# Seismic Retrofit of Piers Supported on Battered Piles Using Lead-Rubber Bearings

Jeff Kilborn, MASCE, PE, SE;[1] Robert Harn, MASCE, PE, SE;[2] Yeliz Firat, PhD[3]

[1] Project Engineer, BergerABAM, 33301 Ninth Avenue South, Suite 300, Federal Way, WA 98003-2600; PH (206) 431-2300; jeff.kilborn@abam.com

[2] Project Manager, BergerABAM, 33301 Ninth Avenue South, Suite 300, Federal Way, WA 98003-2600; PH (206) 431-2300; bob.harn@abam.com

[3] Engineer, BergerABAM, 33301 Ninth Avenue South, Suite 300, Federal Way, WA 98003-2600; PH (206) 431-2300; yeliz.firat@abam.com

## ABSTRACT

The use of battered piles in the design of new piers located in areas of seismic risk is discouraged based on the poor performance of battered piles observed in previous earthquakes. However, there are a significant number of existing piers with battered piles in service that may require seismic retrofitting. Typical retrofit schemes involve driving additional plumb or batter piles that are integrated into the existing deck with new pile caps or other means but permitting restrictions, pile installation difficulties, and interruptions to facility operations may preclude this approach. In this paper, the use of lead-rubber bearings (LRB) is proposed as an alternative seismic retrofit concept for batter pile-supported piers.

The paper summarizes the basic principles of base isolation and presents a case study of an example pier retrofitted using two concepts, one with new driven piles and the other with LRBs mounted on new subcaps supported by the existing battered piles. The seismic performance of the example pier and the two retrofitted structures was evaluated using displacement-based analysis method. Budget cost estimates developed for both retrofit concepts indicate that the LRB retrofit may be more economical than the driven pile concept for the configurations studied.

## INTRODUCTION

Seismic isolation devices have been used worldwide to improve the seismic performance of buildings and bridges, while the use of seismic isolation devices in piers has been limited. The concept of utilizing seismic isolators as a fuse between the pier deck and the battered piles is introduced in UFC 4-152-01 (2005). Despite the simplicity of the concept, the additional complexity of the subcaps, isolators and mounting hardware has made the use of battered piles with seismic isolation devices less favorable than plumb pile systems in new piers.

This paper is focused on the application of seismic isolation devices as fuses for existing piers with battered piles. Lead-rubber bearings have been selected due to their simplicity of construction, tolerance for installation, and durability in the marine environment. The behavior of different types of seismic isolators and their applications are discussed in detail in Priestley, et al. The basic principles of the behavior of LRBs are discussed briefly in the following section.

## BEHAVIOR OF LEAD-RUBBER BEARINGS

A lead-rubber bearing (LRB) consists of a solid lead core and layers of vulcanized rubber reinforced by steel plates bonded to internal plates and mounting plates as shown in Figure 1. The initial lateral stiffness and the energy dissipation capacity are provided by the lead core, while the vertical stiffness and lateral stability are provided by the layers of rubber reinforced by steel plates.

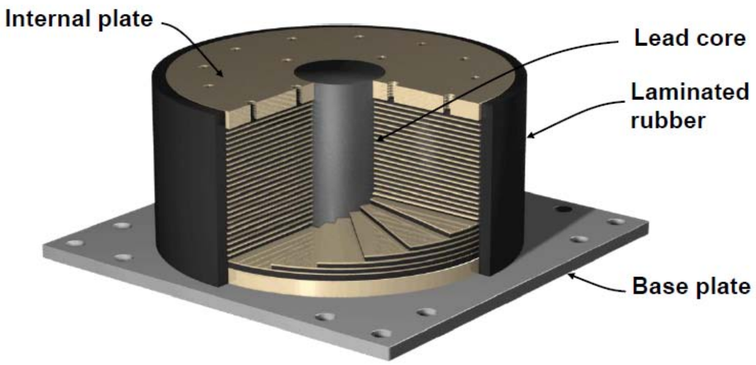

**Figure 1. Typical lead-rubber bearing (Courtesy DIS)**

The energy dissipation capacity, or damping, is governed by the plastic deformation capacity of the lead core. The damping ratio required at the design displacement can be achieved by adjusting the size of the lead core. Typically, the diameter of the lead core is limited to one-third of the bearing diameter in order to provide adequate rubber area for lateral stability. Increasing the plan area of the rubber or reducing the height of the isolator results in higher post-yield stiffness. The lateral displacement capacity of the isolator is governed by the allowable shear strain of the rubber which can approach 200 percent. Note that prototype testing of the bearings is usually required to verify the performance characteristics of the LRB due to variations in properties of the natural rubber typically used. If required, the rubber properties and dimensions of the LRB may be adjusted slightly after the prototype test to achieve the desired performance. Testing requirements are provided in AASHTO (2000) and ASCE 41/ SEI 41-06 (2007).

