Seismic Response of Container Cranes and Effects on Wharf Response and Crane Structure Performance

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ABSTRACT

Adequate seismic performance of marine container terminals is critical to supply chain resilience. Seismic response of cranes and wharves and their performance are key factors in the seismic performance of a container terminal.

This paper will provide a basic understanding of the following:

Seismic performance of container cranes and contributing factors

Concepts for designing new cranes and retrofitting existing cranes to improve seismic performance

Seismic performance of wharves

How container cranes and wharves interact and respond in earthquakes and factors

INTRODUCTION

It is a normal day at a container terminal in Los Angeles; then a large earthquake strikes. At first the ground and wharf begin shaking, and then the container cranes respond, slowly swaying back and forth. Stacked containers begin falling; wharf segments shift, bending the rails and cable trench at expansion joints; landside piles spall where they connect to the wharf, with concrete cover breaking off into the water and exposing reinforcing. Container cranes begin swaying enough that the cranes rock and some legs lift. Some crane wheels that lift off the rails come to rest on the wharf deck. At the leg-to-portal beam connections of some cranes, the steel plates of box sections yield and buckle. Some utility lines sever between the wharf and land. Port buildings experience inelastic yielding of reinforcing and steel members. The earthquake ends, operations have stopped, review of damage begins soon, repair planning begins within hours.

Across the port, damage varies. Some terminals resume operations soon after the earthquake; others do not resume operations for weeks or months.

This paper provides an overview of container crane seismic performance, crane concepts to improve seismic performance, wharf seismic performance, and crane-wharf interaction including how the cranes affect wharf seismic performance.

CRANE PERFORMANCE

Change in Crane Size and Performance

Early cranes were small compared to modern cranes, so in a large earthquake they would often rock and lift from rails, thereby reducing the crane's internal forces and preventing significant damage.

Since modern cranes are larger and more stable, the legs do not lift as easily and larger seismic forces can develop, making damage more likely, particularly in the crane lower portal frame. See Figure 1 for seismic forces necessary to lift the legs of early and modern cranes.

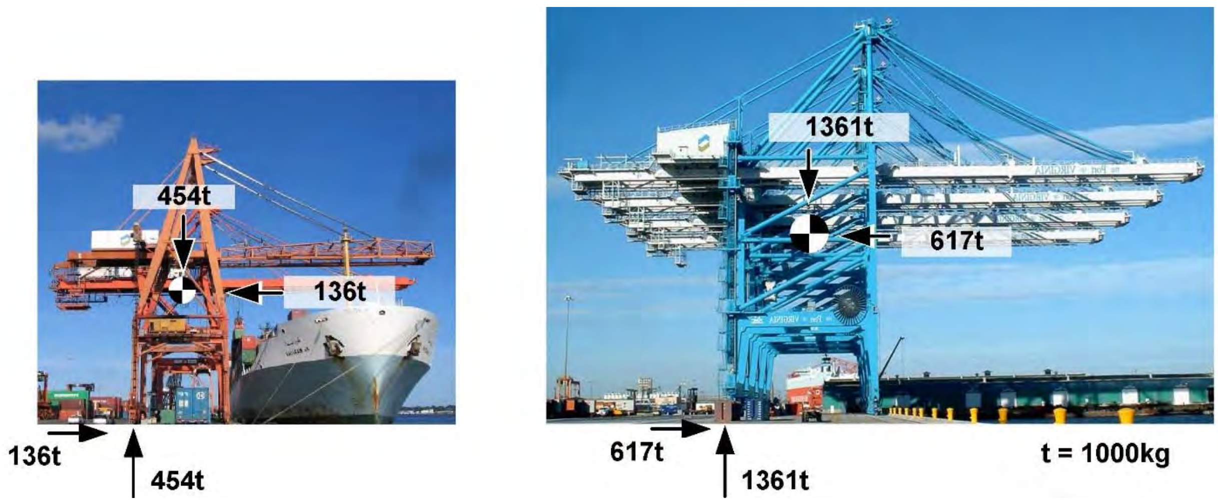
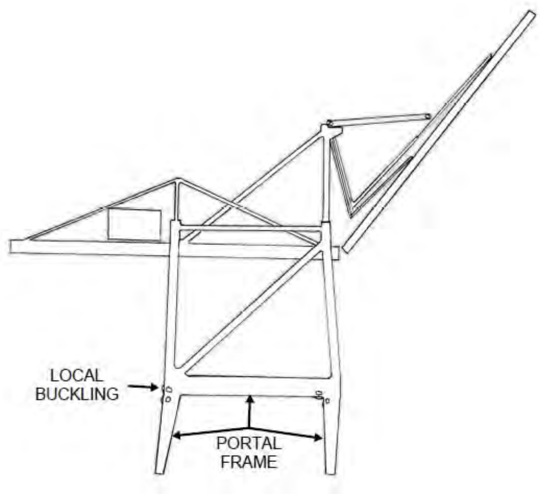


Figure 1. Crane forces: 1960s and 2000s cranes.

