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Monopiles vs. Group Piles in Marine Bridge Construction: A Comparative Case Study of the Mumbai Coastal Road Project

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Abstract: The Mumbai Coastal Road Project (South) Package-1 includes major infrastructure such as a navigational bridge, interchanges, sea walls, and reclamation works, with one of the most complex components being foundation construction in the intertidal zone. This thesis examines the use of monopile foundations for bridge structures in this marine environment, comparing them to traditional group pile systems. Through a case study of the Mumbai Coastal Road Project, it evaluates structural performance, construction methods, environmental impact, and cost-efficiency. Results show monopiles offer advantages in reduced construction time, simpler logistics, and lower material use, particularly in moderate water depths with uniform soils. However, group piles remain preferable in complex loading and variable ground conditions. The study emphasizes the importance of site-specific analysis and contributes to the advancement of sustainable and efficient marine foundation systems.

I. INTRODUCTION

Bridge construction in marine and coastal environments presents unique challenges due to complex geotechnical conditions, dynamic hydrodynamic forces, and environmental sensitivity. In recent years, monopile foundations commonly used in offshore wind turbines have gained attention in bridge construction due to their structural simplicity, ease of installation, and reduced environmental footprint compared to conventional foundation systems such as pile caps with groups of piles or well foundations.

The city of Mumbai, with its dense urban fabric and extensive coastal edge, has undertaken one of the most ambitious infrastructure projects in India: the Mumbai Coastal Road Project (MCRP). A significant portion of this project comprises bridges and viaducts constructed over the Arabian Sea, necessitating robust and efficient foundation systems.

A. Rationale for Monopile Use

In selected segments of the MCRP, monopile foundations have been adopted as an alternative to traditional marine piling techniques. These monopiles offer potential advantages such as reduced construction time, minimized underwater works, and better performance under lateral and seismic loading. However, their application in Indian marine infrastructure is relatively new, and limited data is available regarding their practical performance, cost implications, and environmental impact under local conditions. Given the novelty of monopile application in Indian bridge construction, there is a need to critically evaluate their effectiveness, especially in comparison with conventional marine foundation systems. This research aims to assess the technical feasibility, cost-effectiveness, and practical performance of monopiles within the context of the Mumbai Coastal Road Project.

Objectives of the Study

- To understand the design principles and construction methodology of monopile foundations in marine bridge applications.
- To conduct a comparative cost-benefit analysis of monopile foundations in terms of construction cost, time, environmental impact, and lifecycle maintenance.
- To evaluate the suitability of monopiles for future marine infrastructure projects in India.

Scope and Limitations

This paper focuses specifically on the marine bridge sections of the Mumbai Coastal Road Project, comparing a section utilizing monopiles with one using conventional foundations. The analysis is based on available project data, secondary literature and geotechnical information. The study is limited to structural and cost performance and does not include hydrological modelling or detailed contractor procurement analysis.

Monopile

A monopile foundation is a large-diameter, single, vertical cylindrical pile embedded into the ground to support a superstructure such as a bridge, offshore platform, or wind turbine. Unlike pile groups, which consist of multiple slender piles connected by a pile cap, a monopile functions independently, transferring both axial (vertical) and lateral (horizontal) loads directly into the soil or rock strata.

Key characteristics:

- Diameter typically ranges from 2 m to 4 m
- Can be driven, bored, or drilled, depending on soil conditions
- Designed to resist combined loading: axial, lateral, bending, and torsional
- Commonly used in marine environments for offshore wind farms, sea bridges, and jetties

Structural Behaviour of Monopiles

Monopiles exhibit distinct load-resisting mechanisms:

- Axial Loads: Carried primarily through shaft friction and end bearing
- Lateral Loads and Moments: Resisted by soil reaction along the embedded length and pile stiffness
- Dynamic Loads: Can handle transient loads from waves, wind, and seismic activity

The long slender nature of monopiles requires rigorous analysis of soil–structure interaction, particularly in layered or weak marine soils.

B. Evolution Of Monopile Technology

Monopiles evolved from early single-pile systems in the 1950s–70s, initially used for small coastal structures in shallow waters. Their use expanded in offshore oil platforms (1970– 1990) due to lower costs and suitability for sandy seabeds, though limited by diameter and depth.

The offshore wind boom (2000–present) drove major advancements—larger pile sizes (up to 10 m diameter), improved modelling tools, and widespread adoption in Europe, Asia, and the

U.S. Recent years have seen their application in transport infrastructure, including major marine bridges like the Hong Kong-Zhuhai-Macau Bridge and Dubai Metro, favored for fast- track, space-constrained projects.

Key innovations include drilled and composite monopiles, advanced numerical modelling (e.g., FEM, p–y analysis), and real-time monitoring systems. Structurally, monopiles resist axial, lateral, and moment loads, with performance influenced by geometry, soil conditions, scour, and seismic forces.

Compared to group piles and well foundations, monopiles offer faster installation, smaller marine footprint, better seismic response, and lower lifecycle maintenance—though with higher initial costs. Their efficiency makes them a compelling option for modern marine infrastructure under suitable conditions.

Feature	Monopile	Pile Group with Cap	Well Foundation
Installation Time	Fast (1-3 days per pile)	Slower	Very slow
Marine Footprint	Minimal	High	High
Seismic Resistance	High	Moderate	Good
Equipment Requirement	Specialized	Standard	Heavy and time-consuming
Maintenance Needs	Low	Moderate to High	Moderate
Cost per Unit (indicative)	High initial, lower lifecycle	Moderate	High

Table 1 : Comparison of different types of foundation
(Adapted from Bhattacharya, 2014; IRC 78:2014; IS 2911 Parts I-IV)

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C. Challenges in Using Monopiles

- Soil variability in Indian coastal regions (e.g., soft marine clay over basalt in Mumbai)
- Corrosion resistance and protection in saline environments
- Installation vibration and noise, especially in urban coastal zones
- Regulatory and design code limitations in India

Despite these, engineering studies have shown that when designed with appropriate geotechnical investigations and marine protection measures, monopiles can offer long-term benefits in lifecycle cost and constructability.

While monopiles have been extensively studied in offshore wind and oil industries, their use in urban marine bridge projects in India remains under-researched. There is a lack of:

- Comparative cost-benefit analyses in Indian conditions
- Field performance data of monopiles in Indian coastal infrastructure
- Integrated studies considering seismic, hydrodynamic, and urban constraints

II. MUMBAI COASTAL ROAD PROJECT

The Mumbai Coastal Road Project (MCRP) is one of the largest urban infrastructure projects currently underway in India. Initiated by the Municipal Corporation of Greater Mumbai (MCGM/BMC), the project aims to address the city's long-standing issues of traffic congestion, inadequate east-west connectivity, and coastal land utilization. A significant portion of the project involves bridge and viaduct construction along the Arabian Sea, making it a unique and challenging case for marine foundation systems.

A. Project Background

Mumbai, India’s financial capital, has a linear north-south orientation constrained by the Arabian Sea on the west and the Mumbai Harbour on the east. Due to this geography, traffic bottlenecks are a chronic issue. The MCRP was conceptualized to create an 8-lane, 29.2-km long expressway along the western seafront, from Marine Drive to Kandivali, improving commute times and decongesting inner-city roads.