## CASE STUDY

The following case study compares the performance of an example pier for two retrofit concepts, one using new battered pipe piles driven through the existing deck and one using LRBs mounted on new subcaps supported on the existing battered piles. The performance of the un-retrofitted example pier and the same pier using two different retrofit concepts is evaluated using a two-dimensional (2D) pushover analyses. The analyses used acceleration versus displacement response spectra for a contingency level earthquake (CLE) representative of ground motions in the in San Diego area with a return period of 475 years..

## The Example Pier

The example pier, shown in Figure 2, is 50 feet (15.2 meters) wide by 334 feet (100 meters) long with 16 bents at 22 feet (6.7 meters) on center. The total service level mooring load is 520 kips (2,300 kN). The pier is supported on 16-1/2-inch (420 millimeters) octagonal prestressed concrete piles, 64 plumb and 24 battered. The pile-to-deck connection consists of strand embedded 18 inches (460 millimeters) into the deck. The weight of the pier is 5,000 kips (22,200 kN). The lateral load versus displacement capacity curve for the pier obtained from a 2-D pushover analysis is compared with the base shear versus displacement response spectra as shown in Figure 3.

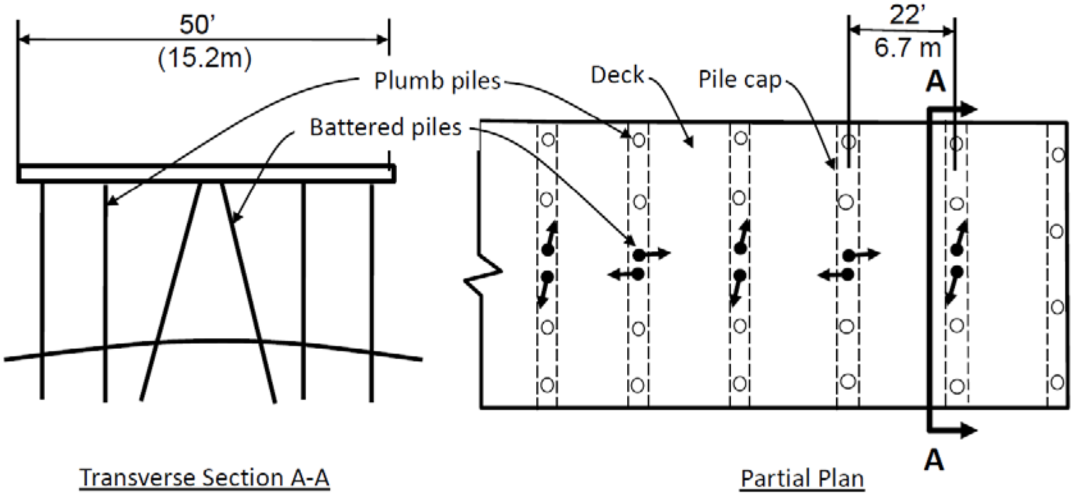

**Figure 2. Plan and section views for the example pier.**

From Figure 3, it is observed that, the elastic base shear demand of 3,800 kips (16,900 kN) exceeds the shear capacity of 1,300 kips (5,800 kN) as limited by the battered pile-to-deck connections. As a result, the battered pile system fails at a displacement of 0.2 inches (5 millimeters). In the remaining plumb pile system, the pile-to-deck connections slip (pullout) at a lateral displacement of approximately 3 inches (75 millimeters). The displacement demand on the plumb pile system in the CLE was found to be 9 inches (230 millimeters) which exceeded the displacement capacity of 7.5 inches (190 millimeters). Consequently, the pier should be retrofitted in order to achieve acceptable seismic performance under CLE. Analysis of two concepts follows.

