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DISPLACEMENT DESIGN OF MARINE STRUCTURES ON BATTER PILES

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SUMMARY

Historically batter piles were used to resist lateral forces in marine structures. However, due to poor performance in recent earthquakes, plumb piles are now the system of choice. Nevertheless, there are situations where batter piles are desirable, for example, where the new structure has to be compatible with an existing batter pile structure or has high service-level lateral loading conditions such as ship mooring. For these situations, using displacement design with carefully-detailed batter piles may result in a significant project savings compared to a force-based seismic design method.

This paper reviews the basic concepts of displacement design. A simplified displacement method is used to show why batter pile structures are vulnerable to seismic loading, and a fused tension fuse connection is proposed.

INTRODUCTION

Some batter pile supported marine structures have performed poorly in past earthquakes. Significant failures have occurred in the Loma Prieta (1989), Northridge (1994), Manzanillo, Mexico (1995), Kobe, Japan (1995) and other recent earthquakes. The primary causes for the poor performance follow.

- Embankment movements were not considered by the designer
- Pile forces were significantly higher than anticipated by the designer
- Forces associated with pile head displacement were not considered

This poor performance has discouraged owners, engineers, and code writers from using batter piles. Consequently, ductile plumb pile systems have become the preferred method of resisting

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seismic loads, although hybrid batter pile systems using base isolation technology or seismic fuse links have been used on some projects.
The engineering profession has made great strides in furthering the understanding of seismic performance of structures in the past few years. What was once considered to be a force problem is now recognized both as a force and displacement problem. The recent publication, ATC-40 "Seismic Evaluation and Retrofit of Reinforced Concrete Buildings" (1997) [1] presents methods to reasonably estimate the nonlinear behavior of a structure in an earthquake. The engineer is able to readily model the soil/structure interaction as well as the inelastic performance of pile-supported structures in earthquakes with modern software.

Historically, one of the chief impediments to seismic design of marine structures historically was the lack of a code designed specifically for marine and waterfront structures. This obstacle has been removed with the publication of a state-of-the-art design code, "Marine Oil Terminal Engineering and Maintenance Standards" (MOTEMS 2003) [2]. MOTEMS is essentially a condensed and codified version of a previous publication, "Seismic Criteria for California Marine Oil Terminals" by Ferrito et al. (1999) [3].

The basic concept of displacement design using the methods and provisions presented in ATC-40 and MOTEMS will be used to explain how to design a pier using a batter pile system with yielding tension connections or fuses. The proposed method results in more economical and better performing structures than those designed using force-based methods. The discussion in this paper is primarily limited to pier structures although the ideas may be applied to wharves, which are much more complicated due to issues related to embankment displacements.

Force -Based Design

In force-based design, elastic forces on the structure are based on initial estimates of the period using a 5 percent damped acceleration spectrum. Design force levels on the structure are reduced from the elastic level by dividing by a code specified force reduction factor, which reflects the assumed ductility capacity of the structural system. Displacements are checked at the end of the design process using assumed relationships between the elastic and inelastic displacements. These displacements are checked against code prescribed drift or material strain limits and the building stiffness and /or strength are adjusted to establish new design force levels.

This process works reasonably well for structures where hinge formation is the primary mode of energy dissipation, and the relationship between elastic and inelastic displacements is reasonably well established. Applying this same relationship between elastic and inelastic displacements to batter pile supported structures results in poor performance for a number of reasons discussed below.

Elastic Versus Inelastic Performance of Batter Piles

Although batter piles appear to be diagonal braces they actually behave much different from bracing used in buildings. One reason has to do with the pile driving, which is shown in Figure 1. To apply the principles of displacement design to batter pile supported structures it is first important to understand the essential differences between batter piles and braces. The most important difference is that piles have to be very robust to resist the driving stresses which are larger than any axial force the pile will experience during its lifetime including seismic. As a result, the axial capacity of the body of the pile in tension or compression will almost always be larger than the capacity of the soil or the connection. Therefore, compression failures of batter piles are rare in earthquakes, and yielding occurs either at the connection to the structure or by pile pullout in the soil. This is different from bracing used in buildings.

