Flood Warning Alert Systems

Requested by
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The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.

Executive Summary

Background

Like many states, California periodically experiences flooding, a problem that is projected to get worse in the coming years. Flooding can have a major effect on the state's transportation infrastructure, causing millions of dollars of damage to roadways and bridges. Consequently, Caltrans is in need of a flood alert system that allows the department to proactively monitor, assess and respond to flood-related disasters and associated hazards in real time. This system would be focused on providing bridge and infrastructure management during destructive flood conditions in order to predict infrastructure failure. Caltrans is beginning a multi-year effort to develop this system, possibly to be called "FloodCast," which would be similar to Caltrans' current ShakeCast system for early situational awareness of earthquake impacts. The system would integrate multiple sources of data and provide automated notifications when conditions exceed preset thresholds.

As a preliminary step in the development of this system, Caltrans is seeking information about:

- Systems being used by other flood-prone states for the early warning of flood hazards to transportation infrastructure and to predict infrastructure failure (and specifically the kinds of data and hydrological modeling that support such systems).
- Available literature on water-depth thresholds thought to be damaging to roadways and structures (such as by causing scour, or through deck submergence).
- Available literature on inundation mapping and hydrological modeling of rainfall runoff, including case histories and the level of effort required to implement this modeling.

To gather this information, CTC & Associates:

- Identified and contacted states with flood warning systems focused on predicting infrastructure failure caused by flooding. We asked the states about specifications for these systems, information about the sources of data they integrate, and relevant information on hydrological modeling and inundation mapping to support the systems. We also asked states whether they knew of other states with such systems, or other systems being used internationally.

- Conducted a broad literature search on flood alert systems, water-depth thresholds for infrastructure damage, inundation mapping, and hydrological modeling of rainfall runoff to identify sources of information that may be useful for Caltrans to reference as the department develops its system. We also looked for literature on the existence of flood alert systems internationally.

Summary of Findings

Interviews with State Agencies and Vendors

We contacted seven state departments of transportation and the commercial vendor of the BridgeWatch product regarding their flood warning systems. Findings include:

- Several states (Connecticut, Iowa, Tennessee and Washington) use or have used the commercial system BridgeWatch, developed by United States Engineering Solutions (USES). This web-based system allows users to set alert level thresholds based on water levels (from river gage data) and rainfall (from NEXRAD weather radar data); it also takes into account environmental hazards, seismic events and snow. Each of the states we interviewed is happy with this system, although they noted it takes time to calibrate thresholds in order to minimize false alerts. Iowa, Tennessee and USES provided brochures summarizing the system (see Appendices A, C.1, C.2, D.1 and D.2). Washington detailed its costs for this system as $150,000 to set up and then $80,000 annually; WSDOT has discontinued use of the system for budgetary reasons (despite being happy with its performance). Other clients include Georgia, Illinois and Idaho. Oregon is considering switching from its custom-built system to BridgeWatch.
- Oregon is using a system called BridgeAlerts, which was developed in-house building on earlier Caltrans efforts in this area. ODOT provided a user manual detailing the workings of this system and its data sources (see Appendix B). ODOT is considering switching to the BridgeWatch commercial system because the current system is not efficient and because they would prefer to have technical support.
- Rhode Island is currently working with the consultant AECOM to develop a custom bridge alert system that is similar in description to BridgeWatch, but also includes data from scour monitoring devices. RIDOT uses HEC-RAS software (see **National Resources** below) and United States Geological Survey (USGS) data for hydrological modeling. RIDOT offered to provide samples of its scour analysis, plans of action, and the scope of work for its system; CTC will forward these materials to Caltrans as soon as they are available.
- Our contact at Tennessee DOT noted that TDOT does not perform hydrological modeling or inundation mapping but uses publicly available models and data to set thresholds.
- Other states that may have developed or may be developing in-house flood alert systems include Alabama, Alaska and Pennsylvania; Virginia may have a system through a commercial vendor other than BridgeWatch. We were unable to reach these states within the time frame for this Preliminary Investigation.
- States were generally unaware of commercial vendors for infrastructure-related flood warning systems other than BridgeWatch, and they were unaware of the existence of such systems internationally; Tennessee noted that several GIS companies are bidding to provide flood alert systems to states, but their systems are not yet mature.

We also contacted the California Department of Water Resources and the California Water Science Center, which provided resources related to flood forecasting, hydrological modeling and inundation mapping.

National Resources

- The standard software for hydrological modeling is the U.S. Army Corps of Engineers' Hydrologic Engineering Centers River Analysis System (HEC-RAS).
- There are also a number of FHWA Hydraulic Engineering Circulars that describe the standard methods for predicting bridge scour and conducting bridge-related hydrological modeling.
- Two NCHRP documents discuss the monitoring and management of scour-critical bridges.

Related Research

We gathered information in three topic areas:

- Flood Warning Systems and Impact Assessment.
- Hydrological Modeling and Inundation Mapping.
- Bridge Scour.

Following is a summary of findings by topic area.

<u>Flood Warning Systems and Impact Assessment</u>

- An Ohio DOT report details the development of flood-inundation maps to estimate the extent of flooding based on water levels measured by stream gages. The maps are designed to be incorporated into a web-based flood warning system from the National Weather Service. The report also describes the development of area flood profiles via hydrologic modeling with HEC-RAS. (See *Development of a Flood-Warning System and Flood-Inundation Mapping in Licking County, Ohio.*)

- A TRB paper describes a method developed for using satellite imagery to rapidly assess the impacts of flooding and other disasters. (See *A Geospatial Methodology for Rapid Assessment of Disaster Impacts on Infrastructure.*)

- A study describes a hydrologic model developed for flood monitoring in South Africa. (See *A Flood Early Warning System for Southern Africa.*)

- Sacramento County, California, uses a flood-warning decision support system using data on water and rainfall levels. The system includes automatic notifications (See *Flood-Warning Decision-Support System for Sacramento, California.*)

<u>Hydrological Modeling and Inundation Mapping</u>

- Several studies discuss approaches to hydrological modeling and inundation mapping, including the use of digital elevation models in Italy (*Detection of Flood-Prone Areas Using Digital Elevation Models*) and a study that develops a simpler way to estimate flow under bridges than HEC-RAS, which is the most commonly used method for computing water surface profiles in rivers (see *A Simple Method for Estimating Flood Flow Under Bridges*).

- A study by the U.S. Geological Survey describes StreamStats, a web-based application for estimating streamflow statistics at un-gaged locations on streams (*A Streamflow Statistics (StreamStats) Web Application for Ohio*).

Bridge Scour

- A 2012 FHWA publication describes a method for calculating bridge scour for a partially or fully submerged bridge in an extreme flood event (*Submerged Flow Bridge Scour Under Clear Water Conditions*).
- A 2011 NCHRP study reviews the current state of knowledge regarding bridge-abutment scour and the veracity of the leading methods currently used for estimating design scour depth (*Evaluation of Bridge-Scour Research: Abutment and Contraction Scour Processes and Prediction*).
- A 2011 paper describes a new hydraulic model for bridge scour prediction and compares it to HEC-RAS (*Comparison Study on Computer Simulations for Bridge Scour Estimation*).
- A USGS report for the Illinois Center for Transportation tests a method for estimating scour depth of cohesive soils and compares it to scour prediction results for non-cohesive soils based on FHWA's *Hydraulic Engineering Circular 18 (Pier and Contraction Scour Prediction in Cohesive Soils at Selected Bridges in Illinois*).
- A Kansas DOT project develops a computer program for analyzing bridge scour using methods in *Hydraulic Engineering Circular 18* and HEC-RAS.

