Concepts for Tsunami-Resistant Design Criteria for Coastal Bridges

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Abstract

This paper discusses ideas on the basic concept of highway bridge design for tsunami and examines a mathematical formula for estimating tsunami forces on highway bridges. The present paper first reviews restoration case histories of highway bridges that underwent tsunami impact in the 2011 Earthquake off the Pacific Coast of Tohoku and on-going studies by road management authorities to develop post-tsunami response to bridge damage. Based on the reviews, this paper proposes controlling the bearing strength to fail at a designated scale of tsunami and prevent the tsunami force onto the superstructure from exceeding the expected level. Second the present work proves that hydraulic mathematical formulas are quite effective to calculate drag and uplift forces due to tsunami loads, with identifying bridges that suffered washout of superstructures and those that did not suffer in the 2011 tsunami using the formulas.

Introduction

In March 2011, a magnitude 9.0 earthquake occurred off the Pacific Coast of Japan's Tohoku Region (hereafter referred to as the 2011 Tohoku Earthquake). The epicenter was at the edge of the oceanic plate in the coastal waters of Tohoku. One of the largest tsunami in history struck the length of the coastline from the Tohoku Region down to the Kanto Region of Japan. As shown in Figure 1, National Highways 45 and 6 were major arterial roads that ran along the Pacific coast. Bridges on these highways seemed to sustain no major damage during the earthquake tremor itself. However, the tsunami run-up after the earthquake washed out the superstructures and/or the soil behind the abutments, as shown in Photo 1 and most towns and roads on the costal line were also inundated and tons of debris was left [1] [2]. Immediate restoration efforts began to secure access to the disaster-stricken region, with a 97% recovery in length of National Highways 45 and 6 achieved within seven days of the disaster. However, the wash-out bridges impeded the full recovery of the routes.

Large tsunami are predicted to hit at the long coastal lines of Japan in the expected the Tokai, Tonankai and Nankai Earthquakes [3]. The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Regional Development Bureaus (RDB) at the respective regions are currently studying tsunami countermeasures to maintain their wide-area road networks for post-event emergency response to reach tsunami run-up zones [4][5]. Two concepts are typically considered in their studies. One is, to enable logistics of massive relief supplies, constructing new roads in locations that appear unlikely to be impacted by the tsunami. Another is securing bridges on existing bare-essential national highways running along the costal areas and communities to distribute the relief supplies. In terms of the latter efforts, the RDBs

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have studied to develop construction methods for temporary bridge and embankment structures and a comprehensive plan to stock construction material reserves to the ends.

However, because no practical guidance is available to predict the possibility in bridge failure due to tsunami forces or to design a countermeasure to minimize the damage to bridges due to tsunami loads, the RDBs' plans somehow end up presuming the situation that all existing bridges are likely to be inundated and out of commission after the tsunami. For this reason, the National Institute for Land and Infrastructure Management (NILIM), MLIT, and Center for Advanced Engineering Structural Assessment and Research (CAESAR) are engaged in a joint study to establish a preliminary guideline for bridges subjected to tsunami. NILIM's Earthquake Disaster Prevention Division has been studying to set out the design tsunami height and flow velocity at any bridge locations and the Bridge and Structures Division has been studying bridge performance requirements including the translation formula to estimate the design tsunami forces on bridges from the given design tsunami height and velocity and the limit state demands of each structural components. CAESAR, meanwhile, has been studying methods to estimate and design the ultimate strength of bearings to the horizontal and uplift tsunami forces transferred from the superstructure, as well as bridge superstructure proportions and special device installations on superstructures to mitigate tsunami impacts.

Of such research efforts, this paper discusses the basic concepts of tsunami design criteria for highway bridges. First, the paper proposes the concept of damage control design that focuses on facilitating traffic recovery for post-event emergency response. An understanding of the tsunami remedial measures for bridges now being studied by the road management authorities is as crucial as an analysis of actual bridge damage and restoration measures taken after the 2011 Tohoku Earthquake in the present work. In particular, the present paper discusses the effectiveness of accepting superstructure washouts. The idea is aimed at reducing tsunami forces transferred on substructures from superstructures, with the intent of preventing loss of substructures. Secondly, hydraulic formulas are examined to estimate tsunami forces on bridges. For 85 bridges that had typical superstructures and were inundated during the 2011 Toshoku Earthquake tsunami, the present paper calculates horizontal and uplift hydraulic forces on bridges and evaluates whether the superstructure would be washed out or not, comparing the actual damages to those bridges.