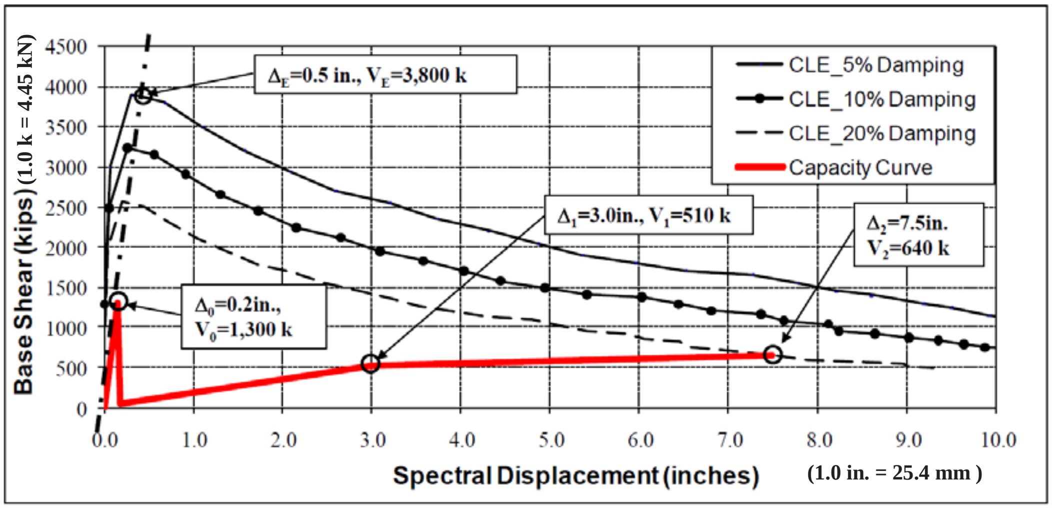

Figure 3. Results from the 2-D pushover analysis of the example pier.

## Retrofit of the example pier using new battered piles

In this concept, shown in Figure 4, the example pier is retrofitted by driving new 24 inch-diameter (61 centimeters) battered pipe piles through the deck which are then integrated into the existing structure with new pile caps located along the centerline of the pier. The goal of the retrofit is to resist the transverse seismic demand elastically with the combined new and existing batter piles. The longitudinal seismic demand is resisted by the combined new and existing piles in frame action.

To minimize damage in the longitudinal direction, the existing longitudinal battered piles are decoupled from the existing pile caps and the gravity load is transferred to the new pile caps supported on the new transverse battered piles.

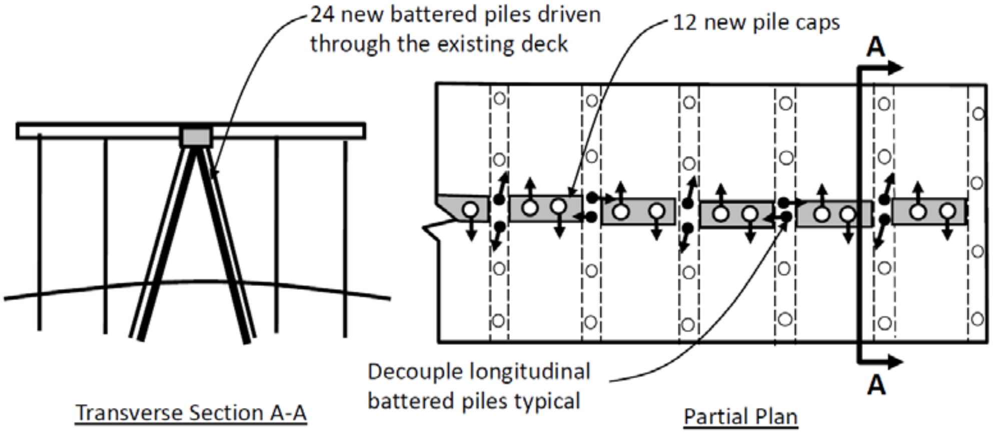

Figure 4. Plan and section views for the batter pile retrofit.

Figure 5 shows a plot of the pushover curve obtained for the retrofitted structure and the base shear versus displacement response spectra for the CLE event. The transverse seismic demand is resisted elastically at a displacement of 0.3 inches (75 millimeters) with a base shear demand of 3,900 kips (17,3~~4~~00 kN). The longitudinal seismic demand is satisfied by the combined moment frame at a displacement demand of 5.5 inches (140 millimeters) which was judged to be acceptable.