Figure 1: Pile Driving

Two types of bracing common buildings are shown in Figure 2[4]. These braces almost always have more capacity in tension than in compression. Building code provisions typically recognize that the compression brace will buckle in an earthquake so the compression component is resisted by the building columns. In an eccentrically braced frame (EBF), the compression and tension braces frame into a girder that yields in shear to accommodate the vertical displacement demand at the intersection of the braces. As a result the building moves horizontally in both the elastic and inelastic range in an earthquake.

Since batter piles don't fail in compression, the failure is limited to the tension piles which fail by yielding of the connection or pullout in the soil. When this happens, the structure will "pole vault" over the compression piles, and the structure will move vertically as well as horizontally in an earthquake, as shown in Figure 3[4]. As the structure attempts to rise, large tension forces are developed in the attached plumb piles as well as the orthogonal batter piles, causing their connections to yield or fail. The pole vault effect is more pronounced with increasing batter.

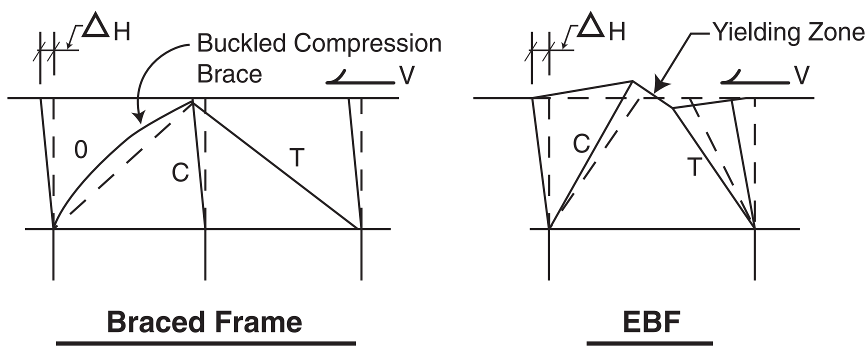

Figure 2: Building Bracing Systems

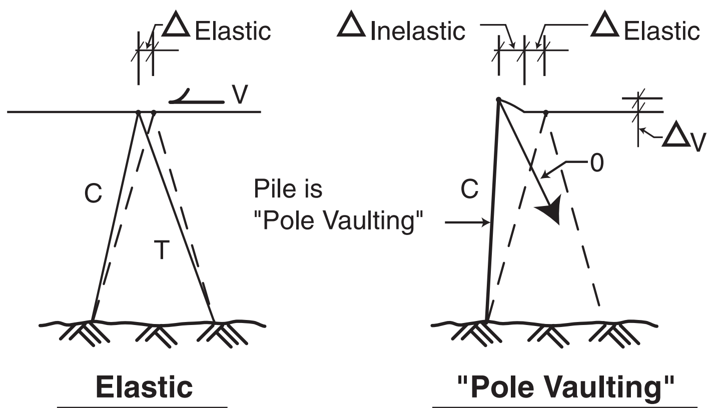

Figure 3: The Pole Vaulting Phenomenon

If the earthquake demand is high enough, the dead load of the structure plus the tension forces in the yielded tension pile connections will be delivered to the compression piles.

During this pole vaulting process, large compatibility forces may be induced in the pile caps or deck system. This paper does not advocate designing pier structures to pole vault, but rather to recognize the phenomenon and design the structure to accommodate or minimize the affects.

Other post-yield phenomenon associated with compatibility may occur with short batter piles found in bulkheads and pile caps near shore. Piles can fail in moment and shear due to embankment displacements or fail in tension at the connection without embankment motions as follows. Although batter piles are primarily axial members, short batter piles resist lateral force by a combination of flexure and axial force. For a fixed-headed pile, as the length of a pile decreases, the flexural component increases and the axial component decreases. In addition, as the fixity at the head of the pile decreases, the axial force increases. Therefore, after plastic hinging occurs in short piles the axial forces continue to increase, sometimes significantly, exactly the opposite of what conventional seismic design wisdom assumes, i.e., that forces don't increase after plastic hinge formation. Combining this effect with "pole vaulting" and including the effects of embankment movement helps explain the tendency of tension connections to fail in short piles. Neither pole vaulting nor axial force increase after hinging can be quantified unless an inelastic or push-over analysis is performed. Consequently, the use of forced-based codes, where elastic forces are divided by an arbitrary force reduction factor to account for yielding and ductility, will result in a batter pile supported structure that behaves radically different from what the designer intended.