The change in seismic performance due to increased size was not recognized by the industry until around 2004, so some cranes have a greater risk of damage than others. The risk of damage is greater than is accepted for building structures and is primarily related to local plate buckling and yielding in the portal structure, which may result in global instability. See Figures 2 and 3.



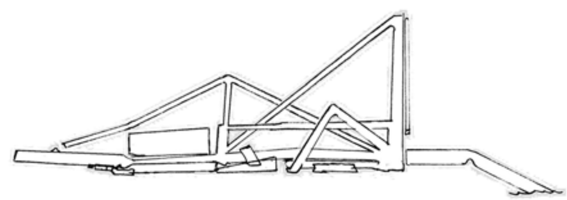


Figure 2. Local without global instability. **Figure 3. Local and then global instability.**

Modern Design Criteria and Retrofit Approaches

The industry has adapted to increasing seismic risks. Design methods include (1) designing to tip (rock) elastically without damage (Figure 4), (2) designing for ductility (plastic deformations) without local and then global instabilities (Figure 5), and (3) isolation and damping (Figure 6).

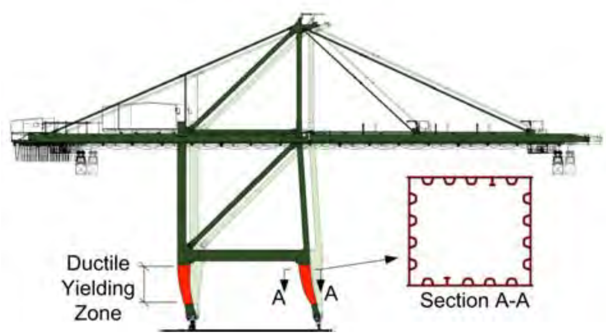
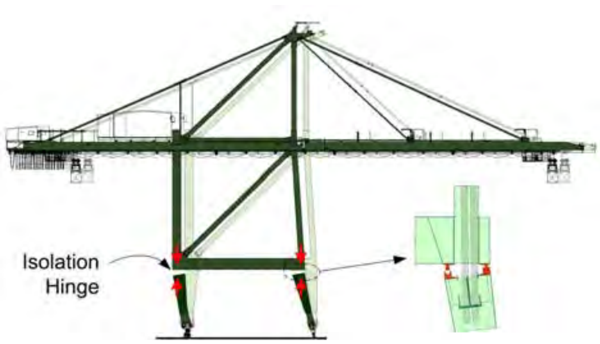


Figure 4. Design to tip without damage. **Figure 5. Design for ductility.**



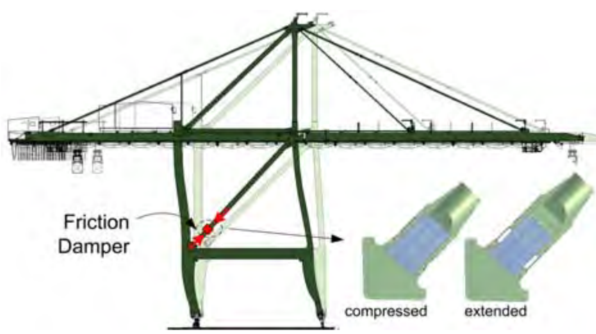


Figure 6. Design for isolation and/or damping.

Expected Performance, Basis, and Significant Factors

Tipping Elastically: Cranes that can tip elastically are expected to have little damage after even large earthquakes and are expected to be operable soon after the earthquake. The wheels may not be on the rails and they may need to be jacked, slid over, and set back in place. Power system interfaces with the wharf may require repairs. Cranes are not expected to move far enough off the rails to fall into the water but could move into the cable channel and require repairs.

Ductile Details with Plastic Yielding: Cranes that are designed to yield in a ductile manner will be damaged and have plastic deformations that may affect operations. If the damage is localized and deformations are not significant, the cranes should be operational soon after the earthquake; otherwise, time will be required to perform repairs, e.g., realign members, strengthen and/or replace damaged sections. The magnitude and duration of the shaking and the resulting plastic deformation will have the largest effect on performance. This approach is rare due to the expected damage and repair costs.

