Evaluation of High-Performance Concrete in Offshore Bridge Monopile Foundation

Saurav Kumar[1], Chaitanya Mishra[2]

[1]Student, Department of Civil Engineering Oriental University, Indore (M.P.), India

[2]H.O.D., Department of Civil Engineering Oriental University, Indore (M.P.), India

Abstract: ***Monopile is the most common form of foundation employed under offshore or Marine works. These foundations are subjected to millions of repeated load cycles from the wind and waves of varying magnitude leading to accumulated displacements and changes in soil-pile stiffness. The purpose of this study was to investigate the behavior of Quality Evaluation of Monopile High strength Concrete in Marine bridge foundation.***

Keywords: monopile foundation, offshore bridge construction, coastal road project, marine engineering challenges, pile integrity testing

1. Introduction

The construction of bridges spanning over waterbodies or in offshore environments poses unique challenges that demand innovative solutions. Among these solutions, monopiles have emerged as a pivotal component, offering a versatile and efficient foundation system for such projects. As our infrastructure needs continue to expand, understanding the capabilities and applications of monopiles becomes increasingly crucial. This paper provides a comprehensive overview of monopiles and delves into their applications in offshore and over waterbodies bridge construction. By examining the design considerations, construction methodologies, challenges, advancements, and case studies, this paper aims to shed light on the significance of monopiles in addressing the complex demands of marine and bridge engineering.

Monopiles, essentially cylindrical steel structures driven into the seabed or riverbed, have gained prominence for their adaptability and cost-effectiveness. Their utilization as foundation solutions offers several advantages, including simplified installation processes, reduced environmental impact, and enhanced structural stability. Understanding the intricacies of monopiles and their integration into bridge construction projects is paramount for ensuring the longevity and resilience of our infrastructure in marine environments. methodologies, challenges, advancements, and case studies, we seek to contribute to the body of knowledge in marine and bridge engineering. By doing so, we hope to facilitate informed decision-making and foster the development of sustainable and resilient infrastructure solutions for the challenges posed by waterbodies and offshore environments. In the subsequent sections, we will delve deeper into the design intricacies of monopiles, explore the various construction methodologies employed, discuss the challenges faced, highlight recent advancements and innovations, present case studies of successful projects, and outline future research directions. Through this comprehensive examination, we aim to provide a holistic understanding of monopiles and their pivotal role in offshore and over waterbodies bridge construction.

Through this study, we aim to provide engineers, researchers, and policymakers with valuable insights into the effective implementation of monopiles. By exploring the design considerations, construction

Municipal Corporation of greater Mumbai proposed developing a coastal road project (MCRP) from Princess Street flyover to Kandivali junction over about 29km to ease the traffic congestion in Mumbai with recreational spaces.

This project is being implemented in 2 phases namely South and North. The South phase starts at Princess Street flyover and ends at Worli end of Bandra Worli sea link (BWSL).

This phase is divided into 3 packages as mentioned below:

Package 4: Princess Street flyover to Priyadarshini park (CH km 1+970 to CH km 5+900) Package 1: Priyadarshini park to Baroda palace (CH km 5+900 to CH km 9+720) Package 2: Baroda palace to Worli end of BWSL (CH km 9+720 to CH km 12+470).

The monopile technique was adopted by the contractor to reduce construction time, and 33 marine modules with monopile foundations were executed in place of group piles.

Two varied sizes of monopiles are executed in the project i.e., 2500mm dia and 3200mm dia and the concrete grade for all the pile is M60.

The reinforcement used for monopile construction corresponds to Fe-550D1.2

Figure 1.1- Google image showing alignment of MCRP package -1

Monopile Foundation

The scope includes 6 test piles and 99 working piles in AGI (Amarsons Garden Interchange), HAI (Haji Ali Interchange), MLB (Main Line Bridge) locations with a diameter of 2500mm and 3200mm. The depth of monopiles varies between 12m to 41m.

- The monopile design follows the AASTHO and IRC standards (as per the DBR) along with the L-pile analysis and WALLAP software.
- Amarsons garden interchange monopiles have the shorter shaft length (starts from 4m) due the basaltic rock outcrop with high UCS values whereas Haji Ali interchange has the deepest pile shafts (upto 41m deep) due to marine deposits and clay on seabed levels.

There are 32 monopiles of 2500mm dia in Amarsons garden interchange, 50 monopiles of 2500mm & 3200mm dia in Haji Ali interchange and 17 monopiles of 3200mm dia in Main line bridge.

