Design and Construction of Rock Socketed Pile Foundation for Bridges - Case Study on Road Project in Madhya Pradesh, INDIA

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Abstract. The design and construction of rock socketed pile foundation involves finalization of required length of rock socket based on the detailed study of the founding rocky strata and also include the establishment the safe load carrying capacities of pile foundations corresponding to its rock socket. Such detailed assessment of safe and allowable load carrying capacities of rock socketed bored cast-in-situ pile foundations are done for the new widened bridges of 4-lane configuration along the project corridor in between Biaora and Dewas section of NH 3 in the state of Madhya Pradesh. Those bridge structures along the project road are founded over the bored cast-in-situ concrete pile shaft which was penetrated through the overburden soil layers and then finally socketed inside the underlying highly to moderately and slightly weathered basaltic rock of varying depth. This paper presents the above said typical project case study on the details of geotechnical design assessment of rock socketed pile foundation covering its safe vertical and lateral load carrying capacities for the bridges. The different types of field load test namely "Vertical and Lateral Pile Load Tests" over the "Test Pile" and "Working Pile" are conducted to establish the estimated safe load carrying capacity of rock socketed pile foundation. The results of these pile load tests are also reported here in this paper. The required "Pile Penetration Ratio (PPR)" of the desired socket length inside the founding rocky strata is fixed based on the nature of rock as explored through investigation. This pre-decided "PPR" is adopted during installation of pile foundation inside the underlying rocky strata.

Keywords: Bored Cast-in-situ Concrete (RCC) Pile Foundation; Rock Socketing of Pile; Pile Capacity

1. Introduction

There are numbers of major river bridges and railway over bridges (ROB) along the project road of 140 Km stretch starting from Biaora to Dewas in the state of Madhya Pradesh. The project road is part of important Agra - Mumbai section of the National Highway No. 3 (i.e.NH-3). Some of the major river bridges and one ROB structure along the said project road were built over the group of bored cast-in-situ concrete (RCC) pile shaft of 1200 mm diameter which was founded through the overlying soil strata of variable thickness and finally socketed into the weathered basaltic rock. The pile foundations of the said bridges and ROB are designed to resist vertical and horizontal forces due action of the different types of loads namely dead loads, live loads, seismic loads, wind loads, water current forces (in case of river bridges) and other loads over those structures. The river bridges have varying unsupported pile lengths due to the occurrence of scour of loose unconsolidated channel bed material of silty / clayey as well as sandy nature overlying the weathered basalt rock. Due to the unsupported pile shaft lengths of the major river bridges in scour condition, there is possibility of occurrence of large deflections under the applied horizontal loads in addition to the large amount of vertical loads in static as well as in seismic condition. In case of ROB structure, the pile foundations are subjected to higher vertical and horizontal loads due to increased height of piers and abutments supporting the long span of the superstructure. So the pile foundations of the above said major river bridges and ROB structures require adequate socketing inside the underlying rock layer after penetrating through the overlying soil strata to provide stability and achieve satisfactory pile capacities to sustain the high vertical and lateral loadings. Again due to the variable depth of underlying rock layer and its engineering quality, the design of socket length of pile shaft inside the rock and finalization of the termination level of pile tip are very much challenging tasks.

The present paper describes the above said one typical project case study on the details of geotechnical design assessment and construction aspects of rock socketed pile foundation for one typical major river bridge and ROB structure.

2. Geotechnical Investigation and Subsurface Stratifications

To characterize and assess the subsurface conditions, a comprehensive geotechnical exploration work covering detailed field and laboratory investigation had been carried out at each and every pier and abutments of the river bridges and ROB structures. The field investigation work was comprised of soil borings & rock drillings, performing in-situ tests, obtaining and preserving soil, rock and water samples and field observations of the subsurface conditions and special phenomenon including ground water table. The laboratory-testing program included testing samples (soil, rock, water) as collected from site to characterize the geotechnical / geological properties. The field and laboratory testing works had been performed as per provision of latest version of related guidelines like Bureau of Indian Standards (BIS), Indian Road Congress (IRC) namely IRC:78 & Ministry of Road Transport and Highways (MORT&H) Specifications for Road & Bridge Works (Fifth Revision). The exploratory boreholes at the pier and abutments locations of the river bridges and ROB structures were terminated by extending up to 10.00 m inside the underlying rock layer. The general geology of the area, position of ground water table (GWT) and site specific subsurface conditions are described in the subsequent sections briefly.

2.1 General Geology of Project Area

The oldest group of rocks comprising of Archaeans and Proterozoic formation constitute nearly 45% area of the State of Madhya Pradesh (MP). The next younger formation of Carboniferous to lower Cretaceous comprising Gondwana Super Group covers 10% area while the formation of Cretaceous to Paleocene comprising mostly of Deccan Trap basalt constitutes 38% area of the State of MP. In the studied project area in between Biaora and Dewas the Deccan trap Basalt is observed.

Biaora and Dewas both the locations are part of Chambal river basin. Biaora is a part of Rajgarh district of and Dewas is a part of Dewas district of Madhya Pradesh. Rajgarh district forms the part of Malwa plateau generally an undulating topography. The Vindhyan hill range occupies the south-eastern part of the district. The basaltic rocks of Malwa plateau occupy almost entire district except south-eastern part. The Vindhyans are having Shale and Sandstone with thin layer of alluvium. The Dewas district lies in the central part of the state. The city is located on the level plains of the Malwa plateau; to the south, the land rises gently to the Vindhya Range, which is the source of the Chambal and Kali Sindh rivers.

