TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 367.2	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE ACCURACY AND PRECISION IN THE ANALYSIS AND DESIGN OF FLOATING BRIDGES		5. REPORT DATE April 1997 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Colin B. Brown		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) University of Washington, Box 354802 University District Building; 1107 NE 45th Street, Suite 535 Seattle, Washington 98105-4631		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Agreement T9903, Task 15
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370		13. TYPE OF REPORT AND PERIOD COVERED Supplemental report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

Measurements of wind characteristics and the kinematic performance of floating bridges are proposed. The relationship between these measurements is then used as a check of detailed analyses and a statement of accuracy. The use of these measurements and the detailed analytical results are applied to the initial design of these bridges.

17. KEY WORDS Wind, floating bridges, forces		18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616	
19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES 16	22. PRICE

Supplemental Report

Research Project T9903, Task 15
Floating Bridge Design Forces

ACCURACY AND PRECISION IN THE ANALYSIS AND DESIGN OF FLOATING BRIDGES

by

Colin B. Brown
Professor Emeritus
Department of Civil Engineering
University of Washington

Washington State Transportation Center (TRAC)
University of Washington, 354802
University District Building
1107 N.E. 45th St., Suite 535
Seattle, Washington 98105

Washington State Department of Transportation
Technical Monitor
E.H. Henley
Special Project Engineer

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

April 1997

DISCLAIMER

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The development of continuous floating bridges has been accomplished largely in the State of Washington; the development of analytical and design methods has not, therefore, involved studies from all over the professional world. The associated reliance on local studies and the incidence of failure places a major responsibility on the State of Washington bridge engineers. The understanding of the behavior of existing bridges under extreme environmental conditions and confidence in predictive schemes in the design of new bridges require methods that are both accurate and precise.

This report reviews the significant studies on floating bridges made over the last 25 years and reveals expert analytical schemes that examine the various aspects of the wind- wave-force behavior and wind-force behavior systems. These schemes study each aspect separately and combine them to obtain the final behavior. They involve uncertainties in modeling of both the wind-wave-force and the structural systems, the assignment of parameters (especially the damping of the structural system), and the expected local wind characteristics to be considered. However, these reductionist schemes produce an understanding of the various features that influence the behavior of floating bridges. The accumulation of the results of these schemes may not, in their integrated form, provide accurate predictions of behavior. Such accuracy can be obtained by requiring that these integrated results be constrained by relations between measured wind characteristics and measured kinematic behavior.

The review found that these measurements had only been completed in the special study of drawspan fatigue maintenance problems. It is suggested that these wind-kinematic behavior relations be obtained for the existing bridges and that they be used as accuracy constraints on the reductionist studies. Persistence in these studies will improve the understanding of floating bridge behavior and the precision of the analytical results. The availability of the wind-kinematic behavior relations will ensure that such integrated studies are accurate.

Availability of the relations between the initial environmental feature, wind, and the consequent structural behavior, bridge kinematics, for existing bridges will display performance changes for the different structural arrangements. The reductionist studies will provide understanding of the reasons for the changes. These results can be applied to a new bridge design if the wind conditions at the site are available. The arrangements needed at existing bridges and at potential future sites are reviewed.

INTRODUCTION

BACKGROUND

The study of forces on continuous floating bridges has been of continual interest to the Washington State Department of Transportation since the early design considerations of the Lacey V. Murrow Bridge in 1940s. The first of Murrow's four concerns was the determination of such forces (Pacific Builder and Engineer 1977). Subsequently, Hartz and his colleagues studied the short crested wave interaction with the structure with the intention of understanding the applied forces. The idea was to replicate the confused seas associated with a mixture of incident and reflected waves by these choppy waves. The final work (Georgiadis 1981; Hartz and Georgiadis 1981: Hartz and Georgiadis 1982) consisted of a finite element modeling of floating bridge behavior in short crested waves. This work was an outcome of empirical studies on the Hood Canal Bridge, where wave characteristics, wave forces on the bridge, and the bridge response were measured (Hartz and Richey 1970: Hartz and Mukherji 1971; Mukherji 1972). In none of these studies were adequate wind measurements obtained to develop wind-wave-force relations. A consequence of the modeling reported was the necessity to reduce the determined forces by an attenuation function in order to obtain reasonable agreement between the measured and predicted values. The design work of Tokola, Earl, and Wright (1979) on the replacement of the western part of the Hood Canal Bridge was based on the assumed superposition of long crested waves.