Working scope of Monopile in study:

S. No	Location	ARM	Diameter (mm)	Scope
1	AGI	1	2500	16
2	AGI	2	2500	16
3	HAI	1	2500	13
4	HAI	2	2500	13
5	HAI	2	3200	10
6	HAI	4	3200	05
7	HAI	8	3200	09
8	MLB	LHS	3200	09
9	MLB	RHS	3200	08

2. Material and Methods

Selection of material used in concrete mix and their specification

1) Coarse Aggregates

Specification of used coarse aggregates table 3.2.1

Particle Size: Sieve Analysis	IS:383-2016/ IS 2386 Part 1-1963	Table 1000-1 of MORTH (5th Revision) for Mximum nominal size =20mm (Clause 1.4.1.3 (3) of Sec 3 Volume 5 Construction specification)

2) Scope of Present Study

Flakiness Index & Elongation Index	IS:383-2016/ IS 2386 Part 1-1963	< 35 % (Flakiness only) As per MoRTH
Deleterious Material	IS:383-2016/ IS 2386 Part 2-1963	Table-2 of IS:383-2016 (Max. 2% for total constituents)
Sp. Gravity	IS:383-2016/ IS 2386 Part 3-1963 Amdt- 1(Reaffirm-2016)	Not specified
Water Absorption	IS:383-2016/ IS 2386 Part 3-1963	Not specified
Aggregate Crushing Value	IS:383-2016/ IS 2386 Part 4-1963	< 45% for Concrete work/IS 383-1970
Aggregate Impact Value	IS:383-2016/ IS 2386 Part 4-1963	< 45% for Concrete work/IS 383-1970
Los-Angeles Abrasion Value	IS:383-2016/ IS 2386 Part 4-1963	< 50% for Concrete work/IS 383-1971
Soundness	IS:383-2016/ IS 2386 Part 5-1963	Sodium Sulphate < 12% & Magnesium Sulphate < 18% - IS 383 1970
Alkali Reactivity	IS:383-2016/ IS 2386 Part 7-1963	Innocuous Aggregates Fig.6 of IS:2386 Part- VII,
Petrographic Examination	IS:383-2016/ IS 2386 Part 8-1963	Identification of Rock as Innocuous as per IS:2386 Part-VIII
Chloride & Sulphate Content	BS 812/IS 2720 Part 26/BS EN 1744	Chloride - Max 0.01%, Sulphate - Max 0.4% (Cl 1.4.2.5 Sec 3 Volume 5)
Moisture Content	IS:383-2016/ IS 2386 Part 3-1963	Actual value

3) **Fine Aggregates**

Specification of used fine aggregates

Particle Size: Sieve Analysis	IS:383-2016/ IS 2386 Part 1-1963	Crushed Rock Sand gradation confirming to Table 1000-2 of MORTH (5th Revision) with permissible limits of max 20% on 150microns Sieve (Fineness Modulus: between 2.0 to 3.5
Deleterious Materials	IS:383-2016/ IS 2386 Part 2-1963	Table 2 of IS:383 Max. 2% for total constituents
Materials finer than 75micron IS Sieve	IS 383-2016/ IS 2386 Part 1-1963(R2016)	Table 1 of IS:383 Max.15% for Crushed sand
Specific Gravity & Water absorption	IS:383-2016/ IS 2386 Part 3-1963 Amdt-1(Reaffirm-2016)	Not specified
Soundness	IS:383-2016/ IS 2386 Part 5-1963	Sodium sulphate < 10% MgSO4<15%/IS 383 1970
Alkali Reactivity	IS:383-2016/ IS 2386 Part 7-1963	Innocuous Aggregates Fig. 6 of IS:2386 Part VII
Chloride & Sulphate Content	BS 812/IS 2720 Part 26/BS EN 1744	Chloride - Max 0.01%, Sulphate - Max 0.4% (Cl 1.4.2.5 Sec 3 Volume 5)
Moisture Content	IS 383-2016/ IS 2386 Part 3-1963(R2016)	Actual value

