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Debris Forces and Impact on Highway Bridges

Forces et impact des débris sur les ponts routiers

Trümmerlasten und Stosskräfte auf Autobahnbrücken

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SUMMARY

Flooding events are the most frequent cause of bridge failure/damage in the United States. During a flooding event, highway bridges submerged in floodwaters are subjected to hydrodynamic forces created by floating debris that accumulate on structures, and impact forces caused by floating debris. This paper presents an overview of the magnitude and distribution of these debris-related forces, determined from a combination of laboratory and analytical studies. The result of this study will be a proposed design specification that will safeguard against bridge failures due to debris loading.

RÉSUMÉ

Les inondations sont aux États-Unis la cause la plus fréquente de la ruine et de dommages aux ponts. Lors d'une inondation, les ponts routiers submergés par les eaux sont sujets à des forces hydrodynamiques créées par des débris flottants qui s'accumule sur les structures et par des forces d'impact causées par ces débris. L'article passe en revue l'importance et la distribution de ces forces de débris déterminées par une combinaison d'études en laboratoire et théoriques. Il résultera de cette étude une proposition de normes de projet, qui protégera les ponts de la rupture du haut charge de débris.

ZUSAMMENFASSUNG

Ueberflutungsereignisse sind der häufigste Grund für die Beschädigung und den Einsturz von Brücken in den Vereinigten Staaten. Bei Ueberflutung sind die eingetauchten Brükken durch hydrodynamische Kräfte infolge des sich stauenden Treibguts ausgesetzt. Der Beitrag gibt einen Ueberblick über die Grösse und Verteilung solcher Kräfte, wie sie aus Laborversuchen und Berechnungen ermittelt wurden. Als Ergebnis wird ein Bemessungskriterium vorgeschlagen, das den Einsturz von Brücken unter Trümmerlasten ausschliesst.

1. INTRODUCTION

Recent bridge failures have occurred throughout the United States due to flooding and have resulted in loss of life as well as significant economic cost. According to the Federal Emergency Management Agency (FEMA), of all man-made and natural hazards (earthquake, tornado, fire, etc.), flooding events cause more economic and financial loss than any other hazard (FEMA, 1991; Trent, 1993). In particular, flooding events are the most frequent cause of bridge failure in the United States (Trent, 1993).

Debris can damage bridges by individual pieces of debris or debris mats colliding with structural components. These debris forces generally, but not invariably, cause only superficial damage such as spalling of concrete from piers or fascia girders. On the other hand, the forces of water on the bridge due to the river/stream flow and debris accumulation, which are termed hydrodynamic and hydrostatic forces, have resulted in some devastating failures. These hydrodynamic and hydrostatic debris forces can be sufficient to overturn bridges, shear bridge roadway decks off their supports, or cause buckling failure of the substructure. Pivotal questions still remain regarding the failure of these systems during flooding conditions, and only limited information exists regarding the precise modes of bridge failure caused by hydrodynamic loads and the magnitude and distribution of debris loading. The existence of debris forces has been realized for many years, and the American Association of State Highway and Transportation Officials (AASHTO) Standard Specification for Highway Bridges (1990), Section 3.18, has stated that this condition must be considered in bridge analysis and design. Although the AASHTO specification provides detailed criteria for evaluating maximum expected loads for stream flow, floating ice, and wind, it provides no guidance in evaluating debris loadings.

This paper presents the current efforts in developing a design specification for debris loading. The information presented is some of the preliminary findings being used to developed a practical method for estimating maximum bridge debris loads, including the probable locations and effective size. A finalized design specification is tentatively due from AASHTO in the spring of 1996.

2. HISTORICAL BACKGROUND AND FIELD OBSERVATIONS ON DEBRIS LOADING

2.1. Field Observations

Debris can be defined as anything that floats and may find its way into a waterway. However, debris primarily consists of woody remains of trees, brush and grass. The mechanics of debris formulation have not been extensively examined, although it is believed that debris is principal formed by erosions of support of roots of trees along waterway embankments. During flooding events, debris that is lodged on the banks of the waterway will be swept into the waterway as the flow depth increases. The debris and logs that lie along the stream banks may also be dislodged by the secondary currents that exist in the turbulent water at the stream's bank.

The formulation of debris piles is dependent upon the individual log sizes, waterway height, distance between bridge piers and/or the waterway embankment. The typical formation of debris piles appears to be that a single large tree becomes pinned between the pier and the streambed or the deck and a pier. Thus, the shorter span and shorter height bridges will be more susceptible to debris accumulation. The debris accumulation region acts like a sieve that progressively traps smaller and smaller debris until leaves and grass effectively clogging the openings so as to allow it to be considered impervious. A typical bridge upstream edge debris accumulation is shown in Figure 1. From examination of the photographs, it is observed that the debris accumulation effectively constricts the flow area, resulting in an increased flow velocity and possible aggravated scour condition. At several locations, islands have been observed, which are thought to have developed as a result of settlement of suspended soil when the flow velocity decreases past the constricted channel opening. In addition, as the upstream debris accumulation grows larger, the accumulated debris takes on an inverted conic shape and produces a slip-stream, resulting in a reduced force on the projected debris area.

