CHAPTER 99

Monopile Foundations in Marine Infrastructure Projects

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ABSTRACT

The construction of bridges in marine environments poses unique challenges that demand innovative solutions to save the ecosystem along with the time and construction cost. Monopiles have emerged as a pivotal component in such conditions and have much reduced impact on marine environment and ecosystem. Monopile foundation is studied to find a good idea for design. It primarily illustrates why a large diameter pile foundation is preferable than a group pile bridge foundation. The motivation behind this study is to analyze the performance of monopile foundation over group pile foundation in marine conditions. This study explores the challenges and advancements, scheduling in utilizing monopiles for such critical infrastructure projects. Through case studies and technical discussions, the paper aims to provide valuable insights for those who are involved in marine and bridge engineering projects.

Keywords: Monopile; Deep foundations; Infrastructure; Marine; Reverse circulation drilling.

1.0 Introduction

The Monopile foundation consists of a single, generally large-diameter structural element that supports the entire load of the above-surface structure. This system is followed because time consumption is less compared to other foundation techniques. Monopile is a hard engineering method of construction in marine conditions where the wave impact is more, and climate is not helpful for the construction works.

The pile foundation undergoes very high combined loading (vertical & lateral), so it is necessary to test the pile for both vertical loads to understand the bearing capacity and for lateral loads to understand the flexural capacity. We will look deeper into the challenges in monopile construction, technologies used in construction, case studies of successful projects, and outline future research directions. Through this study, we aim to study the benefits of Monopiles over pile groups in offshore bridges with case study.

The main objective of this paper is to study the geotechnical parameters and design parameters of Monopiles along with the construction method and time cycle of Monopiles and group piles through actual site visit and case study.

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Figure 1: Bridge Cross Section with Monopile

