portland cement (traditional portland cement and specialty produced portland cements were tested), calcium sulfoaluminate cements (traditionally marketed products and modified blends were tested), ground-granulated blast furnace slag, chopped polymer fibers, and dewatering polymers.

A series of strength, modulus, and dewatering tests were performed to evaluate properties of various soils at different moisture contents with combinations of the aforementioned materials. In total, approximately 20,000 strength tests were performed. The majority of this testing was performed on 3 soils at 3 moisture contents using 14 stabilization materials. Table 1 is an example summary of the type of data collected. Very high moisture content blends were capable of producing strengths comparable to conventional materials. The research revealed many suitable attributes that could be immediately useful in disaster recovery, while others might be useful if first evaluated using a full scale demonstration. The overall conclusion of the research was that the high moisture content cementitiously stabilized slurries are a viable emergency construction material for use on a short-term basis. The overall recommendation related to emergency materials was to use them on a short-term basis.

Table 1. Example Emergency Construction Material Strength Properties

Soil	**Shear Strength (kg/cm^2)**	**24 hour Cure**				**72 hour Cure**				**168 hour Cure**			
1	0.2	☑	✓	×	¥	☑	✓	×	¥	☑	✓	×	¥
	0.5	☑	✓	Ø	¥	☑	✓	×	¥	☑	✓	×	¥
	1.0	☑	✓		Ø	☑	✓	×	Ø	☑	✓	×	Ø
	1.5	☑	✓			☑	✓	×		☑	✓	×	
	2.0	Ø	Ø			☑	✓	×		☑	✓	×	
	3.0					Ø	Ø	Ø		☑	Ø	×	
	4.0									☑		×	
	5.0									Ø		×	
	6.0											×	
	7.0											Ø	
2	0.2	☑	✓	---	¥	☑	✓	---	¥	☑	✓	---	¥
	0.5	☑	✓		Ø	☑	✓		Ø	☑	✓		Ø
	1.0	☑	✓			☑	✓			☑	✓		
	1.5	☑	✓			☑	✓			☑	✓		
	2.0	Ø	✓			☑	✓			☑	✓		
	3.0		Ø			Ø	Ø			Ø	✓		
	4.0										Ø		
	5.0												
	6.0												
	7.0												
3	0.2	☑	✓	Ø	¥	☑	✓	Ø	¥	☑	✓	Ø	¥
	0.5	☑	✓		¥	☑	✓		¥	☑	✓		¥
	1.0	☑	✓		Ø	☑	✓		Ø	☑	✓		Ø
	1.5	☑	✓			☑	✓			☑	✓		
	2.0	Ø	Ø			☑	✓			☑	✓		
	3.0					Ø	Ø			☑	✓		
	4.0									Ø	Ø		
	5.0												
	6.0												
	7.0												

The data in the table indicates whether a given stabilization treatment was able to produce the shear strength shown at the appropriate curing level. The data presented has 10% cementitious material and 100% moisture. GGBFS = Ground-Granulated Blast Furnace Slag.

☑ *Portland Cement* ✓ *Portland Cement and Fibers*

× *GGBFS(75%) and Portland Cement (25%)* ¥ *Calcium Sulfoaluminate Cements*

--- *No testing conducted* Ø *Strength was not achieved*

5.3 Construction Guidance for Using Emergency Construction Materials

Construction guidance was provided for use with the cementitiously stabilized materials discussed in Section 5.2. Information was presented on key construction equipment likely to be useful in a disaster environment. Key equipment discussed was: positive displacement pumps, dredges, pugmill mixers, and concrete ready mix trucks. Construction guidance was given in flowcharts where key equipment was included alongside the appropriate order of activities.

The overall recommendation related to construction was to rely on the aforementioned equipment and consider their use in conjunction with the materials presented in Section 5.3 for disaster recovery. Positive displacement pumps could provide major advantages as material placement in a disaster environment would be a formidable challenge in many cases. Specialty dredges were also discussed that could be useful in some applications. Pugmill mixers and/or concrete ready mix trucks could allow material obtained and conveyed with either positive displacement pumps (recommended for most applications) or dredges (could be useful for some applications) to be mixed with cementitious material and used as an emergency material.

5.4 Geotextile Tubes Used With Emergency Construction Materials

Geotextile tubes are a versatile product that could serve as a useful vehicle for the Section 5.2 emergency construction material to be used in conjunction with some of the construction techniques presented in Section 5.3. Positive displacement pumps could be used to place cementitiously stabilized high moisture content fine grained soil into geotextile tubes for multiple purposes. A key application could be containing contaminated sediments on a temporary basis after a disaster. Construction of walls could be another application.

Geotextile tube research included a workshop where professionals with relevant experience were assembled and provided information that could improve geotextile tube use for disaster recovery. This information was coupled with literature review, site visits to geotextile tube projects of potential interest, laboratory testing, and analysis.

It was concluded that planning, training, and demonstration exercises are needed beyond those currently in existence to effectively use geotextile tubes in a disaster environment. Water filled geomembrane tubes were favored over geotextile tubes for most applications provided they were available. Geotextile and geomembrane tube use appears feasible at some level for disaster recovery, but construction time estimates are not well established. Geotextile tube walls constructed by stacking three 9.14 m circumference tubes in a pyramid that have been filled with the material discussed in Section 5.1 appears to be a stable configuration based on a rudimentary analysis (several foundation issues were not considered) with a wall height of 3.8 m. Figure 12 is an example of a similar structure filled with sand.

Figure 12. Construction of Temporary Dam in Morocco Using Geotube® Units

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