EVALUATION OF BRIDGE FOUNDATION TYPE AND CONDITION USING STATIC RESPONSE MEASUREMENTS

Kenneth Maser
Infrasense Inc.
14 Kensington Road
Arlington Ma
02476-8016 USA

Masoud Sanayei
Tufts University
Dept of Civil & Environmental Engineering
113 Anderson Hall,
Medford, Ma 02155

KEYWORDS: Bridge Testing, Foundation Stiffness, Load Testing, Parameter Estimation, Unknown Foundations

ABSTRACT
Evaluation of bridge substructures for vulnerability to scour or other potential sources of damage requires knowledge of foundation conditions beneath piers and abutments that are often unknown. This paper presents a potential method for determining unknown foundation conditions which is simple and inexpensive. The method is based on strain and rotation measurements which are used to compute a stiffness matrix for the unknown foundation. The stiffness coefficients in the matrix are then matched with values previously determined for known foundations. The objective of the reported work has been to demonstrate the feasibility of this method. A full bridge finite element model has been developed. Field data has been collected on a test bridge and the results have been compared to the model predictions. Based on the model, a parameter estimation procedure has been formulated for the calculation of the foundation stiffnesses from the field rotation data. The paper describes the models, the numerical results, and the results of field testing.

INTRODUCTION
The objective of the work described in this paper has been to develop and demonstrate a simple, low-cost method for determining unknown bridge foundations. Such a method would be of great value in the assessment of the foundations of bridges which are vulnerable to scour and other sources of foundation degradation. Many bridges in the United States have foundation conditions beneath piers, headwalls and abutments that are unknown. For the most part, these bridges are the older ones off the federal aid system for which "as-built" drawings are not available. There is a critical need for a simple, low-cost system which can be used to determine the presence or absence of piles. If the foundation type is known, it is also desirable to determine the stiffness of the foundation to predict its resistance to seismic and other loading events.

The proposed method is based on response measurements at key locations caused by truck loading. The measurements are used to compute a foundation stiffness matrix for the unknown foundation. If sufficient measurements are made, the forces and displacements at the top of the foundation can be calculated, and the stiffness coefficients of the foundation can be calculated by the relationship between forces and displacements. Earlier work carried out under this "direct stiffness" showed that the ratios between the foundation stiffness coefficients could be used as indicators of foundation type (Maser et. al., 1998; Sanayei and Maser, 1999). The problem with the direct stiffness method is that it requires measurements of strains and displacements of piers and abutments, both of which are difficult to obtain.

An alternative approach for calculation of foundation stiffnesses is called parameter estimation. The advantage of parameter estimation is that it allows for the use of fewer, simpler measurements. For example, it may be possible to use rotation measurements alone (Maser et. al, 1998).
The overall concept is illustrated in Figure 1. In the proposed method, the key unknown to be determined is the foundation stiffness matrix \([K_{sss}]\) of a soil-substructure superelement (SSS). The components of \([K_{sss}]\) are then matched with previously determined patterns generated through a combination of field data and analytic foundation models, for a variety of foundation types and conditions. The best pattern match will determine the type and properties of the unknown foundation. The matching process will be supported by other available information, including measurements of the foundation footprint area (e.g., using GPR), estimation of dead loads to determine soil pressure (or pile loadings), and soil property and bedrock depth information from borings.

The concept is illustrated in two dimensions in Figure 1 for the case of characterizing the type and condition of a pier foundation. The figure shows a 2-dimensional free-body diagram of a pier, showing the loads transmitted by the superstructure and the reactions at the foundation. The relationships between the foundation reactions and the foundation displacements and rotations can be expressed as: \([F] = [K_{sss}][U]\), where \([F] = \{F_h, F_v, M_f\}\) is the vector of reactions at the foundation; \([U] = \{d_h, d_v, q\}\) is the vector of displacements and rotations at the foundation; and \([K]\) is the soil-substructure stiffness matrix. In finite element terminology, all of the stiffness properties of the foundation have been lumped into the SSS, and \([K]\) represents the stiffness matrix of this superelement. The SSS element attempts to capture the behavior of a complex soil-structure system in a simplified form, which, in two dimensions, is summarized by the 3x3 matrix as shown in Figure 1:

\[
K_{sss} = \begin{bmatrix}
K_{HH} & K_{HV} & K_{Hq} \\
K_{HV} & K_{VV} & K_{Vq} \\
K_{Hq} & K_{Vq} & K_{qq}
\end{bmatrix}
\]

