SEISMIC AND TSUNAMI DAMAGE TO PORT AND HARBOR STRUCTURES AND FUTURE MITIGATION

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ABSTRACT

After surveying port and harbor damage from the SE Asia earthquake and tsunami of December 26, 2004, there are a number of observations and preventative measures that could have been implemented to save lives and reduce economic losses. Without having historical inspection data, the failure of a marine structure may be apparent, but useful engineering conclusions may not be possible. If decades of marine degradation have occurred, then failure in a moderate earthquake is likely, even if the structure was well engineered and the initial construction was satisfactory. And as recently discovered in California, owners do not regularly inspect and monitor marine deterioration over time.

In California, a program has now become regulatory that requires all marine oil terminals to come up to a standard, which includes periodic underwater inspection, seismic rehabilitation and a continuing evaluation of fitness-for-purpose. This new standard is entitled "Marine Oil Terminal Engineering and Maintenance Standards" (MOTEMS) and is Chapter 31F of the California Building Code. The seismic assessment includes performance standards for two levels of earthquakes. The lower Level I has a 72 year return period, and the higher Level II has a 475 year return period. Structural performance levels are provided in terms of strain limits for both levels of earthquakes for steel, concrete and timber pile supported structures.

KEYWORDS: Port/harbor structures, seismic and tsunami criteria

1. PORT AND HARBOR SEISMIC DAMAGE

Earthquake, inertial load type failures were observed at Port Blair, S. Andaman Island as a result of the earthquake of December 26, 2004. In some cases the wharves/piers just fell into the water, with no failure mechanism visible. In other cases, shear failure at the pile deck interface was the obvious failure mode. One would hope to learn from these failures, but without knowing the previous structural condition, any conclusions would be purely speculation. It is interesting to note that in some cases, even with the complete failure of the pile/deck joint, gravity loads were still being carried, without collapse. If we hope to learn anything from the failures of these types of structures, then we must have recent above and underwater inspection information.

In California, historically we have very limited damage assessments for port/harbor structures from earthquakes. There is some data from the Loma Prieta earthquake of 1989, and its effects on the wharves at the Port of Oakland. One acceleration record has been used to correlate damage to a finite element analysis [Donahue, 2005].

2. PORT AND HARBOR TSUNAMI DAMAGE

Damage to port/harbor structures, from the tsunami of December 26, 2004 was primarily due to vessel impact. The Port of Chennai in S. India was a classic example of the rapid rise in water causing mooring lines to break due to buoyancy, and then the high velocity current allowed the vessels to move about the harbor. Damage to steel or concrete pile supported structures was not a result of wave or current forces. The kinetic energy of a 50 or 100 KDWT vessel impacting a structure at 5-10 knots presents a dynamic load that far exceeds normal structural capacity. Such a load cannot be considered in design. The one unusual feature of the tsunami scenario in S. India was that there was no warning, no ground shaking or inertial loads, just the arrival of the initial tsunami surge/wave.

The first wave arrived at the Port of Chennai at approximately 8:45 AM, with the second wave at 8:50 AM. All vessels experienced a large heave (vertical motion) due to the wave height. The exact height of the waves was uncertain but was reported to be 2 meters above the container wharf deck. Some empty containers floated off the wharf and drifted away. The tide gauges failed to record the event, because of the magnitude of the surge height. The current was reportedly very high, but there were no actual records. Five tugs were put into operation within 20 minutes, and out of the 18 vessels in the port, 13 were sent out to anchorage. One ship tried to exit under its own power, and took out two mooring dolphins of the Ambedkar wharf. A collision occurred, involving 3 vessels that broke free of their moorings. It is believed that the change in tide (heave) caused mooring lines to break, not the high current. The three vessels moved in a circular fashion in the port, according to eye witness accounts.