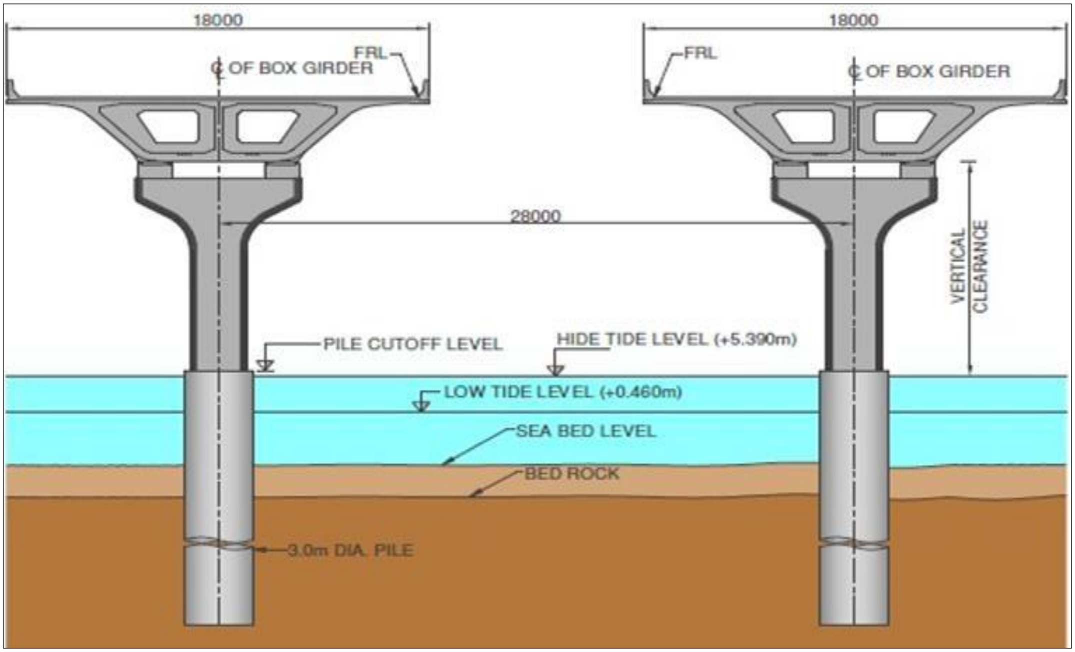
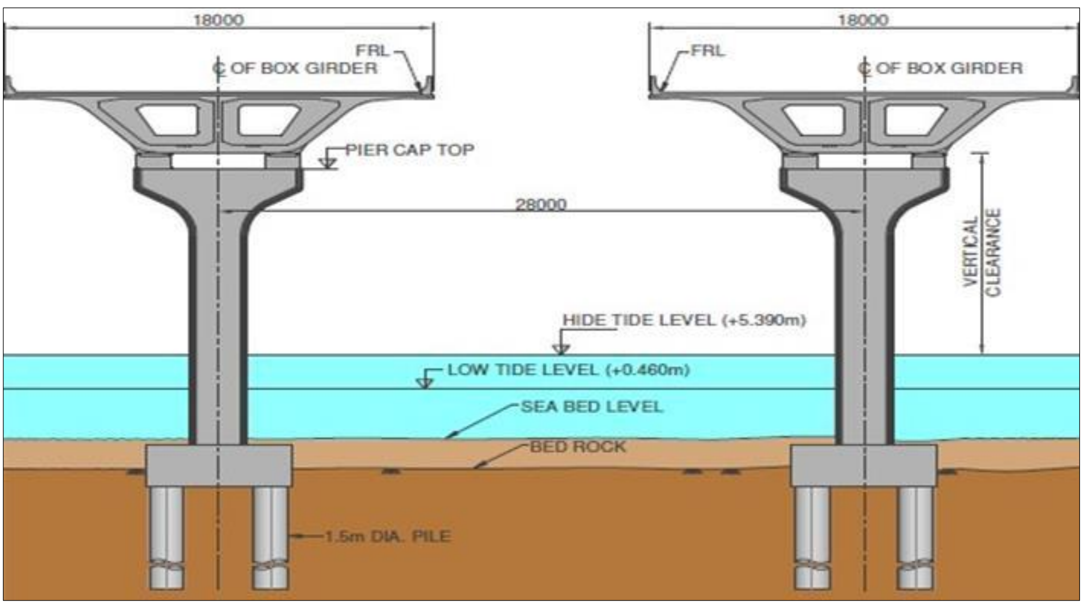


Figure 2: Bridge Cross Section with Group Pile



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1.1 Advantages and disadvantages

Monopile construction has several advantages over the group pile system in a marine construction project.

- The construction time can be reduced to a large extent.
- The cost-effective technique compared to the group pile system.
- Minimal disruption to the marine ecosystem as one location is drilled.
- Reduced barge movements and positioning which in turn reduced the carbon footprints.
- No necessity for pile cap construction and its design.
- Reduced the overall cost of the project.

