February 2010

Research Note

Seismic Assessment of WSDOT Bridges with Prestressed Hollow Core Piles

Washington State Department of Transportation

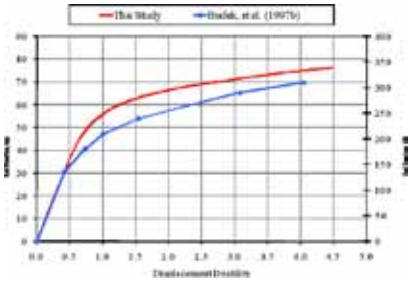
Background

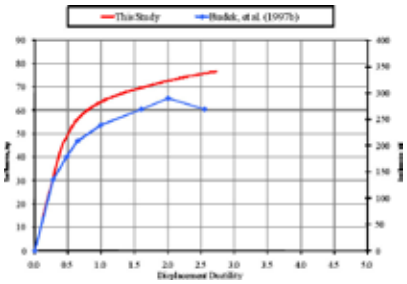
The current Washington State Department of Transportation (WSDOT) began a bridge seismic retrofit program in 1991. A total of 879 bridges statewide have been identified as needing retrofit with 230 of those completed to date. There are an additional 23 bridges that are supported by prestressed hollow core piles mainly located in the Puget Sound area. These bridges have been excluded from the seismic retrofit program since information about their performance following an earthquake and the retrofit options are unknown. The work of this project is directed at learning more about the seismic performance of these bridges.

The Problem

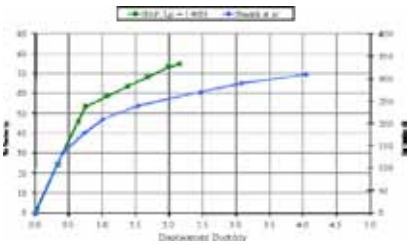
Bridges with hollow prestressed reinforced concrete piles were built in the 1960's at selected locations in the Seattle-Tacoma area on Interstate 5, Interstate 405 and State Route 520. Experimental tests have shown that when piles of this type are loaded to failure, they fail in a brittle manner, which is highly undesirable in seismic regions. The failure mechanism is not well understood and, as a result, the seismic resistance of existing bridges founded on actual piles is difficult to quantify. The objectives of this research were: (1) to develop and verify numerical structural models that can accu¬rately simulate the behavior of prestressed hollow core piles; (2) to use similar models to investigate the effect of soil confinement, locate the plastic hinge, and quantify the strength of actual piles in place; (3) to de¬velop an understanding of the behavior and the failure mechanism of the connection between this type of pile and other struc¬tural members; (4) to assess the seismic performance of a bridge founded on this type of pile using nonlinear static (NLS) and nonlinear dynamic (NLD) analyses; and (5) to assess the effects of the soil type on the response of this bridge.

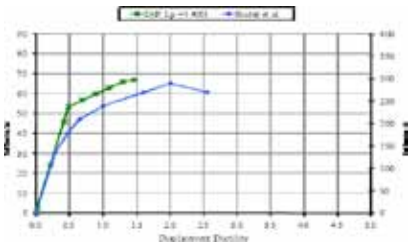
What We Did





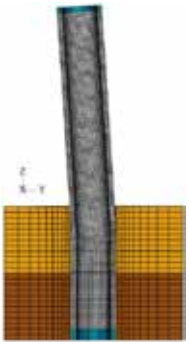
The first task was to develop a detailed Finite Element structural model of two pile specimens that were used in earlier tests. As shown in the figures to the left, the models replicated reasonably well both the behavior and the strength of the specimens.