Five port employees were injured while running to safety, and one person on a merchant vessel was killed. The economic loss to the port of Chennai was put at 2.5 million dollars (US). Sailings of 15 vessels were affected; 346 cars were damaged. There was no indication of damage to the containers on the wharf that was inundated by the tsunami.

At Port Blair, S. Andaman Island, intense ground shaking occurred at about 6:30 AM, and there was 50 minutes between the earthquake and the first wave. Port Blair experienced four waves, with the largest being about 5 meters in height. The approximate time between waves was 30 to 35 minutes. There was no known accelerometer and no record of peak ground acceleration. Reportedly, there were 20 vessels in the port at the time of the earthquake. All mooring lines were immediately cut (primarily using fire axes on the vessels, no steel lines), and were told to depart, immediately. This was the established procedure for seismic events at Port Blair, and was done in the absence of any knowledge of the impending tsunami. Some passengers had already embarked on a ferry, and it departed; others still on the wharf were escorted away, without a single injury. Of the 49 piers and wharves throughout all of the Andaman Islands, 14 were unfit for use and 15 were partially damaged. At the time of our visit about 5 weeks after the event about 75% of all operations had been restored. The Andaman Island ports are their lifeline for all goods, services and almost all civilian transportation.

The dry dock at Port Blair had one vessel jacked up (dry), and on the other side of the lock, another vessel moored. During the tsunami, it is believed that the moored vessel broke free, hit the lock gates and broke it and the vessel that was dry became buoyant, and turned on its side. There is very little that could have been done to remedy this scenario prior to the tsunami. The water level was over the pier/lock height and extended into the port's buildings by almost 2 meters, so the jacked up vessel would have re-floated and created damage in any case. It is not clear if any structural damage was done to the walls of the dry dock; no damage was noted. The adjacent port maintenance building was completely flooded to 1.5 meters above the floor, and all electrical systems, motors and equipment were non-operational.

As an interesting side note, South Andaman Island is a tourist resort location, and during our visit, almost 6 weeks after the event, there were no tourists. As a primary source of income for the Andaman Islands, this vital revenue source had evaporated.

3. NEW STANDARDS FOR CALIFORNIA'S MARINE OIL TERMINALS

In California, a program to rehabilitate and monitor the structural health of geriatric marine oil terminals has been developed and is now enforceable. The average age of marine oil terminals in California is more than 50 years, and to date, maintenance and rehabilitation have been an absolute minimum. This new program, called "Marine Oil Terminal Engineering and Maintenance Standards" or MOTEMS [CBC 2001] requires complete underwater inspections and rehabilitation to bring aging facilities up to some minimum level of capacity, considering mooring, berthing and seismic loads. With historical records of underwater inspections, a post-event evaluation will be meaningful and provide valuable insight into the failure mechanisms of pile supported wharf/pier structures.

MOTEMS provides comprehensive design criteria and analyses procedures for both new and existing marine oil terminals. Currently it is being used for the analysis/design of the largest marine oil terminal in California.

The MOTEMS became part of the California Building Code [CBC, 2001] on February 6, 2006. These standards define criteria for both new and existing facilities and are "performance-based" in terms of structural analysis and design. Some of the relevant sections of this new code include:

a) Comprehensive criteria for underwater and above water periodic inspections. The underwater inspection criteria follows the new ASCE standard for underwater inspections [Childs, 2001].

b) Structural loads including mooring, berthing, seismic, dead and live loads with load combinations

c) Acceptable methods of seismic analysis based on strain limits, with specific values for concrete, steel and timber pile supported wharf/pier structures. Two levels of earthquake are specified, with different performance standards for each. For the frequent event (Level I, 72 year return period earthquake, 50% in 50 years), there is to be only minor damage and temporary interruption in service. For the higher level (Level II, 475 year return period earthquake, 10% in 50 years), there is to be no structural collapse, controlled inelastic behavior and service restorable within months.