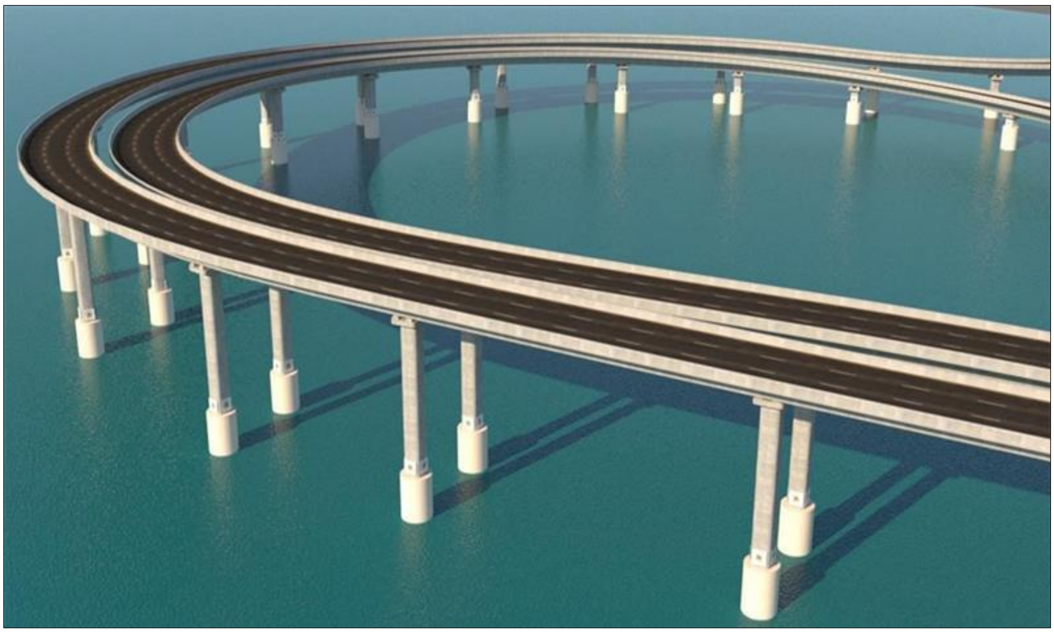
There are some disadvantages in the construction of Monopiles like,

- The preliminary design and its cost are more.
- Expert involvement is required, which in turn increases the cost.
- High precision is required in design and execution.

2.0 Case Study

The construction work of Mumbai's Coastal Road project was recently completed and opened to the public.

Figure 3: Model Representation of Monopile and Bridge Deck



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The preliminary design of the project included group pile system both in land and marine sections. The group pile system found to be time-consuming, and the Engineer agreed to introduce the new technologies to ensure timely completion of work and decided to go with Monopile technology (Leibach 2003). Total 99 piles were done using this technology in Package-1 of Mumbai Coastal Road project.

This technology is environmentally friendly as it reduces construction time and costs significantly. Generally, while constructing a bridge above sea, river, lake, creek among others the ground pile technology is mainly used. However, in this technology for each pier, four or more piles need to be built. While in large diameter pile technology a single pile of large diameter can be raised at one span. Following which, the numbers of piles have been reduced to 99 from 426. By using the large diameter pile technology each pile diameter was of 2.5 meters, 3.2 meters and 3.5 meters.

3.0 Reduction in Scope of Foundations with Monopile

With the use of monopile technology in the project, the number of pile foundations reduced drastically, and it helped the team to complete the project within the timeline. The following tables (see, table 1 & 2) show the reduction in pile foundations with the adoption of Monopile technology. Also, we can see the probable savings (see, table 3), (Khan *et al.,* 2024) with the adoption of monopile technology.

Table 1: Original Scope

Item	Amarsons Interchange	Haji Ali Interchange	Main Bridge
Total Length	1825m	6696m	1410m
No. of spans	60	224	48
No. of footings	64	232	58
No. of piles	256 no's	928 no's	462 no's

Table 2: Scope Change with Monopile

Item	Amarsons Interchange	Haji Ali Interchange	Main Bridge
Monopiles	32 no's	50 no's	17 no's
Group Piles	48 nos	728 nos	205 nos
Reduction in piles	176 nos	150 nos	240 nos

The total of 1646 piles (approx.) was reduced to 1080 piles with the inclusion of monopiles in the seafront area of the project alignment.

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Table 3: Probable Savings and Additional Costs

S. No	Probable Saving Items	Probable additional cost Items
1	Number of piles	Design and Analysis
2	Reinforcement	Construction Expertise
3	Concrete (Pile cap)	Drilling Equipment (RCD)
4	Cofferdams (For pile cap)	Additional costs

4.0 Geotechnical Investigation and Design

Geotechnical Investigations are very important for the design of Monopiles. Unlike group piles, we need the GTI for each and every Monopile. The GTI included Ground characterization and detailed analysis of the geological data in each pile location. The same has been carried out for the design of Monopiles. The geological Profile is developed first. Then derive characteristic values of geotechnical parameters appropriate for each design limit state, the design ground model will be presented in updates of the GIR. Pile load bearing capacities based on the design standards are then produced followed by the identification of critical load cases for the determination of the rock socket length based on compression and lateral load capacity. The monopile rock socket length is then determined based on the lateral pile capacity calculation and the same is checked. Finally, using L-Pile analysis, derive P-Y curves to model the stiffness of the ground supporting the monopile and in the Midas model which combines the behaviour of the monopiles and superstructure.