The void between the choppy waves of Hartz and his people and the design approach using well behaved long crested waves was bridged by a remarkable paper by Hutchison (1984) that related the superposition of directional long crested waves to a short crested wave field in which impulses were reduced by an attenuation function. The form of the function was revealed empirically by Mukherji (1972) by the site measurements of the structural kinematics and strains on elements of the original Hood Canal Bridge and the relating of these to the measured waves. In this manner two apparently conflicting approaches to the determination of forces were

merged. The shortcoming of these studies is the limited wind data available to complete the wind-wave-force relationships. What is available, as well as wave forces, are measurements of wave characteristics and bridge behavior in benign, non-extreme environments and the correlation of wave to force by the attenuation factor.

The 1991 reports of the Glosten Associates provide a sophisticated finite element method for the analysis of floating bridges. The behavior is predicted by perturbation about the steady displaced shape. In this way the non-linearities in the governing equations are dealt with in two steps: the determination of the static state associated with the mean environmental situation, in itself a non-linear problem, and the dynamic state about that mean. The effects of the first step are required to be small in comparison to those of the second. The wave statistics are provided from the approach of Ochi (1973). This view of extreme waves is that they are a part of the general wave population and can be dealt with in the general wave statistics. An alternative view exists in which the extreme waves are generated by different actions than the usual waves, are a separate population, and require separate statistical treatment. The scheme adopted is a step-by-step study of the effect of wind on the water to cause waves and the interaction of these with the structure to cause geometric changes and internal forces.

The application to the Lacey V. Murrow replacement structure related a selected worst case wind direction and 1-minute wind speed over a measured fetch to a maximum wave height by a standard program, NARFET. The evidence for selected wind speeds is discussed. The effects of these waves on the structure are determined by a finite element model that requires the specification of critical parameters. Of these, the damping is the most elusive and reasons for selected values and the use of hysteretic damping are given. The resulting analysis provides extreme values of beam moments, shears, torques, cable forces, and kinematics

In 1995 the Glosten Associates returned to the problem and considered, among other topics, the local wave environment around the bridge and the effect of the interaction of incident and reflected waves, and wave steepness on the forces on the structure. These features are not evident in the linearized potential flow theory generally used to determine wave forces. The

outcome of these refined analyses, together with wave tank studies, was that the additional features made little difference to the usual predictions and that professional prudence would indicate the further use of the traditional linearized potential flow theory.

COMMENTS

The modeling of the floating structure described in the 1991 Glosten Associates report provides the basis for the checking of a design. The efforts to obtain the force system to excite a floating bridge are based on simplifications and require that parameters be assigned and wind characteristics be selected. The report dwells on the difficulties of assigning the damping parameters and the value of actual measurements in determining reliable values. The wind features are dependent on the measurements at distant locations and the extreme sea state is modeled according to the view of Ochi. The earlier work of Hartz and his associates is in the same vein but less sophisticated. Essentially, in both cases the view point is reductionist and intends to predict the final behavior from the accumulation of detailed analyses of facets of the wind-wave-force system. Any improvement in one analysis or in parameter estimation or in wind characterization should lead to an improvement in precision in the results. Evaluation of the accuracy of the analyses associated with shortcomings in the assumptions, analytical methods used, data scarcity, and parameter identification are not available. The exception to this approach is the study of Mukherji, in which actual field measurements were used to establish the model and to examine the accuracy of the results. Even in this work the wind measurements were incomplete, and only low speed correlations were made. Comparisons that exist of the predictions of Glosten of the low-frequency response with the measurements on the original Hood Canal Bridge show that the predictions were up to 20 percent of that measured, where such response accounted for up to 50 percent of the variance about the mean. This attempted matching of empirical and analytical studies has been largely abandoned in favor of the detailed reductionist approach previously described. The position of the various studies is that excellent tools exist to improve the precision of results, but overall accuracy has not been established.

THE PROBLEM

To have accurate predictions of the forces and behavior of existing floating bridges and for the design of new bridges, an approach that utilizes the extensive analytical schemes that exist, which allow improved precision with the availability of additional resources, and that evaluates the overall accuracy of these reductionist predictions should be established. From a practical view, confidence in the accuracy of predictions must exist before the precision of results is sharpened. The existing resources allow for improved precision but have little to say about overall accuracy.

It must be emphasized that even in the studied problem in fluid-structure interaction, the accuracy of predictive analysis is not high. Hogden et al. (1977) reviewed the literature on the determination of coefficients in the Morison equation for wave loads on *vertical* cylinders. Twenty-six examples were considered in which empirical evidence was available on the effectiveness of analytical predictions. For the ten situations in the field the predictions were not accurate. Typically, the measured and calculated local force maxima agreed to between 10 and 50 percent. For laboratory situations the agreement was better. The predictions in the floating bridge problem are more complex inasmuch as the wind and fetch-wave and the force-structure response predictions are required, as well as the wave- force prediction of the cylinder problem. This emphasizes the importance of overall accuracy in evaluating the validity of reductionist predictions.