3. Results and Discussion

3 Load test
Applied Load and result

Loading Stage	Percentage of Test Load	Bidirectional Load (Tons)	Unidirectional Load applied on Jack Assembly (Tons)	Minimum Holding Time (min)
0	0%	0	0	0
1	5%	250	125	30
2	10%	500	250	30
3	15%	750	375	30
4	20%	1000	500	30
5	25%	1250	625	30
6	30%	1500	750	30
7	35%	1750	875	30
8	40%	2000	1000	30
9	45%	2250	1125	30
10	50%	2500	1250	30
11	55%	2750	1375	30
12	60%	3000	1500	30
13	65%	3250	1625	30
14	70%	3500	1750	30
15	75%	3750	1875	30
16	80%	4000	2000	30
17	85%	4250	2125	30
18	90%	4500	2250	30
19	95%	4750	2375	30
20	100%	5000	2500	360
21	90%	4500	2250	10
22	80%	4000	2000	10
23	70%	3500	1750	10
24	60%	3000	1500	10
25	50%	2500	1250	10
26	40%	2000	1000	10
27	30%	1500	750	10
28	20%	1000	500	10
29	10%	500	250	10
30	0%	0	0	10

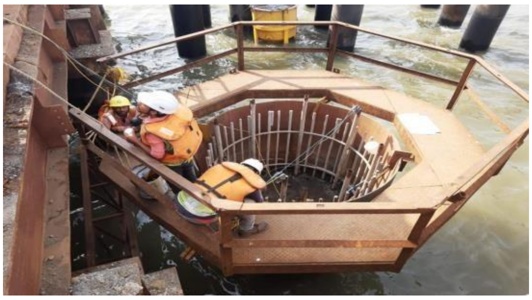


Figure: CHSL testing in offshore monopile

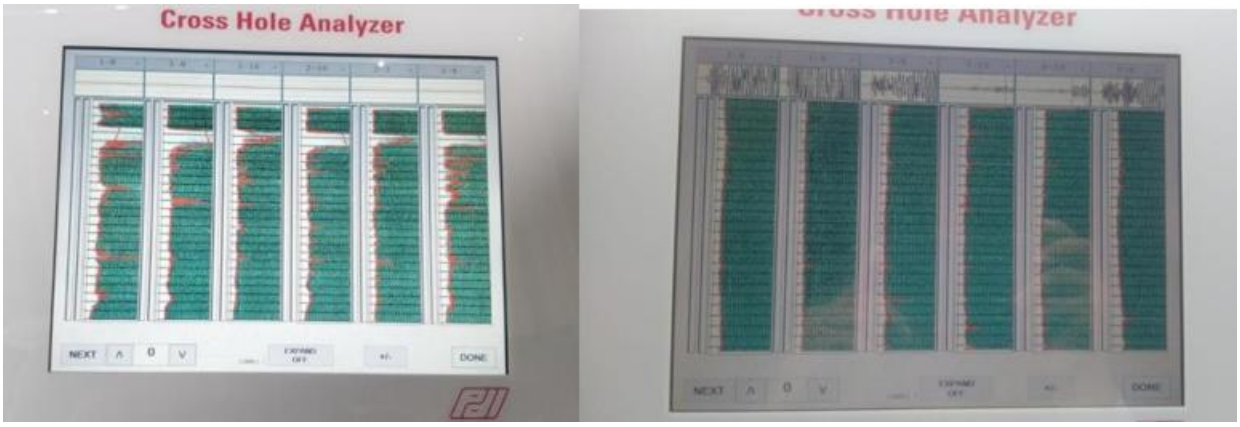


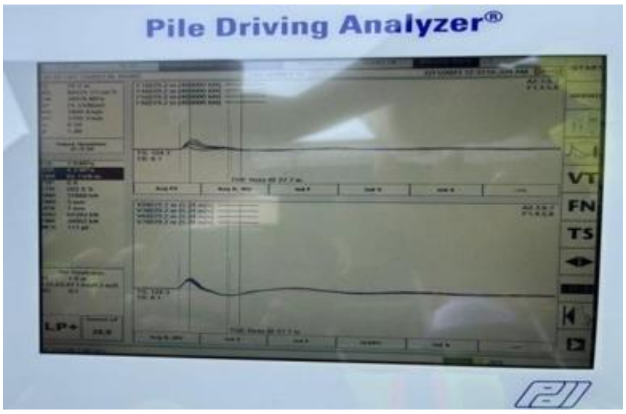
Figure: Field report of CHSL showing some hazy signal