2.2 Location of Ground Water Table

The recorded depth of "Ground Water Table (GWT)" in various explored boreholes in the bridge and ROB structures along the project road was varying from 3.40 m to 11.50 m from the exiting ground level (EGL) or bed level. For designing of pile foundation of structures, the water table was considered at ground level anticipating the fluctuations in the measured water levels due to seasonal variation and corresponding to the critical condition which may arise during or immediately after the monsoon during the serviceability life of the structures.

2.3 Subsurface Stratifications

The site-specific sub-surface conditions at the major river bridges and ROB structure sites have been characterized using the field and laboratory-testing data obtained during geotechnical exploration. Broadly, the foundation profile comprises of following major strata as found in the investigation at the major river bridge and ROB structure locations.

i. Medium Stiff to Hard Silty Clay / Clayey Silt with low to high plasticity (CL/CI/CH) of variable thickness (0.00 m to 17.00 m)
ii. Medium Dense to Dense / Very Dense Silty Sand / Poorly graded Sand (SM / SP) having 0.00 m to 4.50 m thickness
iii. Completely weathered rock in the form of disintegrated granular material (Residual Soil) having thickness maximum up to 1.50 m
iv. Highly Weathered Fractured / Highly to Moderately Weathered / Moderately Weathered / Slightly Weathered Moderately Strong Bed Rock (Basalt) with varying engineering quality and explored thickness maximum up to 10.00 m

The top level of the underlying rock and its engineering quality as encountered was widely varying in all the boreholes in any particular structure location. Intermediate bands of highly weathered rock layers were also found within the moderately to slightly weathered rock in some of the boreholes of the structures. The range of variations of encountered depth of rock top level from existing ground level (EGL), explored thickness, total core recovery (TCR), rock quality designation (RQD), rock crushing strength, rock mass rating (RMR) and the class of rock layers as per its RMR as explored in case of one typical major river bridge and ROB are tabulated below.

Table 1. Range of Engineering Properties of Rock

Name of Structure	Bore Hole Location and Number	Encountered Depth from EGL (m)	TCR (%)	RQD (%)	Rock Crushing Strength (ton/m^2)	Rock Mass Rating (RMR)	Class of Rock
Major Bridge over River Kalisindh	BH-A1	17.00 - 27.00	43.33 - 93.33	0.00 - 93.33	3104 - 6638	19 - 67	Very Poor to Good
	BH-P1	12.50 - 18.50	40.00 - 98.67	0.00 - 94.00	5974 - 7440	19 - 67	Very Poor to Good
	BH-P2	17.00 - 24.00	11.00 - 99.33	0.00 - 84.66	3190 - 7285	9 - 61	Very Poor to Good
	BH-P3	16.50 - 22.50	41.33 - 99.33	0.00 - 92.00	4367 - 6290	9 - 74	Very Poor to Good
	BH-P4	7.00 - 16.00	25.00 - 96.00	0.00 - 88.66	4996 - 7115	19 - 64	Very Poor to Good
	BH-P5	9.00 - 15.00	28.66 - 98.00	0.00 - 97.00	6306 - 7596	22 - 67	Poor to Good
	BH-P6	6.00 - 12.00	13.00 - 94.00	0.00 - 94.00	4052 - 6446	9 - 67	Very Poor to Good
	BH-P7	11.50 - 20.00	8.00 - 93.34	0.00 - 90.00	3888 - 7619	5 - 74	Very Poor to Good
	BH-A2	12.00 - 22.00	26.67 - 94.67	0.00 - 86.00	4372 - 6205	19 - 55	Very Poor to Fair
ROB @ 256+730 Km	BH-A1	7.00 - 17.00	41.33-98.00	0.00-69.00	2186 - 3544	15 - 64	Very Poor to Good
	BH-P1	8.00 - 18.00	29.00-83.00	0.00-83.00	2522 - 5790	12 - 56	Very Poor to Fair
	BH-A2	6.40 - 16.50	32.00-85.00	0.00-69.00	2467 - 5464	18 - 50	Very Poor to Fair

From the above table of engineering properties of underlying rock layers it can be noted that the TCR is varying from 8% to 99.33% and RQD is varying from 0% to 97%. The rock crushing strength of the explored rock layers ranges from 2186 ton/m^2 i.e. 21.86 MPa to 7619 ton/m^2 i.e. 76.19 MPa. At the top part of the rock layer where the RQD is 0% with core recovery, the equivalent rock crushing strength corresponding to the “Point Load Strength Index (PLI)” of the tested rock specimen is reported. In case of rock sample having RQD, the crushing strength is reported as per the “Uni-axial Crushing Strength (UCS)” value of the rock layer. The engineering quality of explored rock layers is varying from “Very Poor/Poor” to “Fair/Good” nature as per the overall rating of rock mass based on the guidelines given in IS 13365 (Part I), in accordance with the “Geo-mechanics Rock Mass Classification System (after Bieniawski 1998)”. Mostly at the beginning say around 2.00 to 3.00 m depth of the rock layers immediately below the overlying granular residual soil is highly fractured, moderately strong and of “Very Poor/Poor” nature. However, the quality of underlying bed rocks becomes stronger and moderately to slightly fractured and of “Fair” to “Good” nature with increase in depth below.

3. Geotechnical Design of Rock Socketed Pile Foundation

Deep Foundations in the form of “Bored Cast-in-situ RCC Pile Foundations” of 1.20 meter diameter having shaft length varying from 8.25 m to 16.60 m were adopted in the design for the structures namely bridges over major rivers and ROB. The selection of foundation was based on the considerations of availability of suitable load bearing strata in the form of underlying rock layers having adequate vertical compression and uplift capacity and also the required horizontal resistance against the various kinds of applied loads which can ensure enough stability of the structure. The penetration of single pile shaft inside the underlying weathered basalt rock i.e. designed rock socket length of the pile shaft was varying from 1.86 m to 2.40 m in case of bridges over major rivers and 2.40 m to 3.18 m for the ROB structure satisfying the availability of adequate resistance i.e. vertical and horizontal load carrying capacity.

