The Design of Earthquake Damage Repairs to Wharves Before the Earthquake Occurs

Gerald M. Serventi*, Michael A. Jordan**, George Fotinos***, and Erik G. Soderberg****

*PE, Director of Engineering, Port of Oakland, 530 Water Street, Oakland, CA 94607; PH 510-627-1268; jservent@portoakland.com **SE, Chief Executive Officer, Liftech Consultants Inc., 300 Lakeside Dr. 14th Floor, Oakland, CA 94612; PH 510-832-5606; mjordan@liftech.net ***SE, Consulting Engineer, 1575 North Castle Road, Sonoma, CA 95476; PH 707-337-8978; george@fotinos.com ****SE, Principal, Liftech Consultants Inc.; esoderberg@liftech.net

Introduction

The issue with the design of a new container wharf is not whether or not it will be damaged in an earthquake, but rather how to manage the damage when it occurs. Currently, wharves on the West coast are designed according to criteria that establish acceptable damage levels for design earthquakes based on probabilities, e.g. 10% chance of exceedence in 50 years. In some cases a vulnerability analysis is performed. This vulnerability analysis follows the methods described in the ASCE *Seismic Guidelines for Ports* and includes estimates of repair costs. The vulnerability analysis does not, however, include the development of detailed designs of the expected repairs.

This paper presents an anticipatory approach to the design of repairs. The paper proposes both the development of design criteria for typical repairs and the preparation of detailed designs for select repairs that would be expected after an earthquake. With established criteria, the design of the repairs may proceed immediately after the earthquake. When the detailed design has been prepared, construction can proceed immediately after the earthquake. This approach expedites restoring the wharves to a safe operating condition.

Considering future repairs during the design of a new wharf encourages the designer to incorporate features that make repairs easier and less costly. This approach also encourages a cost benefit ratio analysis to justify the cost of the added features.

This paper demonstrates the approach with the following case studies of wharves at the Port of Oakland: repairs to the Matson wharf, Berths 32 and 33 after the Loma Prieta Earthquake; repairs to the Ben E. Nutter Terminal wharf, Berths 35 – 37 after the Loma Prieta Earthquake; and the design features of the new Berth 57 – 59 wharves, which are repair friendly.

This paper includes suggestions for improving the ease of repair of new wharves. Discussions of slope stability are beyond the scope of this paper.

Practice

Current

The scope of the design and construction documents is limited to the information needed for initial construction. Although earthquake damage is considered and the design attempts to limit this damage to acceptable levels, the criteria for the design of repairs and the actual design of the repairs are not included.

Only after a damaging earthquake are the criteria for and the design of repairs developed. This takes time and delays returning the facility to useful activities. The consequential damages due to loss of facility while the repair design is completed may exceed the cost of the repairs. When the design is developed in a rush, alternative solutions may not be developed and all issues may not be examined.

If a vulnerability analysis is performed during the initial design, very rough estimates of repair costs are used and no consideration is given to revising the design to reduce the cost of repairs and shortening the construction time.

The implied reasoning is: Why spend time and money now to develop repairs to damage that may never occur? Yet, the implied reasoning justifying a vulnerability analysis is that it is worthwhile to make a study now to help determine the design criteria and establish the acceptable damage as part of the initial design. This reasoning seems inconsistent.

Recommendations

When the design of the initial construction is developed, the criteria for and the design of earthquake repairs should be developed as well. The design of the repairs should be as carefully considered and documented as is the design of the initial construction. The repair documents, criteria, calculations, drawings and specifications, should be complete and ready for issue immediately after the damage occurs.

This approach will not only expedite repairs but will also cause the designer to select solutions that are repair friendly. Repair solutions would be built into the initial construction, not added to it.

How much cost can be justified to facilitate repairs to damage that may never occur? An analysis could be made following the *Seismic Guidelines for Ports.* Based on the cost of repairs and the probability of needing them, only a small increase in initial cost is justified. But once the consequential damages, which are difficult to estimate, but may be very large, are considered, the cost of developing the repairs before the damage occurs is justified. For example, the cost of lost business at the Matson Oakland terminal was much more than the cost of the repairs.

The cost of developing repairs is small compared to the cost of the project. Often, there is no increase in initial construction costs due to repair friendly design changes.

Components Vulnerable to Earthquake Damage

The damage to the components presented below is generally not extensive. However, the impact of repairs on an operating terminal may be significant. A designer should be aware of what components have been damaged and consider the costs of repair not only in terms of the repair itself, but the cost of downtime to the terminal operator.