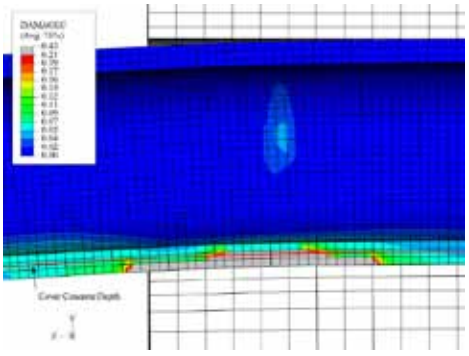




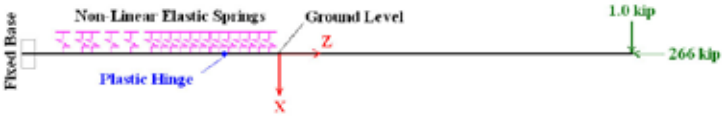
Because the use of a detailed 3-D finite element model is impractical for analysis of a full bridge system, a much simpler beam model using state-of-the-art design tools was also developed and compared with the tests. Results are less accurate, but reasonable, as shown to the left.

The second task was to determine whether confinement of the concrete from the soil pressure affects its behavior in service. Also of interest is the length and location of the plastic hinge that would form in an earthquake. For this, a full 3-D finite element model of a typical pile in service was generated. Two soil types were considered, and the confining pressure, the area of its application, and the plastic hinge length were recorded. The results, consisting of cross section views, are shown below for a flexible clay soil. The damaged region in gray indicates concrete crushing and defines the plastic hinge.

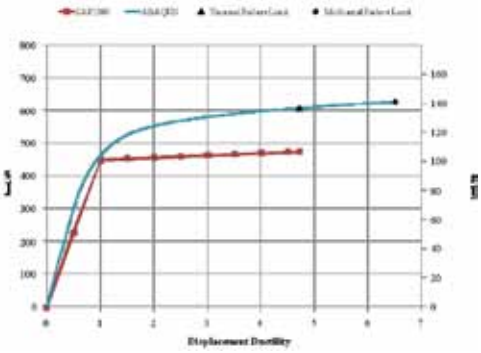




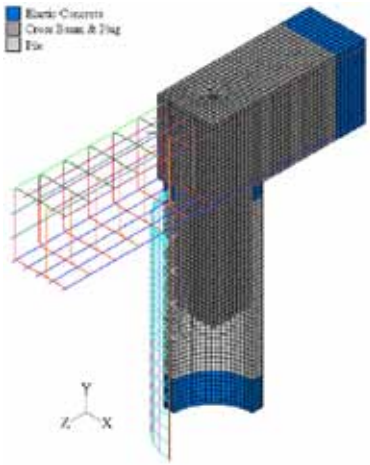
The failure load and the extent of soil pressure applied to the pile were obtained. Then, a simple beam model was developed as before, but with spring supports to account for the stiffness of the surrounding soil.

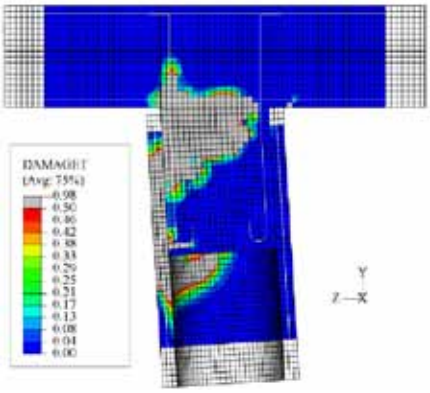


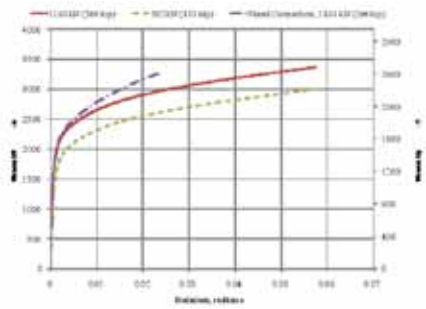
The results of the simple model are compared to those of the full finite element model. Again, the results are less accurate, but they are reasonable and conservative.