Gaps in Findings

We found a number of states making use of the commercial product BridgeWatch, but found only two states that have developed or are in the process of developing their own flood alert systems. During our interviews, we learned of several other states that may have in-house systems (Alabama, Alaska and Pennsylvania) and one state (Virginia) that may be using a vendor other than BridgeWatch for its system. However, we were unable to reach these states within the scope of this Preliminary Investigation, and we were unable to reach staff at Connecticut DOT concerning the hydrological information related to that agency's system. We were also unable to find much information about the existence of infrastructure-related flood alert systems internationally (a South African system described in **Related Research** is one exception).

Next Steps

CTC is currently awaiting documents from Rhode Island concerning the flood alert system that it is developing, and will forward them to Caltrans upon receipt. As next steps, Caltrans might consider:

- Contacting AECOM, the consultant involved in the ongoing development of Rhode Island's flood alert system, for further details; and following up with RIDOT once the development of this system is complete.
- Contacting Alabama, Alaska, Pennsylvania and Virginia for information about their flood alert systems.
- Following up with Connecticut DOT for more information about the hydrological modeling used to set thresholds for that agency's system.

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Vendors

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Other Agencies

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Interviews with State Agencies and Vendors

Departments of Transportation

Connecticut

CTDOT has a contract with US Engineering Solutions for the company's BridgeWatch product. All of its scour-critical bridges are loaded into the system, with preloaded rain and river gage thresholds. CTDOT receives e-mail and text message alerts when an event exceeds the predetermined level.

We interviewed Ted Lapierre, supervising engineer in CTDOT's Bridge Safety and Evaluation Section. CTDOT has had the BridgeWatch system for five years, and Lapierre reported that it has been working well and seems worth the cost. The system includes a database of scour-critical structures, and different thresholds computed for rainfall and river flow. The system is tied to USGS river gages throughout the state, as well as NEXRAD rain gages. If the system identifies a particular intensity of rainfall or peak flow in a watershed area, it will send a notification. CTDOT will then dispatch bridge inspectors. Lapierre didn't know of other vendors or other states with similar systems.

CTDOT's Hydraulics & Drainage Section determines the thresholds for rainfall and river flow; for more information, contact Mike Hogan at (860) 594-3241.

Iowa

IDOT uses BridgeWatch to identify scour-susceptible structures by monitoring National Weather Service rainfall accumulations and USGS stream flow gage information. The program provides e-mail and text message alerts when rainfall amounts or stream gages exceed defined thresholds for potential flooding. IDOT provided a brochure (Appendix A) published several years ago that promotes the use of this technology to monitor its infrastructure.

Massachusetts

MassDOT does not have a flood alert system. We spoke with Vicki Volz in the agency's Bridges & Structures unit, who recommended *NCHRP Synthesis Report 396* as a resource (see *Monitoring Scour Critical Bridges* in **National Resources**). She also recommended contacting Rhode Island DOT about its flood alert system.

Oregon

ODOT uses an in-house system called BridgeAlerts that was developed building on earlier Caltrans work in this area. The system includes a database to track plans of action for bridges that are scour-critical, with triggers based on rainfall or river gage measurements of stream flows.

We interviewed Ed Foltyn, senior hydraulics engineer in ODOT's Bridge Engineering Section, who said ODOT is considering switching to the commercial system BridgeWatch. He said ODOT would prefer a commercial system because of the available technical support, and because its current system is not unified; it requires searches of multiple web sites for each of its 500 scour-critical bridges. The current system also experiences a fair number of false alarms, and would require further programming to refine it. Foltyn expressed that properly running an in-house system requires a dedicated IT group.

ODOT does not do inundation mapping; its hydrological models are based on simple regression models available through USGS. The most important challenge for these systems is finding stream gages in the same basin as the bridge to be monitored; ODOT has installed an ultrasonic water level sensor on one bridge, using the same technology that USGS uses for stream gages. This sensor transmits via satellite and allows ODOT to look at actual water levels in real time. The sensor cost around $3,000 plus a monthly maintenance fee for the satellite system and data server.

Foltyn provided the user manual for ODOT's system (Appendix B). Its database pulls information from a number of sources, including:

- Pontis bridge management software.
- Data derived from the NCHRP Project 24-25 Phase II final report, *Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations* (available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w107.pdf; see **National Resources** for more on this document).
- Data from stream flow gages, rainfall stations, Advanced Hydrologic Prediction Service stations and NEXRAD radar stations.

A hydrology module allows the display and editing of calculated flow predictions at a bridge site for standard recurrence intervals, based on a variety of models' regression equations and the historical analysis for the associated bridge's flow gage. Appendix B includes details of this and numerous other modules, including screenshots.

Foltyn was unaware of any other commercial systems or states that have built their own systems, though he mentioned that Alaska may have tried to build a system similar to Oregon's.

Rhode Island

We spoke with Bob Fura, chief civil engineer in Bridge Engineering, who said RIDOT is currently working with a consultant (AECOM, http://www.aecom.com/) to develop a custom bridge alert system. AECOM is developing a customizable software package that is tied to USGS gaging stations, the National Weather Service, and to scour monitoring devices on bridges. The software will allow RIDOT to set thresholds for water elevation and flow beyond which users are alerted.

In 2010 Rhode Island experienced record flooding, with 15 inches of rain within two weeks in some locations. Some streams and rivers experienced water levels greater than 500-year flood levels. This flood data has changed RIDOT's scour analysis, which previously was based solely on procedures in FHWA's *Hydraulic Engineering Circulars* 18 and 20. After flooding, many bridges that were thought to be scour-critical did not have any scour, while others that were thought not to be scour-critical turned out to be problematic. In general, most bridges held up well. RIDOT is still in the process of revising its scour analysis and plans of action for bridges based on this data. This data will inform the alert system being developed by AECOM, including flow thresholds.

RIDOT has also conducted hydrological modeling and watershed analysis (to determine what flows will produce scour) using the HEC-RAS software and USGS data. Fura offered to provide samples of RIDOT's scour analysis and plans of action, and the scope of work for its system; CTC will forward these materials to Caltrans as soon as they are received.

Fura was not aware of other states that have developed or are developing flood alert systems.

Tennessee

According to Jon Zirkle in the Hydraulics Section of TDOT's Structures Division, TDOT has used the BridgeWatch system since 2004 and has had very good success using it to monitor scour-critical bridges and bridges with unknown foundations. Zirkle provided informational materials on TDOT's system (Appendices C.1 and C.2), which include a diagram of the system architecture and numerous screenshots.

Zirkle said some GIS companies are now bidding on flood alert projects, but their systems are not as robust as BridgeWatch. TDOT has not done hydrological modeling or inundation mapping; it sets thresholds using publicly available models and FEMA scour studies from the mid-1990s.

BridgeWatch has been very successful at TDOT; the system performed well during heavy rainfall in 2010. Zirkle noted that it takes time to adjust thresholds to reduce false alarms, and mentioned that TDOT's system has become more reliable with the addition of more stream gages.