B. Scope and Alignment

The project is divided into multiple phases. This study focuses on Package 1, which stretches from Princess Street Flyover (Marine Drive) to Lotus jetty an approximately 3.82 Km segment that includes:

- Reclamation works, Seawalls and promenade.
- Interchanges
- Marine bridges and viaducts over water bodies Key structures along this section include:
- Marine Viaduct in Haji Ali and Amarson Garden.
- Interchange Bridge structures crossing coastal inlets

  It is in these segments that monopile foundations have been used, making this phase ideal for a comparative case study.

C. Geotechnical Conditions

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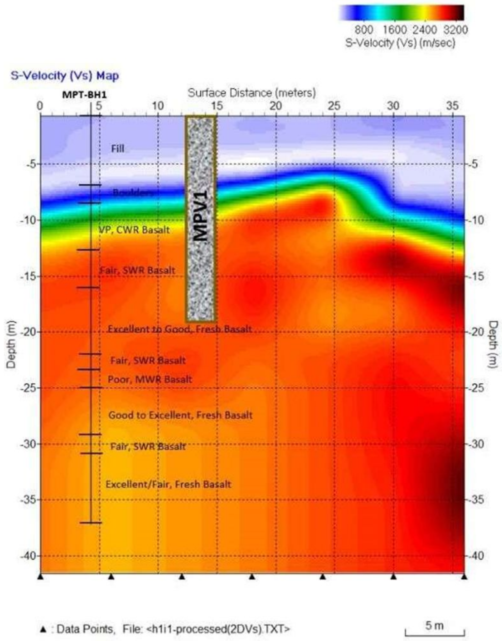
Mumbai's subsurface is primarily composed of Deccan basalt flows from the late Cretaceous– early Eocene period, featuring horizontally bedded, massive basalt with occasional tuffaceous and marine clay deposits. Key project sites—Amarsons Garden and Baroda Palace—are underlain by Malabar Hill basalt, while Haji Ali features marine clays, tuffs, and weathered breccia tuffs.

Comprehensive geotechnical investigations included borehole drilling, rotary core sampling, and MASW surveys to assess subsurface conditions and verify the presence of competent rock. Poor rock quality was observed near the seabed at Haji Ali, with RQD values below 60%.

Monopile foundations were designed as rock-socketed piles, embedded into competent basalt or tuff to a minimum depth of 1.5 times the pile diameter, ensuring structural stability in the varied geological conditions across the project area.



Typical Ground Profile and Bore-log data of one Pile

D. Design and Engineering Features

The marine viaduct and bridge sections include:

- Cast-in-situ concrete superstructures
- Precast segmental superstructure in certain areas
- Monopile diameters: 2500 mm and 3200 mm
- Bridge lengths over water: 40 m to 60 m for selected spans

E. Environmental and Regulatory Considerations

The Mumbai Coastal Road Project (MCRP) traverses ecologically sensitive Coastal Regulation Zones (CRZ-I & II) and intertidal areas rich in biodiversity. Mumbai's tropical climate, marked by intense monsoons, exacerbates flooding risks and influences coastal ecosystems. The intertidal zone supports diverse marine life, including coral patches and benthic organisms.

Prior to construction, a coral transplantation program was implemented under regulatory supervision to minimize ecological disruption. Mumbai's rich biodiversity includes flamingo populations, migratory birds, and the Sanjay Gandhi National Park within city limits.

Key environmental concerns include preserving marine biodiversity, protecting intertidal ecosystems, and controlling sediment dispersion during pile driving. Monopile foundations were preferred in sensitive zones for their reduced seabed disturbance, lower construction waste, and minimal environmental impact.

F. Foundation System Selection Criteria

The choice between monopiles and traditional foundations was based on:

- Depth of water and scour risk
- Availability of staging and access
- Environmental sensitivity of the area
- Construction speed and traffic disruption
- Soil and rock profile

In shallow or easily accessible locations, pile groups with pile caps were used. In deeper water or difficult geotechnical locations (e.g., near rocky outcrops or reclaimed land), monopiles were selected.

Thus Mumbai Coastal Road Project represents a complex case of urban marine bridge construction in India. The use of monopile foundations in key segments highlights an emerging shift toward more efficient, modular, and environmentally responsible construction practices. These segments provide an ideal context for a comparative case study against conventional marine bridge foundations, forming the core of the next chapter in this thesis.

G. Design Considerations of Monopiles

Designing monopile foundations involves assessing structural, geotechnical, and environmental factors. Key design parameters include:

Geotechnical Parameters

- Soil-Structure Interaction: Detailed geotechnical investigations are necessary to understand load transfer through the pile shaft and tip. The monopile must be compatible with varying subsurface conditions (clay, sand, rock).
- Bearing Capacity: Both axial and lateral bearing capacities must be calculated using appropriate soil models (e.g., p–y curves for lateral behavior).
- Scour and Erosion: The pile must be designed to withstand potential scour around its base, especially in intertidal or wave-prone zones.
- Seismic loading and liquefaction potential: Particularly relevant for Mumbai geology.

Structural Analysis

- Monopiles are designed to resist vertical loads, lateral loads, and bending moments
- Analysis typically uses p-y curves, LPILE software, or FEM modelling using MIDAS
- Design codes referenced:
  - IRC-112, IRC-6, IRC-5, IRC-78

H. Installation Methods

Installation of monopiles in marine environments requires specialized equipment and procedures. Techniques used in MCRP and similar projects include:

Rotary Bored Drilling (Reverse Circulation Drilling)

- Most suitable for Mumbai's coastal strata, which include basalt and weathered rock
- Involves drilling a borehole, inserting reinforcement cage, and concrete pouring via tremie method

I. Application in MCRP Project

In the MCRP, monopiles were used in selected bridge sections such as:

- Amarsons garden Interchange (Marine section)
- Bridge at Haji Ali in Lotus Jetty Bay including loop arms (Marine Section) **Characteristics:**
- Diameter: 2500-3200mm (typical)
- Depth: ~25–30 m embedded in soft marine clay over basalt
- Reinforcement: Heavy steel cages with spiral binders
- Construction: Reverse circulation boring using RCD machines mounted on steel liners.

Comparative Case Study – Monopiles vs. Group Piles

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A comparative analysis between monopile foundations and Group Pile Foundation used in marine bridge construction is undertaken. The comparison is based on selected segments of the Mumbai Coastal Road Project (MCRP) where both foundation types were employed. The evaluation focuses on design efficiency, construction methodology, cost, environmental impact, and lifecycle performance.