Piles can be damaged at their wharf connection due to the movement of the wharf deck and below grade if the embankment moves and the soil displaces across a plane. See Figure 1. Batter piles may fail in tension by breaking or pulling from the wharf. Damage to vertical piles typically consists of cracking and spalling of the unconfined concrete cover.

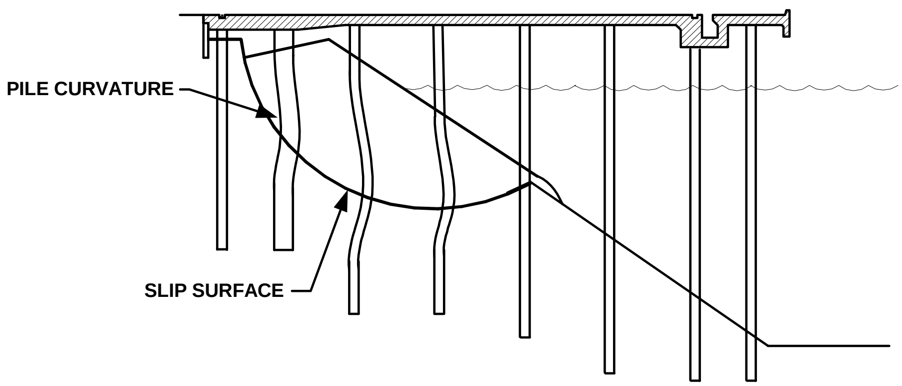


Figure 1. Below Grade Soil Deformations

Relative displacement between wharf sections at the expansion joints may damage the shear key, the crane rail, the expansion joint cover, and the power trench or cable trench. See Figure 2. The designer should consider the use of a ductile shear key element and flaring the crane rail and expansion joint trenches to facilitate realignment of the rail and power or cable trench.

Figure 2. Crane Rail Damage at Expansion Joint

The cut-off wall at the landside end of the wharf may be damaged if it cantilevers from the wharf deck. Spalling at the cut-off wall to wharf deck connection will vary in magnitude depending on the relative displacements between the wharf and the soil behind the cut-off wall. The designer should consider if it is better to avoid using the cut-off wall for lateral resistance and instead provide additional seismic piles.

Utility connections at the wharf-backlands interface should be flexible and meet the required deformation criteria to avoid damage or failure.

The location and design of the fender system as it nears or crosses an expansion joint can be critical. Differential movements between the adjoining wharf sections creates a potential impact on the alignment of the face of the fenders and the subsequent load distribution on the berthing vessel.

Case Studies

Three case studies are presented below to show what repairs have been used and may be required in the future, and to show design details that have been used on recently constructed wharves to mitigate damage and facilitate repair.

Matson Wharf, Berths 32 and 33 after the Loma Prieta Earthquake

The old Matson wharf at the Port of Oakland had many batter piles that failed in tension near their connections to the wharf deck. The detail shown in Figure 3 was used to reconnect the broken piles to the wharf deck. The detail relies on shear friction between the roughened outside surface of the pile and the new confined concrete collar. This detail was successful, requiring little time to construct.

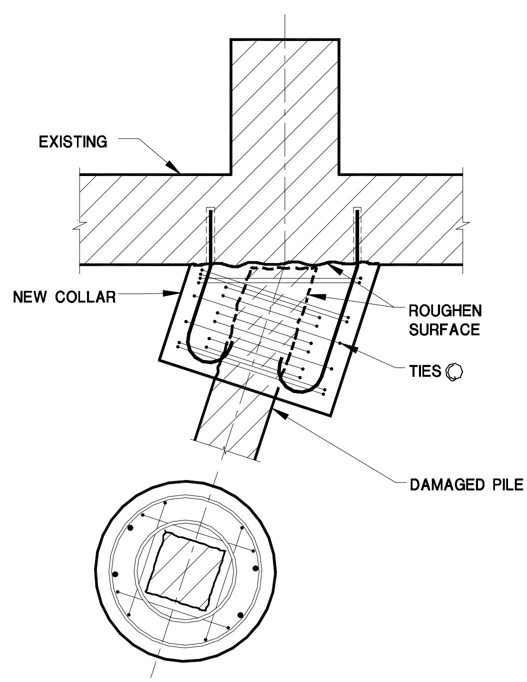


Figure 3. Batter Pile Repair Detail

Repairs to the Ben Nutter Terminal Wharf, Berths 35 – 37 after the Loma Prieta Earthquake

Significant damage to Berths 35 – 37 resulted from the Loma Prieta earthquake. This terminal being constructed along the perimeter of a reclaimed peninsula of land experienced liquefaction of the fine granular soils used to construct the perimeter dike. As a result of this liquefaction, hundreds of piles imbedded in the dike were damaged beyond repair. It was necessary to shut down the terminal for several months to make repairs. Figure 4 shows the type of damage experienced at the terminal.

