" Case Study: Construction of Cast In Situ Piles and Pile Cap for Pier Number 370 at Line 2B Bandra Station"

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Abstract - *This research paper presents an in-depth case study on the construction of cast in situ piles and pile caps for Pier Number 370 at Bandra Station, part of the Mumbai Metro Line 2B project. The study meticulously details the geotechnical investigation process, including borehole drilling, soil sampling, and in-situ testing to assess subsurface conditions and inform design parameters. The construction of metro infrastructure in urban environments requires meticulous planning and innovative engineering solutions.*
This paper elaborates on the engineering design considerations for the piles and pile caps, covering concrete mix design and reinforcement detailing. It describes the construction sequence, from site preparation and pile boring to concreting piles and forming pile caps. The use of specialized equipment and techniques, such as rotary piling rigs and tremie pipes for underwater concreting, is also discussed. Findings from this case study provide critical insights into executing large-scale infrastructure projects in densely populated urban areas. The paper concludes with recommendations for future projects, emphasizing thorough planning, continuous monitoring, and adaptive problem-solving to achieve successful outcomes in complex construction environments. This study aims to contribute to the existing body of knowledge in civil engineering and serve as a reference for practitioners and researchers involved in similar projects.

Key Words*: *Cast in Situ Piles, Pile Cap, Geotechnical Investigation, Borehole Drilling, Soil Sampling In-Situ Testing, Metro Infrastructure, Mumbai Metro Line 2B, Pier Number 370, Reinforcement Detailing, Specialized Equipment.

1. INTRODUCTION

The rapid growth of cities and the need for better infrastructure call for strong and reliable construction methods, especially for large projects like metro systems. The foundation is a crucial part of these projects, as it ensures that the structure remains stable and durable. Among the different foundation techniques, cast in situ piles and pile caps are particularly effective, especially in challenging urban environments. The Mumbai Metro Line 2B project is a significant infrastructure project in one of India's most crowded cities. Pier Number 370 at Bandra Station is a key part of this project, presenting unique challenges due to its complex soil conditions and urban setting. The choice of cast in situ piles for this project was based on their ability to handle heavy loads, adapt to varying soil conditions, and fit within the constraints of the surrounding urban environment.

1.1 Challenges and Solutions:

Building Pier Number 370 came with challenges like controlling groundwater and dealing with varying soil conditions in a busy urban area. Innovative solutions, such as dewatering techniques and advanced monitoring systems, were used to address these challenges effectively.

1.2 CAST IN SITU PILE:

Cast in situ piles are deep foundation elements constructed directly at the project site. This method involves drilling a hole into the ground, placing reinforcement, and filling it with concrete. These piles are particularly useful in urban environments where soil conditions can vary, and large loads need to be supported. This case study examines the use of cast in situ piles for Pier Number 370 at Bandra Station as part of the Mumbai Metro Line 2B project.

1.3 Geotechnical Investigation:

Before construction began, a thorough geotechnical investigation was carried out to understand the subsurface conditions.

- Borehole Drilling: Drilling holes into the ground to collect soil samples.
- Soil Sampling: Analysing the soil samples in a laboratory to determine their properties.
- In-Situ Testing: Conducting tests on-site to measure soil strength and other characteristics.

These investigations provided crucial data on soil stratigraphy, bearing capacity, and groundwater conditions, which informed the design of the piles.

1.4 Design Consideration:

- The design of cast in situ piles involved several key factors:

- Load-Bearing Calculations: Determining the load the piles need to support, including both the weight of the structure and external forces.
- Concrete Mix Design: Choosing the right mix of concrete to ensure strength and durability. Reinforcement Detailing: Designing the steel reinforcement within the piles to handle tensile forces. The design aimed to ensure that the piles could support the heavy loads of the metro structure while remaining stable in varying soil conditions.

2. METHODOLOGY FOR CAST IN SITU PILE:

1. **SETTING OUT:** From the substructure drawings, a general arrangement drawing for pile layout shall be prepared. In this drawing, each pile shall be designated with a specific numbering system with coordinates of pile centre and pile cap. From the principal stations (Bench Mark), reference cardinal points of foundation system of pile caps shall be set out and the survey pillars established. To conduct this technique, the total station is required and surveyor to perform this.