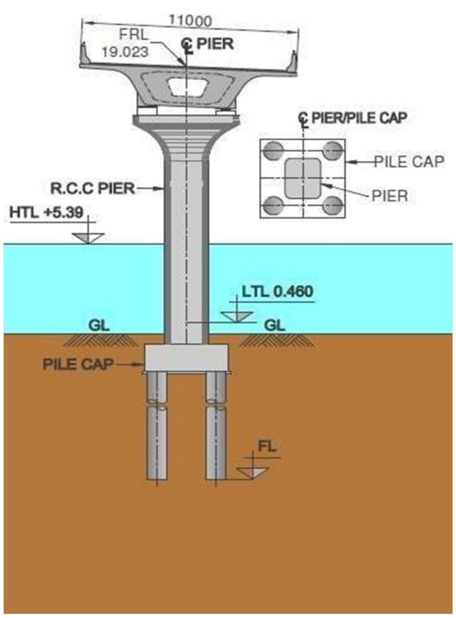
Case Study Segments in MCRP project

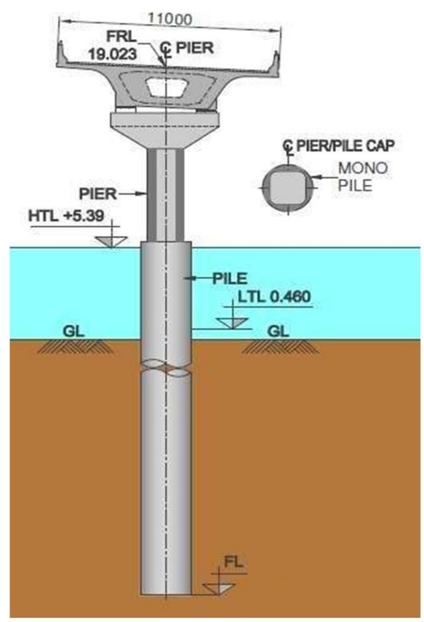
To conduct a meaningful comparison, two structurally and geotechnically comparable bridge segments were selected from Package 1 of MCRP:

Location	Foundation Type	Description
In marine portion	Monopile	Over-deep marine clay and rock base; high seismic sensitivity
On reclamation fill	Pile Group with Cap	Shallow water with reclaimed base; standard marine clay profile with hard rock below

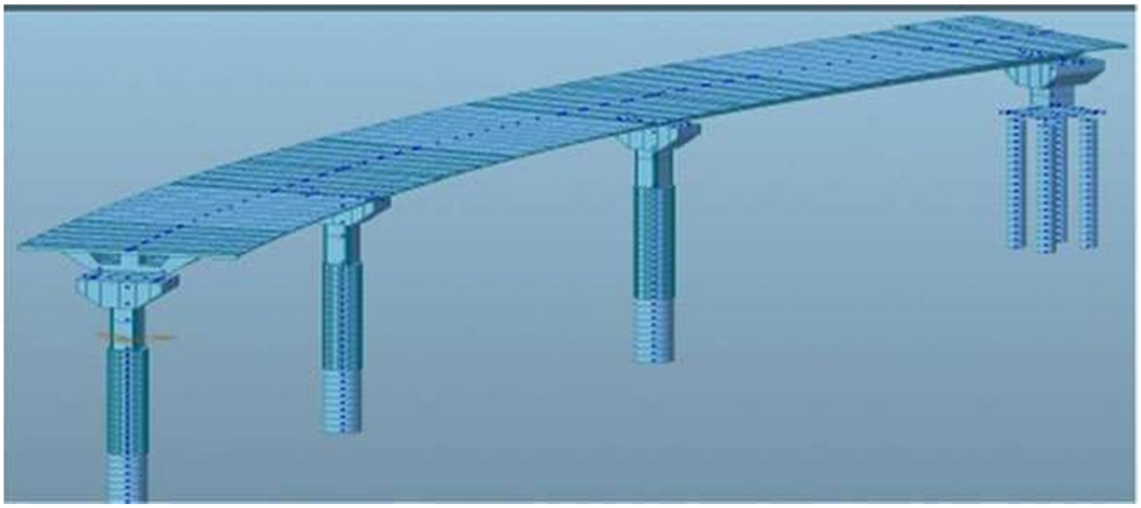
Both sections were constructed over similar timelines and marine conditions, allowing a practical side-by-side evaluation.

5.2.1 Structural details

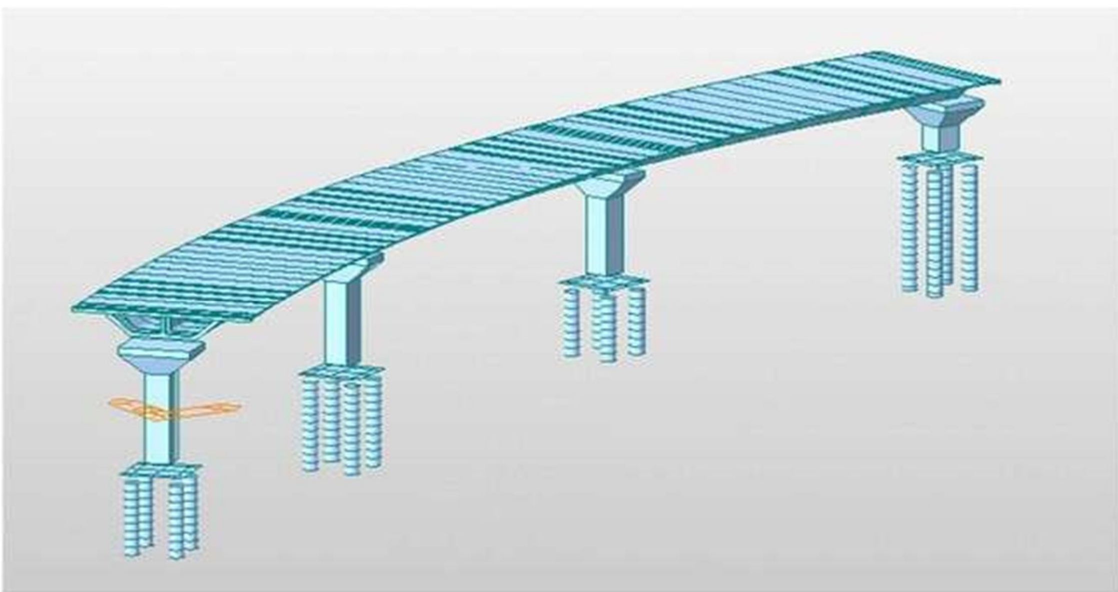




Group Piles Option	Mono Pile Option
Pile Group with 4 nos. of Piles	Large Dia Mono Pile
Pile Dia 1.5m	Pile Dia 3.2m
Larger Pile cap below sea bed level	No Pile cap



Mono Pile - MIDAS Model



Group Pile - MIDAS Model

Ease of construction & Methods

Multiple Piles Option	Mono Pile Option
Each foundation will take on an average 3 months duration to construct	Each pile will take on an average 7 days to complete. Then Pier can be taken up - Fast Completion of foundation

In conventional group pile foundations, the substructure typically consists of two or more piles connected by a pile cap located below sea level. This configuration requires extensive excavation to accommodate a larger foundation footprint beneath the seabed. Additionally, it necessitates the construction of a temporary cofferdam, which must be sealed at the base to prevent water ingress during excavation and pile cap construction, continuing until the pier lifts are built above the highwater level. In contrast, the use of large-diameter monopiles significantly reduces the number of piles required, thereby minimizing the total pile count for the project. Furthermore, monopile foundations eliminate the need for pile caps and the associated construction stages, leading to a substantial reduction in overall foundation construction time.

