VALIDATION OF TSUNAMI DESIGN LOADS FOR BRIDGES USING A LARGE-SCALE EXPERIMENT – A PROPOSAL

Ian G. Buckle[1]

Abstract

In the March 2011 Tohoku earthquake, at least 150 highway bridges were affected by the tsunami, with several superstructures being swept away due to excessive uplift and hydrodynamic loads. Despite this severity of damage, few design specifications have requirements for tsunami loads. This is mainly because tsunami design loads are not well understood and proposed design guidelines have not been validated.

In this paper a large-scale experiment is proposed to validate recommended guidelines. Such an experiment could be undertaken downstream of an irrigation dam using controlled releases of water to inundate the bridge. Results from these experiments would overcome many of the shortcomings in small-scale wave basin experiments, and give greater confidence in the validation process.

Introduction

In both the February 2010 Maule earthquake in Chile and the March 2011 Tohoku earthquake in Japan, bridges were damaged due to tsunami effects (Buckle et.al. 2012, Kawashima and Buckle 2012). The number of bridges in Chile was probably less than 20 but in Japan at least 150 highway and numerous railway bridges were affected by the tsunami, at least to the height of their superstructures. The most severe type of damage was loss or offset of the superstructure due to a combination of uplift (buoyancy) and hydrodynamic loads (drag) (See Figure 1). In some cases this damage was accompanied by loss of the substructure due to undermining of the foundations and/or structural damage to the piers (See Figure 2).

FIGURE 1. GIRDERS FROM KOIZUMI BRIDGE 400 M UPSTREAM IN TSUYA RIVER CHANNEL, TOHOKU EARTHQUAKE, 2011 (PHOTO: E. MONZON)

[1] Professor, Dept. of Civil and Environmental Engineering, University of Nevada, Reno

Loss of approach fills was also a common occurrence. Emergency response and disaster recovery was seriously impaired by the loss of these structures and closure of critical highway and railroad routes.

FIGURE 2. DAMAGED PIERS OF THE JR RAIL VIADUCT CROSSING THE TSUYA RIVER, TOHOKU EARTHQUAKE, 2011 (PHOTO: S. DASHTI)

Neither the AASHTO LRFD Bridge Design Specifications nor the AASHTO Guide Specifications for Bridge Seismic Design require coastal bridges be assessed for tsunami exposure and are silent on minimum requirements to resist tsunami loads. The JRA Specifications in Japan and the Caltrans Seismic Design Criteria are also silent on this matter. As a consequence western states from California to Washington, Hawaii and Alaska have begun to review bridge vulnerability and at least two State DOTs (Caltrans and the Oregon Department of Transportation (ODOT)) have active research programs to determine likely wave heights along their coastlines and appropriate design loads to resist tsunami action (Johnson 2011). Further, the Federal Highway Administration has begun a pilot study to identify bridge damage scenarios due to tsunami effects and develop recommendations for counter measures to improve bridge performance.

Several researchers have shown that analyses of bridge spans damaged in Japan based on simple models for uplift and drag, do not reproduce the observed behavior and either over-predict damage or under-predict, sometimes by a wide margin (Kawashima and Buckle 2012). It is clear these models do not capture the complex interactions that are in play when a wave inundates an elevated bridge span at speed.

More complex analyses have been undertaken by other researchers using both 2D and 3D finite element modeling and computational mechanics software for solving fluid-structure interaction problems such as LS-DYNA. In one case, results have been developed for a bridge on the Oregon coastline (Nimmala et.al. 2006). However these results and accompanying design guidelines remain to be validated. Accordingly, a pool-funded study has recently been proposed by ODOT to undertake experimental confirmation of these results, and it is proposed to use the wave basin at Oregon State University for this purpose. Experimental measurements of forces and deformations would be obtained by subjecting scale model bridge spans to appropriately scaled tsunami waves, and these results compared against numerical predictions.

Rationale for a Large-Scale Tsunami Experiment

As in all hydraulic models the effect of scale is an important consideration. If the scale is too small, the errors involved can render validation studies of doubtful value. One major source of error is the use of the same fluid in both the model and prototype, i.e. water. This means that viscosity and surface tension, for example, are not scaled correctly, among other physical properties. Nevertheless water is the only practical fluid for use in many hydraulic models and it is the responsibility (art) of the modeler to reduce these effects as much as possible.

