Role of Precast Elements in Shaping Marine Structures

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Offshore structures have developed rapidly over the last three to four decades. Much of this has been driven by the need to exploit deeper waters as a result of depletion of shallow water easy-to-reach fields, buoyed by a generally continually rising price of oil and, more recently, gas. This need for deepwater developments and, as well, a desire to continue to exploit depleting shallow water reserves has spawned new forms of offshore structures for production, such as production precast concrete elements, semi-submersibles, tension leg platforms in a variety of shapes and sizes, monohulls (ship-shaped units), spars, monotowers, and production jack-ups. Jackets have continued to be exploited in a variety of ways using different construction methods, all aimed at speeding up design, fabrication and installation.

Precast concrete elements are increasingly used in the construction of Maritime Structures. They offer the prospect of efficient unit production and rapid construction, but that requires the efficient construction of adequate foundation restraint. Foundation design and constructability for these elements is therefore a critical area, but little guidance is available on the different forms of foundation available.

Typical underwater foundation systems that are used commonly includes :-

(A) Pre-levelled Bed

- Stone Layers Base Infill

(B) Base Infill

- Tremie Concrete

- Open Grouting
- Grouted Fabric Formwork (Grout Bags)
- Pumped sand Weak / Inadequate Strata

(C) Weak / Inadequate Strata

- Piled Foundations
- Ground Improvement

Maritime construction is usually a high risk operation that needs efficient and suitably robust design and construction methods to be developed. The relative merits of different foundation systems are also outlined in terms of design and constructability, thus seeking to inform Designers, Contractors and Owners in considering alternative and combinations of foundation systems.

Structure & Precast Element Types

Precast concrete element solutions (Refer Figure 1) are often used on the following range of maritime structures:-

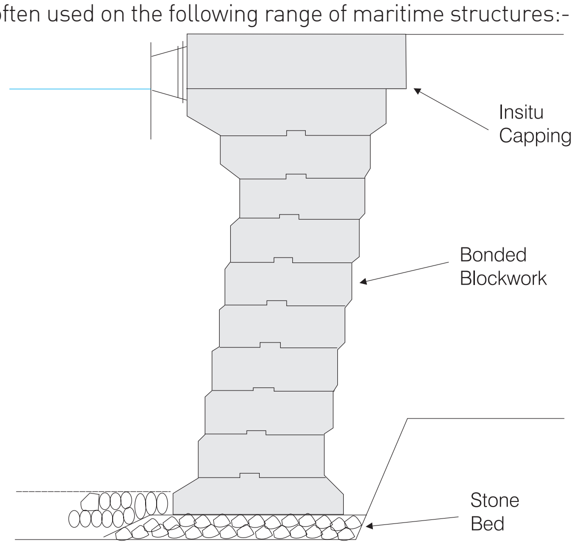


Figure 1: Quay Wall

- Harbour, quay walls and seawalls
- Bridge piers
- Breakwaters
- Immersed tube tunnels
- Barrages (particularly turbine or control sluice housings)
- Wind turbine mast bases
- Other general maritime construction

Types of foundation elements often used:-

- Solid concrete blocks
- Hollow concrete blocks
- Open topped cell caissons
- Open base 'shell' caissons
- Immersed tubes
- Pier bases
- Mast bases
- Counterfort wall
- Other – purpose made

Closed bottom caissons and immersed tube elements are normally floated into place taking advantage of their natural buoyancy, before being lowered into place. Open base shell caissons can be lifted in by cranes or supported by pontoons (sometimes called "camels"). Plain precast blocks are typically unreinforced giving advantages of increased longevity. Due to the generally aggressive exposure conditions of maritime works, reinforced concrete elements are often formed with a combination of protected reinforcement, increased cover and corrosion resistant concrete. This is particularly so in more extreme climates. Precasting often enhances quality control, allows economic repetitive production and a reduction of insitu marine works to a minimum. Adequate plant and space is required within the precasting yard for casting, curing and storage. The elements can be used singularly, joined, stacked and arranged to form efficient and varied structures / foundations working at sea bed level.