Isolation Systems: Isolation systems are integrated into the crane structure, typically at the gantry or portal tie beam level, and permit the wharf below to move while isolating the primary crane structure so that it does not receive high seismic forces. Dampers are also often incorporated. Cranes with isolation systems are expected to have little damage and not derail. It is practical to design isolation systems to accommodate large displacements, so it is unlikely their limits would be exceeded by even extremely large earthquakes. Isolation systems are more commonly used in Japan. Performance is good but isolation systems are less favored due to cost.

Dampers: Cranes with dampers will have reduced damage. Damper connections have a fuse that releases at a design seismic force, permitting the crane structure to effectively become more flexible, which reduces the seismic force into the crane. The damper also absorbs energy, further reducing the forces. Dampers are usually integrated into isolation systems and are rarely used alone due to performance and cost. A friction damper system was used at the Port of Los Angeles Pier 300 to reduce the crane and wharf forces to acceptable limits. See Figure 7.

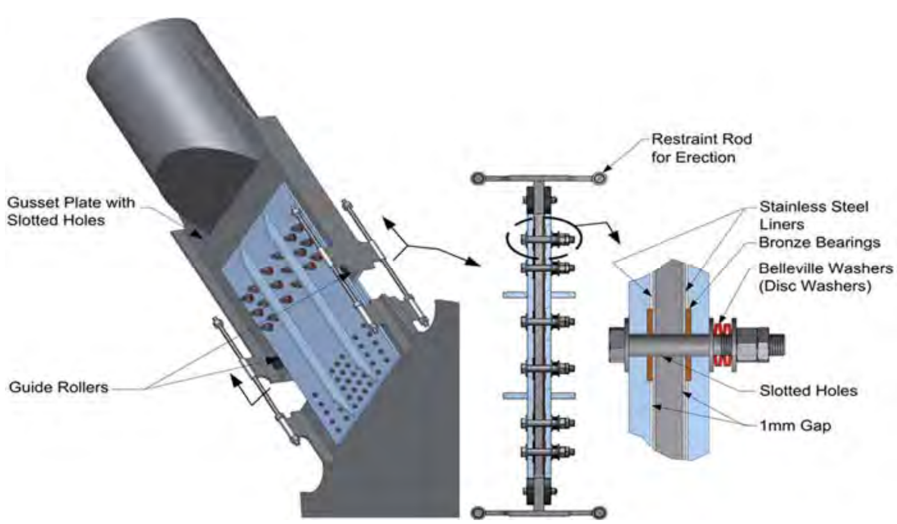


Figure 7. Friction damper – Port of Los Angeles Pier 300 cranes (select cranes).

Most Common Approach – Design to Tip without Damage

Designing the crane to tip without significant damage is typically the most practical approach, since there is usually less than a 5% increase in material and cost.

The tipping (rocking) crane response with the corners uplifting in large earthquakes has been confirmed by performance in past earthquakes, as well as finite element analysis (FEA).

Crane retrofits to improve seismic performance have been practical when cranes have been raised to service larger ships. New structure has been added to the portal frame that raises the crane and is strong enough for the crane to tip elastically. See Figure 8. Relatively minor, local reinforcement may also be required in other areas of the crane structure.

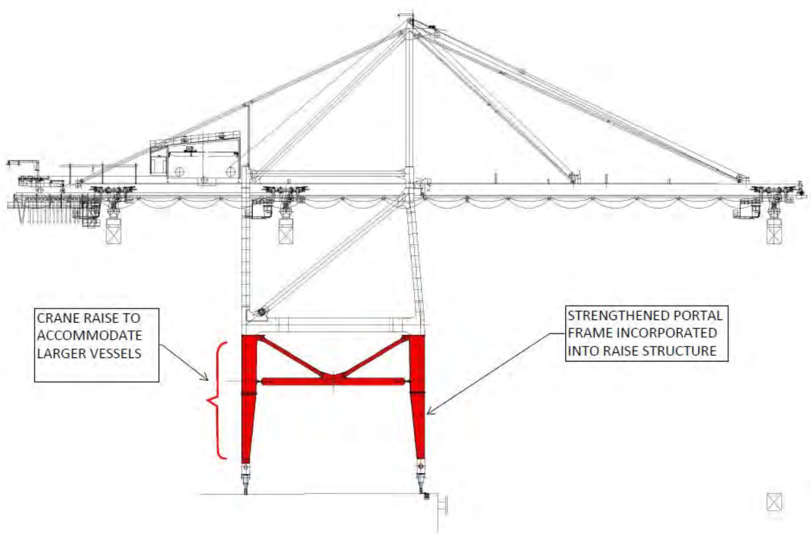


Figure 8. Add new portal structure to raise crane and improve seismic performance.