The geotechnical design of pile foundations socketed into the underlying rock include finalization of socket length inside the rock layer for carrying maximum applied horizontal loads and moments at rock top in addition to the provision of adequate vertical compression and uplift load carrying capacity.

3.1 Length of Rock Socket for Carrying Horizontal Load and Moments at Rock Top

The capacity of the rock socketed pile to withstand the lateral loads depends on the rigidity of the pile as well as the load deformation characteristics, thickness of the soil and rock strata in which the pile is rock socketed. The lateral load carrying capacity and corresponding moment carrying capacity of the single pile has been done with due consideration of the lateral resistance offered by the surrounding soil above the rock socketing portion up to the scour level or pile cut-off level whichever is lower, in addition to the resistance offered by the portion of rock socket. The effect of lateral resistance of the surrounding soil above the rock socket is considered in the form of reducing the “Free Cantilever Moment” at top of rock socket depending upon the ratio of the free i.e. unsupported length of pile shaft below the pile cut-off i.e. “L1” and stiffness factor namely “R” or “T” of the surrounding soil i.e. (L1/T) or (L1/R) corresponding to the pile head conditions namely “Free Headed Pile” for single row of piles and “Fixed Headed Pile” for multiple rows of piles under any group, as per the guidelines given in “Clause No. C-4.3 of Appendix-C of IS 2911 (Part 1/Sec2): 2010”.

The rock socket length i.e. "L_s" of pile having the pile tip as fixed into rock, is satisfied corresponding to the "Moment Carrying Capacity of Pile" as per the following equation given in "Clause no. 9.2 of Appendix C of IRC:78-2014".

$$L_s = 2 * H / (\sigma_1 * D) + SQRT\ [\{4 * H^2 / (\sigma_1^2 * D^2)\} + \{6 * M / (\sigma_1 * D)\}] \qquad (1)$$

where,

i. "D" is the diameter of the pile shaft
ii. "H" is the maximum horizontal force at top of the rock socket,
iii. "M" is the maximum actual moment at top of the rock socket which is obtained from the maximum "Free Cantilever Moment (M')" by multiplying it with the "Moment reduction Ratio (m)" as per the guidelines of IS: 2911 (Part 1/Sec2) i.e. M = M' x Moment Reduction Ratio (m)
iv. "σ_1" is the permissible compressive strength in rock socket which is lesser of 30 Kg/cm^2 or 0.33*q_c, "q_c" being the average unconfined i.e. uniaxial compressive strength of rocks in the socket. The permissible compressible strength in rock socket under wind and seismic conditions are taken as 25% more of its value under static condition i.e. (1.25*σ_1)

The maximum horizontal force (H) and corresponding maximum moment (M) at top of rock socket under static, wind and seismic conditions, diameter (D) of pile shaft, permissible compressive strength (σ_1) in rock socket and the corresponding minimum required socket length (L_s) for the pile shaft under the piers and abutments as estimated using the above equation no. 1 for one typical major river bridge and ROB are tabulated below.

Table 2. Required Minimum Length of Rock Socket for resisting Horizontal Loads and Moments as per IRC:78-2014

Name of Structure	Pier (P) / Abutment (A)	Pile Diameter (m)	Maximum Horizontal Force at top of Rock Socket (ton)	Maximum Actual Moment at top of Rock Socket (ton-m)	Permissible Compressive Strength in Rock Socket (ton/m^2)	Minimum Required Length of Rock Socket (m)
Major Bridge over River Kalisindh	A1	1.20	41	175	375	1.72
	P1	1.20	34	217	375	1.90
	P2	1.20	32	265	375	2.03
	P3	1.20	34	263	375	2.03
	P4	1.20	45	191	375	1.81
	P5	1.20	44	203	375	1.85
	P6	1.20	57	185	375	1.84
	P7	1.20	35	213	375	1.89
	A2	1.20	43	220	375	1.91

ROB @ 256+730 Km	A1	1.20	74	210	375	2.03
	P1	1.20	20	60	375	1.00
	A2	1.20	83	231	375	2.16

From the above tabulated summary, it is observed that the minimum required rock socket length was varying from 1.72 m to 2.03 m i.e. around 1.5 times of pile diameter and even more than that in case of the major river bridge. Similarly, the minimum rock socket length was required as 1.00 m i.e. around one diameter of pile shaft under the pier and 2.03 m to 2.16 m i.e. around 2.0 times of pile diameter for the abutments of the ROB structure.

As per the guidelines given in IRC:78-2014, in case of rock socketed pile, for the satisfactory performance of the socket as fixed tip, the rotation of pile shaft at the top of rock socket for the fixed condition should be very limited and does not exceed 5% of the pile shaft rotation for the pinned condition at the top of socket. The virtual depth of fixity of the pile shaft was designed as located inside the middle of the length of rock socket to satisfy the above said IRC:78-2014 criteria of pile shaft rotation and corresponding permissible pile top deflection maximum up to 1% of pile dimeter of 1.20 m i.e. 12 mm. The rock socket length as decided based on the requirement of resisting the maximum horizontal load and moments at top of rock socket was also verified against the maximum applied vertical loads for any single pile shaft in the group.

