MARINE AND WATERFRONT STRUCTURES

By Bill Paparis

Over the past three decades there have been major changes in the world's ocean going vessels. In addition, new markets have emerged in many previously undeveloped and underdeveloped areas of the world. This has and will continue to lead to the construction of new port facilities, and the expansion and upgrade of existing port facilities. The planning, design, and construction of port facilities, and in particular the structures supporting them, involves consideration of many factors which are unique to these types of structures. These factors include the following:

- Potentially large lateral and uplift loads on the structures. These may include berthing loads, mooring loads, ice loading, wave loading, lateral earth pressure, differential water pressure, and seismic loads.
- Generally poor geotechnical conditions at many locations, with marine deposits which provide inadequate vertical and lateral support.
- Long unsupported pile lengths where structures are located in deep water.
- Corrosion protection to mitigate salt water attack on steel and concrete structures, and marine borer attack and rot/decay on timber structures.
- In most cases, the work must be performed from floating equipment or jack-up barges, which results in more expensive work spreads, reduced productivity, and potentially severe exposure to environmental conditions.
- Tidal conditions potentially reduce the work window for certain types of construction, thus reducing the productivity and increasing the cost.
- Concrete formwork is generally performed over the water, significantly reducing productivity.

Figure 2: Monopile Type Breasting Dolphin

Most structures are designed for dead loads, live loads, wind loads, and in areas where earthquakes are a concern, seismic loads. These loads are generally well defined by the local building code or governing standard/specification. In the marine environment, in addition to the loads identified above, as well as other "defined" loads, it is necessary to consider current loads, wind loads on the vessel, ice loads, and, when the structure is in a location which is exposed to the sea, i.e., outside a protected harbor, wave loading must also be considered. Currents are generally determined by the use of a current meter, while wave heights are determined via hindcast studies and observations. In cases where wave loading must be considered, a dynamic mooring analysis is generally required in order to accurately estimate mooring line forces, and consequently, forces on the mooring fittings and structure. Where mooring line loads are excessive and/or vessel motions are too large to permit cargo transfer operations to proceed safely on a regular basis, a breakwater is provided to "protect" the harbor. *Figure 1* (*see page 34*) illustrates an example of such a breakwater.