Fortunately such discrepancies between design and actual behavior can be avoided by the use of the displacement design methods presented in ATC-40 and MOTEMS. The following discussion describes the application of the above approach as well as a step-by-step procedure for designing a batter pile structure using an axial tension fuse at the top of the pile.

Application of Design Criteria to Fused Batter Pile System

The performance-based MOTEMS was written to outline the design of structural systems to ensure specified behavior at various levels of seismic events. The MOTEMS criteria are oriented towards recent research and experience with similar structures. Seismic systems making use of controlled plastic hinging of plumb reinforced concrete piles are outlined, and generally favored in this document. Lateral systems making use of batter piles are discouraged unless special studies are conducted that show such a system can perform within the limits of the criteria. Past experience with batter piles has shown poor behavior. Because of this, little research has been done to support development of appropriate design criteria for batter pile systems. Consequently, batter pile systems are not well addressed in this or any other seismic criteria. It is left to the designer of a batter pile system to show that such a system will work and meet the limits of the criteria.

Due to their stiffness, batter pile systems attract large tension and compression forces that often make them uneconomical resisting for seismic loads, unless the design is governed by other lateral load requirements. One way to avoid this is by incorporating a tension fuse at the top of each plumb and batter pile.
A sample detail is shown in Figure 4[4]. Similar technology is used in buildings, often with a compression fuse rather than tension fuse. MOTEMS allows the use of fused and seismic release batter pile systems providing that "a nonlinear modeling procedure shall be used and peer reviewed." An example of a fused system under construction is shown in Figure 5.

A fused system offers several benefits that make it better perform, make it easier to design, and make it more economical to construct compared to a non-fused system. The primary benefit of the tension fuse is to limit axial loads to the piles. As a result, the tension piles require less penetration for the development of reliable uplift capacity in the soil. This also results in less risk to the contractor and the owner as pile driving is the largest risk on a waterfront project. In addition, the fuse limits axial compression forces in the piles reducing the size and or number of piles resulting in further economy. The maximum compression force in the pile becomes a function of the dead load of the superstructure and the strength of the tension fuse in the opposing pile. By controlling the number of piles, batter angle, and strength of fuses, the system can be balanced to limit total seismic displacement of the superstructure, without exceeding the axial capacities of the piles.