4.1 Ground characterization

The ground characterization includes the soil description and basic geology of the location along with the starta in that particular work location. It is also concentrating on Soil strength, Soil stiffness and Rock Quality Designation (RQD) (Gurnani *et al.* 2018).

4.2 Detailed analysis

In the detailed analysis, soil models, testing, Geotechnical reports were assessed, and the data is used in the design of the monopiles. The Geotech reports include the Factual report and Interpretative report and with both the geotechnical design is carried out. This also gives the data about the pile socket length (Krolis *et al.* 2010) depending on the load coming from the structures.

The guidelines for large diameter pile design include the calculation of,

- Rock mass modulus
- Lateral Stiffness
- Pile socket length
- Shaft Bearing Resistance
- Pile Settlement
- Lateral resistance.

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5.0 Structural Design

5.1 Design loads

Dead loads: Unit weights of materials are defined in IRC: 6-2017, Cl. 203, are as per the following:

Material & Unit Weight
Plain Cement Concrete - 25 kN/cu.m
Reinforced Cement Concrete (RCC) - 25 kN/cu.m
Pre-stressed concrete - 25 kN/cu.m
Structural steel - 78 kN/cu.m
Earth compacted - 20 kN/cu.m
Asphaltic concrete in wearing coat - 22 kN/cu.m

In addition to the above, unit weight of mass concrete and green concrete will be taken as 24 kN/m3 and 26kN/m3 respectively.

5.1.1 Superimposed dead loads

A load of 5.0 kN/m is considered or utility services which is proposed to be carried through the inside of main line box girder (load to be confirmed based on MEP requirements). For interchange arms, no additional load will be considered for utilities. A load of 0.9 t/m is considered for weight of each crash barrier. Noise barrier loading is to be considered for those stretches where it is required, and load will be considered as per the cross section of noise barrier.

5.1.2 Water current forces

The portion of bridge which may be submerged in running water shall be designed to sustain the horizontal pressure due to force of water current as per the stipulations of Cl. 210 of IRC:6-2017. Maximum mean velocity of water current shall be taken as 1.5 m/s in any direction for design purpose based on the current speed data.

5.1.3 Buoyancy force

100% buoyancy will be considered while checking stability of foundation irrespective of their resting on soil/weathered rock/or hard rock. However, the maximum base pressures shall also be checked under an additional condition with 50% buoyancy in cases where foundations are embedded into hard rock.

5.1.4 Wave and abnormal wave forces

The effect of waves on the structure will be considered in accordance with Cl. 5.7 of IS 4651 Part 3 -1974. For abnormal wave loads, for the design wave heights (taken as 1.89 m as per NIO report). Based on chapter 3 of NIO report, the maximum amplitude of tsunami wave is only 0.73 m and hence it is considered as less critical.

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5.1.5 Wind loads on structure

The basic wind speed to be adopted in the wind load determination is defined as per Cl. 209 of IRC: 6-2017.The basic wind speed at 10 m height in Mumbai, for 50-years return period, is 44 m/s. As per Cl. 209.2 of IRC:6-2017, the wind force is based on hourly mean wind speed (Vz), and horizontal pressure (Pz). The corresponding values to a basic wind speed of 33 m/s, return period of 100 year, for bridges in flat topography is presented in Table 12 of IRC:6-2017.

