Remedial Measures for Upheaval of PQC Panels Adjacent to Piers of Monorail in Mumbai

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ABSTRACT

Mumbai city has several modes of public transport system including 'Monorail'. The Wadala Depot to Chembur is an elevated monorail system which is supported by pier, pile cap and piles. Monorail piers have been positioned in the median portion of cement concrete roads. Since the sub-soil comprises of marine clay in these two roads, stone columns (0.9 m diameter at a spacing of 2.5 m c/c in a triangular patter) were installed before constructing the cement concrete pavement. In the year 2015 the cement concrete pavement near the monorail piers in Sion-Koliwada Connector road and Anik-Wadala Road as well as in front of Wadala Monorail Station is severely distressed in the form of level displacement (which appears as upheaval) and cracking, while the concrete panels away from the piers are intact. This paper presents detailed geotechnical investigation, probable reasons for displacement /settlements in PQC slabs and design of remedial measures.

INTRODUCTION

Many of the metro capital cities in India have been constructed in the coastal / river delta regions. As a result, sub-soil in such cities happens to be soft marine clay. Due to growth in population and increasing demand for better mobility, city development authorities are building flyovers, metro trains and monorails in such cities. Constructing elevated metro or monorail corridor is often cheaper and much easier than construction in the underground. The India's first Monorail project is implemented in Mumbai and is being executed by the Mumbai Metropolitan Region Development Authority (MMRDA). The detailed project report (DPR) for Mumbai monorail project from Jacob circle to Chembur was prepared in the year 2008. Construction work started in the year 2009 and the first operational line from Wadala Depot to Chembur (approximately 8.5 km in length) was opened to the public in February 2014. In this stretch, Monorail alignment starting from Wadala Depot passes through Sion-Koliwada connector road, then to Anik-Wadala road (Northern connector road - Main road) and takes a turn towards Mysore Colony (Figure 1). The Sion-Koliwada Connector road and road in front of Wadala Monorail station are six lane divided cement concrete roads with a median in between. The thickness of PQC is about 300 mm, below which dry lean concrete (DLC) bed has been

provided. GSB layer has been sand-witched between DLC and fill up soil. Since the sub-soil comprises of marine clay in these two roads, stone columns (0.9 m diameter at a spacing of 2.5 m c/c in a triangular patter) were installed before constructing the cement concrete pavement. Near Wadala station and monorail depot, the alignment is adjacent to a creek. In the year 2015 the cement concrete pavement near the monorail piers in Sion-Koliwada connector road and Anik-Wadala road as well as in front of Wadala Monorail Station roads are severely distressed in the form of level displacement (which appears as upheaval) and cracking as shown in Figures 2a and 2b respectively, while the concrete panels away from the piers are intact. The problem of level displacement (upheaval) of slabs near monorail pier and subsequent cracking in such panels can be seen from Wadala Monorail Station upto about Pier No 80 on Anik-Wadala Road (North Connector road) until the alignment takes a turn towards Mysore Colony Station.

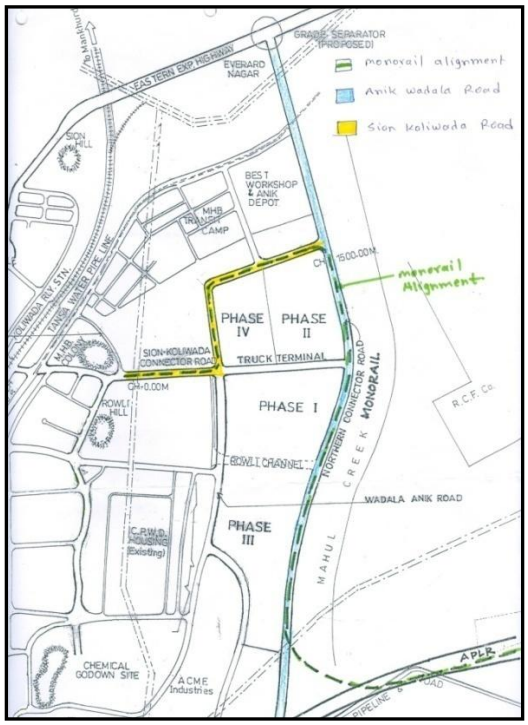

Figure 1 Plan of Monorail Alignment from Wadala Station to Mysore Colony Station

FIELD AND LABORATORY INVESTIGATIONS

Selection of bore holes

The sub-soil investigations were carried out by M/s Soiltech (India) Pvt. Ltd, Pune at five boreholes in the median portion of the road stretch. These borehole locations are presented in Table 1 and locations are marked in Figure 3. The locations of bore holes have been distributed in such a way so as to cover the entire alignment of the proposed stretch of Monorail project.