WHARF PERFORMANCE

Wharf structures are often designed to criteria that vary by region and with time. Similarly, performance will vary. Typically, wharves are not expected to collapse and require reconstruction. In rare cases, slope instabilities are expected that would cause collapse. Although unlikely, if significant damage were to occur, it may put the wharf and terminal out of service for quite some time.

For common pile-supported wharves, damage is mostly expected at pile-to-deck connections. Wharves with non-ductile batter pile connections are more likely to suffer significant damage. Modern wharves are more commonly designed with plumb piles and are expected to perform better. In addition to structural damage, non-structural damage is expected, e.g., power systems may break, crane rails may be bent due to relative displacements at wharf segments. These repairs are not expected to take significant time. See Figure 9.

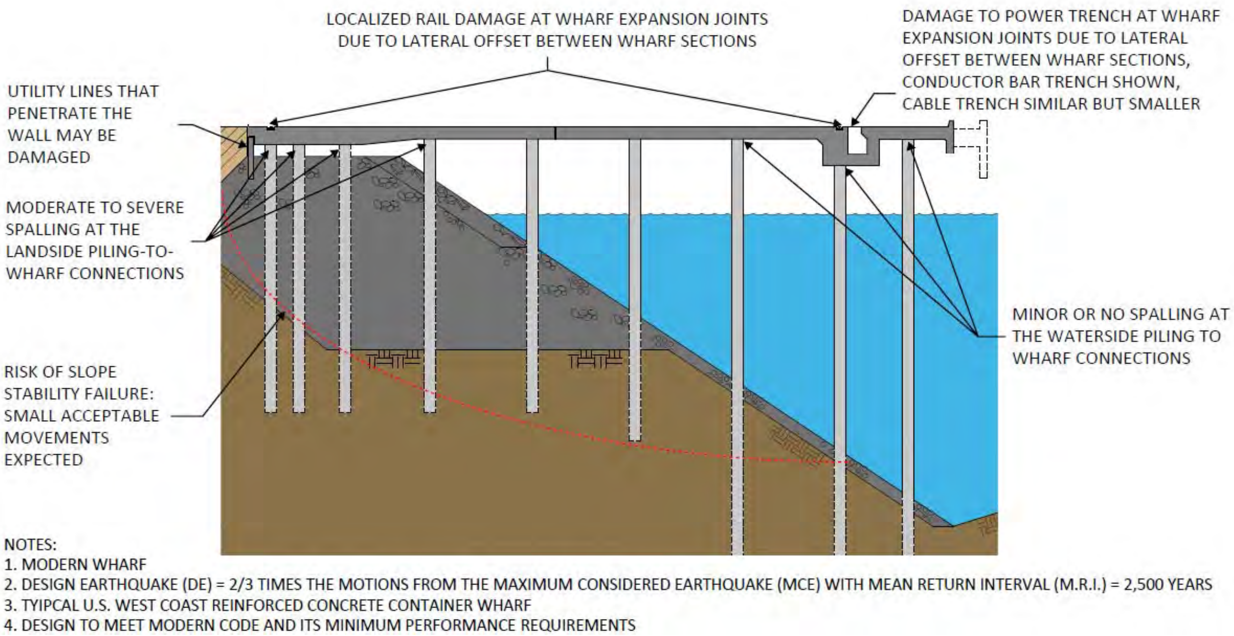
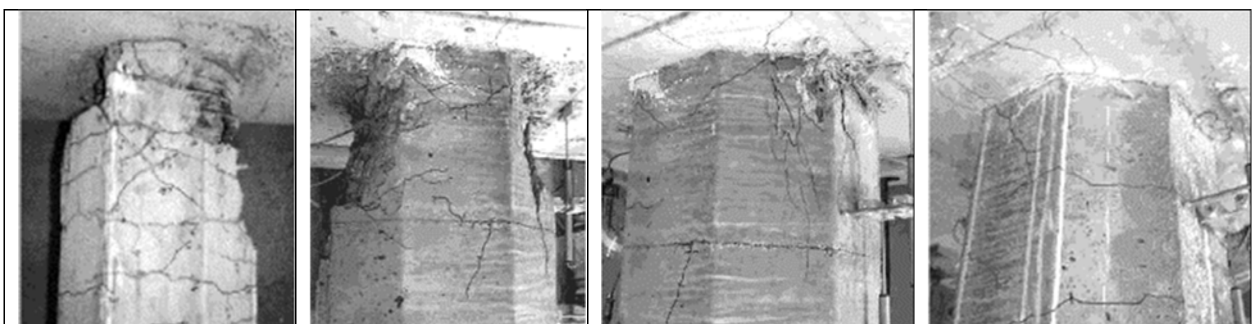