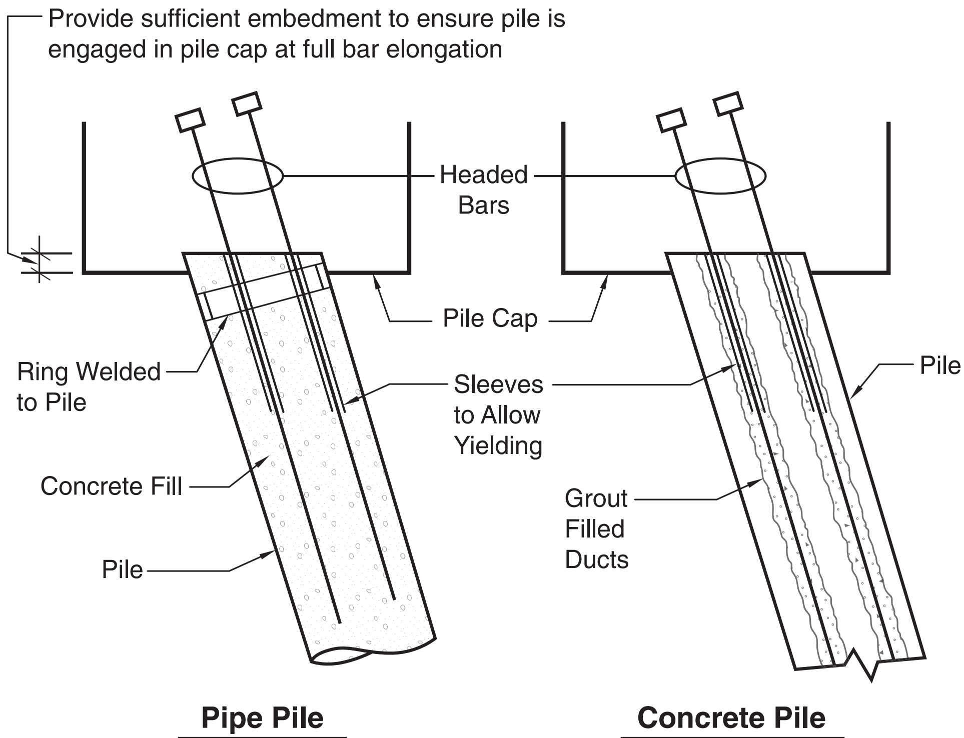

Figure 4: Sample Tension Fuse Details for Concrete and Pipe Piles

Figure 5: Pipe Piles with a Tension Fuse Detail Under Construction

In addition, the use of a ductile yielding fuse element introduces hysteretic damping into the system, which will in turn serves to limit seismic displacements. Chapter 8 of ATC-40 presents a method to estimate the hysteretic damping directly from the capacity spectrum, also known as the pushover curve, for the structure. A sample capacity spectrum showing horizontal displacements, as well as the vertical displacements associated with pole vaulting, is shown in Figure 6[4]. Figure 7[4] shows the derivation of the damping using the capacity spectrum from Figure 6 by applying the methods of ATC-40.

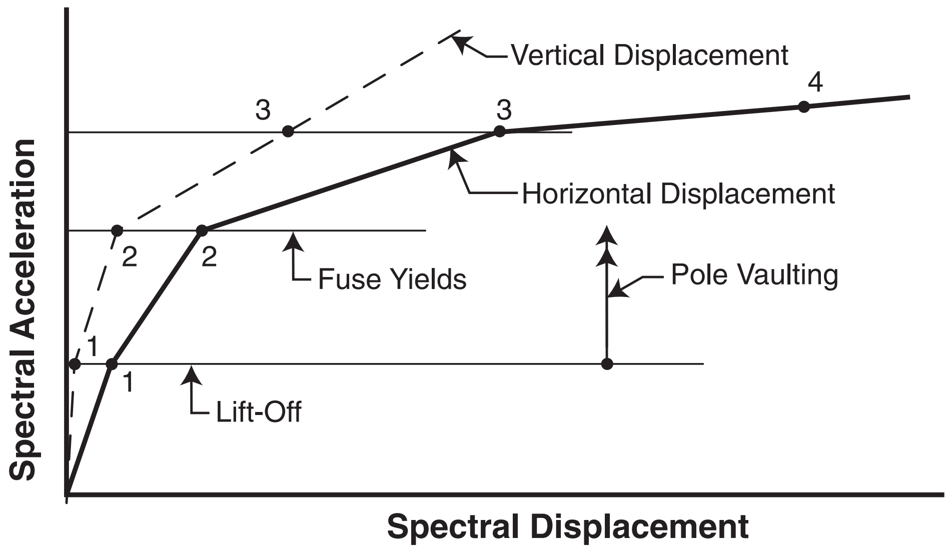

Figure 6: Sample Capacity Spectrum (Pushover Curve)

In a fused pile system, there are typically four points on the capacity spectrum that are of interest to the engineer.

- Point 1, referred to as lift-off in this paper, is when the dead load in the tension pile is relieved and the fuse goes into tension. Up to this point, the tension and compression batter piles are symmetrical; so the structure undergoes only horizontal displacement. Beyond this point, the tension pile becomes significantly softer, creating a nonsymmetrical batter system in which the structure will start to rise, or pole vault.