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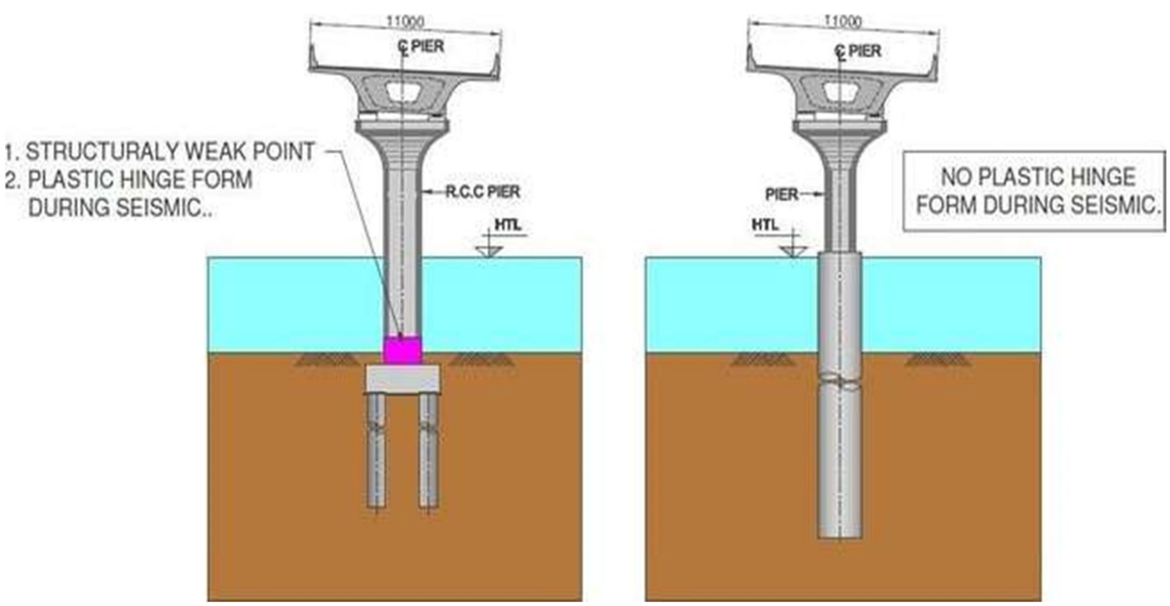
Structural advantage and Maintenance

Table :4

Description	Multiple Piles Option	Mono Pile Option
Plastic Hinge Formation	Potential Plastic Hinge formed at Pier bottom during seismic. Location below sea water	No Plastic Hinge formed during seismic
Maintenance	No accessibility for inspection and maintenance of the possible plastic hinge formations	No maintenance is required

As mentioned in the Table -1, potential plastic hinges will be formed at the junction of pier and Pile cap in case of pile group system. Though the design of the structure will be done as per the proposed seismic conditions, as a maintenance routine these specific locations of plastic hinges needs to be inspected and checked after each seismic activity to ensure the structural safety. Hence it becomes very important to have proper access to these potential plastic hinges location during the life of the structure.

In mono pile option, no plastic hinge formed during seismic

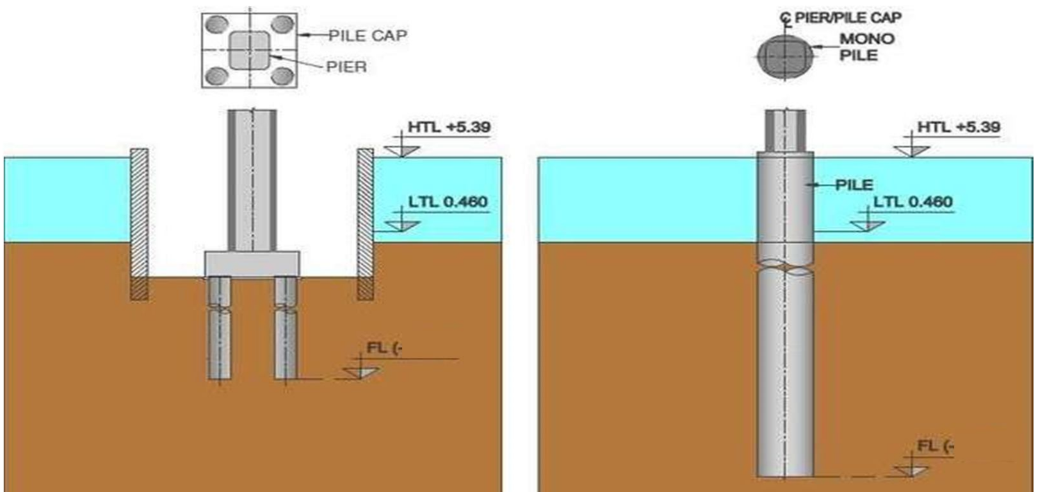


Plastic Hinge formation

J. Impact on Seabed and Environment

In pile group foundation, multiple piles need to be driven and a pile cap need to be embedded below seabed level. Excavation in large foot prints below seabed. Cofferdam of 9 to 10 m diameter until completion of pier portion above high-water level. This causes huge disturbance in the area including impact on the surrounding environment and ecology. Mono pile construction can be done with minimum machinery. Cut off level of pile at 250mm above High Tide Level. No Pile cap. Pier will be constructed directly from pile

Impact of Mono pile construction on seabed is NIL except to the driving piles of around 3m diameter. Construction of entire enabling infrastructure (including cofferdam and other means) of around 8321 sq. m of seabed footprint is eliminated.



Excavation and Coffer dam is required for Group Piles.

K. Faster Construction

Large diameter piles enable reduction in number of smaller diameter piles. Less number of piles involve less time cycle and disturbance in the seabed. There is no need of a pile cap which in terms of cycle time has a considerable saving in construction time.
Impact on quantities for Mono Pile in comparison with group piles

There will be considerable variation on material requirement for bridge in case of Mono Pile in comparison with group pile as follows

- Piles: Due to size, concrete, reinf. & liner quantities are higher per pile
- Pile Cap: Pile cap quantities are eliminated
- Pier: Impact on concrete & reinforcement

Increase in pile quantity – concrete, reinforcement, and liner, Quantity increase is mainly due to the following.

L. Increase in Pile diameter

Type	Description	Pile Group	Mono pile
Type 1	Pile Nos & Dia	4 Nos x 1m Dia	1 no x 2.5m Dia
	Cross section area (sqm)	3.14 Sqm	4.908 Sqm
	% variation in cross section	-	56.25%
Type 2	Pile Nos & Dia	4 Nos x 1.2m Dia	1 no x 2.5m Dia
	Cross section area (sqm)	4.524 Sqm	4.908 Sqm
	% variation in cross section	-	8.5%
Type 3	Pile Nos & Dia	4 Nos x 1.5m Dia	1 no x 3.0m Dia
	Cross section area (sqm)	7.063 Sqm	7.063 Sqm

Table 6: Details of various types of foundations proposed for bridge construction.

Due to the usage of large diameter mono pile, Pile cross sectional area per pier is increasing as mentioned in the above table, which increases the corresponding concrete volume of the foundation.