3.2 Vertical (Axial Compressive) Load Carrying Capacity

The total vertical i.e. axial compressive load carrying capacity of pile foundation is usually a combination of skin friction along the pile shaft surface and end bearing resistance at pile tip. However, as per IS 14593:1998 and IRC:78-2014 guidelines, the vertical compressive load carrying capacity of pile foundation socketed in rock is estimated from the side friction along the pile shaft only in rock socket portion and the end bearing resistance of rock at the proposed pile tip. As per the above-mentioned IS and IRC guidelines, the side friction along the pile shaft in the overburden soil portion has not been considered. As per the available guidelines the important factors which influence the load carrying capacity of rock socketed pile shaft are the available strength inside socket, extent of fracturing and deformation modulus of rock mass, the condition of the walls and base of the rock socket and the geometry of the rock socket.

Since the underlying rock encountered in the project site was weathered “Basalt” of sound nature where cores were obtained mostly with RQD > 0% and uniaxial crushing strength of the rock mass was determined directly from the UCS test, so the method based on the “Uniaxial Compressive Strength of Rock” as per the “Clause No. 6.5.1.1 of IS 14593:1998” was used for the determination of safe vertical (axial) compressive load carrying capacity of the single pile shaft socketed into the rock. As per the IS 14593:1998 guidelines, the expression for the determination of safe vertical load carrying capacity (Qs) of the rock socketed bored concrete pile foundation based on the uniaxial compressive strength is given below.

$$Q_s = (q_c * N_j * N_d * A_p) + (q_c * A_s * \alpha * \beta) \quad (2)$$

where,

i. “q_c” is the uniaxial compressive strength of rock (“q_c” is at pile tip & “q_s” is along pile socket)
ii. “N_j” is the empirical coefficient based on “spacing of discontinuities” in rock mass as per “Fig 2” or “Table 4” of IS:12070-1987
iii. “N_d” is the depth factor i.e.“N_d” = [0.80 + 0.20 * (Length of rock socket / Diameter of pile shaft inside rock socket)] <=2.00
iv. “A_p” is the base area of pile shaft inside rock i.e. A_p = pi() * D^2 / 4, where “D” = Pile shaft diameter
v. “α” is the rock socket slide resistance reduction factor based on rock strength as per “Fig. 1” of IS 14593:1998
vi. “β” is the rock socket correction factor based on rock mass reduction factor (j) as per “Fig. 2” of IS 14593:1998
vii. “A_s” is the surface area of pile shaft inside rock i.e. A_s = pi() * Pile shaft diameter inside rock socket (D) * Length of rock socket (L_s)

The value of “q_c” was taken as the average value of uniaxial crushing strength of rock mass present along the side wall of socket for estimating the side socket shear resistance. For estimating the point i.e. end bearing resistance of pile socket tip, the average value of uniaxial crushing strength (q_c) of rock available at pile tip was considered. The average value of uniaxial crushing strength of rock mass for estimating the load carrying capacity pile shaft socketed into rock should preferably be restricted maximum up to the ultimate value of unconfined i.e. uniaxial crushing strength of the grade of pile concrete from the consideration of pile concrete and rock interaction behavior as it is recommended in many popular guidelines namely FHWA (1999), NAVFAC DM-7.2 (1982) and AASHTO (1996) design methods. In conservative way, the uniaxial crushing strength of rock mass inside socket may also be restricted to the safe strength of grade of pile concrete as per the guidelines of IS 14593:1998.

The concrete grade for the pile shaft adopted was M35 having 28 days characteristics strength (f_{ck}) as 35 MPa i.e. 3500 ton/m^2 and safe value of direct compressive strength as (0.36 * 35) i.e. 12.60 MPa i.e. 1260 ton/m^2 as per the guidelines of IRC:112 -2011.

Since the encountered rock was highly to moderately/slightly weathered and fractured in the socket portion, so the value of ‘Nj’ was taken as 0.10 as per “Table 4” of IS:12070, based on the consideration of moderately close spacing of discontinuities in between 0.30 m to 1.00 m and aperture (opening) of discontinuities as less than 10 mm. The value of “α” i.e. rock socket side resistance reduction factor was considered as 0.03 from the “Fig. 1” of IS 14593 based on the average crushing strength of rock along the wall of the socket. Similarly, the value of “β” i.e. rock socket correction factor was taken as 0.40 as per “Fig. 2” of IS 14593 based on rock mass reduction factor (j) corresponding to the quality of rock present in the wall of socket.

The pile diameter (D), length of rock socket (L_s) and corresponding value of depth factor (N_d), uniaxial crushing strength (q_c) of rock mass present along the side wall and tip of socket, ultimate crushing strength i.e. 28 days characteristics strength (f_{ck}) of the design grade of pile concrete and the safe vertical compressive load carrying capacity (Q_s) of pile shaft as estimated using the above equation no. 2 under different piers and abutments in case of one typical major river bridge and ROB are tabulated below.

Table 3. Summary of Estimated Safe Vertical Load Carrying Capacities of Single Pile as per IS 14593:1998

Name of Structure	Pier (P) / Abutment (A)	Pile Diameter (m)	Length of Rock Socket (m)	Values of "N_d"	Uniaxial Crushing Strength of Rock at Wall of Socket (ton/m^2)	Uniaxial Crushing Strength of Rock at Tip of Socket (ton/m^2)	Uniaxial Crushing Strength of Pile Concrete (ton/m^2)	Safe Vertical Load Carrying Capacity (ton)	
								As per Rock Crushing Strength	As per Concrete Crushing Strength
Major Bridge over River Kalisindh	A1	1.20	2.40	1.20	2554	4533	3500	893	752
	P1	1.20	1.92	1.12	2283	5974	3500	955	642
	P2	1.20	2.10	1.15	2220	4342	3500	776	666
	P3	1.20	2.10	1.15	2809	4367	3500	835	722
	P4	1.20	1.86	1.11	3123	5464	3500	949	702
	P5	1.20	1.86	1.11	3778	6306	3500	1110	734
	P6	1.20	1.86	1.11	2651	4728	3500	817	662
	P7	1.20	1.92	1.12	2106	3433	3500	618	-
	A2	1.20	1.92	1.12	2811	3871	3500	734	688
ROB @ 256+730 Km	A1	1.20	3.18	1.33	2166	2919	3500	751	-
	P1	1.20	2.40	1.20	1886	2522	3500	547	-
	A2	1.20	3.18	1.33	2226	2714	3500	728	-

From the above summary table, it is seen that the estimated safe vertical (compressive) load carrying capacities of the single pile shaft under the piers and abutments were varying from 642 ton to 1110 ton in case of the major river bridge. Similarly, the estimated safe vertical (compressive) load carrying capacities of the single pile shaft under the pier and abutments were in between 547 ton and 728 ton for the ROB structure.

