Overview of Failure Modes

Surge-Induced Loading

A common mode of severe bridge damage during Hurricane Katrina was shifting or unseating of spans, attributed to surge-induced loading. The hydrostatic and hydrodynamic loading imposed on bridge superstructures during hurricane induced surge and wave action includes buoyancy, drag and inertial forces, forces associated with added mass, and vertical slamming forces (Sheppard 2008). These translate into vertical uplift and horizontal loads which are a function of such parameters as surge elevation, wave height, relative deck elevation, and deck geometry. In most cases, the forces resulted in uplift of the deck (note: bearings often provided no positive connection between the superstructure and substructure), transverse and longitudinal displacement. Table 1 summarizes the ten bridges exhibiting residual span shifting or unseating, estimating the surge elevation via GIS interpolation from the FEMA surge contours, as well as number of shifted or unseated spans. Bearing damage often accompanied span unseating or deck displacement. Damage to parapets on the bridge decks was also a consequence of the storm surge coupled with wave and wind loading. Failure modes associated with surge-induced loading occurred in both traditional fixed-type bridges having continuous or simply supported spans, as well as in movable bridges having a swing, lift, or bascule. The traditional non-movable spans in movable bridges also experienced the typical modes of failure associated with storm surge-induced loads. In either bridge type, the damaged sections tended to be low-lying concrete spans over water crossings.

The US-90 Bay St. Louis Bridge (Figure 1) suffered severe damage due to a combination of surge and wind/wave-induced loading sufficient to unseat a majority of the spans. This bridge is a four-lane, 3.06 km (1.9 mile) long, concrete girder bridge with parallel decks simply supported by high-type steel bearings. The spans are low-lying with water navigation permitted through the use of a movable bascule. The bearings were severely damaged and nearly all connections between the deck and bent caps were lost resulting in free movement of the decks. All of the spans on the western half of the bridge completely unseated and were submerged in the Bay. On the eastern half, the north decks (westbound) were submerged and the south decks (eastbound) had shifted north and were partially submerged. This bridge required complete replacement.

Table 1. Summary of bridges having residual shifting or unseating of spans.

Bridge	Facility Carried	State	Surge (ft)	Year Built	Total No. Spans†	Spans Shifted	Spans Unseated
Lake Pontchartrain	I-10	LA	13.0	1963	872	473	64
US-90 Bay St. Louis	US-90	MS	18.0	1953	243	1	242
Biloxi-Ocean Springs	US-90	MS	21.9	1961	153	2	129
Pontchartrain Causeway	LA Causeway	LA	9.0	1956	3002	0	17
Caminada Bay	LA-1	LA	8.0	1961	110	13	0
Popps Ferry	Popps Ferry Rd.	MS	19.0	1976	69	13	0
Henderson Point	US-90	MS	23.0	2000	36	6	1
I-10 Pascagoula River	I-10	MS	15.2	1976	660	6	1
Mobile Delta Causeway	I-10 / US-90	AL	10*	1978	28	5	0
David V. LaRosa	W. Wittman Rd.	MS	23.0	1970	20	3	0

*surge estimate if outside FEMA contour zone

Figure 2. East end of US-90 Bay St. Louis Bridge, showing collapsed spans associated with surge-induced loading.

Figure 3. Pile damage on the Biloxi Back Bay Bridge due to barge impact.

Figure 4. Eroded approach slabs on Pontchartrain Causeway (Courtesy of LADOT)

Figure 5. Wind inundation leading to damage electrical-mechanical equipment of movable bridges, such as Yscloskey.

Impact

Impact damage from barges, tug boats, oil rigs and other types of debris also occurred along the waterways in the Gulf Coast. The impact resulted in span misalignment and fascia girder, fender, and column damage. An example of impact related damaged occurred at the Biloxi Back Bay Bridge in Mississippi. The Biloxi Back Bay Bridge carries four total lanes of I-110 over the Biloxi Back Bay, and served as the only primary route to Biloxi, due to the closure and damage to US-90 and the Biloxi-Ocean Springs Bridge from Katrina. The bridge was damaged due to barge impact, shearing the easternmost pile of the bent directly south of the bascule, which supports a span of pre-stressed girders as well as the bascule anchor span. Other minor damage was sustained, such as guardrail, sidewalk, and drawbridge gate arm damage, as well as differential settlement of the north approach and abutment.