d) Mooring and berthing criteria and acceptable analyses procedures

The MOTEMS are designed to maintain serviceability and functionality of facilities before and during structural rehabilitation. If the mooring or berthing capabilities (post-inspection) are less than required in the MOTEMS for new construction, the operator can downgrade impact velocities or wind speeds, so that operations can continue at a reduced capacity. For seismic rehabilitation, a more scheduled approach has been adopted. Understanding that these structures have remained operational for decades, the seismic rehabilitation is scheduled with completion dates agreed upon by the owner/operator and the regulator. In other words, these facilities are not shut-down, although we know that their seismic vulnerability is not acceptable in the long term. The time to rehabilitate may take years, but is scheduled, planned and followed-up by the regulator. We have seen numerous global structural rehabilitation projects that have not interfered with normal operations.

The first "audits" of the highest risk facilities are due in August 2008, and will include complete underwater inspections, rehabilitation plans with completion dates, along with mooring, berthing, seismic and pipe stress analyses. These audits will then become the rehabilitation road maps. It is anticipated that almost all of these facilities will require seismic upgrades to conform to the Level II earthquake (475 year return period).

Above and below the water line structural assessments are designated as Condition Assessment Ratings (CARs), with one value for above and another value for below the water line. Ratings below "fair" (4) indicate that the structure is not fit-for-purpose, and a downgrade in operational status may be required. Remedial actions must be taken, in order to restore full operational status. Seismic rehabilitation is addressed separately because a low seismic CAR rating would limit operations. The following table describes the various "CAR" values and implications.

CONDITION ASSESSMENT RATINGS (CAR)		
	Rating	**Description of Structural Systems Above and Below Water Line**
	Good	No problems or only minor problems noted. Structural elements may show very minor deterioration, but no overstressing observed. The capacity of the structure meets the requirements of this standard. The structure should be considered fit-for-purpose. No repairs or upgrades are required.
	Satisfactory	Limited minor to moderate defects or deterioration observed, but no overstressing observed. The capacity of the structure meets the requirements of this standard. The structure should be considered fit-for-purpose. No repairs or upgrades are required.
	Fair	All primary structural elements are sound; but minor to moderate defects or deterioration observed. Localized areas of moderate to advanced deterioration may be present, but do not significantly reduce the load bearing capacity of the structure. The capacity of the structure is no more than 15 percent below the structural requirements of this standard, as determined from an engineering evaluation. The structure should be considered as marginal. Repair and/or upgrade measures may be required to remain operational. Facility may remain operational provided a plan and schedule for remedial action is presented to and accepted by the Division.
	Poor	Advanced deterioration or overstressing observed on widespread portions of the structure, but does not significantly reduce the load bearing capacity of the structure. The capacity of the structure is no more than 25 percent below the structural requirements of this standard, as determined from an engineering evaluation. The structure is not fit-for-purpose. Repair and/or upgrade measures may be required to remain operational. The facility may be allowed to remain operational on a restricted or contingency basis until the deficiencies are corrected provided a plan and schedule for such work is presented to and accepted by the Division.

	Serious	Advanced deterioration, overstressing or breakage may have significantly affected the load bearing capacity of primary structural components. Local failures are possible and loading restrictions may be necessary. The capacity of the structure is more than 25 percent below than the structural requirements of this standard, as determined from an engineering evaluation. The structure is not fit-for-purpose. Repairs and/or upgrade measures may be required to remain operational. The facility may be allowed to remain operational on a restricted basis until the deficiencies are corrected, provided a plan and schedule for such work is presented to and accepted by the Division.
	Critical	Very advanced deterioration, overstressing or breakage has resulted in localized failure(s) of primary structural components. More widespread failures are possible or likely to occur and load restrictions should be implemented as necessary. The capacity of the structure is critically deficient relative to the structural requirements of this standard. The structure is not fit-for-purpose. The facility shall cease operations until deficiencies are corrected and accepted by the Division.

We have found that the CAR ratings provide a good indicator of the current structural condition of a facility that can provide a uniform standard for facilities ranging from 30 to 80 years of age.