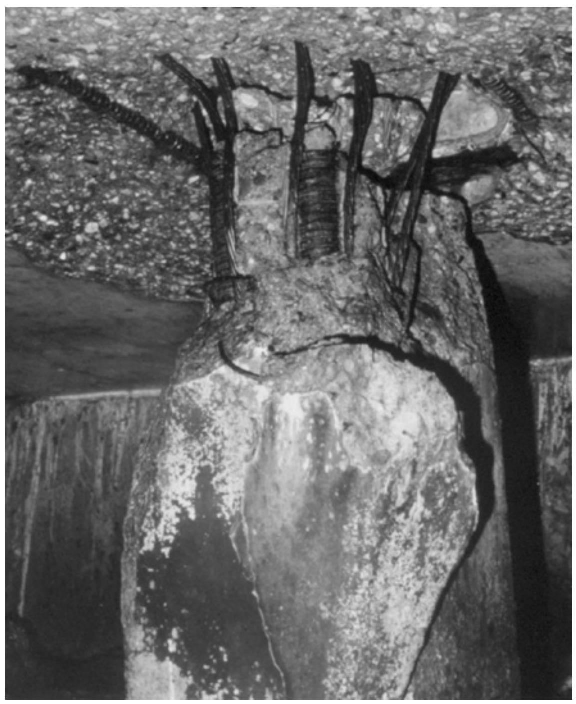


Figure 4. Typical Damage to Piles

The wharf repair consisted of removing the damaged batter piles and replacing them with a ductile frame consisting of a new rear deck section with two rows of 24 inch prestressed concrete piles. The repair section is shown in Figure 5.

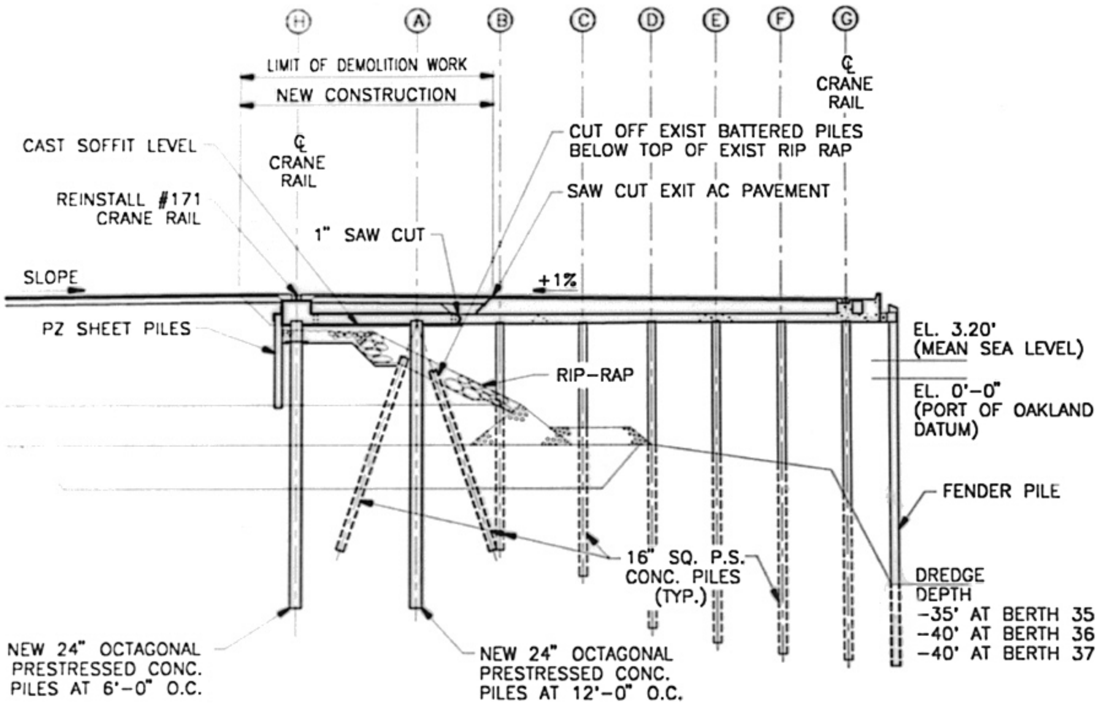


Figure 5. Typical Wharf Section

Damage Limiting and Repair Friendly Design Features of the New Berths 57 – 59 Wharf

The Berth 57 – 59 wharf design at the Port of Oakland incorporated several details to limit damage and to facilitate repairs.