Foundation Design

A. Structure Loadings

Typical load types for maritime structures (Refer Figure 2)

- Dead and imposed loads
- Wave momentum and impact loads, (+ve) and (-ve)
- Wave overtopping downfall loads
- Wave-driven internal and uplift pressures
- Current drag and lift forces
- Water pressures, tidal, uplift
- Seismic, wind loads, earth pressures, ice pressures
- Vessel berthing, mooring and impact

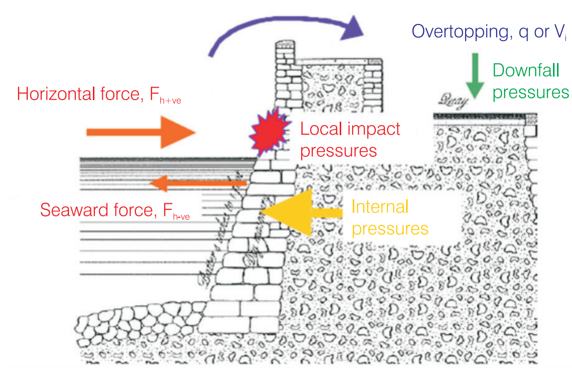


Figure 2 : Wave Driven Loadings

Foundations need to be designed to accept all realistic loads imparted from the precast elements. This can often require design for:-

- Bearing pressures
- Overturning
- Sliding and slip circle failure where appropriate
- Settlement (overall or relative), short or longer-term deflection
- Scour protection
- Seismic and other dynamic effects (including effects of impulsive loadings)
- Suction pressures (from impermeable strata due to seismic / impulsive loadings).
- Filter failure, piping, wash out or suffusion (migration of fines).

In each instance, the full range of soil / foundation /

Strata Type	Marine Foundation Characteristics	Typical Allowable Bearing Pressures (kN/M2)
Hard Rock	Often with Steps or Trenches	>2,000
Soft Rock	Can be dressed to level/slope	500-2,000
Gravel to Sands	Settlement is short term May erode under wave or current action unless protected	75-500 Loose-Compact
Fine Sands and Silts	Increasingly prone to settlement Likely to erode under wave or current action	50-250
Organic Silts & Clays	Highly prone to settlement and erosion	Low and Variable
Clays	Unconsolidated clays particularly prone to long term settlement	50-600
Fill Strata	Prone to variability, settlement and erosion	Low and Variable

Figure 3 : Typical Foundation Characteristics

structure interactions will need to be considered in the analysis. For structures subject to significant wave or tidal action, permeable foundation layers or strata can allow transmission of wave and hydraulic pressures and be at risk of filter failure, piping, washout or suffusion. Due to the very wide range of possible structures, foundation strata and load conditions, the above simplified list is only offered for initial guidance on foundation design and construction issues. Analysis / design procedures should be appropriate to the particular case considered, and should be in accordance with codes of practice and good practice.

B. Foundation Strata

The range of bed materials that may be encountered can be highly variable. Thorough site investigation should be carried out appropriate to the ground conditions, structure, environmental conditions and construction systems being considered. Refer Figure 3 for typical foundation characteristics.

Some precast systems may require the geotechnical assessment of relative and overall settlement during the construction period as well as the long term condition. Over consolidated soils are far less prone to settlement. Soils with inadequate bearing capacity, or weak soil strata that are prone to high settlement, may be strengthened by ground improvement techniques or piling

Foundation systems and materials

A. Pre-levelled bed, stone layer

A stone layer is pre-levelled accurately on the sea bed to allow direct and rapid placement of precast elements. The stone material is usually a crushed quarry rock with a narrow size range to allow water to flow through and avoid small particle loss6. The size range should allow it to be readily screeded accurately into place.