Overview of On-going Tsunami Countermeasure Works

To prepare for the predicted mega-earthquakes, road management authorities have been studying measures to secure post-event road networks for emergency transport. For arterial roads along the coastline, each road management authority has been predicting tsunami run-up areas and potential availability of detours to plan access routes to communities in their jurisdictions. Their study is typically comprised of two major works: seeking locations of new roads that are unlikely to be impacted by tsunamis and strengthening existing arterial routes that run along the tsunami run-up costal areas and communities.

Figure 2 summarizes the plan of tsunami countermeasures for the coastal region of Kii Peninsula [5]. A wide span of the Kii Peninsula coast is predicted to be hit if a tsunami generated from the Nankai Trough, a known potential mega-earthquake subduction zone where multiple epicenters over an extended area could interact in a conjunct series. National Highway 42, the arterial coastal road of the Kii Peninsula, has as many as 20 bridges likely to be inundated in the tsunami. The Kinki Regional Development Bureau, MLIT, has been studying emergency recovery operations to resume the National Highway 42 for emergency transport, presuming all those bridges could become unusable. Table 1 shows temporary restoration measures now being considered to counter bridge washouts along the coastal zones. When a bridge is short, a temporary replacing structure can be built using H-girders and steel plates for example. For sites with slightly longer bridges, the required bridge length can be shortened by temporarily filling the approach embankments on both sides with sandbags, on top of which a temporary bridge of H-girders and steel plates can be installed. When a much longer bridge is required, the plan is to install corrugated pipe culverts covered with sandbags as fillings for a temporary road. These measures have been tested on site, and the road management authorities are planning to stock the reserve materials and equipment needed to implement these temporary restoration works.

Based on these measures by the road management authorities, the following points can be made:

- Even at the worst-case scenario, it should not be necessary to protect a whole bridge structure from a tsunami for the quick restoration after a tsunami washout.

Therefore, the focus is not only to protect the bridge against tsunami; there is also need to study design criteria from the perspective of controlling structure damage levels to facilitate quick emergency restoration of transportation.

Case Study of Emergency Restoration after the 2011 Earthquake off the Pacific Coast of Tohoku

Photos 2(a) and (b) highlight two examples of emergency bridge restorations damaged due to the tsunami in the 2011 Tohoku Earthquake. Photo 2(a) shows an example of emergency restoration that was achieved relatively quickly. Neither the superstructure nor the substructure of this bridge underwent critical damage. However, the soil behind the bridge abutment did wash out. A prefabricated bridge kept in reserve at another location was transported and assembled on site. Since the existing bridge could be served as a foundation for the emergency bridge, the bridge was opened to traffic only 0.5 month after the disaster.

On the other hand, Photo 2(b) is an example that required a longer restoration period. This bridge experienced the wash-out of not only the superstructure but also one of the substructures. With part of the substructure washed out, it was suspected that the remaining substructures also suffered significant damage, meaning that a detailed underwater and underground survey was needed to estimate the reliability of the remaining parts. In this case, a temporary bridge was constructed next to the original bridge. It took 3.5 months after the earthquake to open the temporary bridge to traffic.

Based on these case histories, we learned that:

- Even if the soil behind the bridge abutment is washed out, as long as the superstructure and the substructure remain intact, emergency measures to restore movability can be achieved quickly.

- If the superstructure is washed out but the substructure is in usable condition, emergency measures to restore movability can be achieved quickly.
- Emergency measures are likely to become time-consuming when the substructure is washed out or is tilted.

These experiences indicate that tsunami design criteria need to be studied not only from the perspective of protecting all bridges against tsunamis, but also from the standpoint of controlling the damage so as to facilitate restoration.

Concept on Tsunami Design Criteria for Bridges

Based on on-going efforts by the RDBs and earlier experiences in the 2011 Tohoku Earthquake, the present paper discusses the three options shown below as tsunami design criteria for bridges:

Choice 1: For design earthquake motions and tsunami, the required design goal is to limit the level of damage to both superstructure and substructure so that both of them can remain usable for emergency transport. For given design tsunami, the superstructure and substructure shall be designed to have a sufficient strength so that the designated tsunami does not cause the washout, overturning or tilting of the bridge.