M. Increase in rock socketing length

Pile needs to be socketed inside the hard rock for a minimum depth of about 1 to 2 times the diameter of the pile in line with the technical specification and requirements. Any increase in pile diameter will necessitate increase in rock socketing, thus increase in overall pile length and the concrete volume

Type	Description	Pile Group	Mono pile
Type 1	Pile Nos & Dia	4 Nos x 1m Dia	1 no x 2.5m Dia
	Average Embedded Depth below EGL (m)	12 to 15 m	15 to 20 m
	Minimum socket Length into hard rock (m)	1.5 m	3.75 m
	% variation in socket length	-	150%
Type 2	Pile Nos & Dia	4 Nos x 1.2m Dia	1 no x 2.5m Dia
	Average Embedded Depth below EGL (m)	15 to 18 m	15 to 20 m
	Minimum socket Length into hard rock (m)	1.8 m	3.75 m
	% variation in socket length	-	108%
Type 3	Pile Nos & Dia	4 Nos x 1.5m Dia	1 no x 3.0m Dia
	Average Embedded Depth below EGL (m)	15 to 20 m	20 to 25 m
	Minimum socket Length into Hard rock (m)	2.25 m	4.5 m
	% variation in socket length	-	100%

Table 7: Rock Socketing length.

N. Increase in pile cutoff level

To enhance the environmental friendliness and to make it maintenance free, the pile cut off level is kept above High Tide Level. Thus, increase in overall pile length and the concrete volume

O. Increase in pile liner thickness

As per the technical specification if the pile diameter increases beyond 2m, the liner thickness needs to minimum of 16mm. also as per the equipment manufacturer the recommended liner thickness for 2.5m diameter pile is minimum 16mm and for 3.0m diameter pile it is 20mm. which is comparatively very high in consideration to smaller diameter piles, where the requirement is 6mm. there will be considerable increase in pile liner quantity on account of this increase in liner thickness.

P. Increase in pile reinforcement

Apart from the increased pile reinforcement on account of overall increase in pile length, there will be considerable increase in pile reinforcement due to variation in reinforcement density of large diameter and small diameter pile. The pile reinforcement density of large diameter piles are more than two times the reinforcement density of the smaller diameter pile

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Reduction in pile cap quantity – concrete, reinforcement
As mono pile does not require any pile cap the entire quantity of the pile cap will be eliminated.

Reduction in pier quantity – concrete & reinforcement
Since the pile cut off level is raised from seabed level to above High Tide Level, corresponding height of pier will be reduced and hence reduction in quantity.

Overall quantity variation

Item	Item	UoM	Pile Group	Mono Pile	Variation (B) - (A)	Sub Total
Excavation	Pile cap	Cum	16,037	-	(-) 16,037	(-) 16,037
PCC- Concrete	Pile cap	Cum	447	-	(-) 447	(-) 447
RCC - Concrete	Pile	Cum	24,774	36,814	12,040	(-) 4,568
	Pile cap	Cum	12,655	-	(-)12,655	
	Pier	Cum			(-)3,959	
Reinforcement	Pile	MT	2,106	6,627	4,521	1,931
	Pile cap	MT	1,898	-	(-) 1,898	
	Pier	MT			(-) 692	
Steel Liner	Pile	MT	940	2,583	1,644	1,644

Table 8: Overall quantity variation

Also, apart from the variation in permanent quantity, there will be variation in enabling works on account of reduction in coffer dam construction for marine pile caps.

Description	UoM	Pile Group (A)	Mono Pile (B)	Variation (B) - (A)
Amarsons Garden Interchange	Nos	28	-	(-) 28
Haji Ali Interchange	Nos	62	-	(-) 62
Main Bridge	Nos	16	-	(-) 16
TOTAL		106		(-) 106

Table 9: Total no of marine foundations, planned with cofferdam

Q. Schedule Implication

Reference schedule for considered for checking the schedule implication is initial work program submitted to the Employer's Representative. We have made due modification to account for the changes on account of mono pile construction and the comparison is made in schedule. Overall reduction in the Project duration expected is 6 months.
The consequential benefits to the stake holders on account of early completion are,
1. Early operation of the project to ease he traffic flow and reduce the traffic congestion in the existing roads.
2. Reduction in price escalation will help to reduce the overall project cost.
3. Reduction in supervision cost will help to reduce overall project cost
4. Reduction in EHS risk due to reduction in exposed work duration. **Financial Implication**

This is well established that the proposed monopile foundation is better in terms,

1. Impact of environment
2. Ease & maintenance friendliness
3. Saving in overall project duration

There is also a marginal saving in cost mainly on account of the following,

Description	Variation
Permanent Material	(+) 16.35 Cr
Enabling Works	(-) 19.77 Cr
Reduction in Cost Escalation (Expected) Based on last 4 year average monthly escalation (about 0.1% per month) projected for the last 3 months invoice	(-) 1.77 Cr
Reduction in supervision cost of the Employer	
Total Cost Savings	(-) 5.19 Cr

Table 10: Overall additional cost impact

R. Aesthetics

Aesthetical view of bridge is always an important criterion and in case of Monopile, aesthetics of the bridge is very good. Below are the rendered images of monopile system in marine portion of Amarson Garden Interchange.

3D Rendering during High Tide & Low Tide Level

3D Rendering during Low Tide Level

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S. Design Comparison

Parameter	Monopile	Pile Group + Cap
No. of foundations per pier	Monopile (2.5/3.2 m Dia)	4-6 piles (1.2 m dia) + pile cap
Typical embedment depth	25-30 m	18-22 m
Reinforcement complexity	Moderate	High (Pile cage + cap bars)
Seismic performance	Superior (less differential movement)	Adequate - Need complex modelling
Footprint	Low	High

Table 11: Design Comparison

Observation: Monopiles simplify the design by eliminating the pile cap and reducing lateral load transfer complexity.

T. Construction Time and Methods

Aspect	Monopile	Pile Group + Cap
Drilling time per foundation	2–3 days	1–2 days per pile + 15–20 days for cap
Total foundation time/pier	~5 days	~30 days
Construction staging	Minimal; Liner mounted rigs	Requires heavy staging and cap formwork
Equipment required	Rotary rigs, barge	Piling rig, cofferdams, formwork
Concrete usage	Lower	Higher (due to pile cap volume)

Table 12: Comparison Construction and Time

Observation: Monopiles offer significantly faster execution and reduced material usage, particularly in marine zones where staging is costly and risky.

U. Cost Comparison

An approximate cost analysis based on contractor and public data:

Cost Head	Monopile (per pier)	Pile Group (per pier)
Material (Steel + Concrete)	₹ 22–25 lakhs	₹ 30–35 lakhs
Labour and Equipment	₹ 8–10 lakhs	₹ 12–15 lakhs
Formwork and Staging	₹ 3 lakhs	₹ 10–12 lakhs
Total Estimated Cost	₹ 33–38 lakhs	₹ 52–62 lakhs

Table 13: Cost Comparison

Observation: Despite the high unit cost of large-diameter monopiles, the overall cost per pier was 20–30% lower due to fewer components and faster construction.

V. Environmental and Operational Impact

Factor	Monopile	Pile Group + Cap
Seabed disturbance	Minimal	Significant (pile cap excavation)
Noise/vibration	Moderate (drilling)	Higher (if driven)
Marine life disruption	Low	Higher
Long-term maintenance	Minimal	Higher due to submerged cap

Table 14: Comparison of environmental Impact

Observation: Monopiles are more environmentally sustainable, particularly in sensitive coastal zones like Haji Ali Bay.