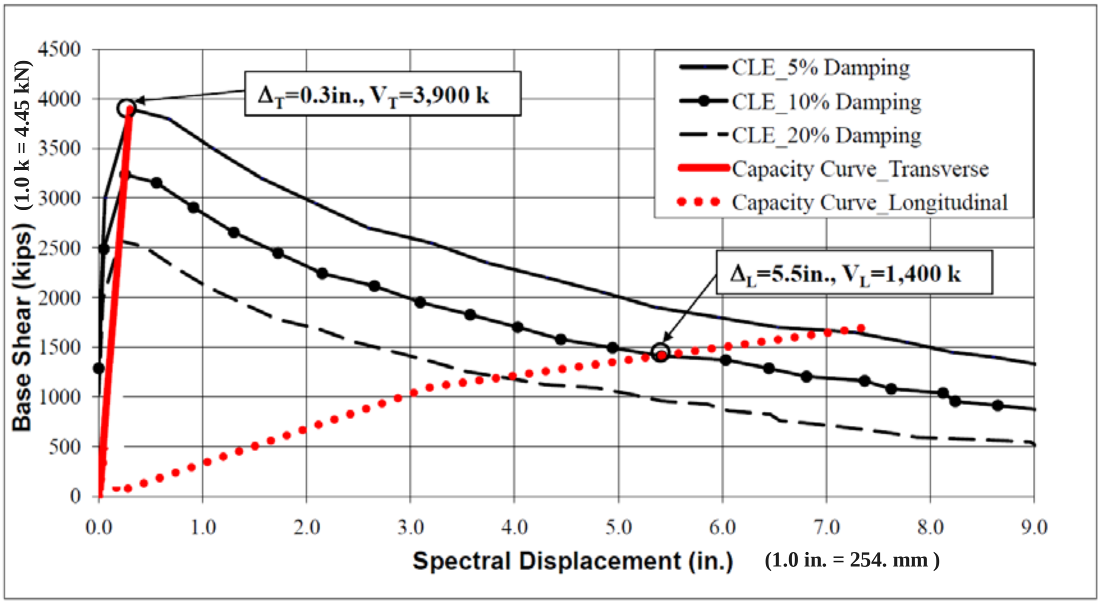

**Figure 5. Results from 2-D pushover analysis of the battered pile retrofit.**

## LRB Retrofit of the Example Pier

While the battered pile retrofit, as shown in Figure 4, improves the seismic performance of the pier notably, more often than not, permit restrictions, pile installation difficulties, and interruptions to facility operations may limit the use of new driven piles. Under these circumstances, mounting LRBs on new subcaps at the locations of the existing battered piles as shown in Figure 6 may be a feasible retrofit solution.

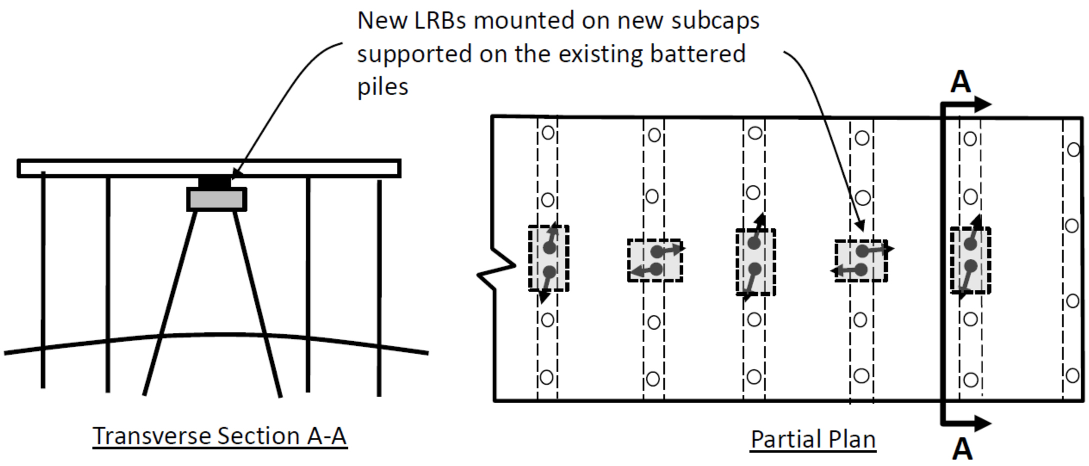

**Figure 6. Plan and section views for the LRB retrofit**

The example pier retrofitted by LRBs has a longer period of vibration and increased damping both of which reduce the seismic demand. The LRBs are sized to act as a fuse limiting demand on the existing batter piles. Torsion in the structure may be minimized by determining an appropriate distribution of LRBs in plan. Mooring and berthing forces should be considered in the design of the LRBs where appropriate.