For new marine oil terminals and for other selected major facilities, strong motion accelerometers have been either placed or planned for wharf decks. These serve multiple purposes in addition to providing in-structure response that can be compared with finite element analyses and provide a verification of actual structural performance. First, they provide in-structure response which can be used to assess possible underwater damage and/or assist in making a decision about remaining operational. If the maximum acceleration recorded on the wharf is well below the seismic criteria and there is no apparent above water damage, then an underwater inspection may not be required. The in-structure response may also provide guidance for adjacent, similar structures and as to whether or not they should be shut-down or inspected underwater prior to further use. The accelerometer can also provide a date/time stamp of a significant impact (allision) of a vessel. One of these rehabilitated wharf/pier marine oil terminals has now been instrumented with accelerometers and will provide an in-structure response during the next moderate (or larger) earthquake. Other instrumentation has been placed on wharves in the Port of Los Angeles, and extensively at the Port of Oakland. And in California, acceleration records in the "Strong Motion Instrumentation Program" are available to the public via the internet.

The MOTEMS also includes a section on post-event inspection criteria and guidance to evaluate structural damage [Childs, 2001]. The ratings are A-D and ratings C and D require that the facility be limited in operations or shut down until repairs are complete. We have successfully used this criteria for a recent major vessel allision incident.

POST-EVENT RATINGS AND REMEDIAL ACTIONS		
Rating	***Summary of Damage***	***Remedial Actions***
A	No significant event-induced damage observed.	No further action required. The berthing system may continue operations.
B	Minor to moderate event-induced damage observed but all primary structural elements and electrical/mechanical systems are sound.	Repairs or mitigation may be required to remain operational. The berthing system may continue operations.
C	Moderate to major event-induced damage observed which may have significantly affected the load bearing capacity of primary structural elements or the functionality of key electrical/mechanical systems.	Repairs or mitigation may be necessary to resume or remain operational. The berthing system may be allowed to resume limited operations.
D	Major event-induced damage has resulted in localized or widespread failure of primary structural components; or the functionality of key electrical/mechanical systems has been significantly affected. Additional failures are possible or likely to occur.	The berthing system may not resume operations until the deficiencies are corrected.

Recent interest and activities along California's coast indicate concern about tsunamis, to the port regions of both Northern and Southern California. An initial study [Synolakis et al, 2002] provided run-up values for the ports of Los Angeles, Long Beach and Port Hueneme. These 500 year return period values are part of MOTEMS and require that oil terminals to have a "tsunami plan" in place, for both far field and near field events. As a result of this initial study, the ports of Los Angeles and Long Beach decided to perform their own study, and the results are on the websites of both ports [Tsunami Hazard Assessment, 2007]. Some possible pre-arrival actions include the shut-down of all petroleum transfer operations, and if there is time and tug boats available, vessels should depart to deep water.

The MOTEMS is also being used as non-regulatory guidance for general pier/wharf analysis and design, and has been used outside of California. It provides a comprehensive tool to evaluate the structural integrity of a marine structure, and will mitigate damage from future earthquakes. And with recent underwater inspection data, seismic performance can be accurately assessed.

4. CONCLUSIONS

After surveying damage as a result of the earthquake and tsunami of SE Asia of December 26, 2004, there are a number of conclusions that can be made.

a. Seismic damage assessment for pile supported pier/wharf structures may not be meaningful if there isn't a historical record of comprehensive underwater inspections.

b. Tsunami damage to a port/harbor structure may be unavoidable and outside of the range of rational design criteria.

c. The MOTEMS provides a comprehensive above and underwater inspection program for pile supported port/harbor structures, and can be used as a tool to evaluate fitness-for-purpose for post-event and also as a method to evaluate continuing fitness-for-purpose. The MOTEMS provides explicit design criteria and analysis methods for new or existing marine oil terminals, and has been used on other types of wharf/pier structures as well.

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