Choice 2: For design earthquake motions, the bridge shall be designed to ensure that the substructure, at least, will remain in a reusable condition for emergency measures to restore movability. For tsunami, bearings shall be designed to have a relevant breaking strength to allow for the superstructure to wash out at the designated tsunami scale, thereby reducing the impact to the substructure and keeping the substructure in an acceptable condition for the re-use in the emergency relief transport.

Choice 3: The design goal is to keep both the superstructure and substructure usable for emergency transport after any tsunami of any scale. Design a special bridge shape or special devices and attachments to smooth the tsunami flow around the bridge and minimize tsunami impacts on the bridge.

During a rare-scale earthquake, bearings and bridge piers are subjected to cyclic loads. In terms of Choice 1, a plastic hinge is induced at the bottom of bridge piers to dissipate the seismic energy through the cyclic plastic deformation during the earthquake, while bearings are designed to remain thriving. When the tsunami hits at the bridge after the earthquake tremor, the bearings and bridge piers are subjected to external pushover forces that will continue for some extended seconds. If the design allows the plasticization of a structural component under a pushover force, a significant residual displacement in the single direction can be accumulated. Accordingly, the bridge should have to be designed so that both bridge piers and bearings remain elastic. The corresponding design criteria can be given as follows:

$$(\text{Bearing Strength}) / (\text{Design Tsunami Forces to the Superstructure}) > 1.0$$

(Remaining Pier Strength) / (Design Tsunami Forces to both Super and Substructures) > 1.0

For simplicity, safety factors are omitted in the above equations. For Choice 1, however, the accuracy of design tsunami height and flow and corresponding design tsunami forces will greatly affect the reliability in design. Furthermore the bridge condition becomes uncontrollable when the tsunami goes beyond the scale the design assumes.

In terms of Choice 2, the design policy for earthquake motions is the same as Choice 1. For tsunami, the design allows bearings to break at the given design tsunami force, so that tsunami forces transmitted from the superstructure on the substructure will not exceed the design tsunami force even when tsunami with a scale larger than the scenario comes. This idea ensures that the bridge pier will not wash out or result in critical damage. While the seismic design for a rare-scale earthquake anticipates energy dissipation in the plastic hinge at the bottom of pier and keeps bearing response within the elasticity range, the tsunami design allows bearings to break, thereby dispersing the energy to keep the bridge pier within the range of elastic response. Design criteria can be written as follows:

(Bearing Strength) / (Design Tsunami Force to the Superstructure) = 1.0

(Remaining Pier Strength) / ($\Phi \times$ Bearing Strength + Design Tsunami Force to the Substructure) > 1.0

where Φ = the overstrength factor to the bearing strength. The flow velocity, wave height and approach angle of the tsunami may depend on the minute topographic boundary conditions of the surrounding areas. Use of flow velocity and wave height to estimate the external forces acting on the bridge therefore involves a great deal of uncertainty. With Choice 2, however, regardless of the scale of tsunami in reality, the design load becomes equal the bearing failure load, which to some extent can be controlled artificially. For this reason, Choice 2 offers a better prediction of damage to bridges and hence is more beneficial than Choice 1 from the perspective of road management and disaster relief operation planning. The challenge for Choice 2 is the development of a bearing structure that allows for the quantitative evaluation of overstrength factor Φ with as a small error as possible.

Choice 3, if technically achievable, is the most favorable option since it is less impacted by the uncertainty in tsunami force estimation, and offers a usable superstructure against any scales of tsunami. Study on superstructure shapes and devices that can minimize the impacts of the tsunami is awaited. Research and development of such technologies is currently underway at CAESAR, Public Works Research Institute (PWRI) [6][7].

Study on the Feasibility of Superstructure Washout Assessment Using Hydraulic Formula to Estimate Tsunami Forces

In Choice 1 and Choice 2 above, the estimation of design tsunami scale and tsunami force is key to make the washout assessment of superstructures practical. A common method to estimate tsunami forces for a given design tsunami flow is to obtain the hydrodynamic horizontal and uplift forces by substituting the given flow velocity and height into hydraulic formulas.