3.1 Pile Dynamic Analysis (PDA) PDA test setup

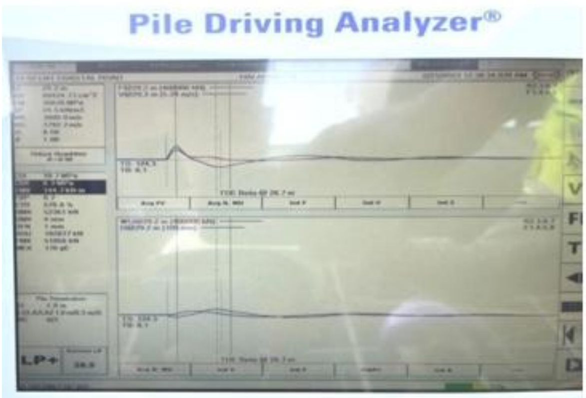
The testing is conducted by impacting the pile with blows of the hammer generally starting with a smaller drop height of 0.5m. This is to ensure the correctness of the data and the setup arrangements. Testing continues by increasing the hammer height by about 0.5m increment till the time the pile set or capacity reaches the required or limiting values.

For each hammer blow, the strain transducers measure strains while accelerations are measured by accelerometers connected on either side of the pile and the settlement/results can be viewed through the monitor with real time readings.

Fig Pile head concrete pou Prepared pile top for PDA. PDA test setup (offshore)fig PDA Sensors fixed at the platform level



Results with height of fall 0.5m



Results with height of fall 1.0m.

3.1.1 Liner driving in AGI:

Amarsons garden interchange boasts Basaltic bedrock with highly undulated bed formation created difficulties in liner placement and driving. Therefore, outer liners were used to nullify the effect of waves in monopile liner placing (wherever possible).

Extra beams were welded with the support piles to hold the liner in position and within tolerance. The gap between the outer and inner was filled with plug concrete to reduce the wave impact that disturbed the liner position earlier.

Figure: Plug concrete between outer & inner liner to counter the wave impact on liner.

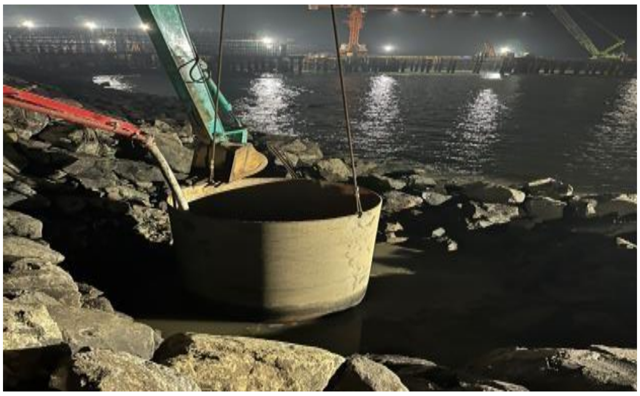


Figure: Plug concrete in the outer liner to get a proper surface for inner liner

Another main issue faced in AGI, is the liner tilt while drilling. Also, severe water loss occurred in piles which is countered by added water input with the help of 2*75HP pumps. Liner tilt during drilling caused the BHA struck inside the borehole which took almost 30 days to retrieve. Several attempts were made to remove the borehole assembly, but everything ended up in vain. Finally, Hydraulic jacks were used to pull out the BHA assembly.

All the above challenges delayed the production rate drastically and almost all the piles in AGI ended up in excess concrete consumption (some piles consumed more than 150% of theoretical concrete consumption). Concrete loss saw at liner tip location almost all the piles. This pattern of concrete loss was inspected with the diver team, and underwater photos revealed a considerable gap between the liner toe and surrounding bedrock. The tremie pipes were kept immersed in the concrete up to 10metres to avoid the choking due to the sudden loss in the concrete level inside the monopile.

To avoid excessive concrete wastage into the sea, sandbags were placed around the pile liner at the bed rock levels. This in turn reduced the amount of concrete loss. Towards the fag end of the monopile construction, concreting was scheduled in hightide time to avoid the excess concrete loss as the wave pressure arrested the concrete loss considerably.

3.2 Borehole collapse while drilling:

In haji Ali interchange and Mainline bridge, 3 monopiles were collapsed at the time of drilling. The main reason for such a collapse is the pile liner which was not driven up to the design level.

Once the collapse is confirmed (the drilling levels stayed the same even after drilling for 4-5 hours), the RCD unit along BHA was de-mounted and the pile was then left idle for a couple of days and then Liner driving done up to the possible level. Once the collapse stopped, the pile drilled up to the roe level and concreted. During the drilling of a collapsed pile, the slush from the collapsed zone clogged the outlet pipe of cutting drum (BHA's part) and then the entire BHA was removed and dismantled into pieces to clear the outlet pipeline.