Figure 1 - Pier Foundation Model -- Spread Footing versus Pile

The elements of \([K_{sss}]\) represent the resistance to movement produced by the foundation, and can be calculated from measured rotations using parameter estimation techniques. These elements (six in 2D and 21 in 3D) can then be used to determine the structural characteristics of the foundation. It is anticipated that each type of foundation (e.g., spread footing on soil, spread footing on rock, friction pile, and end-bearing pile) will have a unique pattern of stiffness coefficients.
One objective of the work described in this paper was to develop parameter estimation as a method which can determine the foundation stiffness coefficients from simple field measurements.

FIELD MEASUREMENT PROGRAM

A field test on an in-service bridge was carried out to provide data to test out the method for calculation of foundation stiffnesses. The bridge (Fruit Street over I-495 in Hopkinton, MA) had been tested previously during an earlier phase of the project (Maser, et. al, 1998), but the tests were repeated with an improved instrumentation system and measurement approach. The tests involved a loaded dump truck with measured axle loads driving slowly across the bridge. The bridge has three spans and is simply supported. It was instrumented for rotations, strains, and displacement as shown in Figure 1. Truck position was continuously recorded using a manual reference marker with a radio link to the data acquisition system. The test bridge (Fruit Street) was closed to traffic briefly while the truck was crossing. Two bridges in eastern Massachusetts were tested. The characteristics of the two test bridges are summarized in Table 1 below. All spans are simply supported, and the superstructures are designed with shear connectors between the girders and the deck, so that composite behavior between the girders and decks can be expected.

Table 1 - Characteristics of the Fruit Street Test Bridge

<table>
<thead>
<tr>
<th>No. of Spans</th>
<th>Span Lengths</th>
<th>Girder Type</th>
<th>Girder # &amp; Spacing</th>
<th>Pier Tested</th>
<th>Deck</th>
<th>Skew</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1 - 98’6”</td>
<td>54” Pl girder</td>
<td>5 at 7’3”</td>
<td>between spans 1 and 2</td>
<td>8” concrete 2½” asphalt</td>
<td>28°±</td>
</tr>
<tr>
<td></td>
<td>2 - 69’9”</td>
<td>36WF135</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 - 101’9”</td>
<td>54” Pl girder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 - Fruit Street Bridge

The bridge was instrumented for rotations on the girders and piers, strains on the columns, and relative displacement at the bearings. A 12 channel custom designed data acquisition system was used to collect, digitize, and download the data to a laptop computer. The tested pier consisted of 3 columns as shown in Figure 3. The tests were carried out by instrumenting the center column, and adjusting the stiffness results to represent the stiffness of the entire pier. The truck loading was along the centerline of the deck, and so symmetry could be assumed for the two side columns. Measurements were made on one side
column to verify the load distribution between the three columns. The arrangement of instrumentation is shown in Figure 4.

![Figure 3 - Layout of the Fruit Street Pier](image)

In Figure 4 the prefixes “T” and “S” refer to tiltmeters and strain gages, respectively. Two strain gage pairs were attached at two different heights of the test column. This arrangement permitted the calculation of bending moments at two different heights, which then allowed for the calculation of the horizontal (shear) force on the column. Axial force can also be calculated from either strain gage pair.

**Bridge Finite Element Model**
A finite element model was developed for the bridge to a) help to understand the observed behavior, and (b) to serve as a basis for the parameter estimation procedure. The actual model consisted of 65 elements and 192 degrees of freedom, and is shown schematically in Figure 5. At the girder-pier interface rigid link elements were used to model the offset of the superstructure neutral axis from the bearing support.
In the model, the bridge was loaded with a 43.6 kip truck (front axle 11.3 kips, rear axle 32.3 kips) at 17 different loading positions in each direction on the deck.