Tsunami forces on bridges can vary depending on multiple factors such as the superstructure type, existence of other structures in the vicinity, and local topography. Bridges that experienced washout in the tsunami of the 2011 Tohoku Earthquake had different superstructure types, materials, shapes, and sizes. As shown in Photo 1, the damage characteristics were also different from bridge to bridge, including the washout of superstructure, the collapse and washout of bridge pier, and the washout of abutment backfill. In some cases, the type and extent of the damage differed greatly among bridges located close to each other. Different bearing types were used in these bridges, the behavior of which may have affected the superstructure washout. Considering all these factors and examining the damage case histories observed in the 2011 Tohoku Earthquake, a feasible and practical method is sought herein to estimate tsunami forces on bridge superstructures.

Bridges Selected for Feasibility Study

Out of all bridges inundated by the tsunami in the 2011 Tohoku Earthquake, 85 bridges were selected for the present study, categorized into typical steel I-girder bridges, concrete T-girder bridges, and concrete slab bridges. These bridges were selected as follows:

1. First, bridges were chosen if the bridge type, structural dimensions could be confirmed through original drawings or post-earthquake site visits.
2. Of those chosen in the first step, bridges were excluded if they were located at sites where a minute difference in site conditions had likely change the tsunami flow velocity, direction, wave height, etc., greatly, such as those located immediately behind flood gates.

Table 2 summarizes the number of washouts by bridge type and Figure 3 shows a breakdown of the bearing types for each bridge type. Four types of bearings were used: rubber pad bearings, direct placement, line bearings and rubber bearings.

Analysis Method

As illustrated in Figure 4(a), a two-dimensional plotting is used in the present study in terms of the inverses of the safety factors, F.S., for horizontal washout and vertical washout (uplift), respectively. If the inverses of both safety factors are less than 1.0 for both the horizontal and vertical directions, the superstructure was theoretically supposed not to wash out. If the inverse of one of the safety factors exceeds 1.0 for either direction, the bridge was notionally supposed to washout. As shown in Figure 4(b), if a set of the inverses of the safety factors of a bridge is plotted above the 1:1 line, it means the uplift force should be prevalent, while the plot below the 1:1 line indicates the prevalence of the horizontal force rather than the uplift force.

The inverses of the safety factors for the horizontal and vertical directions are calculated using the following formulas:

1 / F.S. = (Horizontal Tsunami Force) / (Horizontal Bearing Resistance)

1 / F.S. = (Uplift Tsunami Force) / (Superstructure Weight)

Calculation methods for the tsunami horizontal and uplift forces, as well as for the horizontal bearing resistance, will be described in later sections.

Calculation of Tsunami External Forces Using Hydraulic Formulas

In the wake of widespread tsunami damage to bridges in the 2004 Sumatra-Andaman earthquake and 2011 Tohoku Earthquake, the reaction force on bridge structures due to tsunami waves has been studied in bridge engineering. For example, Kosa et al [8] have conducted wave flume tests and proposed experimental equations to calculate the horizontal and uplift forces for scaled model bridges during tsunami, incorporating factors such as the tsunami flow velocity and height at site. Hoshikuma et al. [6] have conducted water flume tests to examine tsunami forces on scaled-bridge girders, measuring the transmission force between bearings and abutments. They have shown that the response of bridge girders to tsunami can change with the difference in the shape of girders. For example, their test results have indicated that bridges having a simple rectangular shape can be exerted by downward forces while T / I-beam girder bridges can be uplifted and then overturned initiating at the side facing directly to the incoming tsunami. Kataoka et al. [9] and Ezura et al. [10] have simulated the tsunami run-up from the epicenter of the 2011 Tohoku Earthquake up to 10 to 20 bridges at different sites. They have compared simulated and observed bridge wash-out case histories, showing that the tsunami simulation can reproduce tsunami impacts with a reasonable accuracy. Namely these previous works indicate the following aspects:

- It is necessary to consider both horizontal and vertical forces when assessing the influence of tsunami on bridges.
- Hydrological lift and drag formulas may work accurately to some extent when the tsunami velocity and height at site are given.
- Tsunami run-up simulations can estimate the velocity and height of the tsunami at a particular site with an acceptable accuracy including the propagation process from a tsunami source.

