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RESEARCH PROGRAMS

Implementation Report

Performance of Steel Pipe Pile-to-Concrete Cap Connections Subject to Seismic or High Transverse Loading: *Phase III Confirmation of Connection Performance*

http://www.mdt.mt.gov/research/projects/structures/seismic.shtml

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Introduction and Purpose

The Montana Department of Transportation (MDT) has found concrete-filled steel tube (CFT) piles connected at the top by a concrete pile cap to be a very cost effective support system for short and medium span bridges. This type of system offers low initial cost, short construction time, low maintenance requirements, and a long service life. From a structural engineering perspective, these systems must provide acceptable performance under gravity (i.e., self weight and vehicle loads) and lateral loads (i.e., extreme ice, wind, and seismic events). While the gravity load performance of these systems is well understood, their strength and ductility under extreme lateral loads is more difficult to reliably predict using conventional design procedures. Therefore, MDT sponsored a research project at Montana State University (MSU) to investigate the performance of these systems under extreme lateral loads.

In Phase II of this investigation, completed in 2005, MSU conducted five physical tests on half-size models of the CFT to steel pile cap connection. The models were designed to replicate the behavior of full-size connections under reversed seismic loads. Four different connection-reinforcing schemes were evaluated. Based on these tests, in conjunction with established structural engineering principles, MDT developed a new design procedure to determine the reinforcing steel required in the pile cap to produce the desired system performance under lateral loads. While the layout of the reinforcing steel generated by this design procedure is generally similar to the successful layout that was evaluated in the final Phase II pile cap test, there are several differences between the reinforcing configuration that was tested and what the design procedure generates. Notably, the design procedure provides for a simpler arrangement of the reinforcement (a set of U-shaped reinforcing bars that encircle the embedded CFT) that offers some advantages relative to the constructability of the pile cap.

Therefore, Phase III of the project was executed in which the design guide was exercised across a range of design situations and subsequent connection performance was experimentally evaluated. As part of this effort, a fairly thorough review of the design guide methodology beyond just those provisions directly exercised in the test series was completed. The following actions will be taken based on the recommendations from Phase III of this project.

Implementation Summary

- AASHTO incorporated the American Institute of Steel Construction's methodology for calculating the plastic-moment capacity of CFTs into the new seismic design specification. MDT plans to adopt the AASHTO specification.

◊ MDT will reduce allowed concrete compressive strengths and include interior U-bars near the tip of the embedded pile, as appropriate, to delay the onset of crushing in the interior of the cap.

◊ Recognizing the potential benefits of mechanics based models relative to empirical relationships to describe physical behaviors, MDT and MSU either independently or collaboratively may further research and develop such models to better characterize longitudinal yield behavior of the U bars .

◊ Similarly recognizing the advantages of developing a more robust analytical model to predict cap splitting, MDT and MSU either independently or collaboratively may further research and develop such a model.

◊ To address possible unconservative branching of the design process based simply on level of moment demand on the connection as a fraction of CFT plastic moment capacity, MDT will remove this "branch".

Implementation Recommendations

Recommendation 1: Adopt the American Institute of Steel Construction's methodology for calculating the plastic-moment capacity of CFTs.

The MDT design methodology predicts the capacity of the CFT solely based on properties of the steel pipe and ignores the effects of concrete and axial load. In many design scenarios, this simplification would be conservative; however, this simplification would be unconservative if the design of the connection assumes that plastic hinging limits the maximum moment transferred to the cap by the CFT.

One possible improvement to predicting the plastic-moment capacity of CFTs might be to adopt the American Institute of Steel Construction's methodology for calculating the plastic-moment capacity of CFTs, as this methodology has been shown to be accurate at axial load ratios common in bridge applications.

Technical Panel Response:
AASHTO incorporated the American Institute of Steel Construction's methodology for calculating the plastic-moment capacity of CFTs into the new seismic design specification. MDT plans to adopt the AASHTO specification.

Recommendation 2: Reduce allowed concrete compressive strengths and include interior U-bars near the tip of the embedded pile, as appropriate.

The design guide accurately predicts/delays the limit state of exterior crushing of the cap concrete in the connection zone (which signifies/initiates ultimate failure). It is not, however, effective at predicting the onset of crushing in the interior of the cap, which was shown to reduce connection fixity (resulting in a pinched hysteresis response) and increase degradation under cyclic loads.

The concrete crushing limit state could be addressed by reducing allowed concrete compressive strengths and/or including interior U-bars near the tip of the embedded pile, which were shown to delay the onset of this limit state.

Technical Panel Response:
MDT will reduce allowed concrete compressive strengths and include interior U-bars near the tip of the embedded pile, as appropriate.

Recommendation 3: Develop a mechanics model to better describe the effect of U-bars on the longitudinal yielding limit state and reduce reliance upon empirical factors.

Yielding of the longitudinal reinforcement was predicted well by the design guide; however, this provision may still merit further review and revision. The design methodology primarily addresses this limit state by including additional steel beyond that which is required from a normal design of the cap for global bending. This process is dependent upon a calibration factor (75 percent reduction in required steel from a mechanics model) based on empirical data from the test series completed for MDT at MSU in 2005. Although this methodology was shown to be effective in this test series, the efficacy of this calibration factor has not been verified across all possible cap configurations.

To more comprehesively address yielding of the longitudinal reinforcement in the cap, it may be desirable to develop a mechanics model to better describe the effect of U-bars on this limit state, and reduce reliance upon empirical factors.

Technical Panel Response: MDT recognizes the potential benefit of this proposed work, which may be conducted by MDT or MSU in-house, or through a collaboration between MDT and MSU.

Recommendation 4: Develop a more robust analytical model to predict cap splitting.

The splitting limit state (marked by yielding of the transverse reinforcement and formation of splitting cracks) was observed in all test specimens, but not until after other limit states had been reached. While this limit state was not directly a focus of this investigation, this positive performance indicates that the MDT design methodology using AASHTO's specifications for minimum reinforcement in plastic-hinge zones and including U-bars, is effective at delaying it. That being said, the amount of transverse reinforcement specified following this approach is not directly based on the moment demand the connection must carry.

Development of a more robust analytical model to predict cap splitting may be merited to reduce reliability on empirical factors and to generally improve design efficiency.

Technical Panel Response: MDT recognizes the potential benefit of this proposed work, which may be conducted by MDT or MSU in-house, or through a collaboration between MDT and MSU.

Recommendation 5: Address possible unconservative branching of the design process based simply on level of moment demand on the connection as a fraction of CFT plastic moment capacity, by removing this "branch".

In executing this project, a thorough review of the design guide beyond just those parameters directly exercised in this test series was completed. This review revealed a specific aspect of the design guide that apparently could yield unconservative results, and thus should be addressed. The provision of concern determines whether the connection will be specifically designed to carry the moment demand on it or if the reinforcing provided in a normal flexural design for global bending is sufficient. This branching is based on the moment demand's relation to the plastic-moment capacity of the CFT, and is reliant on an assumption that the dimensions and reinforcing of the cap cross-section proportionally increase with increased pile capacity. However, this assumption may not be valid, as some bent configurations may fall outside of those typically encountered in developing this provision.

To address possible unconservative branching of the design process based simply on level of moment demand on the connection as a fraction of CFT plastic moment capacity, this "branch" could simply be removed. If it were removed, the connection would always be designed based on the moment demand and would include additional reinforcement in the form of U-bars.

Technical Panel Response: To address possible unconservative branching of the design process based simply on level of moment demand on the connection as a fraction of CFT plastic moment capacity, MDT will remove this "branch".