The cut-off wall running the entire length of the wharf is designed to rotate relative to the wharf to avoid damage. It is also designed to be easily removed from the wharf deck to permit access to repair damaged seismic piles. Additionally, space is provided between the rock fill and bottom of wharf to permit pile inspection and limited repairs. See Figure 6 and Figure 7.

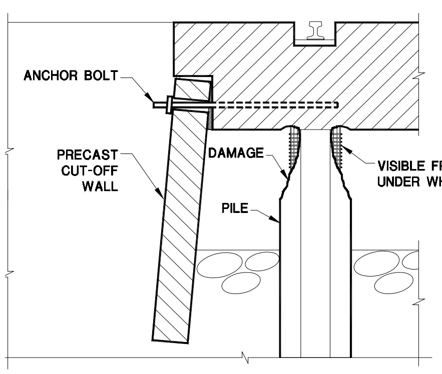


Figure 6. Allowing Rotation of Cut-Off Wall

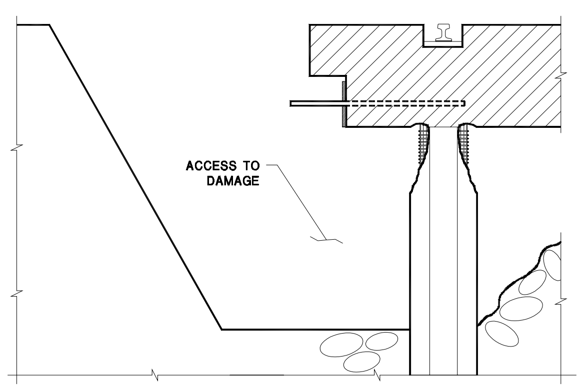
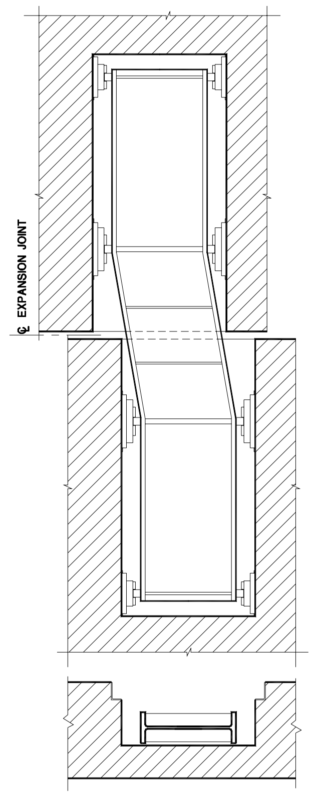


Figure 7. Removable Cut-off Wall for Access

To prevent damage to the concrete wharf resulting from lateral forces on the shear keys, three shear key beams were installed at each expansion joint. The beams are designed to fail in shear similar to the beam in an eccentrically braced framed building. The design limits damage to the shear beams, protecting the concrete wharf. Access to the beams is provided from the wharf deck to facilitate their inspection and, if necessary, replacement.



Expected Deformation **Installed W36x256 Shear Key Beam**

Figures 8 and 9. Accessible, Ductile, and Replaceable Shear Keys at Expansion Joints

To minimize deck reinforcing and reduce the possibility of damage to the landside crane girder or piles supporting the landside girder, the large diameter seismic piles were located one pile row in from the landside end of the wharf. It is important to maintain the integrity of the crane girders and their supports to ensure that the container cranes can operate. As seen in Figure 10, the large pile moment is shared in both transverse directions reducing the required wharf deck strength. If it were located at row H, the entire pile moment would have to be resisted by the wharf deck waterside of the pile.