2. **Utility diversion:** A suitable open pit with 2.50m depth to be excavated manually at the bore pile location to ensure that no utilities are present to avoid damages. The manual excavation shall be finalized in reasonable time in advance to enable utility diversion work to compete without adversely affecting the bore pile works. Any utility encountered shall be diverted prior to drilling in accordance with approved utility diversion plan. For this process the most important part for any infrastructure project is that utility is important with utility you can vary your decision on day by day operation whether the work performed as per schedule or not.

3. **DRIVING OF TEMPORARY CASING:** Rotary drilling rig fitted with suitable tool (soil boring tool) to be positioned at the pile point. After necessary checks for verticality of the mast, boring shall be started. On completion of boring up to about 1m on top, temporary steel casing pipe with suitable length up to 6m will be installed in position using special attachment to the rotary head.

4. **Setting of Piling Rig:** The rig is centered on the pile point and levelled using a spirit level. Drill to a depth of 2-3 meters with an auger or bucket. Drive a temporary MS casing (1.2/1.0m diameter, up to 6m long) with a hydraulic press to prevent soil collapse. Record the top level of the casing and ensure vertical piles do not deviate by more than 1.5%, with a location deviation limit of 75mm for grouped piles and 50mm for single or double piles.


Fig -1: Piling ring machine

These Two figure shows the equipment used in piling work on site i.e. SR285R machine was used for piling and second image is about the screen that shows the how much depth till piling is done and strata for different layer.

5. **Boring of Piles:** Initial Boring of about 1.5/2.5 meters shall be done by using auger. The diameter of cutting tool shall be lesser than the outside diameter of casing minus 75mm. Piles shall be done by using temporary casing up to weathered basalt. As per the Sub-Soil Investigation report (Attached) certified by the agency non cohesive collapsible strata/sandy strata is not present. Therefore, bentonite shall not use for boring.

6. **BENTONITE:** But in case of collapse of borehole bentonite slurry shall be used (if required) for boring & flushing of borehole.

7. **REINFORCEMENT CAGE LOWERING:** The bar bending schedule based on approved drawing is prepared. Reinforcement is cut and bent to required size and shape. Specified cover blocks shall be provided to reinforcement cage for the pile. Reinforcement cage shall be lowered in 2 pieces or more depending on the available length of steel bars & length of pile. Bottom cage is lowered inside the borehole and temporarily supported on the casing pipe top, keeping the dowel length projecting above and second cage is lifted and lapped as per approve drawings or construction drawings. Helical / rings are tied as per approved drawing and main reinforcement laps are tack welded to provide more rigidity to the cage. The cage is further lowered in the borehole. Alternatively, both the cages will be lapped & welded on ground & the entire cage will be lowered inside the bore. The reinforcement shall project 60 times bar diameters above the cut off level.

8. **SONIC TUBE:** Pile must be provided with 4 no's sonic logging tubes which are required to verify the structural integrity of piles by means of the measurement of the time travel of a sound wave from emitter to receiver through concrete of pile. The sonic tube shall be made up of steel having 1mm thickness and 50mm inner diameter.

9. **CONCRETING:** After cleaning the bore hole, attach a funnel to the Tremie pipe for concrete pouring, which must be done within 6 hours. Ensure the concrete temperature meets specifications. Pour the concrete through the Tremie, keeping the pipe 300 mm above the bore bottom and embedded in concrete by 1.0 to 1.5 meters. After concreting to the required level, withdraw the temporary casing and move the rig to the next pile. Check the concrete's workability, and prepare and test concrete cubes for 7 and 28-day strength. Once all piles are cast and weak concrete is removed, submit a drawing showing the exact pile locations relative to the column centerline.

Fig -2: Concrete cube for testing

CONSTRUCTION EQUIPMENT: These are list of equipment required for cast in situ pile as following.

This table shows the requirement of equipment for cast in situ pile for construction work with their number required on site. This data is taken from directly report of detailed progress report of project that is estimating that it requires this much requirement equipment.