In accordance with these findings, the present study will hypothesize the tsunami forces as noted below. The total horizontal tsunami force on superstructures is a superposition of hydrostatic and dynamic pressures. The hydrostatic pressure can be imbalanced at the time or just after the time when the tsunami hits the girders and depends on water elevation. The hydro dynamic force is assumed to account for the compensation of total water pressure on superstructure in addition to the static one.

$$P = P_1 + P_2 \qquad (1)$$

$$P_1 = \rho_s \cdot g \cdot b\int_{z_2}^{z_1}(h'-z)dz \quad (2)$$

$$P_2 = \frac{1}{2}\rho_s \cdot C_d \cdot A \cdot \upsilon^2 \quad (3)$$

whereas,

P_1 = hydrostatic pressure force on the bridge seaward surface,

P_2 = hydrodynamic pressure force on the bridge surface facing the tsunami travelling from the offshore,

ρ_s = seawater density = 1030 kg/m^3,

g = gravitational acceleration = 9.8 m/s^2,

b = girder length (m),

h' = height of the tsunami crest from the static water level or the ground level (m),

z = height from the static water level or the ground level (m),

z_1 = height of the girder bottom from the static water level or the ground level (m),

z_2 = height of the top of the curb blocks on the deck from the static water level or the ground level (m),

A = area subjected to pressure (m^2),

v = horizontal flow velocity of the tsunami (m/s), and

C_d = resistance factor.

C_d should be calibrated to account for tsunami forces based on damage case histories and experiments. As a starting point, the present paper simply employs the following formulas that are used in the Japanese Specifications for Highway Bridges to calculate wind load, although further study is needed for the value of C_d in the future:

$$C_d = 2.1 - 0.1\ B / D \qquad \text{if } 1 \le B / D < 8 \quad (4)$$

$$C_d = 2.1 - 0.1\ B / D \qquad \text{if } 8 \le B / D \quad (5)$$

whereas,

B = total width (m),

D = superstructure height (m) (height from the base of the main girder to the top of curb blocks).

Vertical force U is given as the sum of U_1 (buoyancy force in the inundation area) and U_2 (lift pressure caused by the flow), assuming the water fills up surrounding the bridge. It is calculated using the following formula:

$$U = U_1 + U_2 \quad (6)$$

$$U_1 = \rho_s \cdot g \cdot V \quad (7)$$

$$U_2 = \frac{1}{2}\beta \cdot \rho_s \cdot C_d \cdot A' \cdot \upsilon^2 \quad (9)$$

whereas,
V = volume of the superstructure (m^3),
C_L = lift coefficient, and
A' = footprint of the bottom of the superstructure (m^2).

A lift coefficient of 0.50 was assumed in the present paper. Numerical wave simulations using a software of CADMAS-SURF were separately conducted for a rectangular cross-section object located at different heights in a two-dimensional (2-D) channel, counting the total value of upward water pressure distributions on the cross-section. CADMAS-SURF is based on the non-compressive fluid theory and the Navier-Stokes formula as the basic equations and employs the VOF (Volume of Fluid) method to deal with the free surface of the fluid.

In practice, tsunami horizontal flow velocity (v) and height (h') could be given via tsunami hazard maps and other sources. However better accuracy is needed for the purpose of the present analysis. The horizontal flow velocity and wave height at each bridge site in the 2011 Tohoku Earthquake tsunami is therefore estimated via a tsunami run-up simulation with CADMAS-SURF separately. The Fujii-Satake model Ver.4.6 is employed as the tsunami generation model.

Figure 5 compares tsunami heights at sites between the simulation and post-tsunami measurement, where the actual tsunami height records at bridge locations are shown in the literatures [11] [12]. The difference between the simulation and post-tsunami measurement is generally within 30%, but greater discrepancies are observed at some locations.

Bearing Resistance

The horizontal resistance is the sum of the shear strengths of the bearing anchor bolts of all bearings. The shear strength of each anchor bolt is calculated using the following formula:

$$R_{SH} = A \cdot \sigma_u / \sqrt{3} \quad (10)$$

whereas,
A = effective cross sectional area of the anchor bolt (mm^2), and
σ_u = nominal tensile strength of the anchor bolt (N/mm^2).