Scour

Sour related damage also occurred at several bridge sites, noting that all but one of the bridges damaged during Hurricane Katrina were water crossing structures. Readily visible scour damage included scour and erosion of the abutment, slope failure, and undermining of the approach. As an example, the abutments for the southbound roadway approach of the 24-mile long Pontchartrain Causeway were eroded as shown in Figure 4, requiring temporary repair of abutments and erosion control measures. Following underwater investigations, further scour related damaged was revealed at intermediate piles for some structures, such as the Chef Menteur Bridge in Orleans Parish, LA for with removal of five north approach spans and supporting bents was required due to the effects of slope failure attributed to scour.

Wind and Water Inundation
There is a considerable percentage of movable bridges along the Gulf Coast and in the Katrina exposed region. Several of these movable bridges suffered damage to submerged electrical and mechanical equipment. Debris accumulation also affected the functioning of the mechanical gears along with some cases of bent pivots, fractured mechanical parts, or damaged traffic control gates. Non-engineered operator houses also suffered damage due to high winds. Figure 5 shows the Yscloskey Bridge on Route LA 46 in St. Bernard Parish, which sustained damage due to water inundation. The high waters at the location of the bridge submerged the electrical and control systems in the operator house and completely damaged the system. In addition, the surge itself elevated the movable deck approximately 2.4 m (8ft) and caused it to be skewed and stuck in the lifted position as shown in the Figure.

CASE STUDY COMPARATIVE PERFORMANCE

I-10 Lake Pontchartrain Bridge vs. US-11 at Lake Pontchartrain

Bridges that were relatively close and assumed to sustain similar levels of storm surge loading performed very different in some cases. The distinctions between the bridges in terms of their design details help to provide an explanation for the differences performance. One example for comparison is the I-10 Twin Span Bridge over Lake Pontchartrain in New Orleans, LA and the US-11 at Lake Pontchartrain, each with surges of 4.02 m (13.2 ft) and similar elevations above the lake (Figure 6). The US-11 bridge is a 7.6 km (4.7 mile) long single-span bridge built in 1938, constructed such that a majority of the deck segments are haunched concrete girders which are continuous over multi-pile bents. The I-10 bridge consists of two separate 8.7 km (5.4 mile) long spans of like construction (twin spans) built in 1963. The majority of the bridge has simply supported approach spans constructed of pre-cast prestressed concrete segments, which

Figure 6. US-11 and I-10 Bridges

Figure 7. I-10 Lake Pontchartrain bridge damage

Figure 8. Construction details of US-11 bridge with continuity, air vents, and positive connection.

are supported on three-pile bents using steel and bronze bearings.

The I-10 Lake Pontchartrain Bridge suffered the most damage (Figure 7) of any one bridge in Louisiana, with a total of 473 spans shifted and an additional 64 spans completely unseating and collapsing in the water. Significant damage to barrier railings and bent beams also resulted. Only minor damage was observed on the US-11 bridge, including erosion at the abutment and draw bridge damage. However, unique features of the construction relative to I-10 are attributed to potentially reducing the damage. For example, the US-11 bridge had continuity across the spans, while the I-10 bridge was simply supported, and positive connectivity between the deck and bent beams was provided for US-11 as seen in Figure 8. This positive connection refers to the deck-beam connection which provides resistance to uplift of the deck. Vent holes were also provided in the diaphragms which help mitigate buoyant forces are also believed to be contributing factor to the relatively small damage.