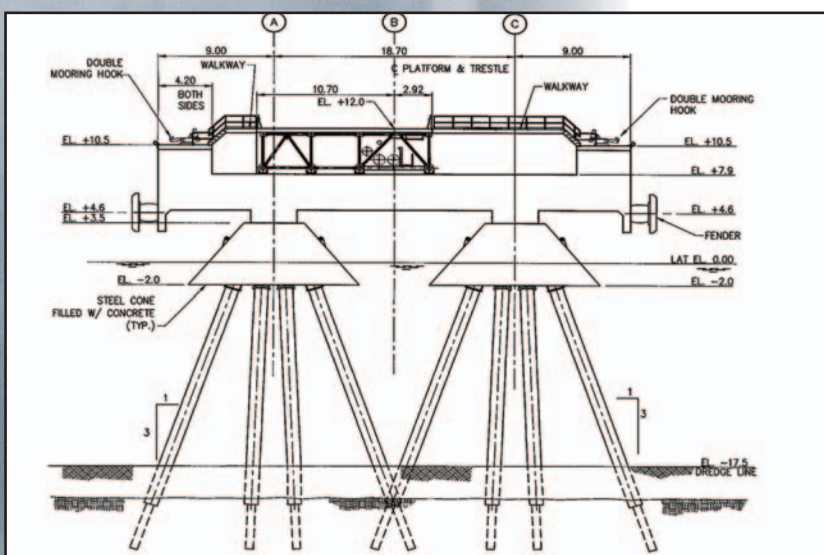

Diagram 1: Conical Structure around Piles

Wind loading on a vessel is generally determined using a 30 sec gust, and the maximum speed is a function of the operating procedures at the terminal, but in general it will not exceed 60 knots. Ice loading data is very difficult to quantify, and there is generally little accurate published data available. The load is a function of both the ice thickness and ice strength. In New York Harbor, ice thicknesses on the order of 12 inches and ice strengths on the order of 100 psi are typically used to calculate loads on structures. On the other hand, in areas such as eastern Russia, which has seen a recent increase in petroleum related marine and waterfront construction, design ice thicknesses of 5 feet, and design ice strengths of 175 psi, are typical. Such ice conditions lead to huge forces on piles, and therefore, it is common to provide a conical skirt around the pile at the water level, so that the ice will "ride up" the pile and fail in bending rather than in compression. *Diagram 1* illustrates an example of such a design.

"Ice loading data is very difficult to quantify…"

As a result of the above, as well as seismic loads, lateral earth pressure, and differential water pressure, marine and waterfront structures are generally subject to very large lateral and uplift loads. As such, the foundations must be designed to resist these forces either by adequate penetration into the underlying soil or rock, or in the case of a gravity structure, the structures must be large enough and heavy enough to resist the loads by their mass. In many pile supported waterfront structures, it is necessary to use batter piles to resist such loads, as the batter piles, which resist forces through axial compression and tension, are most efficient. However, where soil conditions are such that adequate tension capacity cannot be achieved before rock is encountered, the use of rock sockets is necessary. On the other hand, if the soils are too weak to provide adequate compression and/or tension capacity without excessive pile lengths, large diameter piles which provide lateral resistance through bending may be used. *Figure 2* (*see page 31*) illustrates an example of a large diameter monopile type breasting dolphin which was designed to resist impact loads from VLCCs (very large crude carriers). This structure was constructed in a water depth of 100 feet.

"…it is generally necessary to remove the silt in order to minimize lateral earth pressure on the structure…"

locations along the shoreline of the Hudson River, it is necessary to drive piles to depths of 150 ft or more in order to achieve adequate capacity, particularly where significant loads are being supported.

Unlike piles driven onshore, which are supported laterally over their full length, piles supporting waterfront structures are unsupported from the point at which they frame into the pile cap to the point where the soil provides adequate lateral support. This point is generally estimated by performing a laterally loaded pile analysis to determine the "equivalent" point of fixity. This point is a function of the pile diameter and geotechnical conditions. For large piles (i.e. on the order of 24 inches or larger, driven through soft silts or clays), the equivalent point of fixity could be as much as 25 or 30 feet below the mudline. Therefore, if such a pile were in 35 feet of water, and framed into a pile cap at 10 feet above the water level, the "equivalent" pile length would be 70 to 75 feet. Therefore, in many cases, the capacity of piles in the marine environment is governed by structural rather than geotechnical conditions. This is particularly true for old existing piers which are supported on timber piles. As timber starts to deteriorate, usually due to marine borer attack and/or rot, the pile diameter decreases, which results in a much larger decrease in its moment of inertia and consequently its allowable load.

Corrosion Protection

Elements of steel and reinforced concrete waterfront structures which are located in seawater are very susceptible to corrosion. The rate of corrosion increases with salinity (up to the maximum rate in seawater), water temperature, and current velocity. In addition, the location of the element relative to the water level will influence corrosion. Surfaces in the tidal and splash zones are generally more susceptible to corrosion than underwater portions of structures. However, if stray currents are present, the underwater portions may be susceptible to accelerated corrosion.

"…the location of the element relative to the water level will influence corrosion."

Figure 5: Installation of a Precast Pile Cap

Poor Geotechnical Conditions and Long Unsupported Pile Lengths

In many cases, waterfront structures are founded in or are required to retain poor soils. This is attributable to the buildup of silt along the shoreline, particularly if a structure is present which inhibits sediment transport along the shoreline. Where sheet pile or gravity-based structures are to be founded in these conditions, it is generally necessary to remove the silt in order to minimize lateral earth pressure on the structure, and, depending upon the type of operations at the terminal, to minimize settlement. Where soft sediments exist to great depths, as is the case in many

Figure 3: Floating Barges with "Ringer" Crane

For steel structures, proper corrosion protection generally involves the application of a high quality coating in conjunction with a cathodic protection system which will offer protection only below the water level. The cathodic protection may be of the sacrificial anode or impressed current type. In the former case, anodes are typically mounted on the steel piles or sheet piles, and are electrically connected to the steel.