Detailed drawings of bearing did not exist for eight bridges and the present study designed them again following the standards at the time when they were originally designed to predict their horizontal resistances.

The vertical resistance involves the weight of the superstructure and typical design forces of bearing described in design guidance books in the past which equaled 0.30 times the bearing reaction forces for dead loads for rubber bearings and 0.10 times of that for other bearings. Resistances provided by unseating prevention restrainers are also neglected for both horizontal and uplift forces for the sake of simplicity.

Analysis Results

The inverse numbers of the safety factors for 26 steel plate girder bridges are plotted in Figure 6(a). Hereafter in Figures 6(a) to (c), the black dots indicate bridges washed out in the actual tsunami; the white dots indicate bridges that were not washed out in the actual tsunami. The bridges that were washed out in the actual tsunami are plotted in the region where the inverse of the safety factor exceeds 1.0 (i.e., safety factor is below 1.0) in either the horizontal or uplift direction. Some bridges that did not wash out in the actual tsunami are plotted in the region where the inverse of the safety factor exceeds 1.0 in either direction, indicating the present tsunami force formula can give tsunami impact forces on the conservative side. These results show that tsunami external force formulas can be based on hydrodynamic forces to calculate tsunami forces on bridges.

As indicated in Figure 6(a), the inverse of the horizontal safety factor is greater than the inverse of the uplift safety factor (i.e., the uplift safety factor is smaller) in some of the bridges. This is likely because steel plate girder bridges are relatively lightweight.

The inverse numbers of the safety factors for the 24 concrete T-girder bridges are plotted in Figure 6(b). Almost all of the bridges washed out in the actual tsunami are plotted in the region where the inverse of the safety factor exceeds 1.0 (i.e., safety factor is below 1.0). Most of the concrete T-girder bridges were not vertically fixed tightly in the calculation and the bridges that were actually washed out are plotted in the lower right region of the graph, indicating that they were impacted greatly by the horizontal wave force. This is likely because the concrete T-girder bridges are relatively heavy.

Seven black dots of bridges that were actually washed-out were plotted in the region with an inverse of the safety factor below 1.0 in both directions. For six out of the seven, the inverse of the safety factor was close to 1.0 in the horizontal direction. Calculation of the wave force and bearing strength can contain errors, and bridges with an inverse of the safety factor ranging between 0.80 and 1.00 are more likely to be affected by such error. To improve the calculation precision of the wave force and bearing strength, there is need for more accurate tsunami estimates and more accurate evaluation of the bearing strength, all of which require further research.

The remaining two bridges are indicated in Figure 6(b) by ovals marked ‘A’. Calculations show that the inverse of the safety factor for these bridges is smaller than 0.50 (i.e., safety factor of 2.0 or greater). Even with the additive safety factor, the calculations fail to explain the actual tsunami damage experienced. The tsunami travel and run-up simulations for the two bridges show a tsunami flow velocity of 0.6 m/s and

2.1 m/s, respectively, which seems too small to wash bridges out. This is under 50% of the smallest flow velocity calculated for the washed-out concrete T-girder bridges in reality. These discrepancies can likely be improved by reviewing of the setting of the surrounding conditions in the tsunami travel and run-up simulations.

The inverse numbers of the safety factors for the 35 concrete slab bridges are plotted in Figure 6(c). The three bridges indicated by ovals marked 'B' in Figure 6(c) were actually washed out, but had very small inverse of horizontal and uplift safety factors by calculation. The tsunami travel or propagation and run-up simulations for the three bridges show a flow velocity of less than 2.0 m/s. This is approximately 60% the lowest velocity calculated for the other concrete slab bridges that were actually washed out.

In Figure 5, the bridges marked with A and B in Figure 6 are also designated, in which, as mentioned above, the tsunami flow velocities were slower than 2.1 m/s at those bridges in the calculation which is considered too slow to wash the superstructure out. The corresponding tsunami heights are clearly underestimated in two out of those five bridges. Thus we can neglect the analysis results for the bridges marked with A and B to evaluate the effectiveness of Equations (1) through (9). Overall, we consider that the calculation results agree with the actual bridge damage in general and, if the tsunami flow velocity and wave height at the bridge location are provided, standard hydraulic formulas can be used to calculate the horizontal and uplift forces that act on the bridge with sufficient precision.