RESEARCH APPROACH

The integration of the reductionist studies gives an estimation of bridge behavior. The accuracy of this estimate is evaluated from a system theoretic approach in which the input is the wind character and the output the kinematics of the bridge and derived internal forces. The relationship between input and output provides a transfer function. The form of the function is that given by a mathematical match, and little physical insight is evident. A transfer function is also the end product of the integrated reductionist analysis, but here physical insight exists at each step. The intention is to deal with accuracy by the input-output match. The various steps of the reductionist analysis will provide the precision in modeling, together with physical insight, and the integrated effects will be restrained by the input-output match. Thus, any sharpening of the various steps, either by improved modeling or by better parameter estimation, must not reduce the accuracy.

The 1981 paper by Brown et al. establishes the basis for the determination of an input-output relationship or transfer function for floating bridges. The intention of that work was to establish a maintenance program to avoid failure of the draw span of the Evergreen Point Floating Bridge. The measurements provided the frequency of strain levels in critical members of the drawspan mechanism and wind speeds and directions at the bridge site. The relationship between the measured strains and wind characteristics was determined by a linear regression fit of the form

$$y = c + mx + nz \tag{1}$$

where y is the strain, x the mean wind speed, and z the wind direction relative to the normal of the bridge. Regression constants c, m and n are were obtained by the regression fit; the goodness of fit was defined by the following:

$$R = \Sigma\, (y_m)^2 . (y_c)^{-2} \tag{2}$$

where y_m is the actual strain measurement and y_c the value computed from equation (1). The process involved measurements of x, y_m, and z; the computation of y_c by equation (1); and an evaluation of the process closeness of all y_c to y_m from equation (2). As an example, before the study 12,150 wind measurements, collected at 8-hour intervals from March 1964 through June 1975, were available. In the test period from 1974 through 1978, hourly measurements of the means of wind speeds and directions, together with maxima, minima, means, and standard deviations of strains in the same hourly intervals, were collected. These included 429 records of 68 minutes each when the wind speed exceeded 20 miles per hour. Equations (1) and (2) were applied to these 1974-1978 data, where y_c included the standard deviation of strains and the maxima and minima, and the absolute values of the differences of maxima and minima of strains. Values of R were bounded between 0.705 and 0.529, with an average of 0.648. The determination of strains from equation (1) for the 1974-1978 data was then used with the long-term 1964-1975 data to determine the frequency of occurrence of various strain levels over this longer period. This information was then used to determine the fatigue life of critical members by the use of empirically generated S-N curves.

This approach would determine the reaction of a floating bridge to winds without the evaluation of the separate wind-wave, wave-force-kinematics, wind-force-kinematics, and structural behavior characteristics. The intention is to obtain extrema of the internal forces from the kinematics, and the following measured data would be required:

a) regular (usually confined to speeds over 20 miles per hour) wind speeds and directions,

b) regular kinematic measurements at the same time periods as (a),

c) additional long-term wind measurements for which related kinematic values do not exist.

The data from (a) and (b) allow relations such as equation (1) to be established. Improved precision can be obtained, if justified, by using non-linear regression techniques. The kinematic

measurements may be obtained by the same type of scheme reported by Mukherji (1972) and Hartz (1972). The internal forces are provided by finite element programs of Glosten Associates. The validity of these programs can be checked by extending the instrumentation to include internal forces in the manner of the reports of Mukherji and Hartz. The incorporation of the long-term wind data of (c), if available, allows the incidence and values of extrema to be identified over a longer period of consideration.

The methodology described provides a relationship between wind and behavior that must be a constraint on the integrated reductionist studies described in the introduction. However, improved understanding of the performance of floating bridges will only occur from improvements in the individual reductionist studies. The collection of additional local data, sharpening of approximate arguments, and moves toward completeness in modeling are activities that could improve the understanding of bridge performance. Costs are associated with each of these activities. For instance, the actual damping can be measured by separating the structural from the fluid-structure interaction damping and then including the results in the analytical modeling. This is a large undertaking and is a competitor for resources available to study floating bridges. The choice of activity to be pursued can be governed by consistent crudeness arguments (Elms 1985; Castenada and Brown 1991). These arguments show that when many elements combine to produce an overall performance, then an improved understanding of that performance will only occur when the element least understood (the crudest element) is refined. Any sharpening of the less crude elements may increase precision but not accuracy. The methodology of selection of the crudest element in the cited papers is that of defining fuzzy entropies. The element with the highest entropy is the crudest. An optimum state of understanding occurs when the elements have much the same crudeness or entropy.