B. Base Infill

Base infill systems rely on the foundation element being supported on temporary jacks or initial pad foundations whilst the foundation void is infilled. Infill systems are often irreversible so need suitable planning, preparation and control. These systems are particularly common to bridge piers, caissons, immersed tube tunnels and sometimes blockwork wall foundations.

C. Weak / Inadequate Strata

Piled Foundations

Structural piles or shafts can be used to support precast elements although this is not common. Grouted top bearings can be used to large diameter piles. Alternately pile caps can be cast to pile groups and grouted fabric formwork or other bearings cast after the element is positioned. Precast pile cap shells are often used in America to form pile caps around water level.

Maritime piled foundations need to be designed with consideration for marine construction techniques. For high strength bearings, grouts up to 90 N/mm² have been used (Monaco). Due to the lack of structural continuity below the element, sliding resistance may need to be considered. Raking piles, shear key downstands or side bearings may be required.

Foundation System Selection

A. Foundation Influences

The choice of foundation type can be highly influenced by:

- Diver working conditions, health and safety
- Marine plant cost and availability, construction speed, risk management and cost.
- Sea conditions, currents, waves, depth, tidal range, sediment transportation, visibility, environmental restraints, obstructions, location and draft to the casting basin or yard.
- Structures sensitivity to settlement
- Seabed strata type and profile
- Environmental impact and decommissioning
- Material availability, durability and disposal
- Degree of construction repetition
- Seismic, ice flows or other dynamic action
- Required accuracy of installation

The safety and efficiency of divers is often dependent upon the constructability of the design and the working conditions. Apart from repeat structures, divers with relevant experience should be involved in the foundation system selection, providing diving methodology advice. Automated construction options should be considered. Where there is sufficient repetition, installation frames, positioning guides and surface control systems can be considered.

B. Risk Management.

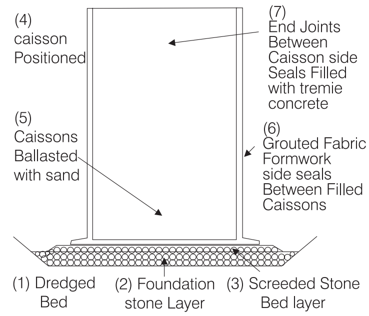
Risk is generally defined as the probability of a hazard multiplied by its consequence. Risks in maritime construction can be more likely than on land, and the consequences can be greater. Good management of risks is therefore essential. The development of good robust maritime construction systems for foundations has many benefits as problems can be costly. Appropriate risk management techniques are best used to manage risk during the design and construction system selection period. Design and system selection should be integrated as both invariably need to be developed together10. This requires the early formation of design and construction teams with relevant experience, for projects other than relatively simple or repeat ones. Risks are generally lower where systems have had similar previous use and where project teams have good experience. Similarly, risks are generally higher for teams with less experience and new bespoke solutions. Multiple partner joint venture groups generally attain better risk management due to their sharing of wider experiences. Engagement of Specialists should be considered where required. For Construction system design and selection, a formal risk management procedure could be adopted with at least two members of the team taking responsibility for areas where they have proven relevant expertise and experience. This is particularly important where construction is irreversible, difficult or costly.

Case studies

(A). Cardiff Barrage Entrance Harbour, Wales

The Cardiff Bay Barrage is 1.1 km long and extends from Cardiff Docks in the North to Penarth in the South. It has created a freshwater lake with over 13 km of waterfront. To the south end of the barrage a protective harbour of 2 curved breakwaters was constructed to protect the locks. The breakwater arms were formed by a series of pre-cast closed bottom caissons, each 17m high and weighing up to 4,500t, which were floated into position with buoyancy 'camels'. The dredge trench was filled with graded rock layers: first a larger rock foundation layer; then a screeded bedding stone layer to accept the caissons, lowered and ballasted into place (Refer Figure 4(b)). The caissons were filled with water, then sand, and the end joints between caissons were sealed with grouted fabric forms (Refer Figure 4(c)). The pairs of seals were located in protective recesses and allowed tremie concrete infilling of the end joints between caissons.