The safe vertical i.e. axial (compressive) load carrying capacities of the single pile shaft was also estimated by using the "Method 1" following the approach given under "Clause No. 9.1 of Appendix-5 of IRC:78-2014" due to the availability of moderately strong "Basalt" rock of igneous nature having uniaxial crushing strength of the rock mass as more than 10 MPa i.e. 1000 ton/m^2 in socket portion with RQD > 0% and (CR+RQD)/2 > 30% at the pile socket bottom. The safe vertical load carrying capacity (Q_s) of the rock socketed bored concrete pile foundation was determined using the following expression as given under "Method 1" of IRC:78-2014 based on the uniaxial compressive strength.

$$Q_s = (q_c * K_{sp} * d_f * A_b) / FOS \text{ as } 3 + (C_{us} * A_s) / FOS \text{ as } 6 \quad (3)$$

where,

i. "q_c" is the uniaxial i.e. unconfined compressive strength of rock in Mpa
ii. "K_{sp}" is the empirical coefficient whose value ranges from 0.30 to 1.20 corresponding to the values of (CR+RQD)/2 varying in between 30% and 100% of the rock mass at pile tip i.e. base of pile shaft
iii. "d_f" is the depth factor i.e."d_f" = [1.00 + 0.40 * (Length of rock socket / Diameter of pile shaft inside rock socket)] <= 1.20
iv. "A_b" is the base area of pile shaft inside rock i.e. A_b = pi() * D^2 / 4, where "D" = Pile shaft diameter
v. "C_{us}" is the ultimate shear strength of rock along socket length = 0.225*SQRT(q_c), but restricted to the shear capacity of concrete of the pile to be taken as 3MPa i.e. 3000 ton/m^2 for M35 grade of concrete in confined condition, which of other strength of concrete can be modified by a factor SQRT(28 days characteristics strength i.e. f_{ck} / 35)
vi. "A_s" is the surface area of pile shaft inside rock i.e. A_s = pi() * Pile shaft diameter inside rock socket (D) * Length of rock socket (L_s)
vii. FOS is the "Factor of Safety" as recommended to be applied over the corresponding ultimate value

The average value of uniaxial crushing strength (q_c) of rock available at pile tip within the depth twice the diameter i.e. 2D depth of pile shaft from its base was considered for estimating the end bearing resistance of pile socket as per the guidelines given in IRC:78-2014. The average value of uniaxial crushing strength of rock mass for estimating the end bearing component of the load carrying capacity pile shaft socketed into rock may be restricted maximum up to the 28 days characteristic crushing strength of the grade of pile concrete. However, the allowable end bearing component after dividing by factor of safety (i.e. FOS as 3) shall be restricted to maximum value of 5 MPa i.e. 500 ton/m^2 by following the guidelines of IRC:78-2014.

Similarly, the average value of unconfined i.e. uniaxial compressive strength (q_c) of rock available along the surrounding wall of socket was taken into consideration for finalizing the value of "C_{us}" as said above following stipulations of IRC:78-2014 while estimating the rock socket side resistance. Again, for evaluation of the side socket friction capacity, the top 300 mm depth of rock socket was neglected and the side socket friction capacity was further limited to the maximum socket depth six times diameter of pile shaft as per the guidelines of IRC:78-2014. Since the encountered rock in the project area was highly to moderately weathered nature, so the socket depth inside such weathered rock was provided more than the minimum requirement of 0.50 times of diameter of pile shaft following IRC:78-2014 criteria.

The value of empirical coefficient i.e. "K_{sp}" was taken as 0.30 corresponding to the minimum value of (CR+RQD)/2 as 30% due to the weathered and fractured nature of encountered rock mass inside the socket in the project area.

By following the above stated approach of IRC:78-2014 and using equation no. 3, the estimated safe vertical (axial) compressive load carrying capacity (Q_s) of pile shaft corresponding to the pile diameter (D), length of rock socket (L_s) and corresponding value of depth factor (d_f), uniaxial crushing strength (q_c) of rock mass at bottom of socket, ultimate shear strength of rock along socket length (C_{us}), 28 days characteristics strength (f_{ck}) of the design grade of pile concrete under piers and abutments for one major river bridge as well as for one ROB are summarized below in the Table 4.

