Montana Department of Transportation **April 2005**

RESEARCH PROGRAMS

Project Summary Report 8144
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Performance of Steel Pipe Pile-to-Concrete Bent Cap Connections Subject to High Transverse Loading: Phase II

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

Introduction

A cost-effective bridge support system used by the Montana Department of Transportation (MDT) incorporates a linear array of concrete filled steel pipe piles connected at the top by a concrete pile cap. The techniques used to design the pile-to-pile cap connection were not developed to explicitly address the situation of a large rigid pipe element embedded in a conventionally reinforced concrete structure. While these connections are expected to perform adequately under in-service gravity loads, their behavior under extreme lateral loads (seismic and ice loading) was uncertain. Therefore, MDT initiated a project at Montana State University (MSU) to investigate the behavior of these connections under extreme lateral loads.

What we did

The behavior of the concrete filled, steel pipe pile-to-concrete pile cap connection was investigated using a combination of experimental testing and analytical modeling. The experiments were designed to provide a general indication of the manner in which these connections behaved relative to their failure mechanism, ultimate capacity, ductility, and energy dissipation characteristics. The results of the experiments were also used to evaluate various methodologies that are available to analytically predict the capacity and/or the behavior of these connections (i.e., simple "hand" calculations, strut and tie modeling, and finite element analysis).

Five ½-size models of the connection were tested to failure under monotonically increasing and/or cyclic lateral loads. The basic model geometry and test set up replicated the behavior of a typical interior connection in a full size bent subjected to lateral seismic loads. The wall thickness of the steel pipe pile, and the amount and arrangement of the reinforcing steel in the concrete cap were varied between tests. The depth of embedment of the pile into the pile cap (set at ½ of the depth of the cap) and the materials used in constructing the pile and cap were kept constant, though some variations did occur in the materials' properties (e.g., strength of the concrete in the cap).

Each model consisted of a single pile and an attendant length of pile cap. The pile cap was held in position on each end (near the theoretical points of inflection in the cap of a full bent when subjected to a lateral load), while a lateral load was applied to the tip of the pile (Figure 1). In addition, a constant

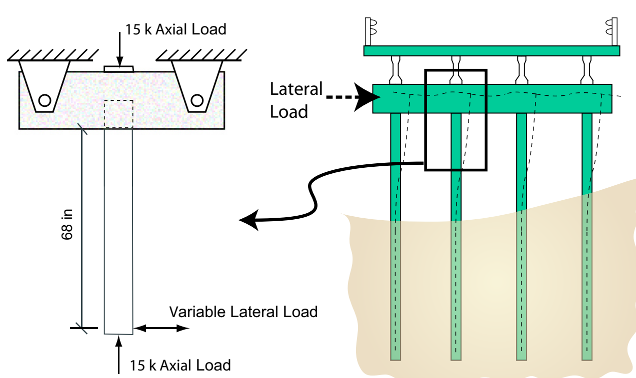

Figure 1. Pile to Pile Cap Connection Study Geometry

axial force was applied to generate the gravity load effects expected to be present in the full size structures during a lateral load event. Measurements were taken during each test of the loads applied to the connection, and of the global displacements and internal strains that resulted from these loads. These results were then compared with those obtained from hand calculations, strut and tie models, and finite element analyses.