- Point 2 is the first yield of the fuse that causes the structure to soften further and both horizontal and vertical displacements increase.

- Point 3 is the nominal strength of the fuse.

- Point 4 is the allowable strain limit of the fuse.

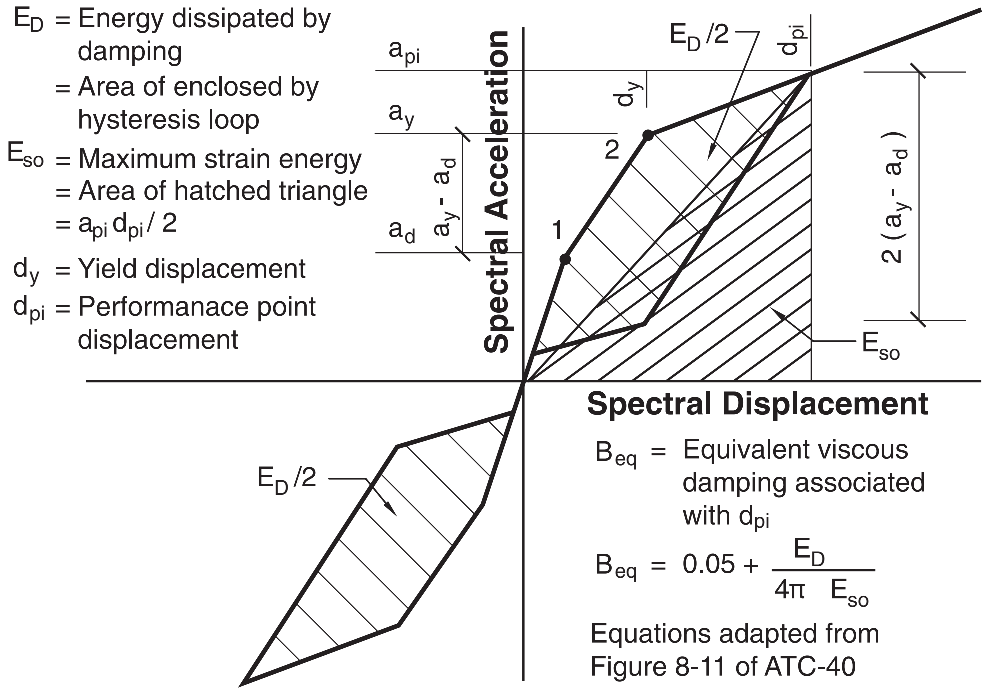

Figure 7: Method of Estimating Damping Per ATC-40

Note the shape of the hysteresis loops of the system is not the full parallelogram shape typically associated with a well-detailed plastic hinge response. This is because much of the displacement is due to elastic fuse elongation, which is not necessarily detrimental as long as it lengthens the period, thereby reducing the seismic demand.

The pinched hysterisis loops of a fused batter pile system are similar to that of a jointed concrete beam to column connection using unbonded prestressing tendons [5]. These jointed systems typically absorb less energy and have less hysteretic damping than monolithic reinforced concrete structures but have higher ductility and exhibit less damage during the design seismic event. This may be an important consideration in marine environment where significant corrosion to the reinforcement in damaged piling can occur in a relatively short period of time.

It may be possible to detail the fuse such that the dead load of the superstructure will exceed the compressive strength of the fuse. In this case, when lateral accelerations have ceased, the dead load only will force the superstructure back to its initial position similar to the unbonded prestress in the jointed system[5] resulting in a self-centering structure. Note that in theory if a pile could be designed to slip in and out of the soil it would provide an almost ideal friction-damped system but in reality this is impractical for a number of reasons such as the unknowns associated with the soil and the pile driving process as well as the difference in soil tension versus compression capacity.