Figure 2a Distress and Cracking of PQC slabs around Monorail pillars (Anik-Wadala Road)

Figure 2b Distress in PQC slabs around Monorail pillars (Sion-Koliwada Road)

Table - 1 Location of Bore Holes

Bore Hole No	Located Between Piers Nos	Remarks
BH – 1	32 - 33	Main road (Anik - Wadala Road, near IMAX Cinema)
BH – 2	24 - 25	Sion - Koliwada road (Behind Wadala Monorail station)
BH – 3	19 - 20	Sion - Koliwada road (Behind Wadala monorail station)
BH – 4	76 - 77	Main Road (Anik - Wadala road)
BH – 5	1L 36a - 37	Wadala Monorail station

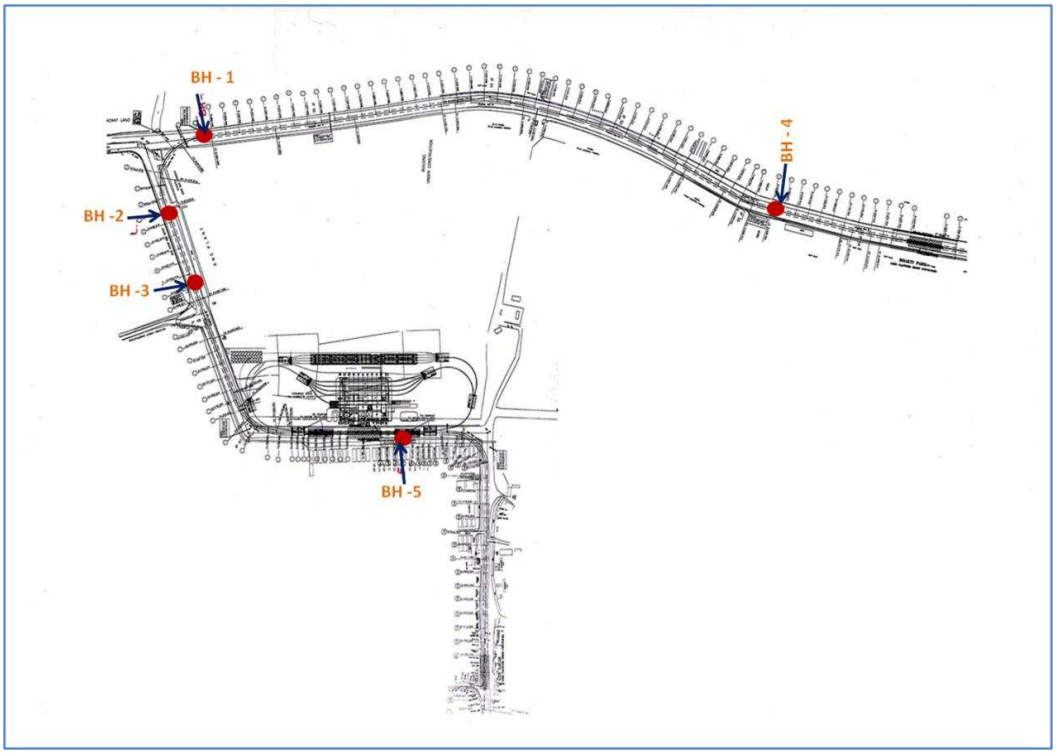

Figure 3 Location of boreholes along the Wadala – Chembur Monorail alignment

Soil profile

The typical bore-log details have been provided in Figure 4. Details of sub-soil layers are presented below:

- ***Fill Material***

  The sub-soil below road pavement has fill material of thickness varying from 3.00 m to 4.50 m. In BH 4, thickness of fill material is about 7.0 m. Fill material comprises of a mixture of soil, boulders and waste refuse materials. Fill material can be classified as Gravelly Clay / Sandy Clay / Sand. This layer is having a good SPT value (>15).

- ***Marine Clay***

  All the boreholes have stiff to very stiff marine clay varying from 5.50 m to 10.0 m thickness except BH 2. In BH 2, soft marine clay of about 7 m thickness was noticed. This soft marine clay is having low SPT value (2 – 5) and high compressibility.

Ground Water

Depth of ground water table in the boreholes varied from 2.5 m to 2.8 m from present finished road top level.