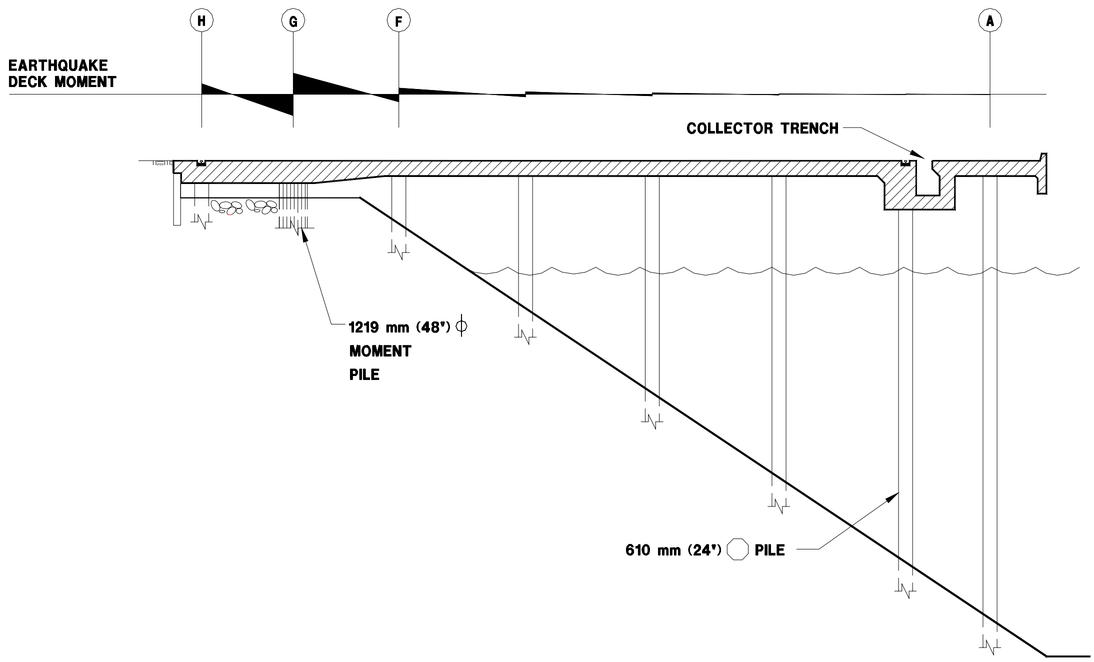


Figure 10. Locate Large Seismic Pile at Row G instead of Row H

Improvements Worth Considering

Allowance for Offsets at Expansion Joint

Even offset of a few inches can interrupt the crane rail so the cranes are isolated between expansion joints. Or worse yet, a crane can be stranded over a joint, such as occurred in the January 22, 2003 earthquake in Manzanillo, Mexico. See Figure 11.

Figure 11. Crane Stranded at Displaced Expansion Joint

Fiber Wrap the Pile Plastic Zone

Fiber reinforced fabric can be wrapped around the pile at the expected plastic zone to provide confinement and additional corrosion protection. The additional confinement will significantly reduce damage to the normally unconfined cover. Wrapping performed prior to casting of the wharf deck is estimated at $500 per pile. Wrapping after damage has occurred would involve providing access and repairing pile spalling damage prior to wrapping.

Figure 12. Fiber Reinforced Wrapping of Pile (Courtesy of FYFE Co. LLC)

Reduce Pile Prestressing for Greater Deformations before Spalling

Partially prestressed concrete piles have been used for fender piles at marine terminals in Kuwait, Singapore, and for the U.S. Navy. These low level prestressed piles have the same ultimate strength of fully prestressed piles but offer the advantage of being more flexible when subject to bending. By using these piles in the rear portion of marginal wharves where the piles are fully imbedded in the dike, the supporting piles will be able to accommodate increased curvatures without spalling of the concrete cover due to dike deformations from seismic motions. Refer to Figure 1.

Dike deformations caused by seismic motions can be further reduced by densification of the dike and supporting soils prior to the construction of the wharf structure. Current practice consists of dumping graded rock by barge to form the dike over native foundation soils. While care is taken in selecting the material for the dike, the dike is not normally densified. Dynamic compaction, vibro-compaction, or other methods can be used to densify the dike and foundation soils to reduce dike deformations from seismic induced ground motions.

Conclusions

The design of earthquake damage repairs and damage limiting measures should be discussed with the owner of the structure during the scoping of the program and made part of the initial design scope. The costs to develop the repair design and to make minor design improvements to limit major seismic damage will result in a small increase in the of cost construction. The damage repairs and limiting measures should be noted on the plan set as such for easy reference when needed. Considering future repairs during the design of a new wharf encourages the designer to incorporate features that make the repair easier, less costly, and quicker to carry out following the event.

References

Werner, Stuart D., ed. *Seismic Guidelines for Ports*, TCLEE No. 12. Aston, VA: ASCE, 1998. ISBN: 0-7844-0327-9.