Figure 9. Typical wharf damage – large earthquake.

Examples of expected pile-wharf deck connection damage, based on testing, are shown in Figure 10. For large earthquakes, cracking and spalling varies depending on design and wharf displacements. Landside piles that will deform over shorter distances will experience the most rotation and damage, while most waterside piles will have less rotation and little or no damage.



Severe	Significant	Moderate	Minor

Figure 10. Piling-wharf connection test damage (Roeder 2013).

CRANE-WHARF INTERACTION

Crane structures are massive enough relative to the wharf that they affect the wharf seismic response, particularly if there is significant mass low in the crane such as due to ballast, if the cranes are closely spaced, or if the crane and wharf periods of vibration and resulting dynamic interaction are unfavorable.

When the earthquake first starts, the cranes reduce the wharf response, but as the cranes are excited, the interaction can increase the maximum wharf movement and resulting damage. The additional damage is often not much and likely the wharf could continue to be used without immediate repair, i.e., the damage can be repaired as convenient.

The Port of Los Angeles (Port of Los Angeles 2010) and the Port of Long Beach (Port of Long Beach 2015) require an analysis to evaluate the effect of the crane on the wharf response if the crane natural period of vibration is not at least twice that of the wharf. FEA are made to study this effect.

A stiff crane (i.e., short period) is favorable for operations; however, a crane with at least twice the wharf period will minimize the interaction between the crane and wharf. For most wharves, these can be balanced such that it is practical for the cranes to have periods at least twice the wharf.

Case Studies

Case studies of crane and wharf interactions are presented below for a location at the Port of Long Beach (Location A) and a location at the Port of Los Angeles (Location B). Three conditions are presented for each location: "Wharf Only," "Wharf+Crane," and "Wharf Design." The "Wharf+Crane" condition represents a detailed model that includes the crane and wharf. The "Wharf Design" condition represents a model that includes the wharf with a fixed seismic mass. Wharf design criteria vary but typically include additional mass for equipment or containers on the wharf (typically 100 psf) and some participating mass for the container crane.

A model of the analysis of a recently procured crane and a portion of the wharf at Location A is shown in Figure 11.

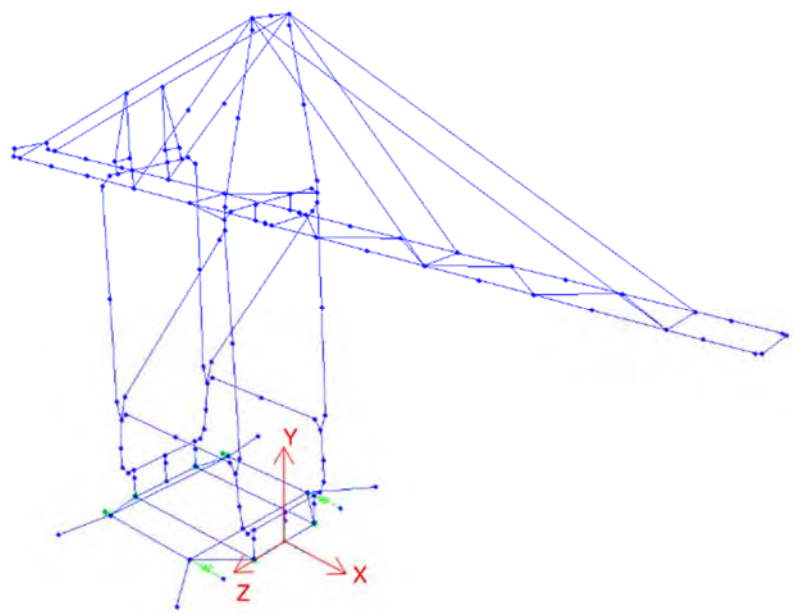


Figure 11. Crane+wharf FEA model at Location A.