US-90 Biloxi-Ocean Springs Bridge vs. CSXT Biloxi Bay Railroad Bridge

Study of the US-90 Biloxi-Ocean Springs Bridge in Mississippi reveals that it performed poorly relative to an adjacent railway bridge (CSXT Biloxi Bay Railroad Bridge). The highway bridge which carries four lanes of US-90 between the two cities over the Biloxi Bay suffered complete damage during Hurricane Katrina. While this bridge had a movable section, the damaged spans included the lower elevation multi-span pre-stressed concrete girder sections near the ends of the bridge. Numerous spans were shifted and unseated due to the storm surge which rose to levels in excess of 6.58 m (21.8 ft) at the bridge site, as well as washout of abutment backfill and settlement of the approach slabs. The damaged bearings were steel sliding bearings with bronze cores which provided no apparent positive connection between the substructure and superstructure. The damage required complete replacement of the bridge.

The adjacent CSXT Biloxi Bay Railroad Bridge suffered limited damage, despite the large surge at that location. Though the rails and ballast were cast into the Bay during the storm, the superstructure remained intact, unlike the highway bridge. The Biloxi Bay Railroad Bridge is composed of four simply supported precast I-girders with a cast-in-place deck, and supported on pile caps with battered piles. While other characteristics inherent to designing railway bridges relative to highway bridges may contribute to difference in the realized design and performance under surge-induced loading (such as weight of the deck), specific features of the CSXT Biloxi Bay Railroad Bridge design details likely resulted it its superior performance. For example 38.1

(a) (b)

Figure 9. (a) Damage to US-90 Biloxi-Ocean Springs highway bridge compared to (b) the superior performance of the Biloxi Bay Railroad Bridge with transverse shear keys.

cm (15 inch) high shear keys restrain the superstructure from lateral movement and 3.2 cm (1.25 inch) diameter through-bolts provide a positive connection and lateral stability to the girders. These types of lateral restraint and connection details are not present in the US-90 Biloxi-Ocean Springs Highway bridge which had considerable longitudinal and transverse deck displacement.

LESSONS LEARNED

Lessons learned from the case studies, as well as the overall damage assessment, reveal potential improvements in design details for bridges in coastal regions as well as potential retrofit measures for existing bridges which may be vulnerable to damage. Examples include designing to higher elevations for future bridges, providing positive connectivity in bearing details, safeguarding against corrosion of connection elements, continuity across spans, and air escape mechanisms such as diaphragm vents. Other potential retrofit, or rehabilitation measures, for existing bridges draw upon these conclusions as well as the experience obtained in past decades from the earthquake engineering community. Such retrofit measures which may help to reduce coastal bridge vulnerability during hurricanes (primarily targeting storm surge) include proving transverse shear keys either in the form of keeper plates or concrete shear blocks, or vertical and translational restraints such as restrainer cables. The caution of employing such restraints is the potential to transfer additional loading to adjacent members of the structure that must be capacity checked. These types of measures are being considered by Gulf Coast DOTs, and design of new replacement structures has considered the potential hydraulic and hydrodynamic loading on low elevation spans as well as elevation of main spans. Moreover ongoing work has been spurred to develop new design codes for coastal bridges. Employing simple elements or design details can have a dramatic effect on the bridge performance, as illustrated in this paper. The relative viability of these different measures, their effect on the structural reliability under future events, and cost-benefit comparisons of the strategies should be addressed in future studies.

ANALYSIS OF EMPIRICAL DAMAGE-HAZARD DATA

Further analysis of the damaged bridges is conducted to evaluate the characteristics of the bridges or hazard at the site, which contribute most to observed level of bridge damage. This is the first step in identifying potential intensity measures for conditional probability models of coastal bridge damage. Surge estimates from Hurricane Katrina (FEMA 2006) are used in the subsequent analysis, with surge elevations for the bridges in the surge zone interpolated via GIS from the surge contours. An additional data set employed during this study is the output of a Katrina hindcast developed by researchers at The University of Notre Dame (Westerlink, J. et al., 2007), which provided additional hazard intensity estimates, including estimates of water velocity and wind speed (ten minute average speed). The damaged bridges are ranked one through four, corresponding to slight through complete damage, and compared to each of the hazard intensities evaluated in this study. Forty of the damaged bridges had sufficient hazard-damage data for use in the analysis. The four intensity measures include peak storm surge elevation, relative surge elevation (surge-deck elevation), water speed, and ten minute averaged wind speed.