Table 4. Summary of Estimated Safe Vertical Load Carrying Capacities of Single Pile as per IRC:78-2014

Name of Structure	Pier (P) / Abutment (A)	Pile Diameter (m)	Length of Rock Socket (m)	Values of "d_f"	Ultimate Shear Strength of Rock along Socket (ton/m^2)	Uniaxial Crushing Strength of Rock at Tip of Socket (ton/m^2)	Uniaxial Crushing Strength of Pile Concrete (ton/m^2)	Safe Vertical Load Carrying Capacity (ton) As per Rock Crushing Strength	Safe Vertical Load Carrying Capacity (ton) As per Concrete Crushing Strength
Major Bridge over River Kalisindh	A1	1.20	2.40	1.20	114	4533	3500	716	625
	P1	1.20	1.92	1.20	108	5974	3500	675	584
	P2	1.20	2.10	1.20	106	4342	3500	685	595
	P3	1.20	2.10	1.20	119	4367	3500	700	610
	P4	1.20	1.86	1.20	126	5464	3500	689	598
	P5	1.20	1.86	1.20	138	6306	3500	701	611
	P6	1.20	1.86	1.20	116	4728	3500	679	589
	P7	1.20	1.92	1.20	103	3433	3500	571	-
	A2	1.20	1.92	1.20	119	3871	3500	647	596
ROB @ 256+730 Km	A1	1.20	3.18	1.20	105	2919	3500	586	-
	P1	1.20	2.40	1.20	98	2522	3500	472	-
	A2	1.20	3.18	1.20	106	2714	3500	560	-

As per the above summary table**,** it can be noted that the estimated safe vertical (compressive) load carrying capacities of the single pile shaft under the piers and abutments were in between 571 ton to 716 ton for the river bridge. In case of the ROB, the estimated safe vertical (compressive) load carrying capacities of the single pile shaft under the piers and abutments were ranging from 472 ton to 586 ton.

By comparing the estimated safe vertical load carrying capacities of single pile shafts as summarized under Table 4 and Table 5 above, it can be seen that the safe capacity evaluated using the approach of IRC:78-2014 was lesser than the safe value derived as per the method prescribed in IS 14593:1998. This is due to the reason of consideration of the restricted side socket shear resistance as predicted in the suggested method of estimation in IRC:78-2014.

By limiting the uniaxial crushing strength of rock mass inside socket maximum up to the safe strength of adopted M35 grade of pile concrete following the guidelines of IS 14593:1998**, t**he safe vertical load carrying capacities of the single pile shaft were reduced to the minimum value of 264 ton to 308 ton for the different piers and abutments of the major river bridge and 308 ton to 371 ton under the pier and abutments for the ROB. However, these evaluated minimum values of safe vertical (compressive) load carrying capacities were also found satisfactory to the required maximum vertical structural load to be carried by the single pile shaft of the group for those respective structures.

3.3 Uplift Load Carrying Capacity

The uplift load carrying capacity of pile shaft was derived only from the side socket resistance component of the vertical compressive load carrying capacity. No side friction along the pile shaft in the overburden soil portion above the rock socket was considered in uplift capacity. Since the self-weight of the pile shaft acts against the uplift load, so the self-weight of the pile shaft was also added with the side socket resistance component to get the total uplift load carrying capacity of pile shaft as per the available IS and IRC guidelines. The entire part of the available side socket resistance of the vertical compression was considered in case of uplift load resistance capacity of the pile shaft as per IS guidelines whereas only the 70% of the ultimate shaft side socket resistance for compression was taken in the estimation of uplift load carrying capacity of pile shaft following the guidelines of "Clause No. 709.3.6.2 of IRC:78-2014". A factor of safety i.e. FOS as 6 was also applied over the ultimate shaft side socket resistance to get its safe value in estimation of uplift resistance like vertical compression as per the stipulations of IRC:78-2014.

The estimated safe uplift load carrying capacity [$(Q_s)_{uplift}$] of pile shaft corresponding to the pile diameter (D), total length of pile shaft (L_p) and the corresponding self-weight of pile shaft (W_p), length of rock socket (L_s) and the corresponding safe side socket resistance in uplift as per the IS 14593:1998 and IRC:78-2014 guidelines for the different piers and abutments of one typical major river bridge as well as for one ROB are summarized below in the Table 5.

Table 5. Summary of Estimated Safe Uplift Load Carrying Capacities of Single Pile

Name of Structure	Pier (P) / Abutment (A)	Pile Diameter (m)	Total Pile Length (m)	Length of Rock Socket as provided (m)	Self-Weight of Pile (ton)	Safe Side Socket Shear Capacity in Uplift (ton)		Safe Uplift Load Carrying Capacity (ton)	
						As per IS 14593	As per IRC:78	As per IS 14593	As per IRC:78
Major Bridge over River Kalisindh	A1	1.20	16.60	2.40	47	277	105	324	152
	P1	1.20	15.32	1.92	44	198	76	242	120
	P2	1.20	19.54	2.10	55	211	84	266	139
	P3	1.20	18.36	2.10	52	267	94	319	146
	P4	1.20	10.33	1.86	29	263	86	292	115

	P5	1.20	11.11	1.86	31	318	95	349	126
	P6	1.20	8.35	1.86	24	223	79	247	103
	P7	1.20	14.73	1.92	42	183	73	225	115
	A2	1.20	12.14	1.92	34	244	85	278	119
ROB @ 256+730 Km	A1	1.20	8.77	3.18	25	311	133	336	158
	P1	1.20	8.27	2.40	23	205	91	228	114
	A2	1.20	8.77	3.18	25	320	135	345	160

From the above tabulation, it can be noted that the safe uplift load carrying capacity evaluated using the approach of IRC:78-2014 was lower in comparison with the safe uplift load value estimated as per the method given in IS 14593:1998. The required maximum design uplift loads for the single pile shaft in the group under the respective pier and abutments of the structures were duly satisfied with corresponding minimum of the safe available capacities as estimated by the above stated methods.