The calculated response of a portion of the Location A wharf for port-designated Contingency Level Earthquakes (CLE) is shown in Figures 12 and 13. At this facility, the crane has a natural period of 1.22 s in the direction perpendicular to the crane rail, which is 1.6 times the wharf period. The wharf is expected to experience ductile yielding during the CLE ground shaking and lateral movement.

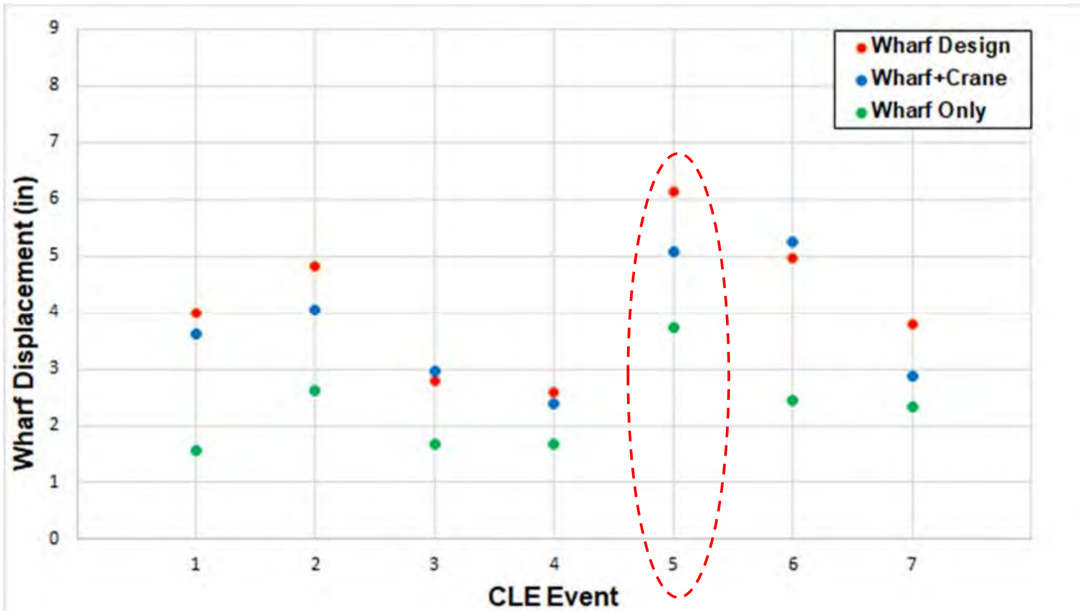


Figure 12. Maximum wharf lateral displacements for seven CLE events at Location A.

"CLE Event" represents different earthquakes; numbering does not indicate magnitude.