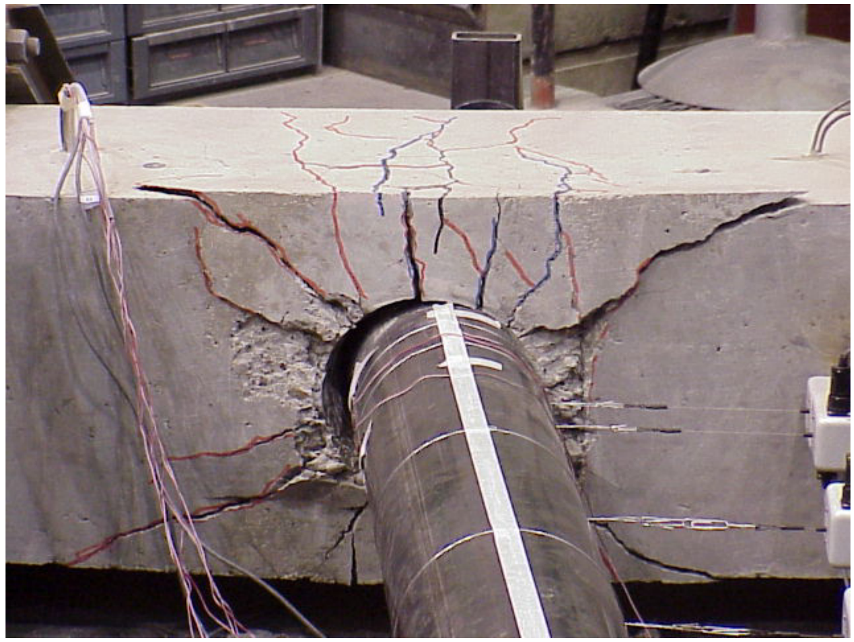

Figure 2. PC-2 Fractured Pile Cap

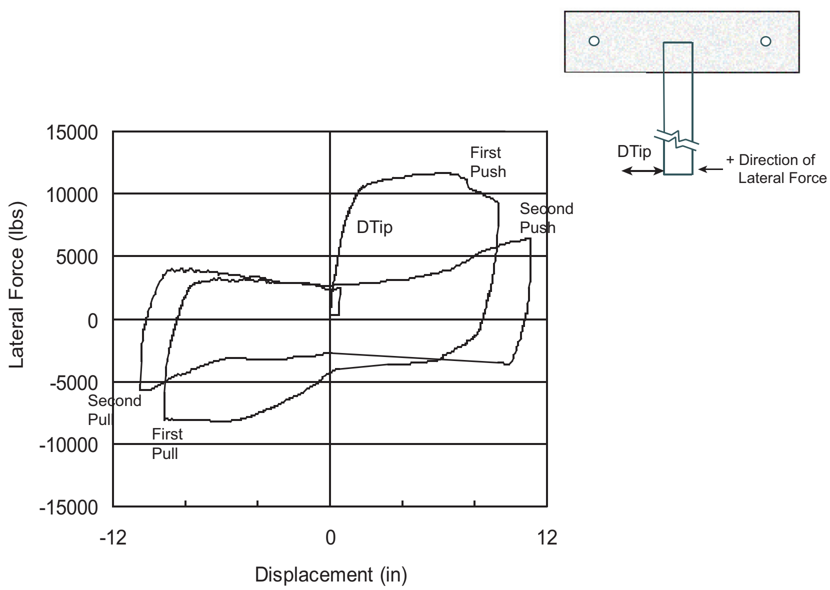

Figure 3. PC-2 Pipe Pile Lateral Load vs. Lateral Displacement

What we found

The first two connection models (PC-1 & PC-2) were constructed consistent with typical practice for full size structure pile cap reinforcement. The reinforcing steel ratios in the longitudinal and transverse directions of the caps were 0.41 and 0.09%, respectively. The steel pipe piles had diameter to wall thickness ratios (D/t) of 27 and 34.5, respectively, for PC-1 and PC-2. The predicted ratios of the moment capacity of the pipe piles to the moment capacity of the caps were 1.46 and 1.2, respectively, for PC-1 and PC-2, as compared to the calculated ratio of 1.1 for the actual full size connections. When these connections were subjected to increasing lateral loads, the caps failed through concrete cracking accompanied by large strains in the reinforcing steel adjacent to the pipe piles. The pipe piles were generally undamaged during the tests. It appeared that the reinforcing steel was unable to carry the tension forces transferred to it when the concrete cracked without sustaining large strains. Following the initial failure of PC-2, this connection was subjected to two cycles of fully reversed load. The maximum resistance of the connection and its energy dissipation capacity decreased during each successive load cycle. The hysteresis curves exhibited the "pinched" behavior often seen in reinforced concrete elements that have inadequate confining steel to maintain their resistance across multiple cycles of damaging response (Figures 2 & 3).

In succeeding tests (PC-3, 3a, and 4), the amount of longitudinal and transverse steel used in the cap was increased. The reinforcement arrangement was also changed in tests PC-3a and 4, to provide better concrete confinement adjacent to the pipe pile and more effective load paths for the reinforcing steel in the cap to carry the tensile stresses generated by the rotation of the pipe pile. In tests PC-3 and PC-3a, failure of the connection still occurred through tensile cracking of the concrete and excessive deformation of the reinforcing steel in the cap, although an increase in the moment capacity of the connection was seen. The amount of longitudinal and transverse steel (2.83 and 0.70%, respectively) in the PC-4 cap was increased to the point at which constructability issues were becoming a concern, due to the number, size, and relatively close spacing of the reinforcing bars. This model failed through the formation of a plastic hinge in the steel pipe pile, accompanied by only nominal concrete cracking in the pile cap.