5.1.6 Differential settlement

Differential settlement of supports is considered as a permanent load. The piles are socketed in rock and there might not be any differential settlement as such. However, for design purpose, 6mm differential settlement between the supports will be assumed as long-term loading.

5.1.7 Earthquake (Seismic)

The seismic design is based on the IRC:6-2017, being the design spectrum defined as per the assuming seismic Zone-III and Zone factor Z of 0.16 and Importance factor I of 1.5.

5.1.8 Barge impact on bridges

The Barge impact force and kinetic energy shall be calculated as per Cl.220 IRC:6-2017. All the piers in the navigational spans of the Main Viaduct shall be protected by providing suitable fender type protection system. IRC:6-2017 states that the bridge should be designed to minimise the risk of structural failure of a bridge component due to collision with a barge. The risk of damage to the barge should also be minimised.

5.1.9 Scour analysis

The purpose of the scour analysis is to estimate the total scour depth at the base of the bridge piers structural supports. The main purpose of this analysis is to evaluate the depth and extent of scour (Da-Wei Guan et al. 2021) during design working life operation of the bridge, so that its potential effect on the design capacity of the bridge foundations can be assessed.

5.2 Design of monopile

The design of monopiles follows the international standards as well as the Indian Standards. The following table (see, Table 4) shows the details of the codes used in the design of monopiles.

6.0 Timecycle for Monopile Construction

The construction time of monopiles is much less compared to the pile group system. The monopile construction normally takes 5-7 days depends on the pile depth and geology of the pile location.

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Table 4: Monopile Design Codes

S. No	Design Standards
1	AASHTO LRFD Bridge Design Specifications (2017)
2	GEC-09: FHWA Design, Analysis, and Testing of Laterally Loaded Deep Foundations that support Transportation Facilities design Methods
3	GEC-10: FHWA-NHI 18-024: Drilled Shafts - Construction Procedures and Design Methods
4	IRC – 078 (2014): Standard specification and code of practice for road bridges, Foundations and Substructure.
5	IS 2911-1-2 (2010): Design and Construction of Pile foundations – code of practice, Part 1 Concrete Piles: Section 2 Bored cast in-situ concrete piles.
6	IS 1892 (1979): Code of practice for subsurface investigation for foundations.
7	IS 12070 (1987): Code of Practice for Design and Construction of Shallow Foundations on Rock.
8	IS 14593 (1988): Design and construction of bored cast in situ piles founded on rocks
9	BS 5930 (1999): Code of Practice for Site Investigation.
10	Caltrans (2015) *Bridge Design Practice* (Volume 2: Substructure Design, Chapter 16 – Deep Foundations)

Table 5: Timecycle for Monopile

Activity	Days
Guide frame positioning and Liner & RCD Installation	1
Drilling	2-4
Rebar cage lowering (In parts)	1
Concrete Pour	1
TOTAL DAYS FOR 1 PILE (On average)	5 – 7 days

The piles are constructed using the Reverse Circulation Drilling technique which considerably reduced the construction time. Table-5 gives a simple insight of the activities associated with monopile construction.

7.0 Timecycle for Group pile construction

The group pile system will take more time (see, table 6) when compared with the monopile method. The pile group system is effective for small scale infrastructure projects. In marine infrastructure projects, monopile system is found effective as the timelines are very critical compared to a project in land. Moreover, the monopile system eliminates the construction of pile cap works which takes much time.

The construction of a 4-pile group will take approximately will take a minimum of 10 days (Maddela Jyothi Kiran et al. 2021). Once the piles are constructed, pile cap construction begins. The timeline of pile cap construction is given below (see, Table 7),

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Table 6: Timecycle for Group Pile

Activity	Days
Guide frame positioning & Liner Installation	0.5
Drilling (Hard Rock)	1-2
Rebar cage lowering (In parts)	0.5
Concrete Pour	0.5
TOTAL DAYS FOR 1 PILE (On average)	2.5 - 3.5 days

Table 7: Timecycle for Pilecap Construction

Activity	Days
Cofferdam installation with pile cap base slab	1-2
Reinforcement installation	3
Formwork and Alignment	1
Concrete pour	1
Formwork removal	1

On average the pile cap construction will take about 7-8 days which is not necessary in case of monopile.In short, the time taken to construct a monopile up to pier starter will take maximum 7 days whereas in group pile system it will take minimum 20 days which is comparatively more time consuming (Smita & Varghese 2022).On an average 60% of time is saved by adopting the monopile technique which helped the contractor to achieve the target on time.