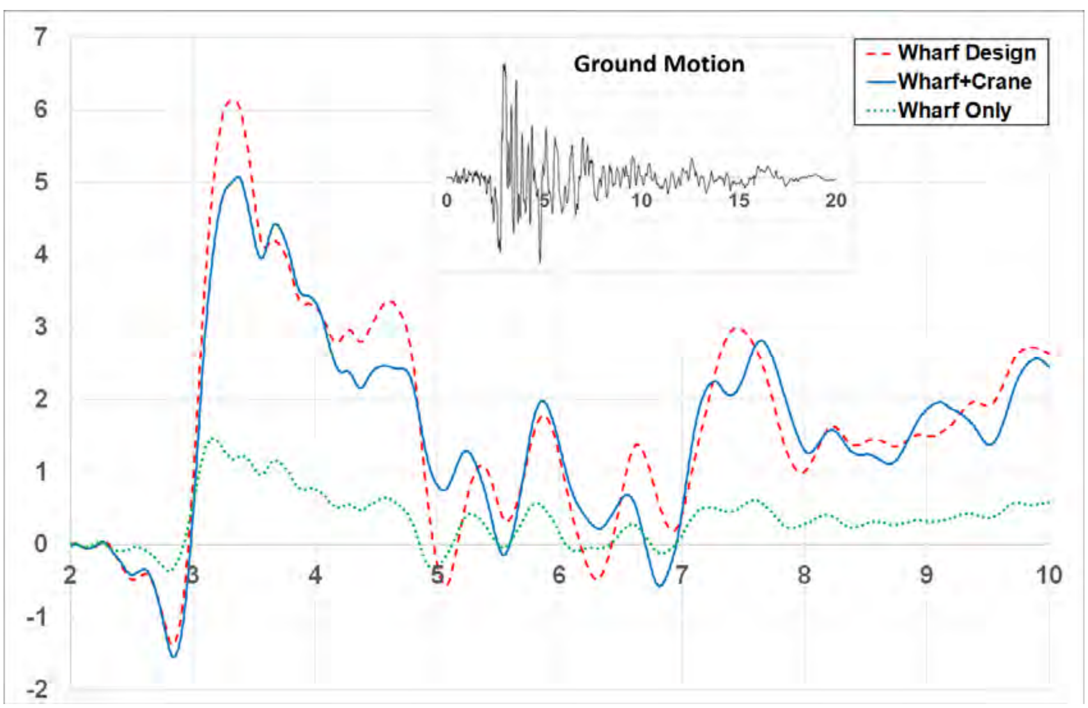


Figure 13. Wharf lateral displacements during "CLE Event 5" at Location A.

The calculated response of a portion of the Location B wharf for CLE events is shown in Figures 14 and 15. At this facility, the crane has a natural period of 1.4 s in the direction perpendicular to the crane rail, which is 1.8 times the wharf period. The wharf is expected to experience ductile yielding during the CLE ground shaking and lateral movement.

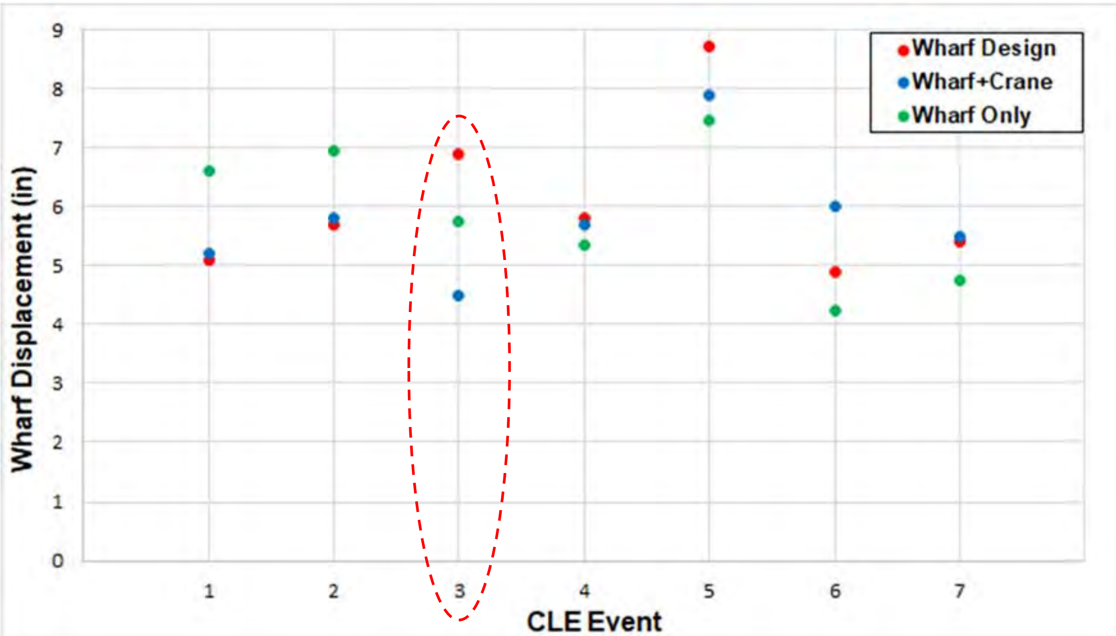


Figure 14. Maximum wharf displacements for seven CLE events at Location B.