The hazard intensity measures and characteristics of the damaged bridges are analyzed through multivariate logistic regression. This analysis is conducted to identify the characteristics that contribute most to observed level of bridge damage, and is commonly performed for discrete outcome situations. In this case, the discrete dependent variable is the damage state classification, deemed slight, moderate, extensive, or complete. The independent variables considered include peak surge elevation, relative surge, water speed, averaged wind speed, number of spans, and year built. These additional characteristics of the damaged bridges are shown in Figure 7, including a categorized breakdown of the number of spans and year built, though treated as continuous variables in the correlation analysis. The software package JMP is used to conduct the logistic regression. The analysis reveals that the most important parameters are the surge elevation, number of spans, and relative surge, with p-values of <0.001, <0.001, and 0.019 respectively. Identification of the number of spans as an important parameter based on the logistic regression may be attributed to the fact the longer bridges with more spans spanning open waterways may suffer a greater exposure to the hazard and have a potential for more damage in at least part of the bridge. This also indicates that further binning of the bridges by number of span may be prudent in the future should sufficient empirical or simulated data become available. The year built is a characteristic of interest in part because of its relation to evolving design codes and construction practices. In addition, the year built can be related to degradation or duration of environmental exposure, such as that which leads to corrosion of reinforcement steel or bearings, thereby degrading the structural resistance to extreme loading. However, the assessment reveals that the year built is not strongly correlated to damage level.

CONCLUSIONS

Devastating events such as Hurricane Katrina can be used as opportunities to learn about the performance of our infrastructure and to prevent failures and undo indirect consequences in the future. The widespread damage across the Gulf Coast resulted in damage to 44 highway bridges which is summarized and presented in this paper, as well as select railway bridge structures. The impact of Katrina's winds, storm surge, and waves yielded bridge failure due to surge induced loading, impact from loose equipment and other debris, electrical or mechanical failure from wind and water inundation, and undermining of soil-structure support mechanisms from scour. A predominant mode of failure that often resulted in the most catastrophic damage was that attributed to combined surge and wave action, where numerous bridge spans were shifted, unseated and collapsed, and connection elements (i.e. bearings, bent beams) damaged.

Select case studies revealed the dissimilar performance between bridges that may be considered to be spatially correlated hazard intensities due to their close proximity, yet have key construction details which differ. Examples include the superior performance of the US-11 Bridge at Lake Pontchartrain over the I-10 Lake Pontchartrain Bridge in Louisiana, and the CSXT Biloxi Bay Railroad Bridge over the US-90 Biloxi-Ocean Springs Highway Bridge. Lessons learned from these types of case studies, as well as the overall damage assessment, reveal potential improvements in design details for bridges in coastal regions as well as potential retrofit measures for existing bridges which may be vulnerable to damage. Examples include designing to higher elevations for future bridges, providing positive connectivity in bearing details, safeguarding against corrosion of connection elements, continuity across spans, and air escape mechanisms such as diaphragm vents.

Not including damage to movable spans, it is estimated that there were a total of 522 spans shifted and 454 spans unseated during Hurricane Katrina. Assessment of the damaged bridges reveals that most of the bridges were multiple span bridges with simply supported concrete superstructures. These bridges tended to be low lying bridges over waterways. Of the bridges analyzed, construction years ranged from 1930 to 2004. A multivariate logistic regression was conducted to evaluate which hazard intensities and bridge characteristics were important parameters in predicting increasing level of bridge damage (slight, moderate, extensive, or complete). While the relationship between surge elevation, relative surge, water speed, and mean wind speed, were all considered, only the surge related hazard parameters showed a strong correlation to damage level as well as number of spans. Future studies will address the development of fragility models for bridge damage under combined surge and wave loading to assess risks to existing bridge inventory, as well as evaluate the effectiveness of different new proposed retrofits and design details.

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Performance of Water and Gas Pipes in Past Earthquakes and Hurricanes

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Abstract:
This paper will summarize the performance of water and gas piping systems during the past 6 earthquakes and in 4 countries: US (1906 San Francisco earthquake; 1989 Loma Prieta earthquake; 1994 Northridge earthquake), Japan (1995 Great Hanshin-Awaji earthquake (Kobe), Thailand (2005 Tsunami) and Columbia. Also, the paper will report about the performance of pipes during the hurricane Andrew hurricane Katrina. Last, the paper will provide multiple references to assist design engineers and owners in selecting pipe materials based on past performance of these systems during earthquakes and hurricanes.