Figure 7 shows the expected performance of the example pier retrofitted using LRBs. It is observed that the lead core of the LRB yields at 800 kips (3,600 kN) which exceeds the 400 kips (1,800 kN) mooring demand. The maximum seismic demand for the retrofitted pier is 4.3 inches (110 millimeters) at a base shear demand of 1500 kips (6,700 kN). The equivalent damping ratio for the retrofitted structure was estimated to be 15 percent. The performance was judged acceptable.

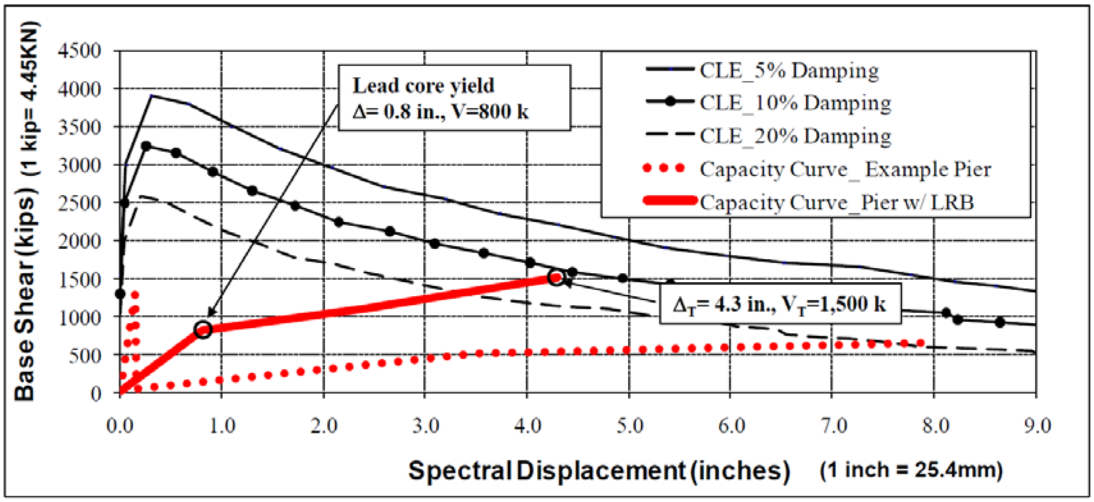

**Figure 7. Results from 2-D pushover analysis of the LRB retrofit.**

## LRB RETROFIT DESIGN ISSUES

The design of the LRB retrofit concept involves determining the size and layout of the LRBs such that pile uplift and bearing capacities are not exceeded and the existing batter piles and the new subcaps remain elastic at the target displacement. Therefore, the piles and the subcaps should be considered as capacity protected elements and designed to elastically resist the maximum demand from the LRBs at the target displacement multiplied by an appropriate overstrength factor.

Despite the simplicity of the concept, there are some design issues arising from pile eccentricities that need to be considered as illustrated in Figure 8. Addition of the new subcap introduces an eccentricity in the transverse direction, $e_1$, that creates a battered frame. As a result, the design shear force for the LRBs may be limited by the flexural strength of the battered pile-to-subcap connections.

Piles driven offset in plan create an additional eccentricity, $e_2$, which causes the subcap to rotate in plan. Because concrete piles are not particularly stiff or strong in torsion, shear keys or other means may be required to resist the resulting torsion.

Therefore, it is recommended that a detailed survey be performed prior to final design to determine the as-built locations of the existing battered piles and pile caps.