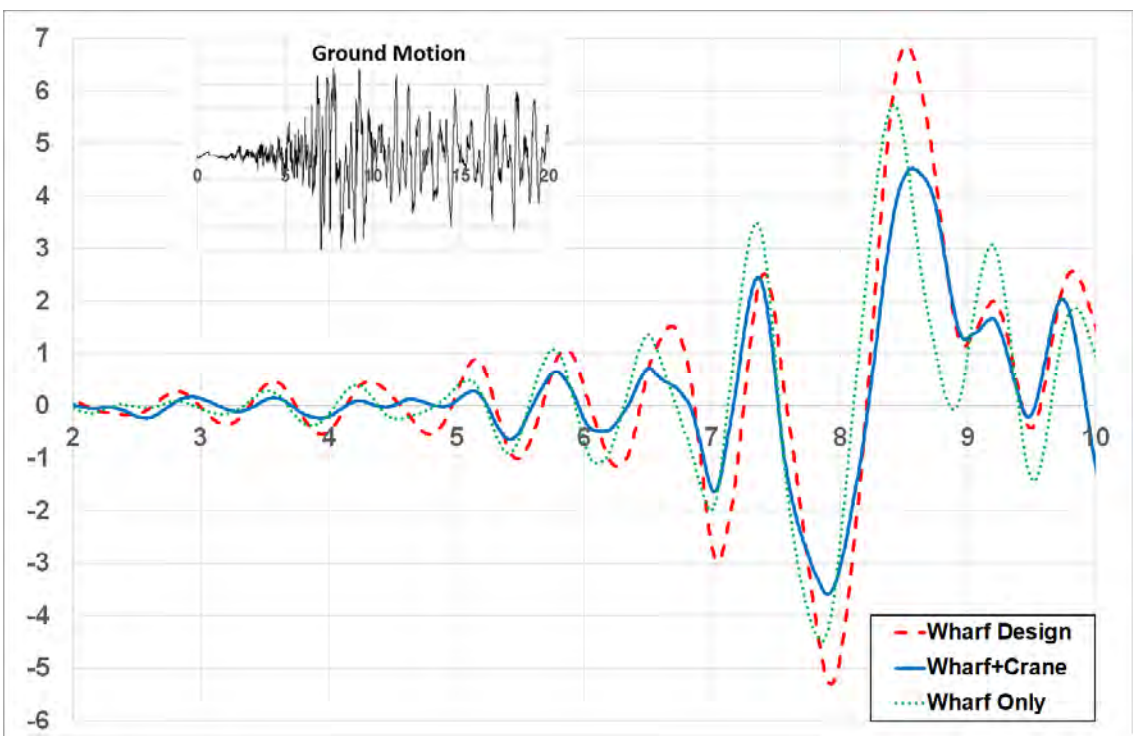


Figure 15. Wharf displacements during "CLE Event 3" at Location B.

As shown in these case studies, wharf response varies for different earthquakes due to different dynamic interactions of the crane and wharf vibration. In some conditions, such as the "CLE Event 3" at Location B, the crane will reduce the wharf response, but for these two case studies, typically the crane increases the wharf response compared to the "Wharf Only" case.

PORT PERFORMANCE

US West Coast major ports have a variety of terminals, wharves, and cranes. Seismic performance of terminals, including the wharves and cranes, will vary.

1. Earthquakes will affect different terminals at a port differently due to the varying orientations, soil conditions, and wharf and crane structures.
2. Some cranes will experience significant damage and, although unlikely, possibly collapse, while other cranes will have little or no damage. Cranes designed and built to modern specifications should perform well. Many are designed to tip elastically with little or no damage.
3. Modern wharves are designed to incur damage. In large earthquakes, the damage will require some repair, particularly with spalling at the pile-wharf deck connections. Lesser damage may include bending of rails and the power trench at expansion joints, and damage to utilities at the land boundary.
4. Typically, there will be some recovery time due to toppled containers or non-structural damage that is not practical or worthwhile to mitigate. This is reasonable.

At large ports, at least some terminals should be designed to perform well in large earthquakes to help ensure at least part of the port can operate soon after the earthquake. This typically involves ductile detailing for the wharf structure and designing the crane to tip with little or no damage. Most US West Coast ports have some wharves and cranes designed to this performance standard.

CONCLUSION

In large earthquakes, ports will be damaged.

Modern wharves with ductile detailing may be damaged but are not typically expected to collapse. Limited repairs are expected to restore unrestricted operations. Other wharves may have more severe damage and a longer recovery, e.g., broken batter piles that require repair before operations.

Container cranes are larger and more stable than in the past. Seismic performance became a significant design consideration and was addressed by Liftech crane specifications around 2004. There are several approaches to designing a container crane to have reasonable seismic performance, e.g., designing it to tip elastically, designing it to yield in a ductile manner, providing isolation and/or damping systems, others. Designing the crane to tip elastically has been the most practical. This approach is often used when modifying a crane to service larger and taller ships.

Cranes and wharf seismic interaction are significant. It is not practical to design the wharf to significantly affect the crane response. It is practical to design the crane to improve or to not increase the wharf response. Cranes with long periods, typically twice that of the wharf, will reduce wharf response. Shorter crane periods may result in increased, but acceptable, wharf movement.

US West Coast ports have a variety of wharf and crane structures with different soil conditions. Overall performance will vary. At large ports, we recommend designing at least one or two terminals to be operational after large earthquakes.

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