8.0 Monopile Construction using RCD Technology

Monopile construction was done using Reverse Circulation Drilling (RCD) technology. The construction of Monopile includes the following steps.

8.1 Liner pitching and driving

The prefabricated liner with bottom shoe is shifted to the location and is lifted with the help of the Service crane. The liner is then placed in the piling platform and lowered gently till it reaches the seabed level. After that, the position of the liner (verticality) is checked. Once it is found within the limits, the liner is driven into the seabed with the help of vibro-hammer (Figure 4) of suitable capacity (12.5 MT capacity used). During the driving, care should be taken to avoid the liner deformation at the bottom and the liner position is checked after the completion of driving.

8.2 RCD mounting and drilling

The mast of RCD is lifted with the crane and is mounted on the pile casing. Once positioned on the casing top, the mount is arrested with the help of clamping unit. The drill

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string unit or Bottom Hole Assembly (BHA) is lifted and installed inside the liner and loacked with the drilling unit on the mast. This is followed by the installation of drill pipe (normally 3m long and variable dia) and the swivel assembly and drill string are fixed (Fig-5).

Figure 4: Liner Driving with Vibro-hammer

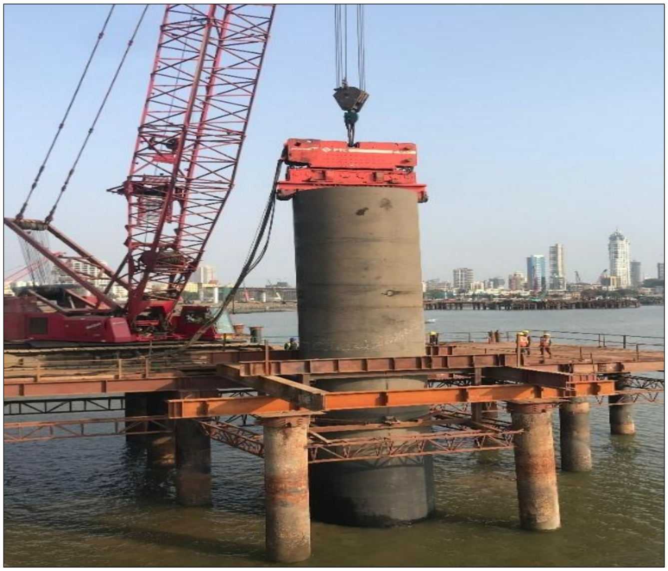

Figure 5: Drilling Setup and BHA Installation in RCD

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The air hose is then connected with a compressor and the ouitlety delivery hose is connected to the collection bin/tank. Water (salt/fresh) will be pumped inside the bore through a pump attached with RCD or through a separate pump. The water will enhance smooth drilling operation. Add the drill pipes and add the Drill Rod Stabilizer (DRS will be added for every 3no's drill rod installed). The cutters can be changed based on the boring strata. The additition of drilling pipes will continue till the borehole reaches the design toe level. Once the drilling works are done up to the design level, bore flushing will be done.

8.3 Rebar cage installation

The rebar cages are fabricated in the yard and later shifted to the pile location.The cross-hole sonic logging (CHSL) tubes should be tied strongly with the inner reinforcement to avoid any deformation.The cages are shifted in parts (as per the crane capacity and boom length) and care must be taken that position of lapping/couplers must be the same.Any mismatch in position will be time-consuming during installation and is difficult to fix the couplers.The installation of the steel cage inside the excavated shaft will proceed by using the service crane (Fig-6). After installing all the elements, the rebar cage is rested at its design level with the help of cage hangers fixed on the casing top. All the CHSL tubes should be water-tight to prevent any slurry entry during the concrete pour.