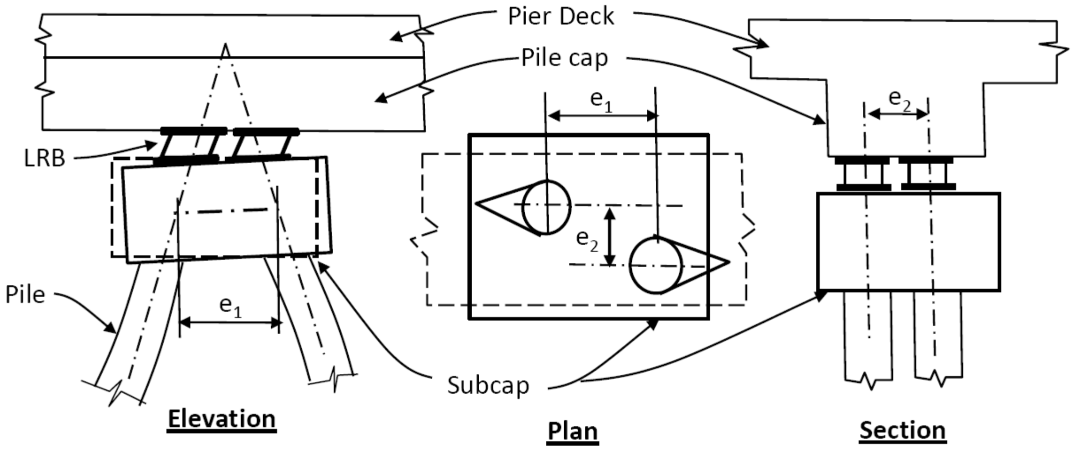

**Figure 8.  Pile eccentricities.**

## CONSTRUCTABILITY ISSUES

In the LRB retrofit concept, the piles are cut off below the deck and integrated into the new subcap prior to installing the LRBs. Once the LRBs are grouted in place, the retrofitted battered piles are re-engaged in the gravity load resisting system. The use of shoring or strongbacks to support the deck during the construction of subcaps and the installation of LRBs is required. The authors have found that substantial engineering effort may be required to detail the LRB installation process particularly where the existing piles are driven out of tolerance.

The LRBs are typically shallow devices. Therefore, the attachment hardware is likely to be installed above the tidal zone. For additional protection against the corrosive marine environment, the LRBs may be fabricated with stainless steel elements or other corrosion-resistant materials. The rubber elements have been found to be durable in the marine environment.

## ANALYSIS CONSIDERATIONS

The authors have found results from 2-D pushover analyses to be sufficiently accurate to determine the feasibility of the base isolation concept. However, for the final design, a three-dimensional (3-D) modal analysis of the pier may be appropriate. The 3-D analysis enables the global analysis of eccentric berthing or mooring forces, which must be resisted by the LRBs below the yield point of the lead core. Response spectrum seismic analysis can be conducted using the 3-D numerical model, which reflects the effects of torsion caused by variations in the stiffness, strength, and mass along the length of the pier. In cases where cranes or buildings are supported on the pier, it may be important to consider higher modes of vibration in the 3D response spectrum analysis.

Because the LRB design is sensitive to displacement demand, it is recommended that the substitute structure method be used in order to estimate the nonlinear displacement demand. The substitute structure method is based on the effective stiffness and damping of the system at the relevant displacement, credible estimates of the displacement demand can be obtained using an iterative procedure.

According to the provisions of ASCE/SEI 41-06, response history analysis is required for the design of buildings and similar structural systems with high damping (exceeding 30 percent) and minimal post-yield resistance. However, in the opinion of the authors, response history analysis is usually unnecessary for the design of the pier retrofits using LRBs, because high levels of overall damping are not required to control the displacements. For example, in the case study, at the CLE design displacement, despite the high damping (20 to 25 percent) provided by the LRBs, the overall damping is expected to be about 15 percent due to the low damping (10 percent) of the plumb piles. Furthermore, the presence of the plumb piles in the pier provides significant restoring force beyond yield of the LRBs. In the retrofitted pier, at the maximum CLE demand, one-half of the base shear demand was observed to be resisted by the LRBs, while one-half was resisted by the existing plumb piles. Note that the authors have observed the total overall damping of 15 percent is a good approximation for preliminary design of an LRB retrofit system.

## DAMPING CALCULATIONS

One of the most crucial parameters in the analysis is the assumed hysteretic damping coefficient for the retrofitted pier ($\beta_{pier}$). $\beta_{pier}$ can be estimated (as shown in Figure 9) using the damping coefficient for the plumb pile system ($\beta_i$), the damping coefficient for the retrofitted battered pile pair ($\beta_{IS}$) at the design displacement, and the shear force resisted by each component ($V_i$, $V_{IS}=V_{LRB}$). The isolated battered piles and the plumb piles are connected in parallel.