4. Construction of Pile Foundation

The pile foundations with the designed depth of socketing inside the underlying rock for the structures were successfully executed in the said project area. Adequate numbers of computerized hydraulic rotary type pile drilling rig having model number "BG-28" of M/s. BAUER, Germany were used in the project. The Photograph 1 as shown here was the typical piling rig actually deployed in the project site. The plant made ready mix concrete i.e. RMC of M35 grade was used for concreting of pile shaft and pile cap. The output of pile construction including its quality was quite satisfactory. All the checklists related to the different phases of piling work namely the fixing of pile position, casing driving and pile boring, drilling through the underlying rock and termination of pile shaft with required socketing inside the rock as designed, recording of the pile history sheet, pile reinforcement and cage lowering, pile concreting including the "Tremie Chart" and "Piling Pour Card" were regularly maintained under quality control program. The safety measures for all the engineers and construction workers were taken care. There were some cases of less consumption of concrete observed during pile foundation construction. The remedial measures were undertaken in various ways namely by introduction of high plastic bentonite, doing construction time management and maintaining the viscosity of pile boring

Photograph 1 : Piling Rig deployed in Site fluid, providing increased diameter of cutting tools etc. Bottom sampler was also used to confirm the proper cleaning of pile bore bottom after adequate & profuse flushing and before start of pile concreting.

The termination of pile shaft was done after socketing the adequate length of pile shaft inside the underlying founding rock as per the design recommendations. In field construction, the termination including the rock socketing of the pile shaft was finalized using the energy criteria which is based on the actual energy consumed while drilling through the founding rock strata and is measured as “Pile Penetration Ratio (i.e. PPR)” following guidelines given in IRC:78-2014. The “Pile Penetration Ratio (PPR)” is defined as the energy in ton-meter required to advance the pile bore of one square-meter of cross-sectional area by 1 cm. For SPT (i.e. Standard Penetration Test), the “PPR” corresponding to the “N” number of blows for 300 mm penetration can be determined as (0.747*N). Since the encountered rock in the said river bridge and ROB was highly to moderately weathered, fractured and moderately strong in nature, so the approximate equivalent SPT, "N" value corresponding to rock classification at beginning of pile socketing zone was taken as minimum as 600 as per the guidelines given in IS 2911 (Part 1/Sec2):2010. The minimum required value of PPR corresponding to the SPT (N) value of 600 for the weathered basalt rock was derived as 448 say around 500 ton-m / m^2 / cm. Now the “PPR” for the hydraulic rotary type piling rig, as it was used in the structure locations of the project, was determined by following the stipulation of IRC:78-2014 and using the equation no. 4 given below.

$$PPR = (2 * \pi * n * T * t) / (A * P) \qquad (4)$$

where, “n” is rotation in ‘rpm’ i.e. revolution per minute, “T” is the torque in ‘ton-meter’ corresponding to “n”, “t” is the time in minutes, “A” is area of pile shaft in ‘m^2’ and “P” is penetration in ‘cm’.

All the above stated values of rotation, torque, penetration and time required for the depth of penetration were recorded all through the depth of boring in soil and drilling in rocky strata in every pile point shaft and the corresponding value of PPR were also calculated. The required depth of rock socketing for the pile shaft was provided from the level of moderately strong rock based on its estimated value of the PPR satisfying with the minimum required value of around 500 ton-m / m^2 / cm.

5. Load Testing of Pile Foundation

The required numbers of different types of pile load tests namely “Initial Load Test” over the “Test Pile” and “Routine Load Test” over the “Working” i.e. “Service Pile” both in vertical and horizontal direction were conducted to establish the estimated safe pile capacities of the single shaft. The pile load test was conducted as per the guidelines given in IS 2911 (Part 4):2013 and IS 14593:1998. The “Maintained Load Test” procedure comprising of gradual continuous loading and then unloading in stages after reaching up to the test load was adopted in the project for conducting the pile load test as per the relevant IS guidelines. The gross settlement at every stage of loading and then net settlement for each stage of gradual unloading were recorded during vertical and horizontal pile load tests. The locations of “Test Piles” were selected based on the variation in subsurface stratifications especially the founding rock level actually encountered in the structure. The typical photographs of conducting vertical (compression) pile load test are shown under Photograph 2 and 3. The vertical load vs pile head deflection curve of "Initial Load Test" from the "Test Pile" as obtained for the river bridge and ROB is shown below in Fig. 1. The maximum applied test load over the "Test Pile" in "Initial Load Test" was limited to the 2.5 times of the maximum required safe design load for the single pile shaft. The recorded gross settlement was varying from 2.63 mm to 5.93 mm and the ranges of applied test load as recorded was in between 570 ton and 1030 ton as per the vertical load-deflection behavior of "Test Pile" for the major river bridge and ROB. The "Working Piles", as selected based on its history i.e. records of construction, were loaded up to the 1.5 times of the maximum required safe design load for the single pile shaft under "Routine Load Test". The gross vertical settlement of the pile head as observed in "Routine Load Test" was in between 3.53 mm to 4.03 mm and the applied test load as noted was varying from 309 ton and 550 for the said structures. The graphs of the applied vertical load vs pile top deflection curve of "Routine Load Test" as conducted over the "Working Pile" for the said river bridge and ROB is shown below in Fig. 2. The maximum permissible total settlement of pile under the test load was considered as 12 mm and 8 mm respectively for "Initial Load Test" and "Routine Load Test" as per the guidelines of "Clause No. 9.2 of IS14593:1998".