W. Risk and Quality Control

Risk Category	Monopile	Pile Group
Construction errors	Lower (fewer elements)	Higher (pile cap alignment, concreting)
QA/QC complexity	Simplified	Complex (multiple piles and connections)
Scour risk	Moderate (single pile exposure)	Lower but complex around group piles
Durability	High (corrosion-resistant detailing)	Moderate to high depending on cap quality

Table 15: Comparison of Risk and Quality

Observation: Quality control is easier with monopiles due to fewer interfaces and simpler detailing.

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X. Lifecycle Cost and Maintenance

Lifecycle Aspect	Monopile	Pile Group
Design life	100+ years	75–100 years
Routine maintenance	Minimal	Periodic inspection of cap, joints
Retrofit potential	Moderate	Difficult (especially cap repair)

Table 16: Comparison of Life Cycle costs

Observation: Monopiles have lower lifecycle costs and better durability in harsh marine conditions.

Y. Summary of Comparative Advantages

Category	Preferred Foundation
Structural Simplicity	Monopile
Construction Speed	Monopile
Cost Efficiency	Monopile
Environmental Compliance	Monopile
Adaptability to Geology	Depends on soil (Monopile in rocky or soft marine zones)
Code Familiarity	Pile Group (currently better covered in Indian codes)

Table 17: Comparative advantages

III. CONCLUSIONS

Structural and Geotechnical Performance

- Monopiles demonstrated excellent structural efficiency, particularly in resisting lateral loads, which are predominant in marine environments.
- Their performance in soft marine clay overlying rock strata, as encountered in MCRP, was found to be favourable, especially with drilled installation techniques and appropriate scour protection.
- Design methodologies adopted from international standards (API, Eurocode, DNV) provided a reliable framework in the absence of detailed Indian codes.

Construction and Time Efficiency

- Monopile installation was significantly faster than conventional pile group foundations, reducing the total foundation construction time by up to 70% per pier.
- The requirement for less staging and underwater construction simplified logistics and minimized risks, especially in high-traffic marine zones.

Cost Effectiveness

- Despite higher per-unit material costs, the overall foundation cost per pier using monopiles was observed to be 20–30% lower due to savings in construction time, formwork, and material quantities.
- Lifecycle costs were also lower, with reduced maintenance requirements and better durability under marine exposure.

Environmental Impact

- Monopiles resulted in lower seabed disturbance, reduced construction noise (in drilled systems), and minimal disruption to the marine ecosystem.
- These factors contributed to easier environmental clearances and compliance with Coastal Regulation Zone (CRZ) conditions in sensitive areas like Haji Ali Bay.

Practical Challenges

- The lack of Indian design codes and contractor familiarity posed initial challenges, often necessitating reliance on foreign consultants or hybrid design approaches.
- Availability of large-diameter drilling rigs and skilled manpower was limited but gradually improving through capacity building during MCRP.

Key Conclusions

Based on the comparative analysis and field data from the Mumbai Coastal Road Project:

- Monopile foundations offer a structurally sound, cost-efficient, and environmentally sustainable alternative to conventional pile group systems in marine bridge construction.
- Time savings and reduction in complexity make monopiles particularly suited for urban coastal projects where rapid execution and minimal disruption are critical.
- Monopiles can be successfully designed for Indian geotechnical conditions using internationally validated tools, pending future updates to domestic standards.
- The successful implementation in MCRP suggests scalability for use in future coastal infrastructure across India.

The Mumbai Coastal Road Project has served as a pioneering case in the Indian context for monopile use in bridge foundations. Its success opens up opportunities to rethink traditional marine construction methods and embrace smarter, faster, and more resilient foundation technologies. With appropriate regulatory, technical, and educational support, monopiles can redefine the future of India's coastal infrastructure.

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MONOPILE BENDING MOMENT PROFILE

Bending Moment:

The bending moment profile obtained from the LPILE analysis is shown in the figure below:

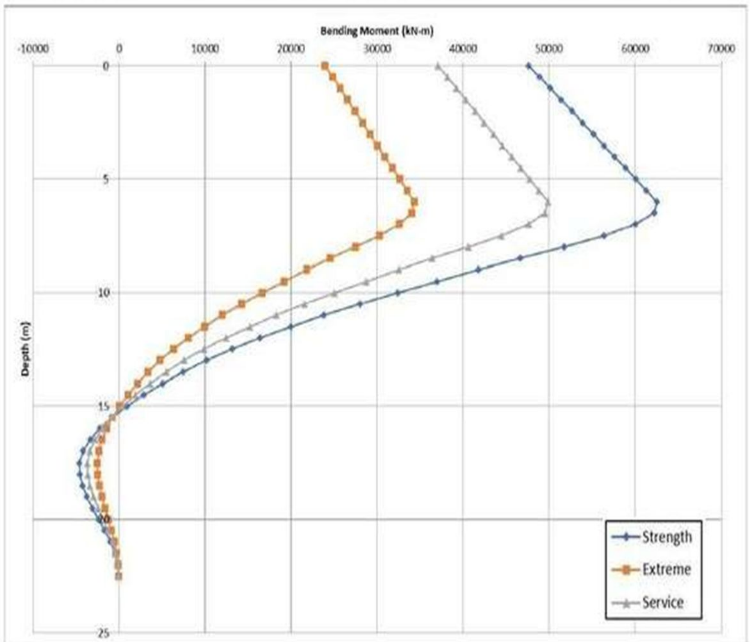

Figure 4: Bending Moment curves at Pier 21-RHS

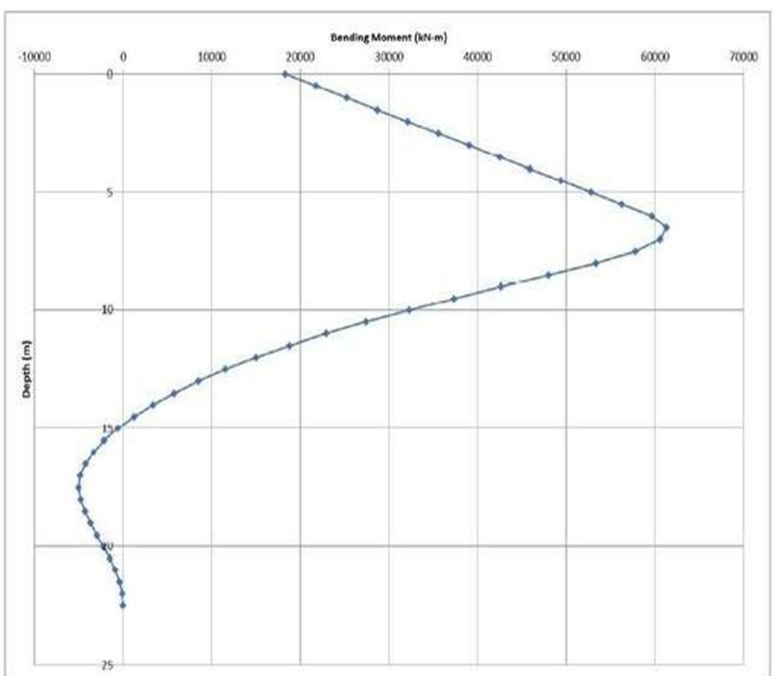

Figure 5: Bending Moment curves at Pier 21-RHS-barge Load case

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Monopile Shear Profile

Shear Force:

The shear force profile obtained from the LPILE analysis is shown in the figure below:

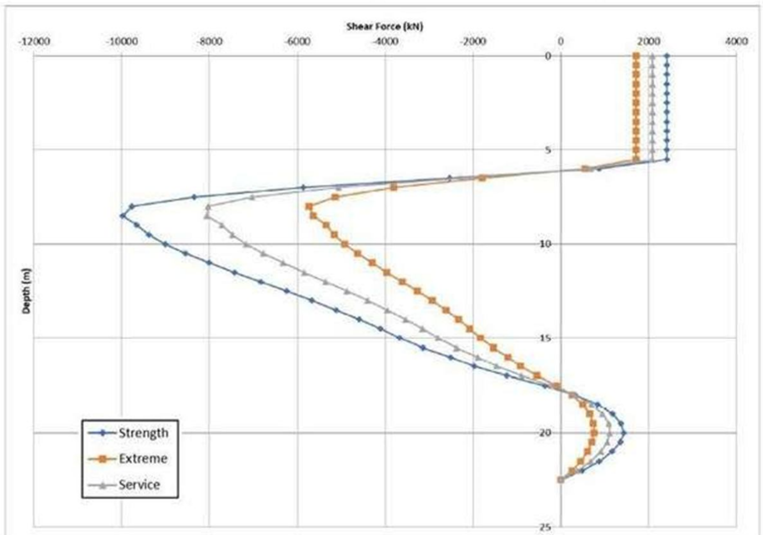


Figure 8: Shear Force curves at Pier 21-RHS

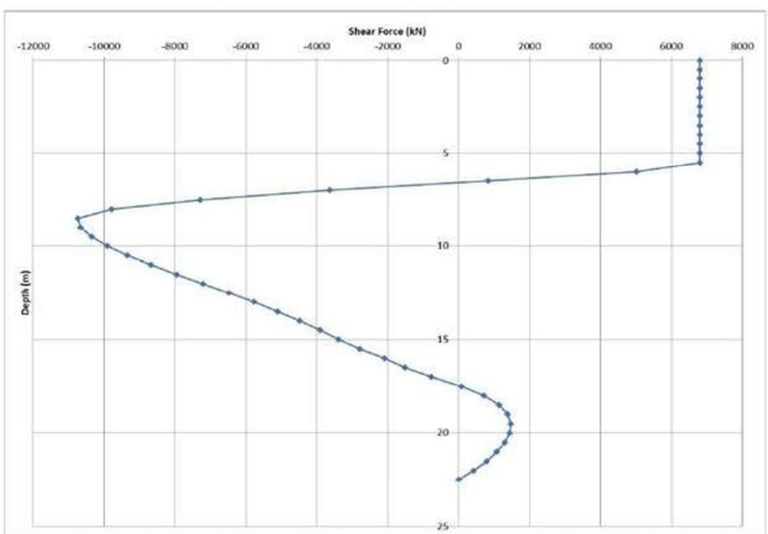


Figure 9: Shear Force curves at Pier 21-RHS-Barge Load case

Monopile Lateral Deflection

Lateral deflection:

The lateral deflection obtained from the LPILE analysis is shown in the figure below:

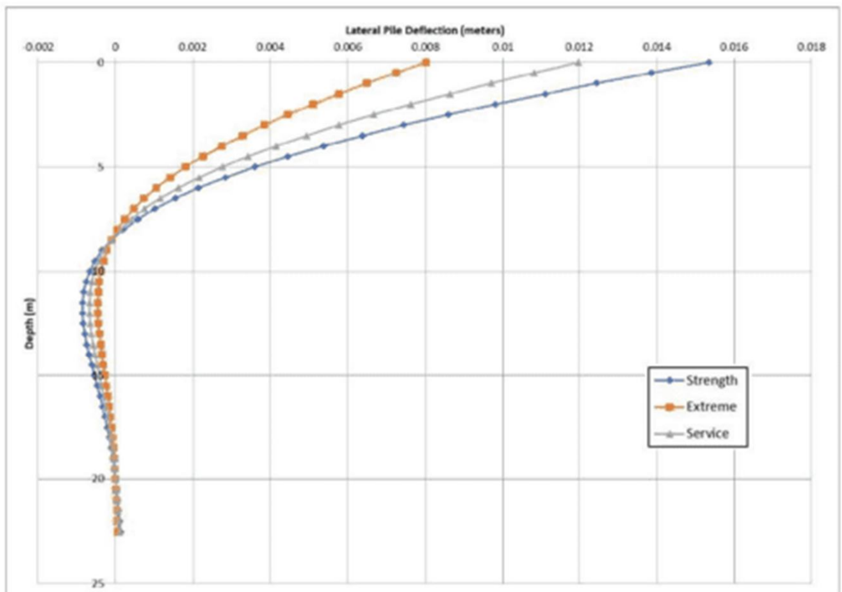


Figure 12: Lateral deflection curve at Pier 21-RHS

Appendix C: Construction Sequence for Monopile Installation

Stepwise different phases of works are being adopted to construct Monopiles

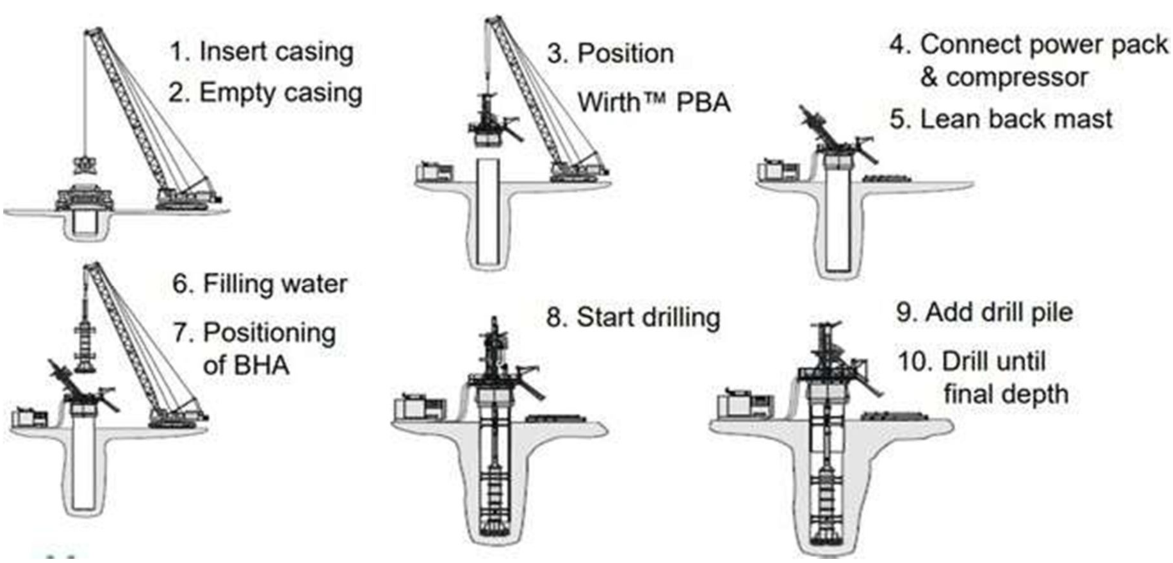


Fig. 6: Different phases of monopile drilling through RCD Step I – Liner Pitching