Capacity Protection Quoting from MOTEMS, "The essence of modern seismic design is the precise determination of where and how inelastic actions may occur (i.e., by inelastic rotations in specified plastic hinge locations), and protection of other locations (e.g., the deck), and other actions (e.g., shear), to assure they remain elastic." Applying the concept of capacity protection to a fused batter pile system requires the deck as well as the tension pile embedment in the soil to be designed for the realistic upper bound strength of the fuse. To do so efficiently requires a fuse with a tightly controlled range of yield strengths. One way to accomplish this is by specifying both the minimum and maximum yield strength for the fuse. The extra cost of providing reinforcing bars to achieve the desired fuse strength should be insignificant given the small number of bars involved in the overall cost of a typical pier project.

Structural Analysis and Modeling

MOTEMS provides two methods to calculate the capacity and three methods to calculate the demand depending on the hazard classification, configuration, and materials used in the structure. The author typically uses a nonlinear static analysis to develop the pushover curve and a nonlinear static demand procedure using the Acceleration Displacement Response Spectrum (ADRS) analysis developed in ATC-40. This procedure involves converting typical acceleration versus period response spectra, into a spectral acceleration versus spectral displacement response plot. This is done through the basic relationship between spectral displacement (S_d), spectral acceleration (S_a), and period (T) for a single degree of freedom system.

$$S_d = (1/4\pi^2)(S_a)(T^2)$$

This format allows the capacity spectrum to be plotted directly on the ADRS response spectra. In the elastic range, the intersection of the two curves defines the displacement. However, in the inelastic range, the point at which these two curves intersect is found by a trial and error process readily adapted to a spreadsheet as follows.

- A trial displacement is chosen
- The spreadsheet calculates the damping at this displacement based on the hysteresis loop obtained from the capacity spectrum, producing a damping reduced ADRS spectra
- The process is repeated until the trial displacement falls on the intersection of the capacity spectrum and the damping adjusted ADRS spectra as shown in Figure 8[4].

The approach outlined in ATC-40 must be modified to fit the batter pile hysteresis loop discussed previously. The hysteresis loop for one cycle of the fused structure consists of two individual loops, one in the first, and one in the third quadrant of the load-versus-displacement curve. The area of the loops varies depending on the fuse and structure configuration. Generally these loops will define an area equal to about one third of that associated with a full loop associated with a plastic hinge. ATC-40 also discusses performance categories, reduction of damping with increasing displacement ductility demand, and increasing expected duration of seismic event. The author's interpretation of these reductions is that they are intended to adequately reduce the system damping levels to account for degrading hysteresis from spalling and crushing of concrete in a plastic hinge. For the fused structure, minimal damage is expected to the concrete at the interface of the pile and pile cap similar to the precast concrete jointed system[5] used in buildings.