(a) Ariel View



(b) Construction Sequence

(c) Side Seals

Figure 4 : Cardiff Barrage Entrance Harbour, Wales

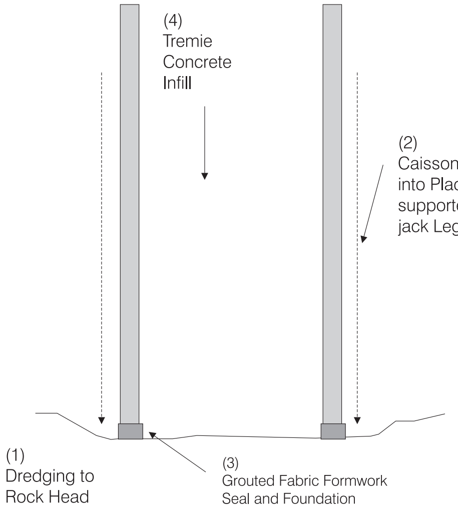
(B). Second Severn Crossing, UK

The Second Severn Crossing comprises a 5.2km crossing of the Severn Estuary. The crossing consists of a 0.9km cable stayed bridge with the main span being 0.5km long and gives a clearance of more than 37m over the highest tide level. The viaducts connecting the bridge to the shores are 2.2km and 1.9km long. Bridge piers were made of 27m to 35m long precast concrete shell caissons, each weighing up to 2,000 tonnes. Fabric formwork units were fixed onto the underside of the caissons before they were lifted into position by a jack up barge mounted crane (Refer Figure 5 (c)). They were supported on temporary jack legs in the pockets excavated into the Sandstone / Mudstone bedrock (Refer Figure 5 (b)). The grouted fabric formwork system was used to found the caissons onto the dredged rockhead, and was designed to be part of the bearing area of the foundation (Refer Figure 5(d)). After grouting the caisson supports were removed and the caisson cells were then tremie filled with mass concrete. The foundation system coped with the extreme tide and working conditions.

(C). Confederation Bridge, PEI, Canada

Confederation Bridge is 13km long and links Prince Edward Island to mainland Canada. The bridge was formed from precast elements including 64 pairs of piers bases and shafts plus cantilever and infill beams. All precast elements were lifted into place by floating crane. Weathered and weak mudstone was removed by clam shell dredging. Initial pad foundations (Refer Figure 6 (c)) were installed onto a weak mudstone rock head in water depths up to 33m by an Installation Frame (Refer Figure 6(b)). It carried three precast pads with condensed fabric forms and was levelled by three hydraulic rams. The Installation frame was fully automated for levelling, grout filling, vent monitoring and removal. Divers were only required to undertake monitoring duties. The hard pads were each formed in 5 compartments to limit risks of local failures, and were filled with a neat cement grout including an anti-shrink additive. The conical pier bases (Refer Figure 6(d)) weighing up to 4,000 t were carried by the Svanen floating crane and lowered accurately into place onto the hardpads. The sheltered dredge pockets were mass filled with a plain concrete, via prefixed tremie tubes, to form the foundation. The pier bases remained unfilled. The precast pier shaft was then lifted onto the pier base and sealed with a grouted fabric formwork seal. This allowed the structural joint between the two elements to be grouted with neat cement grout vertically within the protected void. This joint was below water level to accommodate the ice shield cone detail which aids the local break up of winter ice floes. This large scale, automated and sophisticated construction system was purpose designed. During the second season of element installation, a progress rate of one element per day was regularly achieved, giving a peak bridge construction rate of some 250m per 4 days.