![Diagram of Bridge Model](image)

**Figure 5 - Schematic of Bridge Model using Frame and Foundation Elements**

The model is two dimensional, and is based on the assumption that the truck loading is along the centerline of the deck. In order to model the bridge in two dimensions, the following assumptions were made: (1) the truck load is totally carried by 3 of the 5 girders acting compositely with the contiguous deck area; (2) the vertical load is totally carried by the equivalent of 2 of the 3 columns which make up each pier; and (3) the foundation stiffness reacting against the pier is two thirds of the total foundation stiffness. The sections properties of the superstructure and pier elements were taken from plan drawings of the bridge. The foundation stiffnesses were calculated from theory using Lamb and Whitman (1969) for the diagonal elements and Beredugo and Novak (1972) for the off-diagonal terms.

Calculations using the above model were compared to the field data, and typical results are shown in Figure 6. The data in Figure 6 indicates that the model accurately replicates the observed behavior of the bridge pier.

![Graph of Model Predictions vs. Field Data](image)

**Figure 6 - Model Predictions vs. Field Data**
Parameter Estimation Feasibility Study

In order to test out the parameter estimation procedure for calculating the foundation stiffness from field data, numerical simulations were carried out using the bridge model described above. Bridge rotations are simulated using the model, and these simulated rotations are then treated as “field data.” Numerical simulations are then carried out, in which certain parameters, such as the foundation stiffnesses, are treated as “unknown.” Initial guesses are made for these parameters (values known to be incorrect), and the parameter estimation process is applied. In a successful parameter estimation process, the “unknown” parameters will converge to the “true” values (those used to create the simulated rotations). An additional test of the parameter estimation process is to investigate the influence of small measurement errors, to ensure that the calculation is not grossly affected. This is called “error sensitivity.” In error sensitivity studies, measurement error is superimposed on the simulated field data, and the convergence of the unknown parameters is investigated.

For the feasibility study, the section properties of the deck/girder combination and the piers were taken as unknowns, along with the foundation stiffnesses. This was done because there was reason to believe that these could not be accurately calculated from plan drawings. The parameter estimation studies utilized 9 truck loadings positions, three on each span. The feasibility studies looked at two aspects of the problem: (1) convergence; and (2) error sensitivity. Convergence studies focused on the ability to converge on values for the unknown parameters after a reasonable number of iterations, and on the assurance that the results converged to the “true values.” Once this first step yielded satisfactory results, the second step focused on the ability to achieve a stable solution in the presence of small measurement errors. This second step was accomplished using Monte Carlo simulations with a random uniform error applied to the various measurements.

The results of these two phases of the feasibility study has led to the following results:

A. Diagonal foundation stiffnesses can be calculated from rotation measurements alone. Small errors in measurement do not have a significant effect on this capability.
B. Superstructure and pier component stiffnesses do not have to be estimated. They can be treated as unknowns in the parameter estimation model. Their values are calculated along with the foundation stiffnesses.

CONCLUSIONS

A method has been proposed for identifying unknown foundations through static testing by calculating and evaluating foundation stiffness coefficients. These coefficients represent the overall resistance of the foundation to vertical, horizontal, and rotational loadings, and have been investigated as a means of characterizing the foundation type. Knowledge of these foundation stiffness coefficients is useful not only for determining foundation type, but also for evaluating foundation conditions and for determining baselines for future condition evaluations.

ACKNOWLEDGMENT

The authors would like to acknowledge Ms. Amy Stern and Chitra Javdekar, Graduate Students of Tufts University, for their work in formulating the bridge model and in conducting the parameter estimation simulations; Ms. Laura McGrath of INFRASENSE for her assistance in analyzing the field data, Mr. Abba Lichtenstein, for his overall guidance and direction, and Dr. Steven Chase, FHWA, for his overall direction of the program. The work was carried out under an SBIR Grant from the U.S. Department of Transportation.
REFERENCES

Lambe and Whitman, Soil Mechanics. 1969, Massachusetts Institute of Technology, Cambridge MA.