Table -1: Equipment required for cast in situ pile.

S. No.	DESCRIPTION	CAPACITY	NO.	Maximum Permissible Age(In Yrs)
1.	Piling Rig with all accessories		1	5
2.	Temporary Liner casing pipe (4m to 6m)		As per requirement	
3.	Crawler Crane		1	15
4.	Tyre Mounted crane		As per requirement	10
5.	Bentonite Mixing Set-up comprising of mixing tank and pumps		If Required (1 No)	
6.	Excavator/JCB		As per requirement	
7.	Dumpers		As per requirement	
8.	Batching Plant/Approved Source by MMRDA	60 cum/hr	1	10
9.	Transit Mixers	6/4 cum	As per requirement	10
10.	Welding Generator	400 Amps	1	
11.	Tremie Pipe	Min 200 Dia	25-30mt	
12.	Hopper		2 nos.	
13.	Testing Apparatus			
14.	Measuring cylinder		NA	
15.	Mud Balance Hydrometer		NA	
16.	Weighing balance		As per requirement	
17.	Hot plate		As per requirement	
18.	pH papers		As per requirement	

3. PILE CAP:

Pile caps are essential components in deep foundation systems, serving as the critical link between the piles and the superstructure they support. They play a vital role in distributing loads evenly across the piles and ensuring the structural integrity of the foundation. In the context of urban infrastructure projects like the Mumbai Metro Line 2B, pile caps are particularly important due to the high loads and complex soil conditions encountered.

3.1 Purpose and Function of Pile Caps:

The primary function of a pile cap is to transfer loads from the superstructure, such as bridges or buildings, to the piles below. This load transfer is crucial for maintaining the stability and performance of the structure. Pile cap also helps to distribute load evenly on all over the place. And also it enhances the structural stability to provide solid foundation and reduces the settlement in soil.

3.2 Utility Problems in the Construction of Pile Cap:

The construction of pile caps, particularly in urban environments, can encounter various utility-related challenges. These challenges arise due to the presence of existing underground and above-ground utilities, such as water lines, sewage systems, electrical cables, and communication networks. Addressing these challenges effectively is crucial to ensuring the smooth progress of construction and the safety of both workers and the surrounding community. This section outlines the common utility problems encountered during the construction of pile caps and the strategies used to manage them.

3.3 Solutions to their problems:

1. Identification of Existing Utilities: One of the initial challenges in the construction of pile caps is accurately identifying the location and type of existing utilities. Failure to do so can lead to accidental damage, service disruptions, and increased project costs.

Solution: Conduct comprehensive utility surveys using techniques such as Ground Penetrating Radar (GPR), electromagnetic detection, and potholing. These surveys help create accurate maps of underground utilities.

2.Managing Unexpected Utility Encounters:
Despite thorough planning, unexpected utility encounters can occur during construction, leading to delays and additional costs.

Solution: Establish contingency plans for managing unexpected utility encounters. This includes having standby crews and equipment ready for immediate response, as well as maintaining open lines of communication with utility providers.

Fig -3: Utility drainage diversion slab at pile cap.

So, this is the case while we are working on site the utility problem arise that water comes from the drainage line due choking or failure of drainage line so to counter this we need to satisfy all the stakeholders first and make a way for the drainage water by creating diversion the line. It takes lots of time because of unexpected utility encounters.

This figure shows that while working on the pile cap, a utility problem arose due to a damaged drainage pipeline. To resolve this, a diversion slab was created to redirect the water flow, allowing the remaining water to be pumped out from the site. Such utility problems are common in infrastructure projects like metro bridges. To address this situation, all stakeholders came together, including the senior site engineer, the deputy project manager, and the project manager. Additionally, representatives from the client side, MMRDA, and government bodies such as BMC and MCGM were involved.