Another consequence of small-scale models is the relatively coarse simulation and measurement of the physical processes, which in this case includes the forces and deformations imposed on the bridge deck when overtopped by the tsunami wave. At best, gross (resultant) forces (uplift and drag) can be measured but their spatial distribution remains unknown. The problem is compounded if failure of the structure (e.g., loss of the superstructure) is to be captured. Modeling nonlinear structural response can only be credibly done at large-scale.

It follows that working at as-large-a-scale as possible is clearly desirable, but significantly larger models are not easily accommodated in the laboratory for reasons of cost and space. Three conclusions follow:

(a) Small-to-moderate scale modeling in a wave basin is extremely useful when confirming insight into gross behavior, but is not the last word on the validation of a numerical code or a set of guidelines.

(b) Ideally wave basin work should be supplemented by field data from recent tsunamis (Tohoku in particular) to see if the numerical codes predict observed response. As far as is known, none of the Tohoku bridges were instrumented at the time of the earthquake but imposed forces could be back-calculated from the capacities of the connections and failure modes in various bridges. The distance that spans were swept upstream, and/or overturned due to buoyancy effects, are well documented in the literature. Such a task should be relatively inexpensive to undertake.

(c) Wave basin work could also be supplemented by results from a large-scale experiment in the field. In such an experiment a test site is developed outdoors and performance compared under controlled conditions for a selected number of bridge types. This could be an expensive undertaking but would give a definitive answer to the validity of numerical simulation tools and design guidelines. This outdoor site might be in a river bed downstream of a hydro-electric or irrigation dam from which controlled releases of water might be used to inundate a fully-instrumented bridge specimen 'on demand'.

Proposal for a Large-Scale Tsunami Experiment

In this proposal a large-scale model (half-scale or even full-scale) is constructed immediately downstream of an irrigation dam or hydro-electric dam that is capable of releasing large volumes of water in a short period of time to inundate the bridge.

If the bridge girders, bearings, and restrainers (if any) are instrumented, direct measurements can be made of the induced loads in these components and compared against theoretical estimates. Experiments may be repeated to also determine:

- Variation in uplift forces in bridges of different types: PC girders with diaphragms, steel plate girders with cross frames, and box girders
- Effectiveness of different venting arrangements to reduce uplift effects in T-girder bridges and balancing of hydrostatic loads in box girders.
- Effect of cross-sectional geometry on hydrodynamic forces.
- Effectiveness of retrofit measures.

The barriers to conducting such experiment are significant and include not only the cost of the specimens, instrumentation, and released water, but also finding a suitable site and owner.

The major advantage is a quantum jump in the quality and credibility of the validation data and the necessary confidence the proposed design guidelines are ready for inclusion in AASHTO and DOT design specifications. It is also very likely that these experiments will show behavior not seen in small-scale wave basin experiments, and advance the state of the art immeasurably.

It is noted that this experimental site could also be used to study, at large scale:

- storm surge effects on bridges due to hurricanes, by adjusting the rate and volume of released water, and
- scour around bridge piers due to floods, if the chosen site had an alluvial bed.

This project could therefore be of great interest to many other state and federal agencies, and not just those on the west coast.

Acknowledgments

The author acknowledges many useful discussions on the subject of tsunami effects on bridges with Kazuhiko Kawashima, Genda Chen, Solomon Yim, Wen-huei (Phillip) Yen and engineers in the Caltrans Office of Earthquake Engineering. However the recommendations given in this paper are the responsibility of the author.

References

Buckle, I., Hube, M., Chen, G., Yen, W-H., and Arias, J., 2012. Structural Performance of Bridges in the Offshore Maule Earthquake of 27 February 2010, *Earthquake Spectra* (28) S1, pp S533-S552.

Johnson, B., 2011. Development of Tsunami Design Criteria for Oregon Coastal Bridges, *Proc. 27 US-Japan Bridge Engineering Workshop*, Technical Report 4218, Public Works Research Institute, Tsukuba, pp 67-82.

Kawashima, K., and Buckle, I.G., 2012. Structural Performance of Bridges in the Great East Japan Earthquake of March 11, 2011, *Earthquake Spectra*, accepted for publication.

Nimmala, S.B., Yim, S.C., and Cheung, K.F., 2006. *Tsunami Design Criteria for Coastal Infrastructure: A Case Study for Spencer Creek Bridge*, Oregon Department of Transportation Report No. OR_RD-07-03, Salem OR, 60 pp.