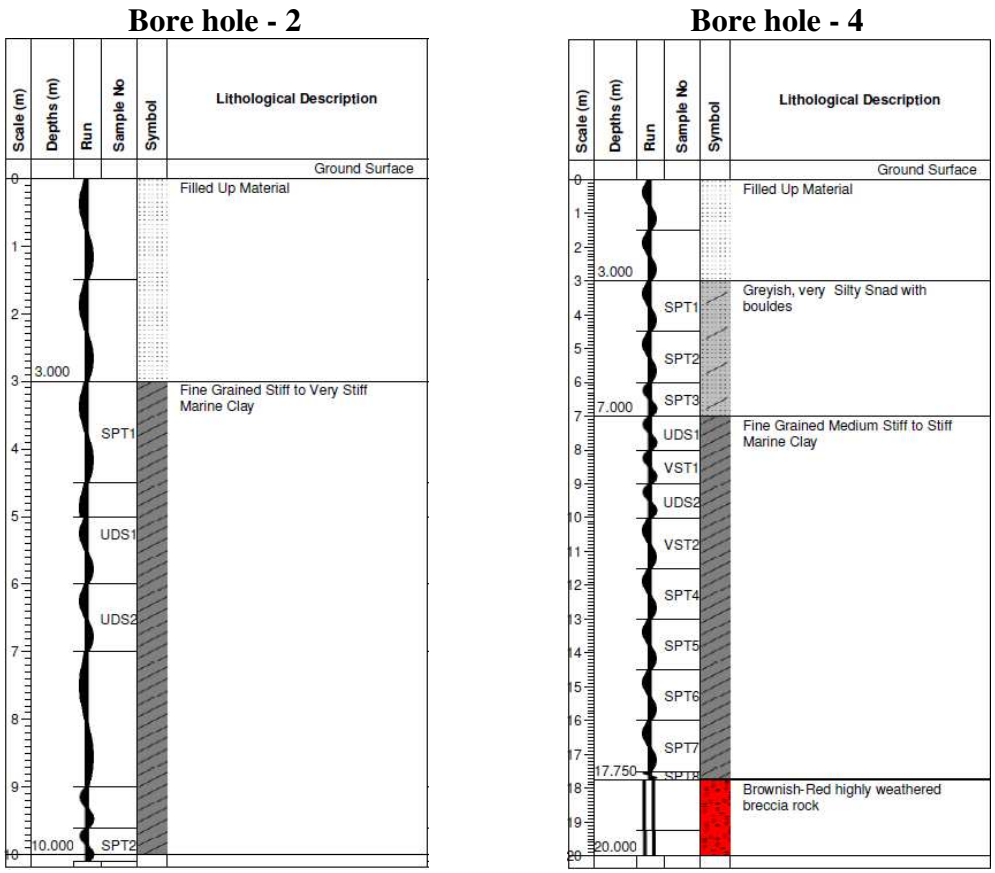

Figure 4. Typical bore-log details

Laboratory Investigations

Two typical undisturbed samples (Sample - 1 is very soft marine clay and sample - 2 is very stiff marine clay) collected from boreholes were tested and their geotechnical properties are presented in Table 2.

Table 2 Geotechnical properties of clay samples

Geotechnical properties	Sample - 1	Sample - 2
Specific gravity (Gs)	2.70	2.69
In-situ moisture content (%)	73	50
Liquid limit (%)	120	110
Plastic Limit (%)	41	41
Plasticity Index (%)	79	69
Shear Strength (kPa)	22	35
Sensitivity	1.22	1.12

SETTLEMENT ANALYSIS

The bore-log data locations selected for analysis is shown in Map 1. To determine the compressibility characteristics of soils, one dimensional consolidation test have been carried out on undisturbed soil samples collected at selected depths and the results are presented in Table 3.

Map1: Bore-log locations selected for settlement analysis

Table 3 consolidation characteristics of soil samples

Property	Sample - 1	Sample - 2
Initial Void ratio (e_0)	1.973	1.438
Compression Index (C_c)	0.59	0.38
Bulk density (kN/m^3)	15.6	16.6

The settlement analysis has been carried based on data from table 3 and bore-log data from DPR reports (RITES Ltd) and latest bore-log data from Soiltech (India) Pvt. Ltd, Pune. The other data considered for settlement analysis as follows

Average density of pavement layers - 20 kN/m^3
Dead load + Live load due to pavement - 24 kN/m^3
Water table is 1 m below the existing road top level.
Terzahgi's equation for settlement calculation due to one dimensional consolidation

$$S_c = \sum_{i=1}^{n} \frac{C_{ci} H_{oi}}{1 + e_{oi}} \log\left(\frac{\sigma'_{vfi}}{\sigma'_{voi}}\right) \qquad \text{---------- (1)}$$

Where S_c = total settlement

C_{ci} = Compression index of respective layer
H_{oi} = Thickness of respective layer
E_{oi} = Initial void ratio of respective layer
$\sigma_{v'fi}$ = final vertical effective stress of respective layer
$\sigma_{v'oi}$ = Initial vertical effective stress of respective layer

The results of settlement calculations for various borehole locations are presented in Table 4a and 4b.