Conclusions

This study yielded the following results:

1. Experiences from the tsunami recovery efforts after the 2011 Tohoku Earthquake backs up a damage control design philosophy to protect the substructure by intentionally allowing the superstructure to be washed out as one of design objectives.
2. The case-history analysis for 85 bridges hit by the 2011 Tsunami shows that typical hydraulic equations works in practice both in the horizontal and uplift behavior.
3. A factor of safety of 1.2 or 0.80 should be considered to predict the horizontal and uplift Tsunami forces or the design bearing strength, respectively. However, the authors believe that the accuracy should be improved by calibrating drag coefficients more relevantly based on damage case histories and experimental results.

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Table 1. Examples of post-event recovery plans for bridges

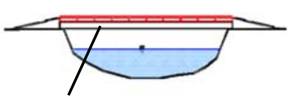
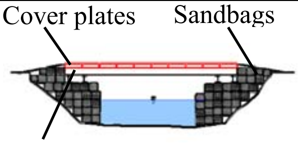
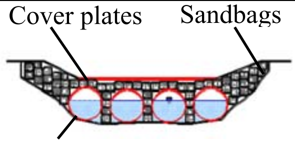
Type	Type1	Type2	Type3
Conditions	Narrow rivers	Wider rivers	Very wide rivers
Restoration Method	H-steel + Cover plates	Sandbags + H-steel + Cover plates	Sandbags + Cover plates + Corrugated pipes
Schematic Diagram	Cover plates  H-steel	Cover plates Sandbags  H-steel	Cover plates Sandbags  Corrugated pipes

Table 2. Numbers of bridges in total, wash-out and no wash-out by girder type

Girder type	Number of bridges		
	Total	Wash-out	No wash-out
Steel I-beam	26	14	12
Concrete T-beam	24	13	11
Concrete slab	35	18	17

Photo 1. Examples of damaged bridges due to the 2011 Tohoku Earthquake Tsunami (From Left to Right: Washout of superstructure, Collapse of piers, and Washout of backfill behind abutment)

(a) Opened to traffic in 14 days of the tsunami strike

(b) Opened to traffic in 3.5 months of the tsunami strike

Photo 2. Examples of emergency restoration for wash-out bridges after the 2011 Tohoku Earthquake Tsunami

Figure 1. Major arterial roads along the Pacific Coast in the region of Tohoku

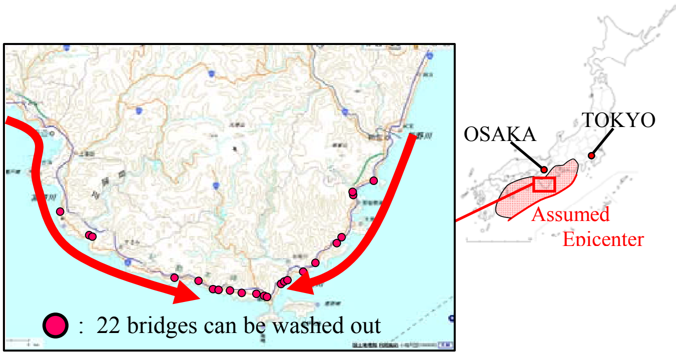
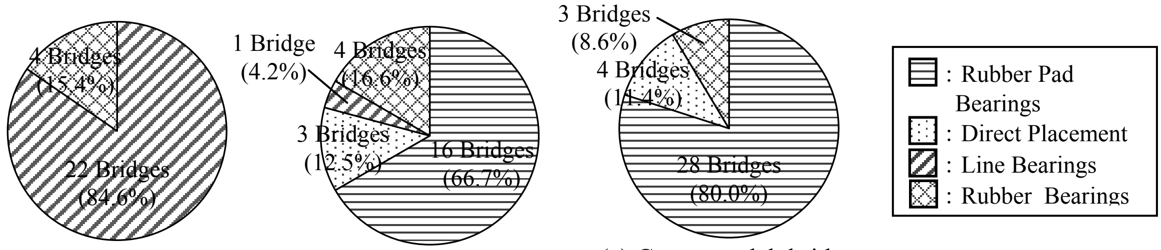
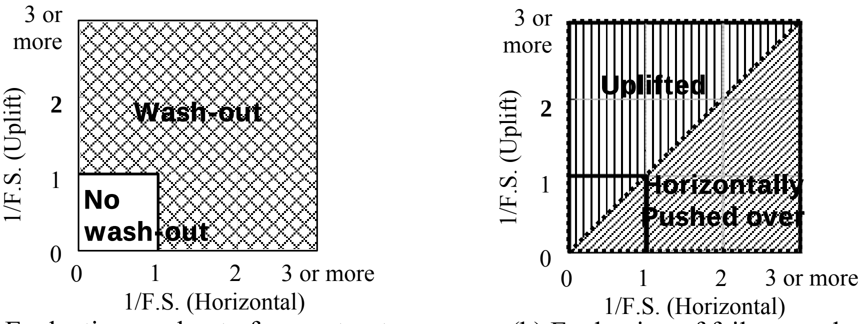