The procedure of constraining the combined results of the detailed analysis of various aspects of the behavior of floating bridges by gross relations between wind and kinematics serves to ensure accuracy. Precision and understanding can only be enhanced by improving the crudest aspects. In the case of the design of a new bridge, various aspects of the behavior studies of

existing bridges become important. The reductionist aspects provide insight into the changes in behavior by alterations in structural features, modeling, and parameter selection. Of particular significance is an understanding of the effects of changes in pontoon connectivity, anchor constraints, bridge width, and connections between the floating and fixed parts of the bridge. The overall response of existing floating bridges will be known by the various relationships between measured wind and behavior. In the design of a new bridge information will be available. For instance, the pontoons will be constrained in geometry by available casting facilities and towing limitations. The pontoons will have much the same length, height, and freeboard as the existing bridges. The connectivity, anchorage, width, and length between fixed parts will be matters for design decisions. The crucial data that must be available are the wind characteristics. With these available, the behavior of existing bridges in that location can be forecast, and adjustments can be made to these using the proven reductionist analyses to account for connectivity, anchorage constraint, width and floating length, and location to exhibit the behavior in a proposed design. By this procedure a design that has the best local arrangements to produce acceptable behavior in known extreme winds can be produced. When built, the actual behavior can then be compared with the design forecasts.

A more detailed discussion of the instrumentation of existing floating bridges follows. The forces on these structures are due to direct wind attack on the freeboard of the bridge and to wind generated waves at the water level and below. The direct attack on the freeboard will produce at the most 25 percent of the total force. The wind velocity along the length of the bridge may vary at a given time from location to location. This absence of coherence may produce varying forces of the first source along the bridge. The second source occurs in an extreme case when fully developed seas exist. This means that the average wind must be of sufficient duration to induce these seas. Interest here is in the far-field wind velocities, their duration, and the consequent behavior of the bridge. These classes of information from field measurements are required:

1. Wind Data

   a. far-field wind velocities at hourly intervals of five-minute duration when the speed is below a set value (e.g., 20 miles per hour) and continuous when above that value. A single gauge located 1 mile up-wind of the bridge will be required.

   b. wind velocities at the bridge in the manner described in the first part of this report ("Floating Bridge Design Forces (Wind on the Evergreen Point Bridge: January 27 to March 31, 1994")). To test coherence, three gauges should be employed at distances apart of the pontoon length. This length is much the same for extant bridges and about 250 feet.

2. Kinematic Data

   a. vertical translation and twist about the longitudinal axis. Two gauges to measure vertical motions, one at the up-wind and one at the down-wind wall of the pontoon at the same longitudinal location.

   b. lateral translation. Single gauge to measure lateral motion at the same longitudinal location as 2a above.

   Three sets of these gauge should be established at longitudinal locations at the interface of contiguous pontoons. In this way the gradients of these motions can be determined with respect to the critical characteristic length of the bridge as well as the flexure about the vertical axis. The measurement regime should be the same as that of the wind gauges in 1b above. The kinematic gauges should measure accelerations and velocities, and displacements can be obtained by integration with respect to time.

3. Strain Data

   a. strains on the windward side anchor tendons. Strains should be measured on all tendons holding three contiguous pontoons.

b. strains on the up-wind and down-wind outside tendons connecting pontoons. Three sets of strains should be obtained from adjacent pontoon interfaces with a measurement regime as the wind gauges in 1b above.

The wind at the bridge, kinematic and strain gauges will be located at the ends of the same pontoons. The wind data are denoted as W_a and W_b, the kinematic data as K_a and K_b, and the strain data as S_a and S_b. The change from the windless state in bending moments about the vertical axis and the change in forces in the anchor tendons over a prescribed time interval can be determined from S_a and S_b. These values, denoted as $y^m{}_m$ and $y^f{}_m$, can be checked, as previously mentioned, by introducing the K_a and K_b changes over the same time interval into the available finite element program. The W_a and W_b contain the wind speeds x_a and x_b, and the wind directions, z_a and z_b. Of interest is the introduction of x_a,z_a and $y^m{}_m$ or $y^f{}_m$ into equation (1) to determine either the best fit for $y^m{}_c$ or $y^f{}_c$. The goodness of these regression fits can be provided by equation (2). In this way a relationship between the far field wind and internal forces and moments can be attained. Also of interest are the bridge wind velocity data, W_b. Their coherence can be related to $y^m{}_c$ or $y^f{}_c$ at various locations and times. Additionally, the correlation between W_a and W_b can be established.

