



# A Driven Pile Advantage: Batter Piles

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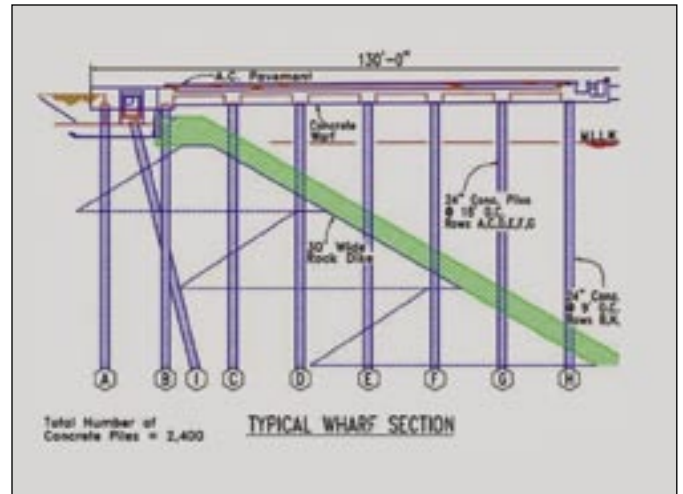
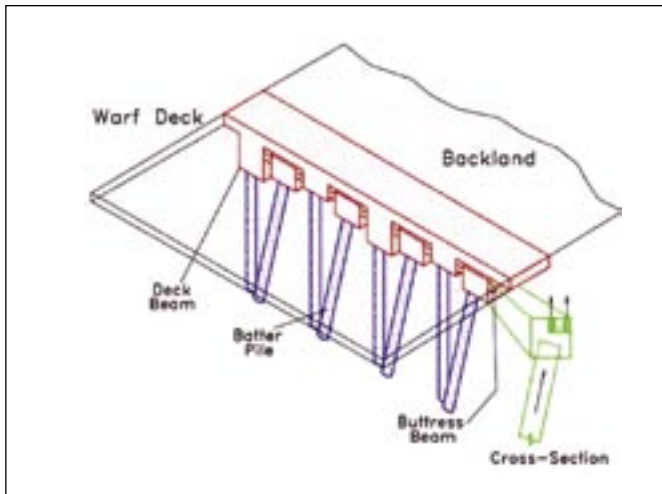
## Introduction

The ability to install driven piles on an angle, or batter, gives them a distinct advantage with respect to their ability to carry lateral loads. Batter piles carry lateral loads primarily in axial compression and/or tension while vertical deep foundations carry lateral loads in shear and bending. When subjected to lateral loading, batter piles will therefore generally have a greater capacity and be subject to smaller deformations than vertical piles of the same dimensions and material. Large shear and moment loads induced at the pile head have been a source of performance problems with batter piles in some cases. However, these problems can be mitigated by appropriate design and detailing of the pile-structure connection.

Until the 1990s, batter piles were a common means for carrying lateral loads, particularly when the lateral loads were large, there was a large unsupported length, or there were weak soils at the ground surface. Examples of such situations include seismic design of bridges and design of marginal wharfs and other port and harbor structures. In the 1990s, following the poor performance of batter piles in a series of earthquakes, some engineers began advising against the use of batter piles. However, once the reason for the poor performance of batter piles was understood, engineers developed design strategies to address these problems. Using these strategies, batter piles have once again become an important weapon in the engineer's arsenal for designing foundations subject to lateral loads.

## Historical Overview

Sources of lateral loads on deep foundations include not only seismic loads but also winds, blasts and other impacts, waves and currents, and lateral earth pressures and displacements. Throughout most of the 20<sup>th</sup> century, batter piles were employed routinely to carry lateral loads. Retaining walls founded upon soft soils, anchored bulkheads, pile supported decks, breasting dolphins, and bridge piers regularly employed batter piles. In fact, batter piles were the preferred methods for deep foundations subject to lateral loads until well into the second half of the 20<sup>th</sup> century. Reasons for this include the extremely poor moment (bending) capacity of some of the more common deep foundation types employed in



Graphics Courtesy of Mukhopadhyay, G., 2001, Geotechnical Challenges and Solutions for a Fast-Track Container Terminal Project at a Contaminated and Seismically Active Site at Pier A At the Port of Long Beach. *Proceedings of Ports 2001 Conference in Norfolk, Virginia, April 29 – May 3, 2001.*

## STRUCTURAL FUSE SCHEME

the first half of the 20<sup>th</sup> century, e.g. timber piles, Franki™ piles, Raymond Step Taper™ piles, and the difficulties in analyzing vertical piles subject to lateral loads.

Through the 1960s, major bridges routinely employed a large number of relatively small driven piles (e.g.