Zirkle said TDOT did not consider building an in-house system, which they considered too labor-intensive. He added that one advantage of the BridgeWatch system is that it is available over the web and is not resident on TDOT computers, so that the system does not go down when TDOT computers are down.

Zirkle said Alabama may be trying to set up its own system, and he said Pennsylvania has an in-house system but may soon switch to BridgeWatch. He added that Virginia may have a system through a commercial vendor other than BridgeWatch.

Washington

According to Bridge Scour Engineer James Dorgan, WSDOT used BridgeWatch until recently to monitor 428 bridges, but discontinued its use for budgetary reasons (the agency was happy with the product and customer service). Dorgan said the program cost $150,000 to initiate plus an $80,000 annual monitoring fee.

Dorgan said the initial challenge with this service is developing reasonable monitoring thresholds for the scour-critical bridges in order to minimize false alarms. This process can take a few flood cycles, and WSDOT hadn't finished this process before the agency was compelled to discontinue the BridgeWatch service. Dorgan believes it is more cost-effective to use BridgeWatch than to develop a custom system.

Vendors

United States Engineering Solutions

USES provides its BridgeWatch system to the following states: Connecticut, Georgia, Tennessee, Iowa, Illinois, Idaho and Washington. This system takes into account environmental hazards, seismic events, snow, river flow and rainfall. It allows users to set alert level thresholds and is accessible through a web interface.

We spoke with Joseph Scannell, president of USES, who noted that there is a long history between his company and Caltrans, including a number of meetings. Scannell declined to share proprietary technical documentation for the BridgeWatch system, but he did provide two brochures (Appendices D.1 and D.2).

Other Agencies

California Department of Water Resources

We spoke with Sudhakar Talanki, chief of the River Forecasting Section in the Hydrology Branch of the department's Division of Flood Management. He shared information about flood forecasting in California, pointing to an online resource called the California Data Exchange Center (http://cdec.water.ca.gov/). This site is a one-stop shop for data related to weather, forecast, hydrology, reservoir conditions, snow, and related topics in California.

Another important tool is the National Weather Service's California/Nevada River Forecast Center (http://www.cnrfc.noaa.gov/). Forecast locations are represented on a map and color-coded according to whether or not they are expected to surpass thresholds. There are 94 forecast locations within the state of California. For each location, there is information about flow and stage (see an example at http://www.cnrfc.noaa.gov/graphicalRVF.php?id=FTDC1); if the stage is over predefined levels it will trigger an emergency response.

This data can be accessed by government agencies for integration into their systems (including a flood alert tool).

California Water Science Center/USGS
USGS staff referred us to the California Water Science Center, where we spoke with Public Information Officer Patricia Orlando. She pointed to the following resources on the USGS web site:

- USGS Water Resources: Cooperative Water Program, Flood Hazard Risk and Assessment: http://water.usgs.gov/coop/products/hazards/flood.html. This page includes information about monitoring technology, models, analysis tools, and robust data management and delivery systems.
- USGS Flood Resources: http://water.usgs.gov/floods/resources/. This page includes USGS tools, web sites, publications and other resources for monitoring, studying and communicating flood information.
- USGS Flood Inundation Mapping Science: http://water.usgs.gov/osw/flood_inundation/
- USGS Office of Surface Water: http://water.usgs.gov/osw/

National Resources

In addition to the sources listed in this section, see the previous page for national resources recommended by the California Department of Water Resources and the California Water Science Center.

Hydrologic Engineering Centers River Analysis System (HEC-RAS), U.S. Army Corps of Engineers
http://www.hec.usace.army.mil/software/hec-ras/
HEC-RAS is the most commonly used software for hydrological modeling. Components include:

- Steady Flow Water Surface Profiles.
- Unsteady Flow Simulation.
- Sediment Transport/Movable Boundary Computations.
- Water Quality Analysis.

Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance, Third Edition, *Hydraulic Engineering Circular 23*, FHWA, September 2009.
http://www.fhwa.dot.gov/engineering/hydraulics/pubs/09111/index.cfm
Abstract: The purpose of this document is to identify and provide design guidelines for bridge scour and stream instability countermeasures that have been implemented by various state departments of transportation (DOTs) in the United States. Countermeasure experience, selection, and design guidance are consolidated from other FHWA publications in this document to support a comprehensive analysis of scour and stream instability problems and provide a range of solutions to those problems. The results of recently completed National Cooperative Highway Research Program (NCHRP) projects are incorporated in the design guidance, including: countermeasures to protect bridge piers and abutments from scour; riprap design criteria, specifications, and quality control, and environmentally sensitive channel and bank protection measures. Selected innovative countermeasure concepts and guidance derived from practice outside the United States are introduced. In addition, guidance for the preparation of Plans of Action (POA) for scour critical bridges has been expanded to include a standard template for POA and instructions for its use.

Monitoring Scour Critical Bridges, *NCHRP Synthesis 396*, 2009.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_396.pdf
From the abstract: This synthesis is a report of the state of knowledge and practice for fixed scour monitoring of scour critical bridges. It includes a review of the existing knowledge and research and an examination of current practice. The project included a survey of transportation agencies and other bridge owners to obtain their experiences with fixed scour monitoring systems.

Tidal Hydrology, Hydraulics and Scour at Bridges, First Edition, *Hydraulic Engineering Circular 25*, FHWA, December 2004.
http://www.fhwa.dot.gov/engineering/hydraulics/hydrology/hec25.pdf
Abstract: The purpose of this manual is to provide guidance on hydraulic modeling for bridges over tidal waterways. This document includes descriptions of: (1) common physical features that affect transportation projects in coastal areas, (2) tide causing astronomical and hydrologic processes, (3) approaches for determining hydraulic conditions for bridges in tidal waterways, (4) applying the hydraulic analysis results to provide scour estimates. By using the methods in this manual, better predictions of bridge hydraulics and scour in tidal waterways will result. In many cases, simplified tidal hydraulic methods will provide adequate results. However, when the simplified methods yield overly conservative results, use of the recommended modeling approaches will provide more realistic predictions and hydraulic variables and scour.

Evaluating Scour at Bridges, Fourth Edition, *Hydraulic Engineering Circular 18,* FHWA, May 2001.
http://isddc.dot.gov/OLPFiles/FHWA/010590.pdf
This document presents the state of knowledge and practice for the design, evaluation and inspection of bridges for scour.

Stream Stability at Highway Structures, Third Edition, *Hydraulic Engineering Circular 20,* FHWA, March 2001.
http://isddc.dot.gov/OLPFiles/FHWA/010591.pdf
This document provides guidelines for identifying stream instability problems at highway stream crossings. It covers geomorphic and hydraulic factors that affect stream stability and provides a step-by-step analysis procedure for evaluation of stream stability problems. Stream channel classification, stream reconnaissance techniques, and rapid assessment methods for channel stability are summarized. Quantitative techniques for channel stability analysis, including degradation analysis, are provided, and channel restoration concepts are introduced.

Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations, *NCHRP Web-Only Document 107*, October 2006.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w107.pdf
From the abstract: This report presents a risk-based approach to managing these bridges in the absence of foundation information. The general framework in this report, which is primarily applied to scour failure, can easily be applied to other hazards such as earthquakes and tsunamis. The guidelines illustrate how to collect appropriate data, estimate risk of failure from an estimated failure probability and associated economic losses, and use risk in a structured approach to select an appropriate management plan. Risk analysis is specifically used to select appropriate performance standards for various bridge classifications and justify the costs of nondestructive testing of foundations, monitoring activities, and countermeasures. The scour guidelines were then applied to sixty case studies in the US to validate the management plan that it selected for bridges with known foundations, and to illustrate its specific application in a variety of settings.

Related Research

Flood Warning Systems and Impact Assessment

Development of a Flood-Warning System and Flood-Inundation Mapping in Licking County, Ohio, U.S. Geological Survey, 2012.
http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Reports/2012/Hydraulics/134517_FR.pdf
This report details the development of flood-inundation maps for parts of Ohio to estimate the extent of flooding based on water levels measured by stream gages. The maps were provided to the National Weather Service (NWS) for incorporation into a web-based flood-warning system that can be used in conjunction with NWS flood-forecast data to show areas of predicted flood inundation associated with forecasted flood-peak stages. The report also describes hydraulic modeling using HEC-RAS in order to establish flood profiles for areas. For a similar project, see also:

> **Development of a Flood-Warning Network and Flood-Inundation Mapping for the Blanchard River in Ottawa, Ohio,** U.S. Geological Survey, 2011.
> http://pubs.usgs.gov/sir/2011/5189/pdf/sir2011-5189.pdf

"A Geospatial Methodology for Rapid Assessment of Disaster Impacts on Infrastructure," Waheed Uddin and Katherine Keller Osborne, *Transportation Research Board 91st Annual Meeting Compendium of Papers DVD,* 19 pages, 2012.
Abstract at http://trid.trb.org/view/2012/C/1130488
From the abstract: This paper describes a satellite imagery based geospatial methodology developed and validated for classifying surfaces of spatial samples from Gulfport, Mississippi and New Orleans, Louisiana in the United States. The maximum residual error for all surface types by the developed geospatial methodology is < ±7%, with respect to groundtruth, and is significantly more accurate compared to traditional supervised classification methods. This methodology is further used with pre- and post-disaster high resolution multispectral satellite imageries for post-Katrina storm debris and erosion estimates in the Gulf Coast areas. The developed models are applicable for hurricane impacts on transportation and other built infrastructure assets, flood damages, and vulnerability of inhabited built-environment. Due to readily available worldwide coverage of commercial satellite imagery, the geospatial methodology facilitates rapid assessment of disaster impacts, recovery, and restoration for coastal and inland flood-prone areas almost anywhere in the world.

"Natural Hazard Risk Analysis on Florida Bridge Structures," Ayodeji Agbale, Doreen Kobelo, and John Sobanjo, *Transportation Research Board 91st Annual Meeting Compendium of Papers DVD*, 16 pages, 2012.
Abstract at http://trid.trb.org/view/2012/C/1129673
Abstract: Significant life and property damage emerging from the occurrence of natural disasters including the recent earthquake in Haiti, the Tohoku earthquake and tsunami in Japan, as well as flooding and tornado activities in the central parts of the United States, has emphasized the significance of knowing the risks that natural hazards pose on the population and the infrastructure. Bridges are very important structural facilities in the road network system of any state, and this study will show and discuss ideas for the calculation of these risks, using the Florida bridges as a case study. The model used in the study incorporated statistical bridge data from the Department of Transportation, as well as historical data of natural disasters including hurricanes, tornadoes, earthquakes, wildfires, and flooding from the National Oceanic and Atmospheric Administration. The concept, analysis and model used the likelihood and consequence of natural disasters to evaluate the risk they pose on the Florida bridges. This model can be used by researchers and practitioner in greater depth for development of other models, including but not limited to the ranking of bridges for natural hazard mitigation, as well as the ranking of bridges for remediation acts after the occurrence of a natural disaster.

"Long-Term Performance of a Flood Alert System and Upgrade to FAS3: A Houston, Texas, Case Study," Zheng Fang, Philip B. Bedient and Birnur Buzcu-Guven, *Journal of Hydrologic Engineering*, Volume 16, Issue 10, 2011: 818-828.
Abstract at http://trid.trb.org/view/2011/C/1121984
Abstract: The second-generation radar-based flood alert system (FAS2) has been operational for more than a decade, and provides accurate advanced warning to the Texas Medical Center (TMC) in the Brays Bayou watershed of southwest Houston. Over the past nine years, FAS has generally predicted floods with average differences of 0.88 h in time of peak and 3.6% in peak flows and a R^2 value of 0.90 for the overall performance. After years of urbanization in the watershed, the hydrologic model as a core engine in the system has been updated with recent routing information and loss rate factors to provide more reliable prediction information. Recently, the system has been upgraded into its third generation (FAS3) by incorporating a hydraulic prediction tool—FloodPlain Map Library (FPML)—so that mapped warning information in geographic information systems (GIS) and Google Maps can be provided to emergency personnel in real time. In addition to briefly reviewing the theory and design of the flood warning system for Brays Bayou, this paper focuses on recent improvements with a summary of the flood alert system's performance over the past years, including three recent major events: Hurricane Ike on September 13, 2008, a smaller event on April 27–28, 2009, and a complex event on July 2, 2010.

Application of Sensor Networks to Intelligent Transportation Systems, Missouri University of Science and Technology, 2009.
http://transportation.mst.edu/media/research/transportation/documents/R180_CR.pdf
Abstract: The objective of the research performed is the application of wireless sensor networks to intelligent transportation infrastructures, with the aim of increasing their dependability and improving the efficacy of data collection and utilization. Examples include health monitoring of bridges, flood level detection, and other applications of real-time data collection and analysis. This project will enable modeling, prediction, and improvement of trustworthiness for a variety of transportation infrastructures. In collaboration with the Center for Infrastructure Engineering Studies (CIES), a prototype of a base station with data acquisition and long range communication capabilities has been developed. The current application is the measurement of water levels for low-water bridges, and the prototype will be deployed by MoDOT in the immediate future. The research is directly tied to embedded computing (which is the subject of a course previously taught by the principal investigator) and to digital network communications (a new course developed and recently taught by the principal investigator). Three graduate students, one of whom is funded by the UTC, and two undergraduates are involved in the research. Planned future activities include collaboration with service learning activities at Missouri S&T, as well as the National Engineering Projects in Community Service (EPICS) program.

"A Flood Early Warning System for Southern Africa," Guleid A. Artan, Miguel Restrepo, Kwabena Asante and James Verdin, *Pecora 15/Land Satellite Information IV Conference,* 2002.
http://earlywarning.usgs.gov/fews/pubs/Pecora15%20FloodEarlyWarning%20GAetal.pdf
Abstract: Sizeable areas of the Southern African Region experienced widespread flooding in 2000. Deployment of hydrologic models can help reduce the human and economic losses in the regions by providing improved monitoring and forecast information to guide relief activities. This study describes a hydrologic model developed for wide area flood risk monitoring for the Southern African region. The model is forced by daily estimates of rainfall and evapotranspiration derived from remotely sensed data and assimilation fields. Model predictive skills were verified with data observed stream flow data from locations within the Limpopo basin. The model performed well in simulating the timing and magnitude of the stream flow during a recent episode of flooding in Mozambique in 2000.