Figure 1. Typical Upstream Debris Accumulation

2.2. Historical Background

Debris forces apply basically to non-navigable waterways, since ship/barge collisions will control lateral loading in navigable waterways. Although the main thrust of bridge failure investigation to date has focussed on ship/bridge collisions in navigable waterways, a few investigations have been conducted on bridge failures at non-navigable waterway sites. A Federal Highway Administration (FHWA) survey of bridges subjected to a major flooding event (O'Donnell 1973) found that the roadway decks of several bridges throughout New York and Pennsylvania had separated from their supporting substructures. These failures were attributed to shear at the connection between the bridge superstructure and substructure, i.e., at bearing devices. FHWA concluded that these bearing devices need to "....be designed to resist dynamic flood forces, such as the horizontal forces due to impacting debris". In a report to FHWA, Chang and Shen (1979) reported that the most frequent cause of damage to bridges is related to debris accumulation.

3. HIGHWAY BRIDGE DEBRIS FORCES

During a flooding event, the total hydrodynamic force on a bridge is the sum of all pressure forces on the bridge surface created by water and the force transmitted by lodged debris from water. The total force system, excluding impact, consists of 1) hydrodynamic drag forces, 2) hydrostatic forces, 3) buoyant forces, and 4) hydrodynamic lift forces. Although these forces fluctuate with vortex shedding and wave propagation, computation of mean forces is sufficient to determine debris related bridge forces. Additionally, impact forces will develop from floating debris colliding with bridge substructures. The impact force on a bridge during debris collision is influenced by the drag force on the debris, the deceleration of the debris mass, the hydrodynamic effect of deceleration of fluid particles permanently displaced by the debris

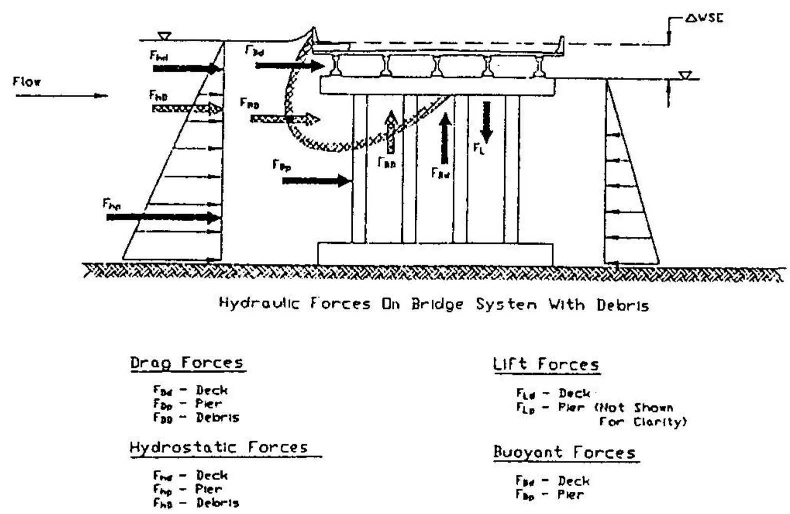

Figure 2. Hydrodynamic Bridge Loads

mass, i.e., the "added mass" effect, and the fluid-structure mass, damping and stiffness. The hydrodynamic and hydrostatic bridge forces that occur during a flooding event are illustrated in Figure 2.

4. DEBRIS FORCE MODELS

4.1. Hydrodynamic Drag Model

Hydrodynamic drag is the net force resulting from boundary layer pressure drag (form drag) and viscous drag. Bridge elements are hydrodynamically bluff and predominantly cause pressure drag. Although the drag forces fluctuate with vortex shedding, computation of the mean force is sufficient for determination of bridge drag forces due to the high natural frequency and high dampening of bridges. Drag forces on the projected area of the structure may be computed using the following proposed analytical drag model:

$$F_D = C_D \, \rho A \frac{V^2}{2}$$

where A equals the reference area for computing the drag coefficient, ρ equals the fluid density, V equals the reference velocity, and C_D equals the drag coefficient. The velocity required in the proposed design equation can be computed using a reasonable estimate of the horizontal and vertical velocity distribution.

4.2. Dynamic Impact Model

Impact can be defined, in a general manner, as "the collision between two or more objects". Floating debris or ice, shipping traffic, and recreational boats may collide with the bridge substructure in the case of a bridge over a waterway,. This collision can cause substantial damage or even catastrophic collapse. The proposed impact force model is:

$$F_i(t) = CF\left(\frac{MV^2}{S}\right)$$

where Fi(t) equals the impact force, M equals the effective mass of the debris, V equals the velocity of debris at level of impact, S equals the stopping distance, and Cf equals the correction factor accounting for variation of stiffness of the bridge, relative angle of impact, fluid damping and mass. The stopping distance is controlled by the bridge lateral stiffness, effective design mass, effective fluid-structure damping and mass, the flow velocity and the localized failure mechanism of a particular debris (wood) type.