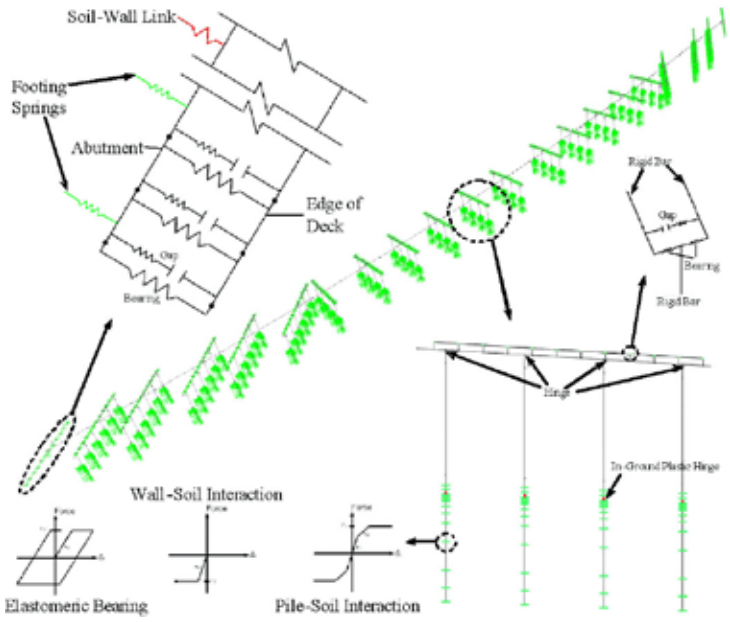
A related task was to develop an understanding of the behavior and failure mechanism of the connection between the pile and the cross beam of an actual bridge. In addition, its moment-rotation response was desired to allow better modeling of this type of connection in the overall seismic analysis of a bridge. A full 3-D finite element model of the connection was developed. Moment was applied until failure occurred for two values of axial force in the pile. A cutaway view of the model and the damage at failure are shown to the right. The damaged areas shown in gray indicate concrete cracking. Moment-rotation results are given below for two values of axial force and the case of the assumption of fixity in the connection.







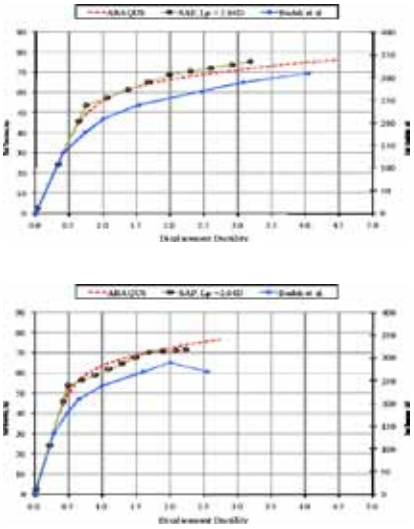
Using the above results, a three-dimensional "spine" model of a representative bridge (the I-5 Ravenna Bridge) was developed, as shown below, including the effects of bridge bearings, expansion joints, and soil-structure interaction.



The nonlinear dynamic response of the bridge was investigated by using three ground motions with different return periods, one designated as Moquegua (Peru earthquake, 2001), and two from the Olympia, Washington earthquake (1949). The Moquegua earthquake had a 2475-year return period (hereinafter referred to as EQ3), while the other two earthquakes had 975-year and 475-year return periods (hereinafter referred to as EQ2 and EQ1), respectively. The Moquegua ground motion is a long-duration earthquake, while the other ground motions are short-duration events. Because of the influence of the inherent uncertainties in boundary conditions on the expected displacements of the structure, the pile and abutment springs were also modeled on the basis of two other soil types besides the one that most likely exists at the site. One was relatively stiff (dense sand), while the other was relatively flexible (clay).