Figure 2 Bridges located on the major national highway in the predicted tsunami run-up zone along the Kii Peninsula Coast



(a) Steel I-beam bridge (b) Concrete T-beam bridges (c) Concrete slab bridges

Figure 3. Types of bearing used in the bridges chosen in Table 2



(a) Evaluation washout of superstructures (b) Evaluation of failure mode

Figure 4. Illustrative understandings used in the present analysis

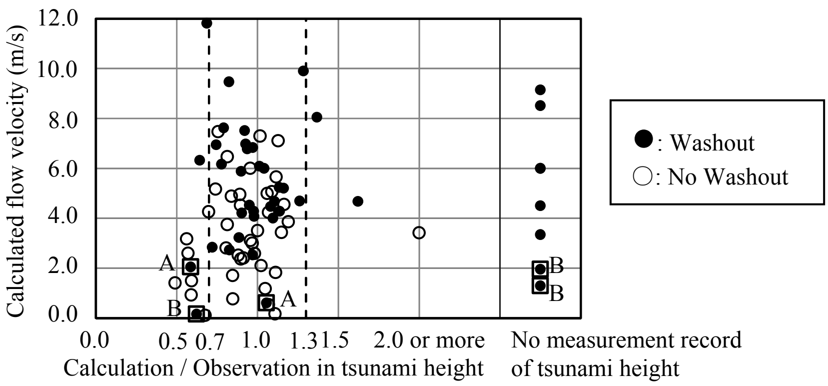
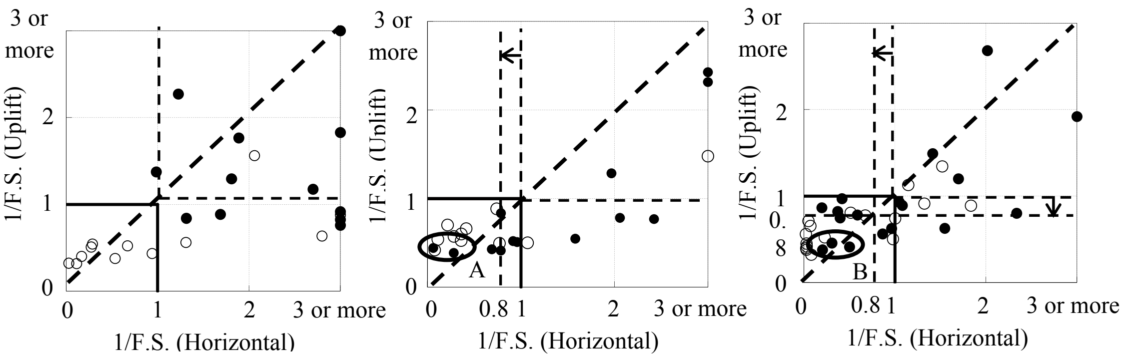


Figure 5. Calculated tsunami flow velocities and comparison in tsunami height at bridge site between the calculation and post-event measurement



(a) Steel I-beam bridges (b) Concrete T-beam bridges (c) Concrete slab bridges

Figure 6. Inverse values of safety factor in horizontal and uplift directions (Black dots: Wash-out bridges, White dots: Not washed-out)