Paper ID: SR25926135819 DOI: https://dx.doi.org/10.21275/SR25926135819

Figure: RCD/BHA dismantling from Pile

Figure: Slush blocked the drum outlet

Figure: Clogged Drum outlet

Figure: Outlet pipeline after slush removal

3.3 Anomalies in CHSL test:

Each monopile was tested for CHSL as per the contract specifications. In the first stages of monopile construction, hazy signals were seen in the longer corridors of sonic tubes, while the adjacent tubes showed satisfactory results and were ruled out as debonding between the Concrete and CHSL tube.

As the same pattern continued in successive tests, concrete coring was done. The cores retrieved from the pile were tested for water permeability and visual examination of cored samples. In some pile core samples, there was a continuous breakage in the cores at the same levels of defects seen in the CHSL report. The piles with such defects are then tested for water permeability and optical televiewer & hydro-jetting. The test results showed the presence of weak concrete/honeycombing in the defect levels of CHSL reports.

Epoxy & Microfine grout was used to fill those piles with defective cores and in some piles 32mm dia rebars were inserted into the core holes and then grouted.

3.4 Cost estimation of the work

Table 4.15: Abstract

S. No	Properties	As per Present ITP	If revised	Qty	Cost (Ind. Rup.)
1	Deleterious material	1/Source	1/3 months	32	14080
2	Crushing value	1/15 days	1/6 months	16	5600
3	Soundness	1/Source	1/6 months	16	16000
4	Petrographic examination	1/Source	1/Year	6	
5	Alkali Reactivity	1/Source	1/6 months	16	7040
6	Chloride & sulphate content	1/Source	1/3 months	32	16640
7	OPC	1/Source	1/6 months	4	7600
8	Admixture	1/Source	1/3 months	20	37200
9	Microsilica	1/Source	1/6 months	4	5400
10	corrosion inhibitor	1/Source	1/6 months	4	15000
11	Durability	1/ 6 months	1/1000 cum	200	3291000
12	Reinforcement steel	1/1500 MT	1/500 MT	40	20000
13	Strand	1/Source	2/Lot	36	90000
Total amount of the work is					RS=3525560

4. Conclusions

The construction of Monopiles delayed from initial schedule due to various issues like heavy downpour, rough sea and construction & Quality related delays. Executing the monopiles in 3 different locations with a totally different geology is itself a biggest challenge as the drilling rate and method in each location varies from another.

The test results of 3 piles with maximum defects in AGI, HAI & MLB shows that the pile is capable of taking the loads from the superstructure as the piles were tested with an impact load approximately 10-15% more than the design load. Many of the delays could have been eliminated if the liner driving was done up to the design level and a proper mix design of the concrete.

Though the construction works posted many challenges, the construction of new piles never stopped which added to the further delay in the schedule.

- It may be possible to achieve optimum performance by positioning a relatively small number of piles in the right place rather than using more heaps or increasing the raft thickness.
- In monopile case, the vertical load reduces the maximum bending torque as well as the lateral deformation when subjected to single rod lateral load.
- Safety against a bearing capacity failure, average settlement and different settlement are the quantities to be controlled by monopile foundation.
- Monopile foundations are suitable for the stability of structures and improve performance.

References

[1] S. Piras, A. Palermo & G. Chiaro "Development of dissipative controlled rocking system for bridge columns supported on monopiles", University of Canterbury, Christchurch New Zealand Society for Earthquake Engineering, 2021 Annual Conference-Paper 26.

[2] Maddela Jyothi Kiran, Gomasa Ramesh and Dr. Annamalai Rangasamy Prakash, "Soil- Structure Interaction study on Group pile over Monopile Foundation", International Journal for Modern Trends in Science and Technology, Vol. 07, Issue 03, March 2021, pp: 290-294.

[3] Kementzetzidis E.; Metrikine, A, Versteijlen, Willem Geert, Pisano, F (2020) "Frequency effects in the dynamic lateral stiffness of monopiles in sand: insight from field Tests and 3D FE modeling". Geotechnique: International journal of Soil mechanics, 71(9), 812-825.

[4] Boominathan Adimoolam and R. Varghese "A study on the effect of pile cap on the vertical impedance of a single pile",16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Oct-14-18, 2019, Taipei, Taiwan.

[5] V. S. Phanikanth, Deepankar Choudhury, and G. Reddy "Behavior of Single Pile in Liquefied Deposits during Earthquakes" International Journal of Geo-mechanics Vol. 13 July/August 2013 pp 454-462.

[6] Vanapalli S.K and Taylan Z.N, "Design of Single Piles Using the Mechanics of Unsaturated Soils" International