What We Learned

- Failure in this type of pile occurs when concrete in the compression zone spalls, exposing the reinforcing steel and prestressing tendons, allowing them to buckle. The 3-D finite element model was shown to be capable of capturing this behavior and is thus a valid tool to evaluate piles in service.
- The simplified beam models were adequate and conservative for predicting pile behavior. However, accuracy in predicting pile ductility was sensitive to the plastic hinge length specified. The behavior shown above was based on current design values



used in practice (i.e., 1.4D, where D is pile diameter). The subsequent detailed analysis of in-service piles indicated significantly higher plastic hinge length (i.e., approximately 2.64D). When these values were used in the simplified model, accuracy improved, as shown to the left for both specimens.

- Concrete tensile strength, fracture toughness, and pile prestressing force are the most influential parameters on the performance of the pile. External confinement was small, and it had little effect on load capacity and displacement ductility due to the hollow core.
- The behavior of the pile to crossbeam connection was dominated by cracking in the concrete. While it can resist significant moment prior to widespread cracking, most of the stiffness would likely be lost for subsequent cyclic loading.
- Relatively stiff soil led to the most conservative results of the three soil models considered. Piles are much more vulnerable to failure in that type of soil, where even the low level earthquake, EQ1, induced overall bridge failure. Relatively flexible soil led to the least conservative results, because the bridge behaved elastically for both EQ1 and EQ2 in NDL analysis. Failure was still induced to the bridge for EQ3, however.
- Overall performance of the piles is nonductile, and failures are very brittle. The shear force-displacement hysteresis curves reinforce this observation, where elastic behavior of piles is followed by an immediate and abrupt failure in all failure cases. Ductility values are on average less than 1.5 considering overall bridge performance.
- Including the stiffness of the pile-crossbeam connection, as defined by the finite element model, improved the predicted performance of the bridge significantly. NLS analysis resulted in no failure for all earthquake levels. Also, the performance displacement for the maximum level earthquake, EQ3, was on average less than 62% of the Ultimate Limit State, compared to that for the model with no connection stiffness. However, the NDL analysis showed that, while a large portion of the connections experience yielding, the failure of the bridge is still governed by the piles.
- Since the bridge that was considered was curved and quite long, the NLS analysis proved to be inaccurate in comparison with the NLD analysis due to the increased significance of the relatively higher modes of vibration.
- The bridge under consideration is safe for a 475-year-return-period earthquake, but the larger earthquakes will probably cause failure.

What The Researchers Recommend

- For seismic modeling of bridges with this type of pile, beam elements with spring supports for the soil are adequate and conservative for representing the behavior of the piles. Moment-curvature properties may be obtained from cross section analysis. While the use of plastic hinge lengths from current practice are conservative, accuracy is increased when the hinge length is increased by a factor of approximately 2.
- The pile-crossbeam connection is capable of developing significant strength before widespread cracking occurs. The use of a nonlinear, damaging rotational spring to represent this connection in bridge models is recommended for accuracy. However, if such a spring is not available, consideration of the connection as a pin is reasonable and conservative.
- NLS analysis offers great insight into the ultimate capacity of the bridge, but it cannot be relied on in practice to accurately predict performance under actual earthquake loads. It is highly recommended for future studies that research be conducted in the area of "Multi-Modal Pushover Analysis", where the higher mode effects are accounted for.
- Based on the research conducted, the piles of the Ravenna Bridge are prone to failure under large earthquake loads. Considering that the failures are likely to be brittle, it is recommended that research be conducted to determine the most effective way to increase their ductility.

How WSDOT Plans To Use The Results

WSDOT plans to use the results of this research to provide supporting information on developing a seismic retrofit plan from bridges with hollow core piles. WSDOT needs to review possible retrofit options for these bridges to determine the best plan of action.

Report Titles and WA-RD

Seismic Assessment of WSDOT Bridges with Prestressed Hollow Core Piles

Part I – WA-RD 732.1
www.wsdot.wa.gov/research/reports/fullreports/732.1.pdf

Part II – WA-RD 732.2
www.wsdot.wa.gov/research/reports/fullreports/732.2.pdf

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