The principle of the sacrificial anode method is that the anodes, which are generally composed of an aluminum-alloy (for marine structures), have more positive potential than does iron or steel, so that an electric current flows through the seawater (in the form of ions) from the anode to the steel. In this system, the steel becomes the cathode of a large electrochemical cell and its potential is reduced to a level where the only current that flows is onto the steel and corrosion currents are cancelled.

The impressed current system consists of a DC source in the form of a transformer-rectifier, which delivers current from its positive terminal to the anode(s), through the seawater, onto the structure, and back to the negative side of the source. The steel structure is protected as long as the flow of electrical current onto the structure is maintained. Where corrosion of steel in the tidal and splash zones is a major concern, one solution is to provide an encasement over the portion

Figure 4: Driving of a King Pile System with a Vibratory Hammer

of the steel pile which is in these zones. Such an encasement could consist of a concrete jacket or a fiberglass jacket, with the annular space between the pile and fiberglass jacket filled with grout or other material.

For reinforced concrete structures, a dense concrete with a low water/cement ratio is critical for minimizing ingress of chloride ions and subsequent corrosion of rebar. Epoxy coated rebar is used in most waterfront applications.

Timber elements exposed to salt water must be creosoted in order to provide protection against marine borers and rot. In some instances, South American or African hardwoods are used in lieu of creosote, but these types of woods are more expensive and, in some instances, ineffective against marine borer attack.

Figure 1: Breakwater

Construction Considerations

Equipment, Tidal Conditions, and Over-Water Formwork

Marine and waterfront construction is generally performed by contractors who are experienced with this type of work, and who have suitable equipment at their disposal. Typical equipment generally consists of barges, floats, and jack-up barges. *Figure 3* (*see page 32*) illustrates floating equipment being used for the construction of a pier and trestle. The crane is mounted on a ring, which is installed on the barge and provides additional lift capacity. Crane lift capacities are generally "derated" when they are mounted on floating equipment, due to the fact that they are subject to motion from waves and swells. The use of floating and jack-up rigs results in increased time for mobilization, moving from one location to another, and stabilizing the rig. Production is therefore generally much lower than for land based work. In some cases, particularly in swift current conditions, it is necessary to install a template prior to driving piles to insure that driving tolerances can be achieved. *Figure 4* (*see page 33*) illustrates a "king pile" type sheet pile wall being driven with a vibratory hammer. This structural system requires very tight installation tolerances.

"Crane lift capaci…"ties are generally 'derated' when they are mounted on floating equipment"

Another issue affecting waterfront construction is the fact that tidal conditions must be considered in performing the work. For example, if there is any element being installed within the tidal zone, e.g., a bracket being welded to a pile, it will only be feasible to carry this out when the water level is at or near low tide. Similarly, formwork in the tidal zone is also generally done only at low tide. This, and the fact that there is no stable platform off of which to work, results in very time consuming and expensive formwork/cast-in-place concrete operations. Therefore, it is generally advantageous to use precast work in the marine environment where possible. Precast work also generally results in higher quality concrete. *Figure 5* (*see page 32*) illustrates a precast pile cap being installed on steel pipe piles.

Conclusion

Marine and waterfront structures pose unique challenges for engineers. These challenges include development of appropriate environmental design loads, consideration of what are, in many cases, difficult geotechnical conditions coupled with large lateral loads on structures in large water depths, protection against severe corrosive conditions, and a thorough evaluation of constructability in order to minimize cost. A comprehensive review of all these factors for each project is vital in order to carry out a design which minimizes life cycle costs.▪

Bill Paparis is with Han-Padron Associates, LLP, a marine engineering firm with offices in New York, California and Florida. Bill specializes in the design, inspection and evaluation of waterfront structures.