Roadway Flash Flooding Warning Devices Feasibility Study, ITS-IDEA Program Project Final Report, 2001.
http://onlinepubs.trb.org/onlinepubs/sp/its-idea_79.pdf
Abstract: This Intelligent Transportation Systems (ITS) Innovations Deserving Exploratory Analysis (IDEA) project explored the feasibility of a flashflood warning system for motorists on the road. A system with a modular design was proposed to allow flexibility in technology implementation and its components or subsystems were identified. These included water level sensors, data processing subsystem, data dissemination subsystem, alerting subsystem, monitoring subsystem, motorist warning subsystem, traffic control subsystem and power subsystem. The system needs to be rugged, reliable and durable with a high operational capability. Recommendations for system development and testing were made. It was concluded that it is feasible to develop a low cost, durable system based on available technology that will automatically warn motorists and control traffic with devices such as railroad crossing gates. The next phase will involve development of and testing of such a system.

"Flood-Warning Decision-Support System for Sacramento, California," *Journal of Water Resources Planning & Management*, Volume 127, Issue 4, 2001: 254-260.
Abstract at http://cedb.asce.org/cgi/WWWdisplay.cgi?126956
Abstract: An automated flood-warning decision-support system (FW-DSS) increases flood warning lead time for Sacramento County, California, and thus has the potential to save lives and reduce flood damage. The FW-DSS components measure rainfall depths and water levels, transmit these observations in real time to an emergency operations center, and store and display these data. The FW-DSS includes an electronic version of the county's flood emergency operations plan, automating flood threat recognition with the real-time data. It also automates information dissemination, notifying county emergency managers when a threat is detected. The FW-DSS includes forecasting models also, thus permitting recognition of and response to future threats.

"Road Flood Warning System," Y.K. Yung, *8th World Congress on Intelligent Transport Systems,* 2001.
Abstract at http://trid.trb.org/view/2001/C/688813
Abstract: In the remote open spaces of Queensland, Australia, flooding from tropical downpours can close roads without warning. Intelligent transportation systems (ITS) based on remote sensors are currently being developed to monitor creeks and rivers in unpopulated areas and report such disruptions to the police and the road authorities. Motorists are then warned not to venture out from regional centers as they could face several days or weeks of being held up by flooding. The warning system is designed to improve the reliability and timeliness of advice given to motorists by obtaining real-time and predictive information. The Queensland Bureau of Meteorology's flood forecast models could then be used as a basis for estimating when particular roads will flood and for how long. This information can then be disseminated to road users via existing Department of Main Roads/Royal Auto Club of Queensland Internet and dedicated toll-free number, with interactive voice response, services.

Hydrological Modeling and Inundation Mapping

"Comparative Case Study of Rainfall-Runoff Modeling Between SWMM and Fuzzy Logic Approach," Keh-Han Wang and Abdusselam Altunkaynak, *Journal of Hydrologic Engineering*, Volume 17, Issue 2, 2012: 283-291.
Abstract at http://trid.trb.org/view/2012/C/1134283
Abstract: A comprehensive hydrological model, like the storm water management model (SWMM), has been widely used for rainfall-runoff simulation. In recent years, simple and effective modern modeling techniques have also brought great attention to the prediction of runoff with rainfall input. A comparative case study between SWMM and a presently developed fuzzy logic model for the predictions of total runoff within the watershed of Cascina Scala, Pavia in Italy is presented. A data set of 23 events from

2000 to 2003 including with the total rainfall and total runoff are adopted to train fuzzy logic parameters. Other data (1990–1995) with detailed time variations of rainfall and runoff are available for the setup and calibration of SWMM for runoff modeling. Among the 1990–1995 data, 35 independent rainfall events are selected to test the prediction performance of the SWMM and fuzzy logic models by comparing the predicted total runoffs with measured data. Comparisons and performance analyses in terms of the root-mean-squared error and coefficient of efficiency are made between the SWMM and the fuzzy logic model. The predicted total runoffs from either the SWMM or the fuzzy logic model are found to agree reasonably well with the measured data. For large rainfall events, the fuzzy logic model generally outperforms the SWMM unless the modification of the impervious ratio is applied to improve the SWMM results. However, the SWMM can produce the time varying hydrograph whereas fuzzy logic is subject to limitation of the methodology and is unable to generate such an output.

"Detection of Flood-Prone Areas Using Digital Elevation Models," Salvatore Manfreda, Margherita Di Leo and Aurelia Sole, *Journal of Hydrologic Engineering*, Volume 16, Issue 10, 2011: 781-790.
http://www.unibas.it/utenti/manfreda/List%20of%20pubblications%20-%20Salvatore%20Manfreda_file/2010_Manfreda_et_al_HEENG.pdf
Abstract: The availability of new technologies for the measurement of surface elevation has addressed the lack of high-resolution elevation data, which has led to an increase in the attraction of automated procedures based on digital elevation models (DEMs) for hydrological applications, including the delineation of floodplains. In particular, the exposure to flooding may be delineated quite well by adopting a modified topographic index (TI_m) computed from a DEM. The comparison of TI_m and flood inundation maps (obtained from hydraulic simulations) shows that the portion of a basin exposed to flood inundation is generally characterized by a TI_m higher than a given threshold, T; (e.g., equal to 2.89 for DEMs with cell size of 20 m). This allows the development of a simple procedure for the identification of flood-prone areas that requires only two parameters for the calibration: the threshold T; and the exponent of TI_m. Because the modified topographic index is sensitive to the spatial resolution of the DEM, the optimal scale of representation for the performance of the method is investigated. The procedure is tested on the Arno River Basin by using the existing documentation of flood inundations produced by the Arno River Basin Authority for calibration and validation. This approach is applied on 11 subcatchments with areas ranging from 489–6,929 km^2 utilizing DEMs of different resolutions with cell sizes ranging from 20–720 m. Results show that the proposed procedure may help in the delineation of flood-prone areas, especially in basins with marked topography. The method is sensitive to the DEM resolution, but a cell size of ~100 m is sufficient for good performance for the catchments investigated here. The procedure is also tested by adopting DEMs from different sources, such as the shuttle radar topography mission (SRTM) DEM, ASTER global DEM (GDEM), and national elevation data. This experiment highlights the reliability of the SRTM DEM for the delineation of flood-prone areas. A useful relationship between model parameters and the reference scale of the DEM was also obtained, providing a strategy for the application of this method in different contexts. The use of the modified topographic index should not be considered as an alternative to standard hydrological-hydraulic simulations for flood mapping, but it may represent a useful and rapid tool for a preliminary delineation of flooding areas in un-gaged basins and in areas where expensive and time-consuming hydrological-hydraulic simulations are not affordable or economically convenient.