Step II – Positioning of Pile Top Drill Rig (PBA)
Step III – Positioning of the Bottom Hole Assembly (BHA)

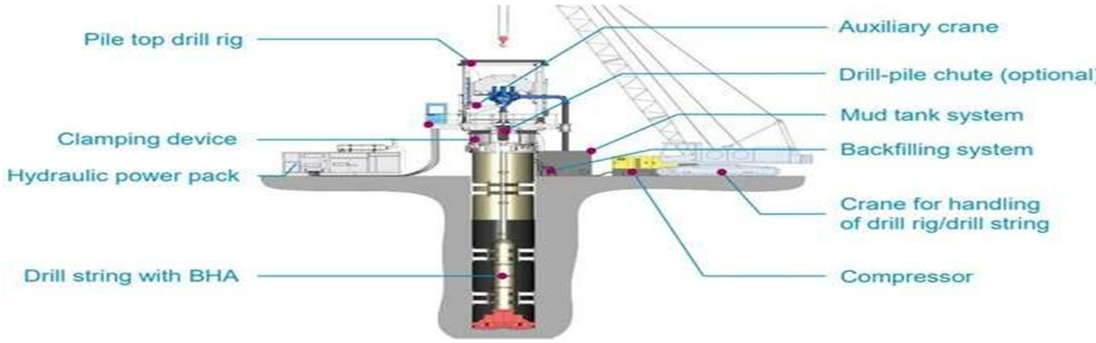


Fig. 7: Different components of top load drilling rig

Step IV – Reverse Circulation Drilling

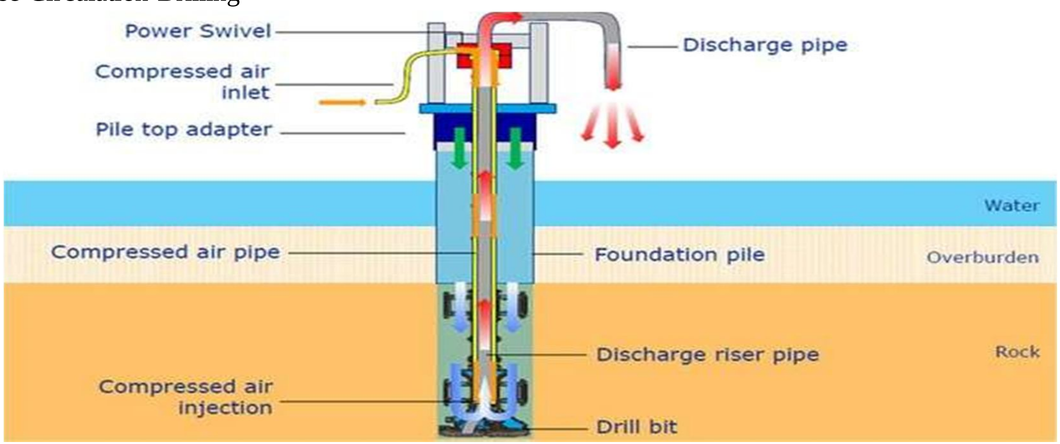
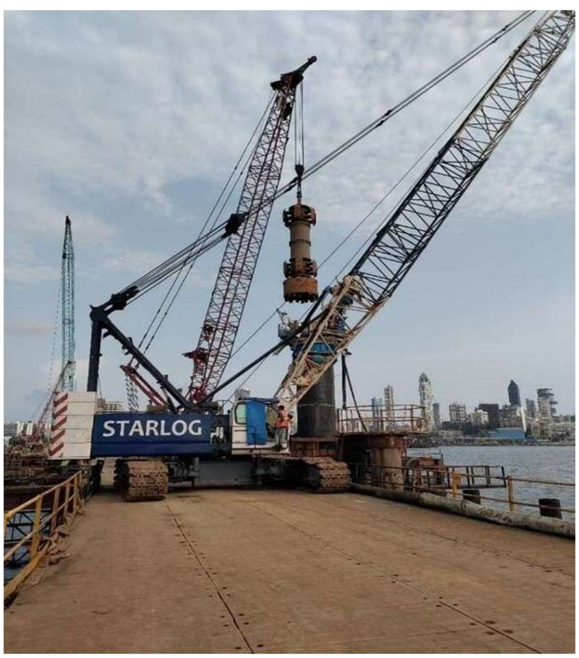


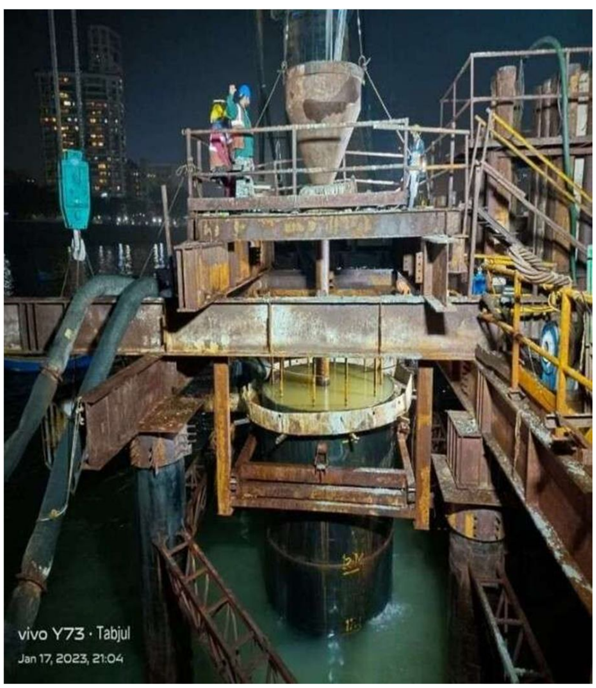
Fig. 8: Reverse Circulation Drilling through airlift Step V – Flushing and Reinforcement Cage Lowering
Step VI – Concreting and Chipping Step VII Testing of the monopile



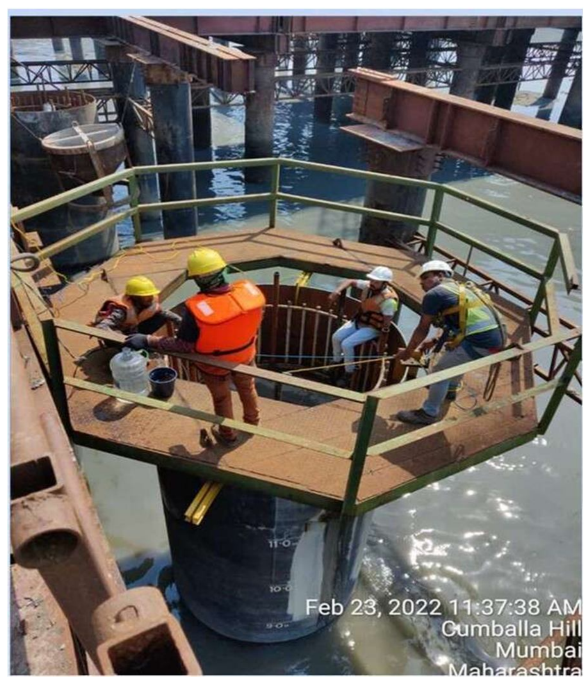
Step II *Step III*

Step IV

Step V



Step VI



Step VII

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Typical Cross-Section drawing