The empirical relationships between far field winds, local winds and interior forces can now serve the purpose of checking the accuracy of existing methods of predicting the behavior of floating bridges reviewed in this report. Improvements in these methods and consequent confidence will be critical in the design of new bridges when only limited far field wind data are available.

FINDINGS

Existing Bridges

To examine the accuracy of existing methods of predicting the behavior of floating bridges, the wind characteristics and kinematics of the bridges should be measured and related. The extent that the methods predict the kinematic behavior for the measured winds confirms the level of accuracy of the methods. Where shortcomings in the predictions exist, then those aspects of the methods with the greatest crudeness should be refined until satisfactory accuracy of the scheme is attained. The final outcome would be confidence in both the accuracy of the predictions and understanding of the effects of each aspect of the modeling on the final behavior. The effects of changes in structural features and parameter assignment would be known for the range of wind characteristics measured and would be understood with good confidence beyond the range

Design

Potential sites for future floating bridges should be identified, and wind measurements at the location should be collected. These measurements should be related to longer term wind data that exist at nearby sites. The behavior of designs should be predicted from the refined methods developed in the work on existing structures. Extreme winds should be determined from the analysis of nearby wind data and their relationship with the on-site measurements; the related predictions of bridge behavior to these extreme conditions would have to meet safety specifications for the design to be acceptable.

REFERENCES

Brown, C.B., Christensen, D.R., Heavner, J.W., Landy, M.A. and Vasu, R. (1981), "Floating Bridge Drawspan Maintenance," Journal of the Structural Division, ASCE, Vol. 107, ST 11.

Castenada, D.E. and Brown, C.B. (1991), "Consistent Crudeness Principles in Design and Forensic Decision Making," Civil Engineering Systems, Vol. 8, No.3.

Elms, D.G. (1985), "The Principle of Consistent Crudeness," Proceedings, N.S.F. Workshop on Civil Engineering Applications of Fuzzy Sets, Purdue University.

Georgiadis, C (1981), "Wave Induced Vibrations of Continuous Floating Bridges," Ph.D. Dissertation, University of Washington.

Hartz, B.J. (1981), "Dynamic Response of the Hood canal Floating Bridge," Proceedings, ASCE-EMD Specialty Conference, Atlanta.

Hartz, B.J. and Georgiadis, C. (1981), "A Computer Program for the Dynamic Analysis of Continuous Floating structures in Short Crested Waves', Proceedings, 2nd. Conference on Floating Breakwaters, Seattle.

Hartz, B.J. and Georgiadis, C. (1982), "A Finite Element Program for Dynamic Response of Continuous Floating Structures in Short Crested Waves," Proceedings, International Conference on Finite Element Analysis, Shanghai.

Hartz, B.J. and Richey, E.P. (1970), "Structural Response of Floating Bridge under Wind Wave Loading," Proceedings, ASCE National Structural Conference, Portland, Oregon.

Hartz, B.J. and Mukherji, B.(1971), 'Response of Floating Bridges to Random Wave Forces," Proceedings, ASCE-ASME National Transportation Engineering Conference, Seattle.

Hogden, N., Miller, B.L., Searle, J.W. and Ward, G. (1977), "Estimation of Fluid Loading on Offshore Structures," Proceedings, ICE, Pt.2, 63.

Hutchison, B.L. (1984), "Impulse response Techniques for Floating Bridges and Breakwaters Subject to Short-crested Waves," Marine Technology, Vol.21, No.3.

Mukherji, B. (1972), "Dynamic Behavior of a Continuous Floating Bridge," Ph.D. Dissertation, University of Washington.

Ochi, M.K. (1973), "On Prediction of Extreme Values," Journal of Shop Research, Vol. 17, No.1.

Pacific Builder and Engineer (1977), "The Lake Washington Floating Bridge: An Unprecedented Achievement," October 7.

The Glosten Associates (1991), "Wind and Wave Load Analysis Lacey V. Murrow Replacement Bridge," Vol 1., Pts. 1 and 2, Vol. 11, pts. 1 and 2, Appendixes, prepared for the Department of Transportation, State of Washington.

The Glosten Associates (1995), "Nonlinear Wave Forces and Wind Interactions on Floating Bridges," Preliminary Draft Report for Department of Transportation, State of Washington.

Tokola Offshore, and Earl and Wright (1979), "Hood Canal Floating Bridge Study: Phase 1: Determination of the Cause of Failure, Phase 11, Report on Recommendations for Replacement Structure', prepared for Washington State Department of Transportation.