Future Flooding Impacts on Transportation Infrastructure and Traffic Patterns Resulting from Climate Change, Portland State University, 2011.
http://ntl.bts.gov/lib/45000/45000/45072/OTREC-RR-11-24_Final.pdf
Abstract: This study investigated potential impacts of climate change on travel disruption resulting from road closures in two urban watersheds in the Portland metropolitan area. The authors used ensemble climate change scenarios, a hydrologic model, stream channel survey, a hydraulic model, and a travel forecast model to develop an integrated impact assessment method. High-resolution climate change scenarios are based on the combinations of two emission scenarios and eight general circulation models. The Precipitation-Runoff Modeling System was calibrated and validated for the period 1988-2006, and

simulated for determining the probability of floods from 2020-2049. The authors surveyed stream cross sections at five road crossings for stream channel geometry and determined floodwater surface elevations using the HEC-RAS model. Four of the surveyed bridges and roadways were lower in elevation than the current 100-year floodwater surface elevation, leading to relatively frequent nuisance flooding. These roadway flooding events will become more frequent under some climate change scenarios in the future, but climate change impacts will depend on local geomorphic conditions. While vehicle miles traveled were not significantly affected by road closure, vehicle-hours delay demonstrated a greater impact from road closures, increasing by 10 percent in the Fanno Creek area. Results indicate that any cost analysis is extremely sensitive to the occurrence of human fatalities or injuries and fairly insensitive to delay costs. In addition, this research presents a comprehensive classification of flooding costs, identifies preventative measures, and makes short- and long-term recommendations. The authors' research demonstrated the usefulness of the integration of top-down and bottom-up approaches in climate change impact assessment, and the need for spatially explicit modeling and participatory planning in flood management and transportation planning under increasing climate uncertainty.

Estimating the Magnitude of Peak Flows for Steep Gradient Streams in New England, University of New Hampshire, Durham, 2010.
http://docs.trb.org/01331165.pdf
Abstract: Estimates of flood events are used by federal, state, regional, and local officials to safely and economically design hydraulic structures as well as for effective floodplain management. The regression relationships developed to predict flows at un-gaged sites do not always hold true for steep slope watersheds in New England. This study developed the regression relationships to predict peak flows for un-gaged, unregulated steep streams in New England with recurrence intervals of 2, 5, 10, 25, 50, 100, and 500 years. For watersheds having a main channel slope that exceeds 50 ft per mile, peak flows are well estimated by the watershed drainage area and the mean annual precipitation. No metric of watershed steepness provided a statistically significantly improvement to prediction capability. For these steep watersheds, the series of regression equations was found to perform as well or better than the individual state regression equations.

"Uncertainty in Flood Inundation Mapping: Current Issues and Future Directions," Venkatesh Merwade, Francisco Olivera, Mazdak Arabi and Scott Edleman, *Journal of Hydrologic Engineering*, Volume 13, Issue 7, 2008: 608-620.
Abstract at http://trid.trb.org/view/2008/C/864081
Abstract: This paper presents key issues associated with uncertainty in flood inundation mapping. Currently flood inundation extent is represented as a deterministic map without consideration to the inherent uncertainties associated with various uncertain variables (precipitation, stream flow, topographic representation, modeling parameters and techniques, and geospatial operations) that are used to produce it. Therefore, it is unknown how the uncertainties associated with topographic representation, flow prediction, hydraulic model, and inundation mapping techniques are transferred to the flood inundation map. In addition, the propagation of these individual uncertainties and how they affect the overall uncertainty in the final flood inundation map is not well understood. By using a sample data set for Strouds Creek, N.C., this paper highlights key uncertainties associated with flood inundation mapping. In addition, the idea of a probabilistic flood inundation map is articulated, and an integrated framework approach that will connect data, models, and uncertainty analysis techniques in producing probabilistic flood inundation maps is presented.

"A Simple Method for Estimating Flood Flow Under Bridges," G. Seckin, T. Haktannir and D.W. Knight, *Proceedings of the Institution of Civil Engineers: Water Management,* Volume 160, Issue WM4, 2007: 195-202.
Abstract at http://trid.trb.org/view.aspx?id=843111
Abstract: The software program HEC-RAS from the Hydrologic Engineering Center of the US Army Corps of Engineers is probably one of the most commonly used methods in the world for computing

water surface profiles in rivers. The energy method (one of the four bridge subroutines within HEC-RAS) computes the bridge backwater (the upstream surface increase) by applying standard step calculations five times from the end of the expansion reach up to the beginning of the contraction reach, using two different transition loss coefficients and different reach lengths. The aim of the study was to estimate the backwater in a less cumbersome and practical way, without sacrificing accuracy. A one-step energy method is suggested, based on a comprehensive set of laboratory bridge backwater data for compound channels. The proposed method gives an absolute mean error of 10% when applied to these laboratory data and an absolute mean error of 25% when applied to field data collected by the United States Geological Survey including actual flood profiles through many bridges.

I-99 Environmental Research, Task B: Hydrologic Modeling and Monitoring, University of Pittsburgh, 2007.
ftp://ftp.dot.state.pa.us/transfer/District_02-0/I-99%20Env%20Research/Task%20B.pdf
Abstract: The primary objectives of Task B are to identify a watershed runoff model that would capture the special features of watersheds that are formed by highway construction and to use the model to monitor the impacts on surface and groundwater. After a comprehensive review of existing watershed models it was decided to develop a model which would satisfy Pennsylvania Department of Transportation (PENNDOT)'s requirements. The computer model was coded, calibrated and tested on two test watersheds. Both watersheds were instrumented with monitoring wells, water level recorders and flow measuring flumes which were used in conjunction with hydrometeorological data to determine how well the model performed. Data on precipitation data was provided by Skelly and Loy, Inc. Testing was carried out for several more months to cover a broad range of conditions. The tests show that the model performed well and that it may be used by PENNDOT as hydrologic software support in assessing the impacts of future highway construction projects. Procedures in the modeling process are documented. Instrumentation requirements are identified and recommendations on instrumentation procedures are provided with a view of reducing future costs of monitoring the hydrologic variables in evaluating the environmental impacts of highway construction.

A Streamflow Statistics (StreamStats) Web Application for Ohio, U.S. Geological Survey, 2006.
http://pubs.usgs.gov/sir/2006/5312/pdf/sir2006-5312.pdf
Abstract: A StreamStats web application was developed for Ohio that implements equations for estimating a variety of streamflow statistics including the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year peak streamflows, mean annual streamflow, mean monthly streamflows, harmonic mean streamflow, and 25th-, 50th-, and 75th-percentile streamflows. StreamStats is a Web-based geographic information system application designed to facilitate the estimation of streamflow statistics at un-gaged locations on streams. StreamStats can also serve precomputed streamflow statistics determined from streamflow-gaging station data. The basic structure, use, and limitations of StreamStats are described in this report. To facilitate the level of automation required for Ohio's StreamStats application, the technique used by Koltun (2003) for computing main-channel slope was replaced with a new computationally robust technique. The new channel-slope characteristic, referred to as SL_{10-85}, differed from the National Hydrography Data based channel slope values (SL) reported by Koltun (2003) by an average of -28.3%, with the median change being -13.2%. In spite of the differences, the two slope measures are strongly correlated. The change in channel slope values necessitated revision of the full-model equations for flood-peak discharges presented by Koltun (2003). Average standard errors of prediction for the revised full-model equations presented in this report increased by a small amount over those reported by Koltun (2003), with increases ranging from 0.7 to 0.9%. Mean percentage changes in the revised regression and weighted flood-frequency estimates relative to regression and weighted estimates reported by Koltun (2003) were small, ranging from -0.72 to -0.25% and -0.22 to 0.07%, respectively.