(a) Second Severn Crossing



(b) Construction Sequence

(c) Lowering

(d) Grout Bag Foundations

Relative Merits of Various Foundation Systems

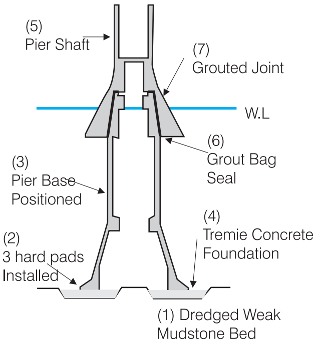
The above case studies show use of various types of foundations for marine structure construction and quite good examples of pre-cast structure use in marine structure construction. This, in conjunction with the range of precast element types and possible element arrangements, gives good scope for solutions. Proposed solutions should take advantage of the relative merits of the various systems. Refer Figure 7, which gives merits and demerits of various types of foundation system's using precast technology.

(a) Confederation Bridge

(b) installation Frame

(c) Initial Pad, Forms Condensed

(d) Pier Bases



(e) Construction Sequence

Figure 6 : Confederation Bridge, PEI, Canada

A Marine Structure Under Construction (Picture Courtesy : http://www.gerwick.com/menu/project/offshoremarinestructures/PublishingImages/Offshore.jpg)

Conclusion

Precast marine systems are being increasingly used and applied to a greater scale in construction of marine structure's and to more challenging depths. Improvements in the efficiency of forming foundations are expected to continue with the developing use of more automated systems for rock layer placement, precast element placement and grouting

Foundation Systems	Advantages	Disasvantages	Typical structure / Element Types
Pre-levelled Bed Stone Layers	Allows rapid placement of elements Quarry material is generally readily available Generally good sliding resistance	Prone to compaction settlement and possible seismic settlement, filter failure, piping or suffusion (migration of fines) May not be suitable for highly loaded foundations Can be prone to wash out of screeded bedding layer in construction and may require permanent edge scour protection Requires large level tolerance and structure level tolerances	Bridge Piers Harbour / Quay Walls Caisson Break waters I.T.T.'s Barrages Mast Bases
Base Infill Tremie concrete	Good compressive strength and sliding resistance Cost effective system when conditions allow	Prone to wash out before set Difficult to divide size of pour Fluidity insufficient for wide bases High wastage in dredge pockets Concrete plant / pumping required Temporary support needed	Bridge Piers Caisson Break waters Harbour / Quay Walls
Open Grouting	Good fluidity for wide bases Good compressive strength and sliding resistance Cost effective in sheltered conditions	Highly prone to washout (Oresund) Possible washout environmental risk Diffcult to divide size of pour, control uplift and avoid entrapped water to large pours Permeates open bedding layers Grout provision & pumping required Temporary support needed	I.T.T.'s Caisson Break waters Bridge Piers
Base Infill Grouted Fabric Formwork (Grout Bags)	Grout wash out prevented Good fluidity for wide bases Compartment size and uplift controlled Allows engineered risk management Good compressive strength and designed sliding resistance	Relative cost of the system, protection in transit and lowering required after fixing Grout provision & pumping required Often a Specialist system Temporary support needed	Bridge Piers I.T.T.'s Barrages Caisson Break waters Harbour / Quay Walls
Pumped Sand	Cost effective Suitable for wide bases	Prone to washout Prone to compaction settlement Prone to seismic liquefaction Specialist technique Cast-in pumping pipes often required	I.T.T.'s
Weak/Inadequate Strata Piled Foundations	High load capacity Minimal settlement	High cost May required pile cap construction Grouted bearings required Shear keys or bearings may be needed	I.T.T.'s Bridge Piers
Ground Improvement	Useful when the most cost effective option[4,10]	All systems are relatively costly Surface compaction, surcharging and replacement may be effective Other systems tend to be specialist techniques.	All Structures

Figure 7 : Relative Merits & Demerits of Foundation Systems

or concreting. These improved systems may be increasingly applied, both generally and to the further development of marine gravity structures for energy generation.

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