3.4 METHODOLOGY FOR PILE CAP:

- **Preparation and Layout:** Clear the site and set out the pile cap dimensions as per the design. Ensure all necessary materials and equipment are available on-site.
- **Excavation:** Excavate the area to the required depth and dimensions of the pile cap. Maintain stable excavation sides with shoring if needed.
- **Pile Head Preparation:** Trim the piles to the correct level, ensuring they are clean and free from debris. Expose the pile reinforcement to allow for proper bonding with the pile cap reinforcement.
- **Formwork Installation:** Erect formwork around the excavation to create the shape of the pile cap. Ensure the formwork is secure and well-supported to hold the weight of the concrete.
- **Reinforcement Placement:**
  Place reinforcement bars as per the design specifications, ensuring proper spacing and alignment. Tie the reinforcement bars securely and ensure they are positioned correctly within the formwork.
- **Concrete Pouring:** Pour concrete into the formwork, ensuring it is evenly distributed and properly compacted. Use vibrators to eliminate air pockets and ensure good bonding with the pile reinforcement.
- **Curing:** Cure the concrete properly to achieve the required strength. Maintain the curing process for the specified duration, typically using water or curing compounds.
- **Formwork Removal:** Once the concrete has gained sufficient strength, remove the formwork carefully. Inspect the pile cap for any defects or irregularities and make necessary repairs.
- **Finishing:** Apply finishing touches to the exposed surfaces of the pile cap. Ensure the pile cap is clean and ready for the next stage of construction.

4. RESULT AND DISCUSSION:

These results are based on the different parameter of the primary objective of this study was to analyse the construction and performance of cast in situ piles and pile caps for Metro Line 2B in Mumbai, with a specific focus on Pier Number 370 at Bandra Station. The results presented herein provide insights into the structural integrity and load-bearing capacities of these components, contributing valuable data to the field of metro bridge construction.

1. **GEOTECHNICAL INVESTIGATION:** The geotechnical investigation for the construction of cast in situ piles

is crucial for understanding the subsurface conditions, which directly influence the design and execution of the piling work. This report presents a detailed analysis of borehole data obtained from the construction site at Bandra Station for pier number 370. The borehole details include soil stratification, groundwater levels, and the engineering properties of each soil layer. These data are used to calculate the bearing capacity and settlement characteristics of the piles. The borehole investigation involved drilling multiple boreholes at strategic locations around the site. Each borehole was logged to document the various soil layers encountered. The following table summarizes the key details from the borehole logs:

Table -2: Soil investigation details

Preparation of soil report							
Borehole ID	Depth (m)	Soil type	N-value	Moisture Content (%)	Density (KN/M^3)	Cohesion (KPA)	Angle of Internal friction phi
BH-01	0-2	Slit sand gravels	5	18	17.5	10	25
BH-01	4-9	Clay silt	15	22	18	25	28
BH-01	9-14	Dark moderate rock	25	20	19.5	15	30
BH-01	Spacing	Dark hard strata	25	23	20	15	25

Calculation of Bearing Capacity:
The bearing capacity of the pile is determined using the soil properties obtained from the borehole logs. The calculation is performed for each layer encountered, using the following equation for ultimate bearing capacity (Qu):

Qu= qf = c'Nc + γDNγ + 0.5γBNγ
c is the cohesion of the soil.
σ is the effective overburden pressure.
γ is the unit weight of the soil.
B is the width or diameter of the pile.

Nc, *Nq*, *Nγ*N c, N q, N γ are bearing capacity factors dependent on the surface friction angle

Now calculate one value from table for ultimate bearing capacity for BH-01 at depth of 9-14meter having c=15
We can calculate from this theoretical formula also but as we work on site the formulate to calculate the bearing capacity is required as following

Step 1: End Bearing Capacity (Qb)
The end bearing capacity for a pile in cohesive soil is given by:
Qb=Ap×c×Nc

Calculate the cross-sectional area of the pile base (Ap):
Ap=π/4×d2=π/4×(1.2)2=1.131m

Calculate the end bearing capacity (Qb):
Qb=1.131m2×15kN/m2×9=152.685kN

Step 2: Skin Friction (Qs):
Qs=Perimeter of pile×Length×c×α
perimeter of pile = π×d
Length = 5 meters (from 9m to 14m)
α is the adhesion factor, typically around 0.7 for cohesive soils.