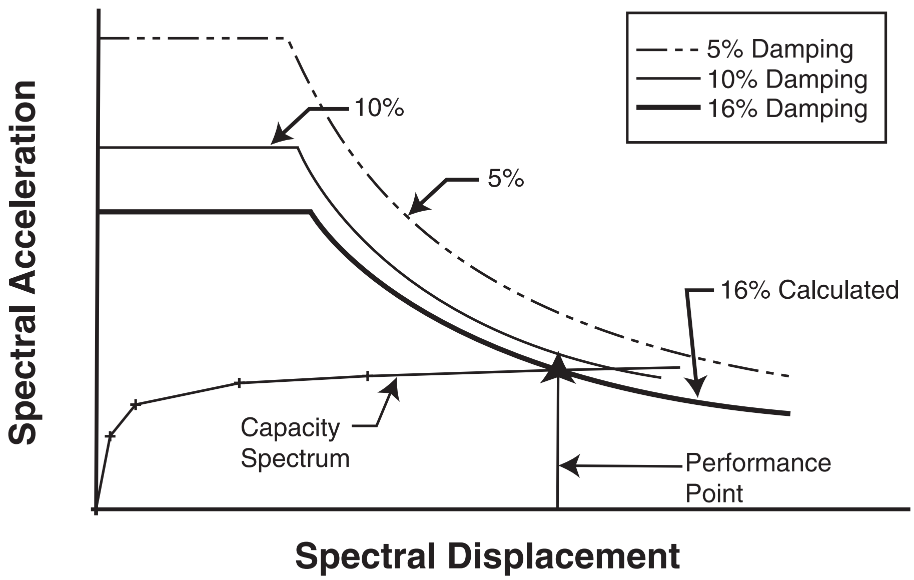

Figure 8: Plot of Pushover Curve Superimposed on ADRS Spectra

Since dead load lift off of the tension pile usually occurs at a very small lateral displacement, flexure in the top of the pile is minimal. Because of this, the tension pile response is characterized almost completely by axial strain in the fuse (reinforcing bars) only. The compression pile side of the joint must be checked for flexural hinging strains in both the concrete and reinforcing bars. The concrete strains are expected to be minimal because the long unbraced lengths of the piles in a pier structure will limit allowable compression in the section due to buckling concerns, and will limit flexural demand due to very flexible frame action at the lateral displacement being considered. Consequently, the joint performance is and that of the structure considered to fall under Category A of the ATC-40 criteria, which is for structures with reasonably full hysterisis loops.

Because displacements along the superstructure vary somewhat in a pier structure due to variations in the mud line an average response displacement versus total structure lateral acceleration force is recommended for the capacity response.

Torsion should be considered for structures with large eccentricities between the center of mass and center of stiffness of the piles.

Vertical Accelerations

MOTEMS does not discuss the effects of vertical accelerations on the response of the structure. Reference 3 indicates a concern for the sensitivity of batter piles to vertical accelerations but makes no provision for checking their ability to withstand such forces.

Sample Design Procedure

To summarize the proposed concept, a sample step by step design procedure follows.

1. Develop a preliminary structural layout using only plumb piles providing the minimum number of plumb piles required to resist dead plus live loads.
2. Using the largest lateral load other than earthquake, develop another pile layout converting as many of the plumb piles as possible into batter piles with an equal number of batter pairs in each direction. Select the batter as required. Batters from 2:12 to 4:12 are typically economical.
3. With the new pile layout, calculate the maximum pile tension force for the largest lateral load other than earthquake. Select the fuse (material and size) to resist this load using normal load factors and ultimate strength design. Use a fused connection on all piles, including plumb piles. For simplicity consider making all connections the same. Using the upper-bound strength of the fuse determine the soil embedment for the tension piles at a reasonable factor of safety.
4. Select a trial sleeve length to control the strain in the fuse. Suggested limits from Chapter 7 of MOTEMS are reproduced in Figure 9.
5. Develop the capacity spectrum for the structure including fused piles.
6. Plot the capacity spectrum on the ADRS spectra. Using the method previously described, iterate by trial and error to determine the horizontal and vertical performance points. Verify that the calculated horizontal and vertical displacements and strains are acceptable. If not adjust the fuse length and/or area and iterate as required.
7. Design the capacity-protected members for the upper-bound fuse force, and detail the seismic joints and utilities for the displacement.

TABLE 7-5 LIMITS OF STRAIN		
Component Strain	**Level 1**	**Level 2**
MCCS Pile/deck hinge	$\varepsilon_c \leq 0.005$	$\varepsilon_c \leq 0.025$
MCCS In-ground hinge	$\varepsilon_c \leq 0.005$	$\varepsilon_c \leq 0.008$
MRSTS	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.05$
MPSTS In-ground hinge	$\varepsilon_p \leq 0.005$ (incremental)	$\varepsilon_p \leq 0.04$ (total strain)

MCCS = Maximum Concrete Compression Strain
MRSTS = Maximum Reinforcing Steel Tension Strain
MPSTS = Maximum Prestressing Steel Tension Strain

Figure 9: Strain Limits from MOTEMS

CONCLUSION

Concepts and methods were presented to do a displacement design for a batter-pile supported pier structure. The method gives the engineer a better understanding of the structural performance, and a more reasonable displacement estimate than force-based methods, but engineering judgment is still required; the procedure is a simplified representation of a very complex problem. Therefore, calculating the displacement to a fraction of an inch is not realistic.

The concepts may be applied to marginal wharves if embankment displacement is considered, the fuse connection is detailed to accommodate or eliminate the high moments at the heads of the short piles under the bulkhead, and the deck is detailed to accommodate pole vaulting.

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