Introduction:
Due to the lack of a national seismic code for piping systems, the piping systems have not been designed and detailed properly to resist such hazards. Also, most design consulting firms are not requested by the clients (owners) to address these hazards perhaps due to lack of awareness about the effect of these hazards on the pipe, cost issues, performance, damage, and priorities. Unlike standards for buildings and highways (published by ASCE, AASHTO, ACI, AISC, AISI) that require designers and owners to design pipes for earthquake loads and movements, all pipe standards that are published by AWWA do not include specific requirements for the design, detailing and/or construction of pipes in seismic and hurricane regions. However, AWWA and ASCE have published multiple reports on pipes and earthquakes and many pipe designers may not be aware of these resources. As such, this paper will highlight the relevant conclusions of these publications and will refer readers to the actual publications for full review and implementation in their local design specifications to minimize the effects of these hazards on the local and national hidden pipeline assets.

Earthquake History in the US:
In the US, every state has experienced some level of earthquakes as documented on the US Geological Services (USGS) website. The website www.earthquake.usgs.gov/regional/states/state_largest.php lists the largest recorded earthquake (by magnitude) with epicenter in each state; in some states, the highest intensity occurred from earthquakes in nearby states. A summary of this data is shown in

Table 1. Table 1 also shows the earthquake intensity for the states that have the lowest and the highest magnitude earthquake. Seven states did not have a 'magnitude' reported and instead, the note below Table 1, lists the Intensity in these states.

Table 1: Magnitude of Largest Recorded Earthquakes in each State in the US (Intensity shown in brackets)

MD 2.6 (V)	RI 3.5	LA 4.2	VT 4.2	GA 4.5	SD 4.5	WV 4.5	MI 4.6	MN 4.6	MS 4.6	TN 5.0
AL 5.1	IN 5.1	KS 5.1	ME 5.1	NE 5.1	KY 5.2	NC 5.2	PA 5.2	IL 5.4	NJ 5.3	OH 5.4
OK 5.5	NH 5.5	ND 5.5	AZ 5.6	NY 5.8	TX 5.8	VA 5.9	CO 6.2	WY 6.5	UT 6.6	OR 6.8
WA 6.8	ID 6.9	NV 7.2	MT 7.3	SC 7.3	CA 7.9	HI 7.9	MO 8.0	AR 8.2	AK 9.2 (X)	

Note: Some states had only the intensity reported: MA (VIII), NM (VII), CT (VII), DE (VII), FL (VI), IA (V) and WI (V).

I-EARHQUAKES HISTORY AND EFFECTS ON PIPES

In the following section, the paper will review the effects of 6 earthquakes on the performance of water and gas pipes in 4 countries.

1.San Francisco Earthquake (ASCE-NPFA)
On April 18, 1906, the city experienced a major earthquake with magnitude of 8.3. All the city downtown was destroyed, along with 300 water mains and over 23,000 water services (Van Dyke). Fires burned for 3 days due to lack of water to control them. 28,000 buildings were destroyed and 80% of the damage was due to the fire rather than the earthquake. This was the largest earthquake loss in US history which resulted in the death of 3,000 people and the loss of $524 million using 1906 dollars.

2a.Northridge Earthquake and Water Pipes (AWWA, ASCE 1999)
On January 17, 1994, the city experienced a major earthquake with magnitude of 6.8 and the Peak Ground Acceleration (PGA) exceeded 1g at the epicenter area. The city of Northridge is located about 20 miles from Los Angeles. The quake resulted in damage to the 3 transmission pipes that deliver water from Northern California. Also, over 1,500 water system pipeline failures occurred in the San Fernando and Santa Clarita valleys. It was noted that if this earthquake had occurred in other locations in North America, the water system would have experienced more damaged than was seen in Northridge. The facilities that were exposed to Northridge are owned and operated by utilities that were