Photograph 2 : Set-up of Vertical Pile Load Test

Photograph 3 : Jacks and Dial Gauges in Load Test

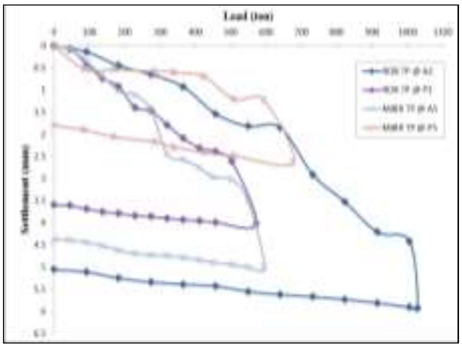

Fig. 1 : Results of Initial Vertical Pile Load Test

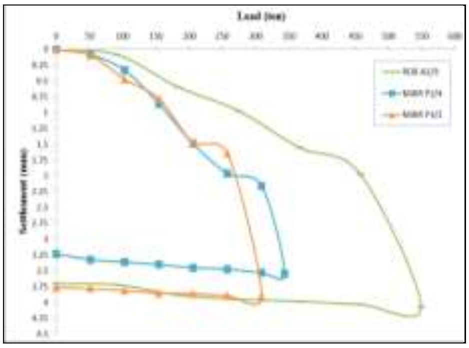

Fig. 2 : Results of Routine Vertical Pile Load Test

The pile head vertical displacement i.e. settlement was also estimated corresponding to the applied different stages of loads of "Initial Load Test" by following guidelines as given in "Clause no. 6.6 of IS 14593:1998" and also in "Clause No. 9.1 of IS:8009 (Part II)-1980". It was noted that the recorded settlement was almost in line with the estimated value up to the test load applied in site. So beyond the test load of 2.5 times of safe required design load as actually applied and for the total load corresponding to the 2.5 times of safe estimated pile capacity i.e. up to say 1650 ton, the anticipated maximum value of settlement as per the IS guidelines was derived as 9.60 mm which is found as less than permissible value of 12 mm for the single pile shaft under the structures of the project. Hence the estimated safe pile capacity in the range of 600 to 650 ton was also achievable within the limit of allowable settlement as per IS guidelines. This comparison of the estimated and observed settlement under the vertical loads of "Initial Test" for the said river bridge and ROB is shown here in Fig. 3.

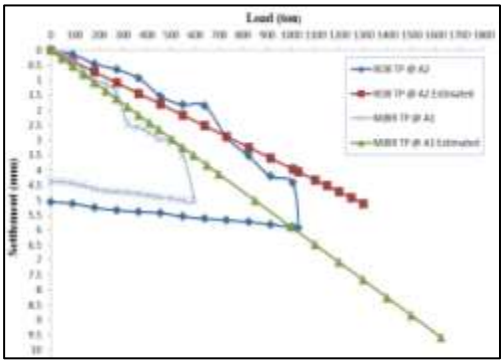

Fig. 3: Comparison of Observed and Estimated Settlement under Vertical Loads of Initial Pile Test

Similarly, the results of "Initial Lateral Pile Load Test" and "Routine Lateral Pile Load Test" for the major river bridge and ROB structures are shown respectively in Fig. 4 and Fig. 5 below. The recorded gross horizontal deflection was in between 2 mm to 3 mm and the applied lateral test load was varying from 19 ton to 90 ton as per the lateral load-deflection behavior of "Test Pile" in "Initial Load Test" for the major river bridge and ROB. The observed total horizontal deflection of the pile head in "Routine Load Test" was varying in between 2.14 mm to 3.38 mm and the applied test load was ranging from 40 ton and 57 ton for the river bridge and ROB structures. The maximum permissible total horizontal deflection of pile head under the lateral test load was considered as 8 mm and 4 mm respectively for "Initial Load Test" and "Routine Load Test" as per the stipulations of "Clause No. 9.3 of IS14593:1998".

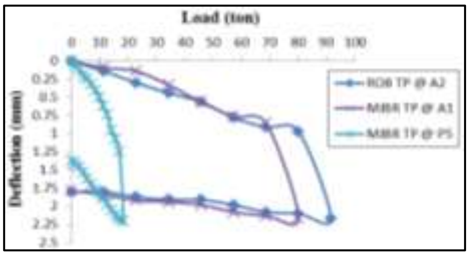

Fig. 4 : Results of Initial Lateral Pile Load Test

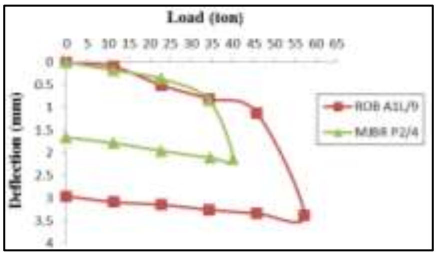

Fig. 5: Results of Routine Lateral Pile Load Test

6. Conclusions

This paper discusses about the detailed design philosophy and construction methodology of the pile foundation socketed into the underlying rock as per the available IS and IRC guidelines and technical specifications which was adopted for the major river bridge and ROB structures along the Biaora and Dewas project road (a section of NH3) in the state of Madhya Pradesh. It was quite challenging situation for installing the pile foundations penetrating through the overburden soil layers and then finally socketed inside the underlying highly to moderately and slightly weathered basaltic rock of varying depth. The socket length of pile shaft was decided with provision of adequate resistance against the maximum applied horizontal loads and corresponding moments and also by satisfying the required maximum vertical compression and uplift loads to be carried by the single pile shaft. The socket length of pile shaft as designed was also executed in site by using the hydraulic rotary piling rig based on the criteria of minimum required “Pile Penetration Ratio (PPR)” for the founding basalt rock of highly to moderately weathered and fractured nature following the guidelines of IRC:78-2014. The required maximum safe design vertical and horizontal loads for the single pile shaft were also established by conducting the adequate numbers of actual field pile load tests over the “Test Pile” as well as over the identified “Working Pile”. The Photograph 4 and 5 shown here are respectively the completed major river bridge and ROB structure which are already open to the road traffic.

Photograph 4 : Major River Bridge

Photograph 5 : Railway Over Bridge (ROB)

7. Acknowledgements

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