Calculate the perimeter of the pile: π×d=π×1.2≈3.77m

Calculate the skin friction (Qs): 3.77m×5m×15kN/m2×0.7=198.225kN

Step 3: Total Ultimate Bearing Capacity (Qu):
The total ultimate bearing capacity is the sum of the end bearing capacity and the skin friction:

Qu= Q b + Q s=152.685kN+198.225kN=350.91kN

Summary :

- **End Bearing Capacity (Qb)**: 152.685 kN
- **Skin Friction (Qs)**: 198.225 kN
- **Total Ultimate Bearing Capacity (Qu)**: 350.91 kN

Thus, the ultimate bearing capacity of the pile for the given parameters is approximately **350.91 kN.**

The ultimate bearing capacity of the pile, combining the end bearing capacity of 152.685 kN and skin friction of 198.225 kN, results in a total of approximately 350.91 kN. This value indicates the maximum load the pile can support before failure.

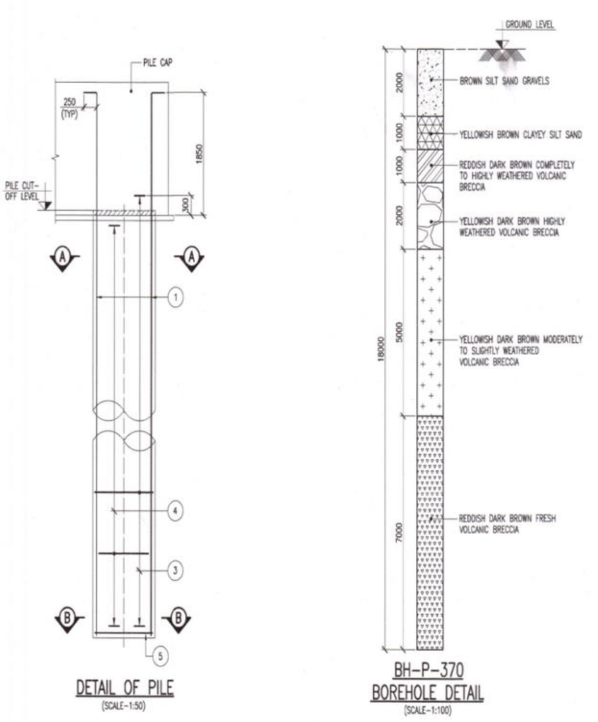

Fig -4: Borehole details of soil.

This figure shows about the borehole detail of soil at different strata from we execute the pile work on site.

2. **Load Combinations in Cast in Situ Piles:**
   The structural integrity and safety of cast in situ piles are critically dependent on the accurate assessment and application of various load combinations. These load combinations are essential for ensuring that the piles can withstand the different forces they will encounter during their service life. The primary load combinations considered for cast in situ piles include dead load, live load, wind load, seismic load, and any additional environmental or accidental loads.

Load Calculations

Dead Load (DL): Weight of the structure itself.

DL = Volume of concrete ×Density of concrete

DL=Volume of concrete × Density of concrete

For a pile of diameter d=1.2m

d=1.2m and length L=18m L=18m,

Volume=$\pi(d2)$ 2L=π (1.22)2×30=33.93m

Live Load (LL): Imposed load from traffic and utilities.

L=Design value as per IRC specifications

LL=Design value as per IRC specifications

Assuming an estimated live load of 500kN,

Ultimate Load (UL): UL=1.5× (DL+LL) =1.5× (848.25kN+500 kN) = 2022.375kN

UL=1.5×(DL+LL=1.5×(848.25kN+500kN) =2022.375kN

1. **Reinforcement Calculation to calculate Bars:**
   Bar bending schedules (BBS) are critical in the construction of reinforced concrete structures, ensuring that reinforcement bars are accurately fabricated and placed according to design specifications. In cast in situ piles, vertical bars provide essential support against compressive and tensile forces, contributing to the pile's overall stability and load-bearing capacity. This section provides a detailed calculation of bar bending for vertical bars, demonstrating the process through a sample calculation.