Figure 6: Rebar Cage Installation

8.4 Tremie installation and airlifting

Airlifting is done with water/stabilization fluid. The aim is to remove the slush/debris from the bottom of the borehole.Airlifting is done with the help of an air compressor by blowing

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in the air to the bottom of the borehole and the pressure shift cleans the bottom surface and the slush/water will come up through the pipes (200mm dia).Water will be poured from top of the borehole and the airlifting should continue till the entire borehole is cleaned.At the end of tremie installation, make sure that the minimum space (normally 300mm) is maintained between the tremie bottom and borehole bottom.

8.5 Concrete pour

Concrete can be either transported to the location with a Transit Mixer. A concrete pump (Fig-8) with hose supporting boom will be provided to supply the concrete to the tremie hopper during casting. To prevent contamination and segregation of the concrete during it falling inside the tremie pipes, a "sacrificial buffer" made of lightweight material (such as vermiculite or similar material or ball) will be introduced inside the tremie hopper prior to the start of concreting operations.

Figure 7: Concrete Pour with Two Placer Booms

A charge plug will be paced at the bottom of the hopper/tremie neck, and the hopper is filled with concrete and is charged with the help of a service crane.Once started, there should not be any delays in concrete supply as the choking chances are higher.Make sure that the tremie pipe bottom is always inside the concrete (maintain at least 2m to 3m inside the concrete).Remove the tremies as per the volume of concrete filled inside the bore and concrete should be stopped either after overflow and 1m above cut-off level. The hopper can be replaced with a smaller one during the first set of tremie removal.

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9.0 Recommendations for Monopile Construction

After a careful examination in the construction method of large diameter pile by RCD technique, the following things are recommended for the smooth Construction of Large diameter piles in marine conditions.

- The liner shoe is mandatory for the liner driving in hard strata.
- Additional water supply pumps must be deployed in case of head loss inside the pile liner.
- Sonic tubes must be water-tight till the completion of the concrete pour.
- Pile-penetration ratio is mandatory for the end bearing piles.
- The volume of the concrete funnel must be equal to one meter built-up inside the shaft.
- The concrete overflow must be more than one meter above the cut-off level.
- Pile top flooding must be done after the concrete in order to avoid de-bonding effect during Cross-Hole Sonic Logging test.

Figure 8: Bridge Deck with Monopile (Actual Picture)

References

(2019). Design and construction approach of marine rock-socketed piles for an oil jetty project. In *Geotechnics for Transportation Infrastructure* (pp. 427–439).

Alderlieste, E. A., Dijkstra, J., & van Tol, A. F. (2011). Experimental investigation into pile diameter effects of laterally loaded monopiles. In *30th International Conference on Ocean, Offshore and Arctic Engineering*, June 19–24, 2011, Rotterdam, the Netherlands.

Badole, S. K., & Varghese, V. (2022). A review study on aspects of monopile as bridge foundation. *International Journal of Advances in Engineering and Management (IJAEM)*, 4(4), April.

DOI: 10.17492/JPI/NICMAR/2507099 ISBN: 978-93-49790-54-4

Baker, C. N., Drumwright, E. E., Briaud, J.-L., Mensah-Dumwah, F., & Parikh, G. (1993). *Drilled shafts for bridge foundations* (FHWA Publication No. FHWA-A-RD920004). Washington, DC: Federal Highway Administration.

Carter, J. P., & Kulhawy, F. H. (1992). Analysis of laterally loaded shafts in rock. *Journal of the Geotechnical Engineering Division, ASCE*, 118(6), 839–855.