4.3. Additional Force Models

In addition to the hydrostatic pressure forces, drag and impact forces, buoyant and lift forces may also be significant forces on the bridge structure. Hydrostatic forces on bridge elements result from differences in water surface elevation between the upstream and downstream sides of a bridge caused by significant flow constriction of the waterway opening and related energy dissipation. Buoyant force acts vertically upward and results from the displacement of water by bridge elements and debris lodged under the bridge. Hydrodynamic lift is the force perpendicular to the flow direction. Lift forces can develop in a vertical direction for bridge decks that are partially or fully submerged. The direction of the lift force on the deck is downward. Lift forces tend to be greatest under partially submerged conditions.

5. EXPERIMENTAL TESTING RESULTS

Experimental testing has been conducted using small-scale, medium-scale, and full scale testing model. The small-scale testing was conducted at the Queensland University using 1/25 scale models. The medium scale testing was conducted at the Waterways Experiment Station, Vicksburg, Mississippi, at approximate 1/10 scale. The full-scale impact testing was conducted at Hodgensville, NY. The debris was modelled using either flat plate models, conic section with protrusions, or proportional debris elements which were allowed to accumulate on the bridge models.

Four superstructure models and three substructure models were examined. The bridge models selected to be experimentally investigated represent bridge systems that would reasonably be expected to be subjected to debris loading. The superstructure models consisted of AASHTO Type IV prestressed concrete girders, steel girders with composite decks, and both adjacent and spread prestressed concrete box girders. The substructure models included two-column piers (round and tied), solid piers, and four column bents . A partial illustration of the bridge models is shown in Figure 3.

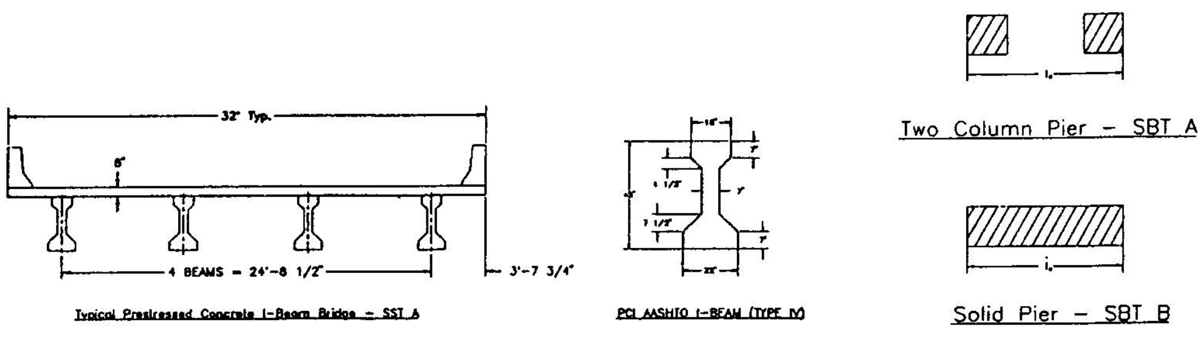

Figure 3. Partial Bridge Superstructure and Substructure Model

Graphical displays of part of the testing results are given in Figures 4 and 5. Comparing the maximum theoretical value for a flat plate model, and the conic section results, it is apparent that the slip stream effect does have an impact on the magnitude of the debris loads. From field observations and experimental testing, it is realized that the actual debris loading is significantly less than that which would be generated when considering the flat plate model.

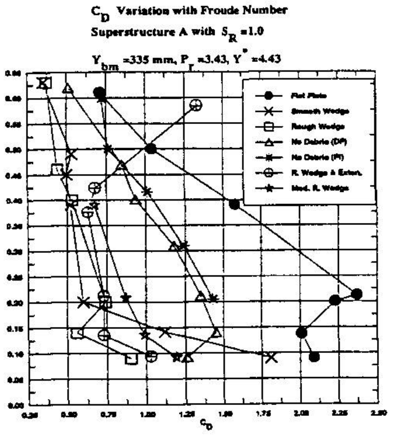

Figure 4. Superstructure A

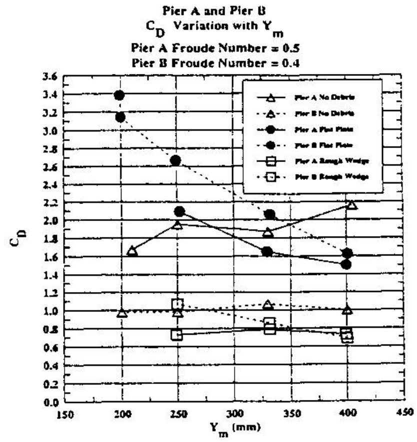

Figure 5. Substructure A and B

7. CONCLUSIONS

Debris loading occurs on all waterways systems with bridges with short spans and/or low heights being more susceptible to debris loading influence.. The results presented here are the first effort in classifying and quantifying these loads. This loading information will be developed into an AASHTO debris specification.

8. ACKNOWLEDGMENT

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