Sample Calculation: Vertical Bar Bending in Cast In Situ Pile

Given Data:
Diameter of vertical bar (D) = 20 mm
Length of pile (L) = 14 meters
Concrete cover = 75 mm
Number of vertical bars = 16
Length of pile = 1.585m
Lap Length =63D
Dia of Pile - 1200mm

Calculation Steps:

Step 1: Determine the Length of One Vertical Bar:

cutting length of bar = L section + length of pile up to cut off level + length of pile cap + lap length - (cover + bend + bar)

= 250 + 15850 + 1850 + 1260 - (75 + 75 + (2 x 20) + 40) = 18,980 mm

= 18.98m

Step 2: Calculate the Total Length of Vertical Bars Required:

= 18.980 x 16= 303.68m

Step 3: Weight of Steel Required:

weight of bar = d^2 / 162 = 2.46 kg,

for total bar =46.86kg

for 16 bar = 750kg

This sample calculation outlines the process of determining the length and weight of vertical bars needed for a cast in situ pile, ensuring precision in bar bending schedules and optimal material usage.

Also, there are three kinds of majorly bar required for calculation of pile in bar bending schedule such as master ring, outer ring and vertical main bar.

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Fig -5: Pile reinforcement details.

2.**Concrete Mix Design:** The concrete mix design is a critical aspect of constructing cast in situ piles, as it determines the durability, strength, and workability of the concrete used. For pier number 370 at Bandra Station, the mix design process involved meticulous planning to meet the specific requirements of the site conditions and structural demands. The mix design for M35 Grade Of Concrete for pile foundations provided here is for reference purpose only. Actual site conditions vary and thus this should be adjusted as per the location and other factors. The following outline process and calculations involved in designing the concrete mix for this project:
Grade of Concrete: M35
Characteristic Strength (Fck): 35 Mpa
Test Data for Material:
Aggregate Type: Crushed
Specific Gravity
Cement: 3.15
Coarse Aggregate: 2.67
Fine Aggregate: 2.62
Water Absorption:
Coarse Aggregate: 0.5%
Fine Aggregate: 1.0 %
MIX DESIGN
Take Sand content as percentage of total aggregates = 36%
Select Water Cement Ratio = 0.43 for concrete grade M35
Select Water Content = 172 Kg
Hence, Cement Content= 172 / 0.43 = 400 Kg / M3
M35 mix design ratio: Mixture of cement: sand: aggregate - 1:1.6:2.907

PILE CAP CALCULATION: The pile cap is a critical structural element in the foundation system of metro elevated bridges, designed to distribute loads from the superstructure to the piles embedded in the ground. For the Metro Line 2B project in Mumbai, the calculation of the pile cap involves determining the appropriate dimensions and reinforcement to ensure adequate load transfer and structural integrity. Accurate calculation of the pile cap dimensions and reinforcement is essential for ensuring the stability and durability of the structure.

PILE CHIPPING IN PILE CAP:
Pile chipping is a vital post-construction process for cast in situ piles, ensuring a smooth surface for pile caps and proper pile alignment. For the Metro Line 2B project in Mumbai, the procedure begins with site inspection and marking the cut-off level on the pile head. Using pneumatic or hydraulic chipping hammers, excess concrete is gradually chipped away to the marked level. The pile head surface is then finished smoothly. Throughout the process, strict safety protocols and quality control measures are maintained, including inspections and non-destructive testing to ensure the integrity and dimensions of the chipped pile head. This systematic approach ensures the pile's readiness for subsequent structural elements.

LOAD TRANSFER MECHANISM ON ELEVATED BRIDGE:

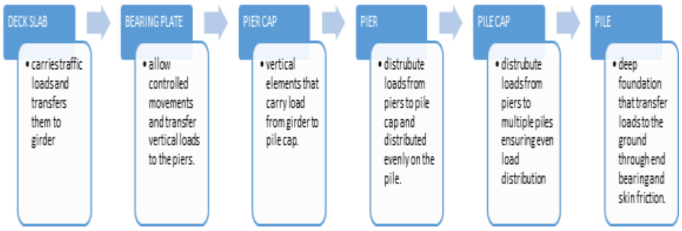

Fig -6: Load distribution on bridge.