Bankfull Characteristics of Ohio Streams and Their Relation to Peak Streamflows, U.S. Geological Survey, 2005.
Abstract at http://trid.trb.org/view/2005/M/771480
Abstract: Regional curves, simple-regression equations, and multiple-regression equations were developed to estimate bankfull width, mean bankfull depth, bankfull cross-sectional area, and bankfull discharge of rural, unregulated streams in Ohio. The methods are based on geomorphic, basin, and flood-frequency data collected at 50 study sites located on unregulated natural alluvial streams in Ohio, of which 40 sites are located near streamflow-gaging stations. The regional curves and simple-regression equations relate the bankfull characteristics to drainage area. The multiple-regression equations relate the bankfull characteristics to drainage area, main-channel slope, main-channel elevation index, median bed-material particle size, bankfull cross-sectional area, and local-channel slope. Average standard errors of prediction for bankfull width equations range from 20.6 to 24.8 percent, mean bankfull depth equations range from 18.8 to 20.6 percent, bankfull cross-sectional area equations range from 25.4 to 30.6 percent, and bankfull discharge equations range from 27.0 to 78.7 percent. Field surveys were conducted at each of the 50 study sites to collect the geomorphic data. Bankfull indicators were identified and evaluated, cross-section and longitudinal profiles were surveyed, and bed- and bank-material were sampled. Field data were analyzed to determine various geomorphic characteristics, such as bankfull width, mean bankfull depth, bankfull cross-sectional area, bankfull discharge, streambed slope, and bed- and bank-particle size distribution. Various geomorphic characteristics were analyzed using a combination of graphical and statistical techniques. Simple-regression equations were developed to estimate 2-, 5-, 10-, 25-, 50-, and 100-year flood-peak discharges of rural, unregulated streams in Ohio from bankfull cross-sectional area. The average standard errors of prediction are 31.6, 32.6, 35.9, 41.5, 46.2, and 51.2 percent, respectively. The logarithms of the annual peak discharges for 40 gaged study sites were fit by a Pearson Type III frequency distribution to develop a flood-peak-frequency relation for each site. The peak-frequency data were related to geomorphic, basin, and climatic variables by multiple-regression analysis. The study and methods developed are intended to improve the understanding of the relations between geomorphic, basin, and flood characteristics of streams in Ohio and to aid in the design of hydraulic structures, such as culverts and bridges, where stability of the stream and structure is an important element of the design criteria.

Bridge Scour

Submerged Flow Bridge Scour Under Clear Water Conditions, Genex Systems, LLC, FHWA Office of Infrastructure Research and Development, 2012.
http://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/12034/12034.pdf
Abstract: Prediction of pressure flow (vertical contraction) scour underneath a partially or fully submerged bridge superstructure in an extreme flood event is crucial for bridge safety. An experimentally and numerically calibrated formulation is developed for the maximum clear water scour depth in non-cohesive bed materials under different approach flow and superstructure inundation conditions. The theoretical foundation of the scour model is the conservation of mass for water combined with the quantification of the flow separation zone under the bridge deck superstructure. In addition to physical experimental data, particle image velocimetry measurements and computational fluid dynamics simulations are used to validate assumptions used in the derivation of the scour model and to calibrate parameters describing the separation zone thickness. With the calibrated model for the separation zone thickness, the effective flow depth (contracted flow depth) in the bridge opening can be obtained. The maximum scour depth is calculated by identifying the total bridge opening that creates conditions such that the average velocity in the opening, including the scour depth, is equal to the critical velocity of the bed material. Data from previous studies by Arneson and Abt and Umbrell et al. are combined with new data collected as part of this study to develop and test the proposed formulation.

"Hydrologic Uncertainty in Prediction of Bridge Scour," *Transportation Research Record: Journal of the Transportation Research Board*, Issue 2262, 2011, 207-213.
Abstract at http://trid.trb.org/view/2011/C/1092157
From the abstract: NCHRP Project 24-34 was initiated in April 2010 to develop a methodology that was based on risk and reliability and that could be used in calculating bridge pier, abutment, and contraction scour at waterway crossings so that scour estimates could be linked to a probability. The developed probabilistic procedures will be consistent with LRFD approaches used by structural and geotechnical engineers. This paper discusses sources of uncertainty in hydrologic estimates as those sources relate to bridge scour computations and summarizes a conceptual approach to the problem.

Evaluation of Bridge-Scour Research: Abutment and Contraction Scour Processes and Prediction, *NCHRP Web-Only Document 181*, 2011.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_W181.pdf
Abstract: This report reviews the present state of knowledge regarding bridge-abutment scour and the veracity of the leading methods currently used for estimating design scour depth. It focuses on research information obtained since 1990, which is to be considered in updating the scour estimation methods that are recommended by AASHTO, and used generally by engineering practitioners. Though considerable further progress has been made since 1990, the findings indicate that several important aspects of abutment scour processes remain inadequately understood and therefore, are not included in current methods for scour depth estimation. The state-of-the-art for abutment scour estimation is considerably less advanced than for pier scour. Moreover, there is a need for design practice to consider how abutment design should best take scour into account, as scour typically results in the geotechnical failure of an abutment's earthfill embankment, possibly before a maximum potential scour depth is attained hydraulically. Abutment scour herein is taken to be scour at the bridge-opening end of an abutment, and directly attributable to the flow field developed by flow passing around an abutment. This definition excludes other flow and channel-erosion processes such as lateral geomorphic shifting of the bridge approach channel but includes contraction and abutment scour as part of the same physical processes that should be treated together rather than separately in their estimation. The review shows that, since 1990, advances have been made in understanding abutment-scour processes, and in (1) estimating scour depth at abutments with erodible compacted earthfill embankments, and at those with solid-body (caisson-like) foundations; (2) identifying the occurrence of at least three distinct abutment scour conditions depending on abutment location and construction; and (3) utilizing the capacity of numerical modeling to reveal the flow field at abutments in ways that laboratory work heretofore has been unable to provide. The review identifies and evaluates leading scour formulas and suggests a framework for developing a unified abutment scour formula that depends on satisfying several targeted future research needs.

"Comparison Study on Computer Simulations for Bridge Scour Estimation," Xinbao Yu, Junliang Tao and Xiong (Bill) Yu, *The GeoRisk 2011 Conference: Geotechnical Risk Assessment and Management* (GSP 224), 2011.
Abstract at http://trid.trb.org/view/2011/C/1112221
This paper compares the use of 1D and 2D hydraulic models for bridge scour prediction. Two representative computational software developed by Federal Highway Administration (FHWA), HEC-RAS and Flo2dh, are used as the benchmark comparison bases. The procedures for model construction and scour estimation are illustrated by developing simulation examples. The comparison shows that 1D model using HEC-RAS, while is easy to construction, does not account for the effects of flow disturbance due to hydraulic obstructions. These include the spatial variation of the alignment angle, which significantly affects the depth of scour prediction. Higher dimensional mode such as Flo2dh captures the effects of flow field distribution. It is however difficult to use and requires deliberations to run proper simulations. Further development of computational simulation and visualization technologies is necessary and will help place computer aided bridge scour simulations into the hands of practitioners.