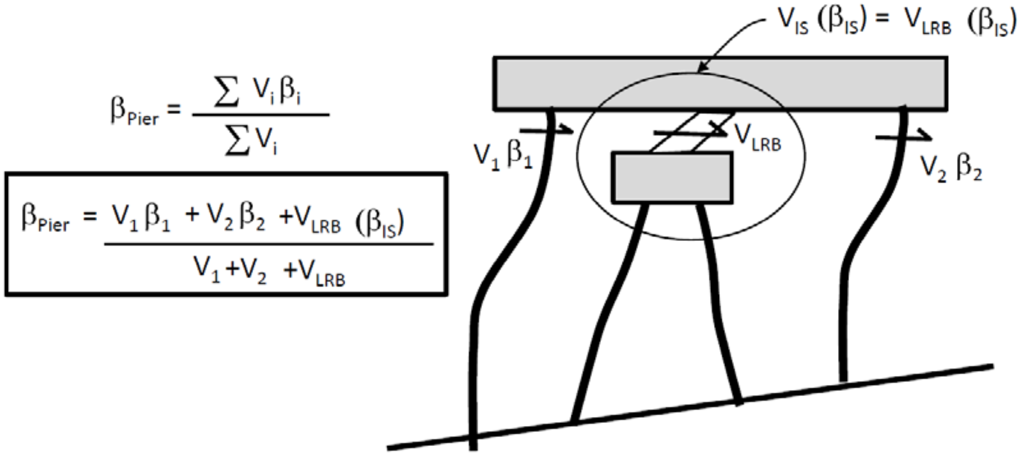

**Figure 9. Hysteretic damping for the retrofitted pier ($\beta_{pier}$).**

The hysteretic damping coefficient for the retrofitted battered pile pair ($\beta_{IS}$) can be estimated (as shown in Figure 10) using the lateral displacements for the battered pile pair ($\Delta_{sub}$) and for the LRB ($\Delta_{LRB}$) at the design shear force, and the corresponding damping coefficients ($\beta_{sub}$, $\beta_{LRB}$). The battered pile pair and the LRBs are connected in series.

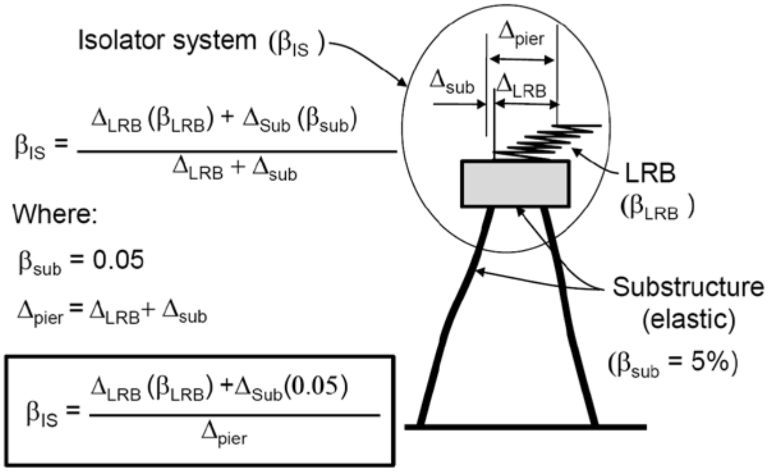

**Figure 10. Hysteretic damping for the retrofitted battered pile pair ($\beta_{IS}$).**

## COST COMPARISON OF RETROFITS

Budget cost estimates were developed for the retrofits and summarized in Table 1. The cost estimates included the demolition and construction costs, but excluded the cost of permitting and facility interruptions for the driven pile concept. Comparison of the cost estimates indicated that using LRBs instead of new driven piles offered a potential savings of approximately 35 percent for the configurations studied.

**Table 1. Comparison of Retrofit Costs in US Dollars.**

| Item | Driven Piles | LRBs |
|---|---|---|
| Deck Demolition | \$100,000 | NA |
| Batter pile cutoff | \$20,000 | \$60,000 |
| New pipe piles (24) | \$360,000 | NA |
| Shoring | NA | \$80,000 |
| New pile caps | \$300,000 | \$250,000 |
| New LRB’s installed (24) | NA | \$120,000 |
| **Total** | **\$780,000** | **\$510,000** |

## SUMMARY

In this paper, the feasibility of using LRBs in the retrofit of existing piers with battered piles was investigated. The case studies demonstrated that potential improvements in the seismic response are achieved using LRBs with reduced construction costs, permitting effort, and schedule.

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