14-in. H-Piles) to support the main piers, including several rows of batter piles to carry the lateral loads. In the 1970s and 1980s, more and more bridges employed large diameter drilled piers as foundation elements. The increased popularity of large diameter drilled piers for bridge foundations

was due in large part to the development of reliable procedures for their design and construction, including the development of p-y analyses for design of piles and drilled piers subject to lateral loads. However, batter piles still remained a popular means of carrying the large lateral loads associated

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with pile-supported decks and for limiting the displacement of foundations subjected to lateral loads.

Towards the end of the 20<sup>th</sup> century, poor performance of batter piles in a series of earthquakes cast batter piles in a poor light. The performance of prestressed concrete batter piles supporting container cranes at the Port of Oakland 7<sup>th</sup> Street Terminal in the 1989 Loma Prieta earthquake was the first of several such incidents. Liquefaction-induced lateral displacement of a rock fill dike through which the batter piles were driven resulted in shearing of the pile heads. The pier was retrofitted using large diameter vertical drilled piers to replace the batter piles at this location. Similar damage was observed in prestressed concrete batter piles in the Port of Los Angeles in the 1994 Northridge earthquake and in the 1996 Manzanillo, Mexico earthquake. As a result of these incidents, some engineers began advising against the use of batter piles. For instance, a 1998 monograph on Seismic Design of Port and Harbor Facilities published by the American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering advised that "The use of batter piles at ports is typically not encouraged because of their poor seismic performance during past earthquakes."

As the cost of not employing batter piles for many seismic design problems became apparent, many engineers began to question the conclusion that batter piles were unsuitable for seismic loading. Forensic analysis of the observed failures suggested that the poor performance of batter piles in seismic events was due to the fact design analyses typically assumed the head of the pile was "pinned", i.e. free to rotate, and thus was not designed to sustain any moment loading. However, due to the design details, the heads of the prestressed concrete piles could not rotate freely and thus were subjected to large shear and moment loads, resulting in failure at the pile head. This suggested that the observed deficiency in the performance of batter piles could be remedied by a combination of strengthening the pile head so that it could resist the applied moment and shear loads and providing sufficient ductility to the pile head or

pile-structure connection to allow it to rotate without a loss of capacity. With this understanding of the source of the observed poor performance and how it could be mitigated, in the past few years batter piles have re-assumed their traditional role in withstanding large lateral loads applied to deep foundations. The piers for the new San Francisco Bay Bridge East Span Replacement structure are perhaps the best example of this renewed acceptance of batter piles for lateral loads. Each pier is supported by six 8-ft diameter steel pipe piles driven on a batter through the underlying bay mud to firm bearing.

### Batter Pile Design Philosophy

Several different approaches to the design of batter piles are now used in practice. One approach, presented in Chapter 7, Foundation Design Requirements, of the 2000 National Earthquake Hazard Reduction Program design guidance for buildings, states that "The connection between batter piles and grade beams or pile caps shall be designed to resist the full strength of the pile acting as a short column. Batter piles shall be capable of resisting forces and moments from the load combinations ...". An alternative to this "brute force" method of batter pile design is the use of a structural "fuse" to limit the forces at the pile head. One manifestation of this approach is the proposed AASHTO guidelines for seismic design of bridges, which allow for "capacity protected" pile caps in which the columns above the pile caps are designed to yield without forming a collapse mechanism before the elastic limit of the batter piles and pile cap connections are exceeded. Another example of this approach is the innovative design of the Port of Long Beach Pier A pile supported deck, where the prestressed concrete piles are connected to a steel beam below the deck that is designed to yield and rotate after the piles undergo 1 inch of elastic compression.

### Conclusion

Batter piles can provide driven pile foundations a significant advantage over drilled piers and other vertical elements for deep foundations subject to lateral loads. Batter piles are particularly advantageous when there is a large unsupported



Wharf Construction - Structural fuse can be seen in foreground.

Photo Courtesy of Mukhopadhyay, G., 2001, Geotechnical Challenges and Solutions for a Fast-Track Container Terminal Project at a Contaminated and Seismically Active Site at Pier A At the Port of Long Beach. *Proceedings of Ports 2001 Conference in Norfolk, Virginia, April 29 - May 3, 2001.*

pile length or in weak soils where there is little lateral support, as vertical foundation elements typically carry lateral loads by bending over their top 10 diameters of length below the pile cap. Over the range of batters typically employed in practice the bending capacity of a batter pile is essentially the same as that of a vertical pile, thus lateral load carried as axial load by the batter pile is essentially entirely "additional" lateral capacity for the pile. Batter piles are not suitable in all situations. Batter piles are particularly problematic when the soil through which the pile is driven may settle, as the settlement will impose lateral loads and bending moments along the entire length of the pile. Furthermore, careful attention is required to the design of the pile / structure connection to provide either sufficient strength to resist applied moment and shear loads or sufficient rotational ductility to limit loads at the pile head to the pile capacity. However, with proper attention to these details, batter piles remain the most economical way to carry lateral loads in many common situations, providing a true driven pile advantage. ▼