This diagram shows about the load transfer path summary mechanism of elevated bridge and from this we can understand about the load transfer off components.

CALCULATION OF REINFORCEMENT OF PILE CAP:
To calculate this, we need to know about the given data so that we can calculate the cutting length of required for pile cap. Before that in calculation of reinforcement of pile cap that is bar bending schedule the required bar is

- Distribution bar
- Binder bar
- Link bar
- Main bar

STEP 1) given data:

- pile cap size:7700x5700x2000mm
- clear cover: 75mm
- spacing: 150mm
- bottom reinforcement bar 25mm
- diameter of binder bar 16mm

Now we calculate one bottom main bar for pile cap from the drawing given data as follows:

Calculate Cutting length: width of pile cap+2(length of l)-(cover+bend+bar)

=5700+2x(300)(2x75+2x2x25+2x16)

=6018mm

Number of bar= Effective length of pile cap/spacing+1

Effective length of pile cap= Pile length-(2xcover+2xbinder)

=7700-(2x75+2x16)

=7518mm

Number of bar = 7518/150 +1 = 51.12

STEP 2) Weight of steel required: D^2/162

=25x25/162

=3.858kg

Total weight of steel required at length= weight of steel x cutting length of bar x no. of bar

=3.858x7518x51.12

= 1482.706kg

This calculation is based on drawing and only we calculate for bottom main bar reinforcement for paper purpose only.

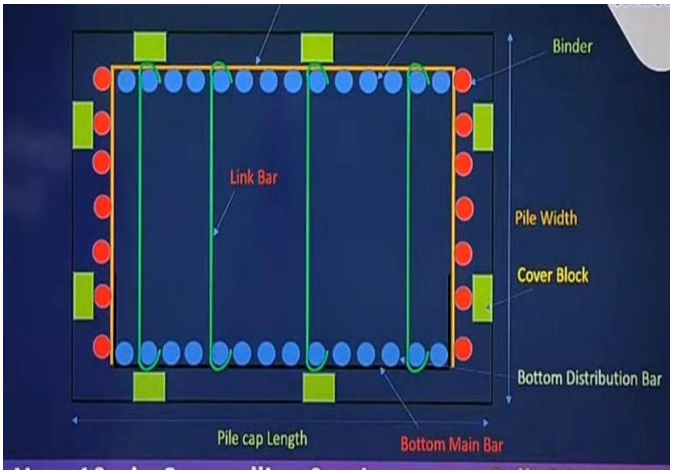

Fig -7: Layout plan of pile cap.

Result and Discussion Interpretation:

The integration of geotechnical data, precise reinforcement detailing, optimized concrete mix design, and thorough load analysis created a strong foundation system for the Metro Line 2B project. Geotechnical investigation guided pile depth and placement, ensuring proper load-bearing capacity. The reinforcement BBS maintained structural integrity and met design standards. The concrete mix design provided the necessary strength and durability. Comprehensive load analysis ensured the foundation could handle different load conditions, guaranteeing safety and stability. This approach shows how combining detailed engineering practices leads to a reliable and durable foundation system.

3. CONCLUSIONS

This research paper detailed the construction of cast in situ piles and pile caps for Pier Number 370 at Bandra Station, part of Mumbai Metro Line 2B. It covered the geotechnical investigation process, including borehole drilling and soil sampling, which informed the design parameters. The paper described the concrete mix design, reinforcement detailing, and construction sequence, from site preparation and pile boring to concreting and pile cap formation. Advanced equipment like rotary piling rigs and tremie pipes for underwater concreting were essential for overcoming construction challenges. The study highlighted the importance of thorough planning, continuous monitoring, and adaptive problem-solving in urban infrastructure projects. These findings provide valuable insights for future projects and contribute to the body of knowledge in civil engineering.

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BIOGRAPHIES

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I am currently pursuing MBA, in Advanced Construction Management and I have already published two research paper on IRJET.

I am currently pursuing MBA in Advanced Construction Management student at NICMAR, specializing in industry-standard software and have hands-on experience through internships and projects.