Chan, F. W., & Tsang, S. W. (2006). Quality assurance of concrete foundation elements using an ultrasonic evaluation technique. *Insight—Non-Destructive Testing and Condition Monitoring*, 48(6), 360–367.

Das, B., & Sivakugan, N. (2019). *Drilled-shaft foundations—Drilled shafts extending into rock*. Cengage Learning, Inc.

Datey, K. R. (1990). Bored piling in Bombay region. In *Proceedings of the I.G.S. Conference*, December 1990, Part VI, Session IX, 571–587.

Federal Highway Administration. (2018). *Drilled shafts: Construction procedures and design methods* (8th ed.). Developed following AASHTO LRFD Bridge Design Specifications.

Gazetas, G. (1984). Seismic response of end bearing single piles. *International Journal of Soil Dynamics and Earthquake Engineering*, 3(2).

Goble, G. G., Scanlan, R. H., & Tomko, J. J. Dynamic studies on the bearing capacity of piles. Paper presented at the 46th Annual Meeting, Committee on Substructures, Retaining Walls and Foundations.

Guan, D.-W., Xie, Y.-X., Yao, Z.-S., Chiew, Y.-M., Zhang, J.-S., & Zheng, J.-H. (2022). Local scour at offshore windfarm monopile foundations: A review. *Water Science and Engineering*, 15(1), 29–39.

Karatzia, X., & Mylonakis, G. (2017). Horizontal stiffness and damping of piles in homogeneous soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 143(4), Article 04016113. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001622

Kementzetzidis, E., Metrikine, A., Versteijlen, W. G., & Pisano, F. (2020). Frequency effects in the dynamic lateral stiffness of monopiles in sand: Insight from field tests and 3D FE modeling. *Géotechnique*, 71(9), 812–825.

DOI: 10.17492/JPI/NICMAR/2507099 *ISBN: 978-93-49790-54-4*

Khalil, M. M., Hassan, A. M., & Elmamlouk, H. H. (2020). Dynamic behavior of pile foundations under vertical and lateral vibrations: Review of existing codes and manuals. *HBRC Journal*, 16(1), 39–58. https://doi.org/10.1080/16874048.2020.1729586

Khan, T., Gamre, Y. S., Chowdary, A. A., Sayyad, A. S., & Saiyyed, A. A. A. (2024). Monopile implementation in offshore bridge. *International Journal for Multidisciplinary Research (IJFMR)*, 6(2), March–April.

Kiran, M. J., Ramesh, G., & Prakash, A. R. (2021). Soil-structure interaction study on group pile over monopile foundation. *International Journal for Modern Trends in Science and Technology*, 7(3), 290–294.

Li, D., Zhang, L., Tang, W., & Tang, H. (2005). Reliability evaluation of cross-hole sonic logging for bored pile integrity. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 131(9), 1130–1141. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:9(11 30)

Liebich, B. A. (2003). High-capacity piles confirming the viability of cost-efficient bridge designs. *TR News*, (228), September–October.

Loaiza, J. E. P., di Prisco, M., & Galli, A. Structural design optimisation of single piles.

Randolph, M. F. (2003). Science and empiricism in pile foundation design. *Géotechnique*, 53(10), 847–875. https://doi.org/10.1680/geot.53.10.847.37518

Roesen, H. R., Ibsen, L. B., & Andersen, L. V. (2013). Experimental testing of monopiles in sand subjected to one-way long-term cyclic lateral loading. In *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris.

Zhang, L. (2005). The axial load capacity of drilled shafts in rock. In *Capacity of Drilled Shaft Related to Rock*. A.A. Balkema Publishers.

Zheng, C., Kouretzis, G. P., Ding, X., Liu, H., & Poulos, H. G. (2016). Three-dimensional effects in low-strain integrity testing of piles: Analytical solution. *Canadian Geotechnical Journal*, 53(2), [page range]. https://doi.org/10.1139/cgj-2015-0173

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