The displacement ductilities were 3.3, 3.3, 3.5, 2.6, and 3.9, respectively, for the connection configurations in tests PC-1, 2, 3, 3a, and 4. The reduced displacement ductility in test PC-3a may be related to the increased reinforcement used in the cap and a possible shift in the failure mechanism. The displacement ductility of 3.9 reported for model PC-4 is conservative, in that this test had to be terminated when the maximum allowable displacement of the test frame was reached; there was no evidence at this point that the full plastic capacity (or plastic displacement) of the connection had been realized. Model PC-4 was also subjected to a fully reversed cycle of lateral load, with no reduction in the maximum capacity of the connection or in its energy dissipation capacity.

Simple hand calculations and strut and tie models reasonably predicted the nature of the failure and failure capacity in moderately to heavily reinforced cross-sections in each test. However, the strut and tie models offered significantly more information on the behavior of the various elements of the cap without stepping up to the level of complexity of solid finite element models. While hand methods only address compression in the concrete and tension in the longitudinal reinforcing immediately adjacent to the pile, the strut and tie models provided an indication of the stresses in the transverse ties, along the length of the longitudinal steel, and throughout the concrete, using commonly available structural engineering analysis software. The attraction of using such software was the ability to create and analyze strut and tie models that offered highly redundant load paths through the structure. The one drawback of implementing strut and tie models in conventional structural engineering software was that such software generally only performs elastic analyses, so the load redistribution that takes place during plastic behavior was not well represented.

Similarly, the finite element models (ANSYS, NIKE3D, DYNA3D) worked well for evaluating the initial elastic response of the connection, providing useful information on the nature, location, and load levels at which permanent deformation initiated, and evaluating three-dimensional variations in the stress-strain responses. However, the codes had difficulty tracking the nonlinear behavior associated with concrete damage (notably, cracking), particularly for cases with cyclic loads where significant concrete damage was involved. Despite these difficulties, finite element analysis still offers an approach to assess the possible desirability of any given connection design, relative to the type of failure that will first initiate, as well as the load level at which failure will initiate.

What the researchers conclude

Based on the results of this research, MDT can more accurately estimate the expected performance of the steel pipe pile, concrete pile cap bridge support system under extreme lateral loads. More specifically, this investigation provided useful information on how the amount and arrangement of the pile cap reinforcing steel affects the load carrying capacity and ductility of the pile-to-pile cap connection. Traditional designs, using 0.41 and 0.09% steel in the cap in the longitudinal and transverse directions, respectively, were found to fail in the cap as the lateral load on the system was increased. It was found that by significantly increasing the amount of reinforcing steel in the cap (i.e., to 2.83 and 0.70%, respectively, in the longitudinal and transverse directions) and altering its arrangement, the cap could be sufficiently strengthened so that failure of the connection occurred through formation of a plastic hinge in the pipe pile, with improvements in the ductility and energy dissipation characteristics of the connection, as well. None of the existing analysis approaches (simple hand calculations, complex strut and tie analyses, or finite element models) adequately address all of the issues associated with the design and subsequent behavior of these connections. Nonetheless, using the data collected during the physical tests on the connection models, it was possible to evaluate the accuracy and determine the best manner in which each approach could be used in connection design.

This study was focused primarily on a single parameter known to influence the behavior of steel pile-to-concrete pile cap connections (reinforcement used in the pile cap). Further work could be done to address other parameters known to affect the performance of such connections, including the depth of embedment of the pile in the cap and nature of the cyclic load history. Additionally, more work could be done on the specific arrangement of the reinforcement steel used in the cap. Further study of these issues should include both experimental and analytical components.

For More Details . . .

The research is documented in Report FHWA/MT-05-001/8144, *Performance of Steel Pipe Pile-to-Concrete Bent Cap Connections Subject to High Transverse Loading: Phase II.*

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MDT Implementation Status
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This research will be implemented immediately. Bridge design crew chiefs will review their projects to determine which bridges would benefit from this new design procedure. Very little training is required for engineering staff to understand and use the new procedure. The additional training can be accomplished informally as needed. Initially the new technique will be dynamic in nature and will evolve as we gain experience with it.

The new Bridge Design Manual will include information on the theory and practice of using the new procedure.

For more information, contact Kent Barnes, kbarnes@mt.gov, 406-444-6260.

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