"Analysis of Bridge Performance Under the Combined Effect of Earthquake and Flood-Induced Scour," Swagata Banerjee and Gautham G. Prasad, *The ICVRAM 2011 and ISUMA 2011 Conferences: Vulnerability, Uncertainty, and Risk: Analysis, Modeling, and Management,* 2011.
Abstract at http://trid.trb.org/view/2011/C/1109624
From the abstract: The study evaluates the combined effect of earthquake and flood-induced scour on the performance of bridges located in regions having moderate to high seismic and flood hazards. For the analysis California is chosen as the bridge site where the probabilities of having these two natural hazards are reasonably high. Two example reinforced concrete (RC) bridges are considered. A 100-year flood event with discharge rate of 158.6 m3/s, velocity of 0.8 m/s and upstream depth of 11.9 m is chosen to represent regional flood hazard. Finite element analyses are preformed to evaluate performance of these bridges under regional seismic events in presence of scour resulted from the scenario flood event. Result shows that in presence of flood-induced scour bridges become more vulnerable under seismic excitations.

Pier and Contraction Scour Prediction in Cohesive Soils at Selected Bridges in Illinois, U.S. Geological Survey, Illinois Center for Transportation, 2010.
http://ict.illinois.edu/publications/report%20files/FHWA-ICT-10-074.pdf
Abstract: This report presents the results of testing the Scour Rate in Cohesive Soils-Erosion Function Apparatus (SRICOS-EFA) method for estimating scour depth of cohesive soils at 15 bridges in Illinois. The SRICOS-EFA method for complex pier and contraction scour in cohesive soils has two primary components. The first component includes the calculation of the maximum contraction and pier scour (Zmax). The second component is an integrated approach that considers a time factor, soil properties, and continued interaction between the contraction and pier scour (SRICOS runs). The SRICOS-EFA results were compared to scour prediction results for non-cohesive soils based on Hydraulic Engineering Circular No. 18 (HEC-18). On average, the HEC-18 method predicted higher scour depths than the SRICOS-EFA method. A reduction factor was determined for each HEC-18 result to make it match the maximum of three types of SRICOS run results. The unconfined compressive strength (Qu) for the soil was then matched with the reduction factor and the results were ranked in order of increasing Qu. Reduction factors were then grouped by Qu and applied to each bridge site and soil. These results, and comparison with the SRICOS Zmax calculation, show that less than half of the reduction-factor method values were the lowest estimate of scour; whereas, the Zmax method values were the lowest estimate for over half. A tiered approach to predicting pier and contraction scour was developed. There are four levels to this approach numbered in order of complexity, with the fourth level being a full SRICOS-EFA analysis. Levels 1 and 2 involve the reduction factors and Zmax calculation, and can be completed without EFA data. Level 3 requires some surrogate EFA data. Levels 3 and 4 require streamflow for input into SRICOS. Estimation techniques for both EFA surrogate data and streamflow data were developed.

Simplified Method for Estimating Scour at Bridges, Texas Transportation Institute, 2009.
http://tti.tamu.edu/documents/0-5505-1.pdf
Abstract: This research proposes a new method to assess a bridge for scour. It is made up of three levels of assessments. The first level is termed Bridge Scour Assessment 1 (BSA 1). The second and third levels are termed BSA 2 and BSA 3, respectively. BSA 1 overcomes the qualitative nature of current initial evaluation procedures by extrapolating present scour measurements to obtain the scour depth corresponding to a specified future flood event. It utilizes computer-generated extrapolation charts based on a large combination of hypothetical bridges, which relate the future scour depth/maximum observed scour depth ratio to the future flood velocity/maximum observed flood velocity ratio. BSA 2 has to be carried out if BSA 1 does not conclude with a specific plan of action for the bridge. BSA 2 determines the maximum scour depth. Though conservative, BSA 2 was introduced due to its simplicity. BSA 3 has to be carried out if BSA 2 does not conclude with a specific plan of action. BSA 3 involves the calculation of time-dependent scour depth rather than simply using the maximum scour depth. BSA 3 is valuable in the case of highly erosion-resistant materials that do not achieve the maximum scour depth within the lifetime of a bridge. Both BSA 2 and BSA 3 utilize erosion classification charts that replace site-specific erosion testing for preliminary evaluations. The scour vulnerability depends on the comparison of the

predicted scour depth and the allowable scour depth of the foundation. Hydrologic and hydraulic computer programs were developed to obtain the flow parameters. These programs generate maps of the maximum previous flood recurrence interval experienced by a specified bridge in Texas and converts flow into flow velocities. The 11 case histories used as validation showed good agreement between predicted and measured values. BSA 1 was then applied to 16 bridges. In this process, 6 out of 10 scour-critical bridges were found to be stable in terms of scour. The proposed bridge scour assessment procedure allows for the economical and relatively simple evaluation of scour-critical bridges. It also overcomes the over-conservatism in current methods.

"Vulnerability of Highway Bridges for Scour Problems," Dario Espinoza, Consuelo Gomez-Soberon and Juan Javier Carrillo, *IABSE Symposium Bangkok 2009. Sustainable Infrastructure. Environment Friendly, Safe and Resource Efficient,* 2009.
Abstract at http://trid.trb.org/view/2009/C/982029
Abstract: This paper presents a study of the behavior of common types of highway bridges in response to scour of their bearing elements, when exposed to design floods. For this purpose, the authors considered the inherent characteristics of the substructure and assessed potential failure conditions in relation to easily measurable parameters, which associate flood characteristics with a certain level of erosion of the stream bed. To conduct this investigation, the authors analyzed some of the expressions proposed in the literature to determine local scour at the pier base, in order to define the most influential parameters, which will be used jointly with the forces produced by the stream pressure of the water to reproduce the process of collapse or partial failure of piers. Simplified models were constructed, where the authors obtained the response for rectangular piers considering the effect of scour.

Comparison of Observed and Predicted Abutment Scour at Selected Bridges in Maine, U.S. Geological Survey, 2008.
http://pubs.usgs.gov/sir/2008/5099/SIR2008-5099.pdf
Abstract: Maximum abutment-scour depths predicted with five different methods were compared to maximum abutment-scour depths observed at 100 abutments at 50 bridge sites in Maine with a median bridge age of 66 years. Prediction methods included the Froehlich/Hire method, the Sturm method, and the Maryland method published in Federal Highway Administration Hydraulic Engineering Circular 18 (HEC-18); the Melville method; and envelope curves. No correlation was found between scour calculated using any of the prediction methods and observed scour. Abutment scour observed in the field ranged from 0 to 6.8 feet, with an average observed scour of less than 1.0 foot. Fifteen of the 50 bridge sites had no observable scour. Equations frequently overpredicted scour by an order of magnitude and in some cases by two orders of magnitude. The equations also underpredicted scour 4 to 14 percent of the time.

KU-HR Bridge Scour Program User's Manual First Edition, University of Kansas, Lawrence, 2007.
Abstract at http://trid.trb.org/view/2007/M/815192
Abstract: This study was performed to develop a computer program for analyzing bridge scour. The visual basic program used the methods presented in HEC-18 (Evaluating Scour at Bridges, Fourth Edition, Publication No. FHWA NHI 01-001, May 2001) and the hydraulic modeling results of HEC-RAS Version 3.1.2 (River Analysis System, US Army Corps of Engineers Hydrologic Center, April 2004). The program allows users to compute contraction, abutment and pier scour at bridges using hydraulic and geometry parameters from HEC-RAS output. The complex pier scour calculations presented in HEC-18 can be used with this program. This option is not available in the scour module of HEC-RAS 3.1.2. The report serves as a user's manual for the computer program. Several bridge scour samples are presented.