PROBABLE REASONS FOR DISPLACEMENT / SETTLEMENTS IN PQC SLABS

Based on the field study, other technical data provided by MMRDA and laboratory studies the following observations can be made:

- The Monorail structure (Pear, Pile cap and Piles) is intact and the structure has been designed for a settlement ≤10 mm.
- Since monorail operations are going on unhindered, this indicates no differential settlement of monorail track.
- Before construction of existing concrete pavement in Sion-Koliwada Connector road, ground improvement using stone columns was undertaken. The design of stone column was verified and it was found to be conforming to IS 15284 (part 1) - 2003.
- It may also be noted that, provision of stone columns accelerates the rate of settlement. Also, stone columns help in reducing the total settlement, but they cannot completely eliminate consolidation settlements (IS 15284 (part 1) - 2003).
- Difference in elevation between PQC panels located just adjacent to monorail piers (0.5 m) and panels away from piers (9.5 m away from median) was obtained through levelling by MMRDA in October 2010 and February 2015. This level difference as reported varies from 250 to 550 mm at different chainages in this stretch.
- Analyzing these aspects, it emerges that soft marine sub-soil found in this stretch has undergone consolidation settlement due to load imposed by fill soil and pavement. The monorail piers and pier cap did not settle since they have been rested on piles which rest on hard stratum (Basalt Rock). As a result, PQC slabs which are resting on monorail pier pile caps stayed at their original position while all other slabs away from piers gradually settled. Hence, it appears as though PQC slabs near Monorail piers have suffered upheaval.
- By considering the level differences already recorded (settlements) in the field and the settlements calculated based on sub-soil properties, it can be seen that about 85 per cent of the degree of consolidation has already occurred in the field. Hence, it is expected that further settlements / increase in level differences between PQC slabs near the pier and PQC slabs away from pier would be minimal.

Table 4a: Settlement of the existing road along the monorail alignment

Bore Hole No	Thickness of			Settlement of (mm)		Total settlement (mm)	Remarks
	Fill (m)	Soft clay(m)	Stiff clay (m)	Soft clay (m)	Stiff clay (m)		
1	3	6	0	0.325	0.000	325.1	Bore hole locations are shown in map1.
2	4	3.5	3	0.187	0.102	289.4	

3	3	8.5	0	0.418	0.000	417.9	Bore-log data taken from DPR reports (FUGRO Geotech Pvt. Ltd, Navi Mumbai, India).
4	3	6	2.5	0.325	0.081	406.6	
5	3	7	2	0.364	0.063	427.0	
6	0.5	6.5	3	0.486	0.117	603.4	
7	4.5	4.5	2	0.219	0.064	282.8	
8	3	6	4.5	0.325	0.137	462.2	
9	2.6	6.4	4.5	0.358	0.138	496.1	
10	4.5	4.5	7.5	0.219	0.202	420.6	
11	4.5	6	5	0.277	0.134	411.0	
12	2	10	0	0.518	0.000	517.7	
13	3	9	1.5	0.434	0.043	477.2	
14	4.5	7.5	2	0.329	0.054	383.3	
15	1.5	7.5	0	0.459	0.000	459.1	
16	4.5	5.5	0	0.258	0.000	258.1	
17	4.7	5.8	0	0.264	0.000	264.1	
18	3	9	1	0.434	0.029	463.4	
19	3	7.5	1.5	0.383	0.046	429.3	
20	4.5	6	0.5	0.277	0.015	292.1	
21	4.5	6.5	0	0.295	0.000	294.7	
22	4.5	6	0.5	0.277	0.015	292.1	
23	4.5	6	0.5	0.277	0.015	292.1	
24	4.5	6	0.5	0.277	0.015	292.1	
25	3	6	1	0.325	0.034	359.5	
26	4.5	6	0	0.277	0.000	276.7	
27	4.5	7.5	0	0.329	0.000	328.9	
28	4.5	7.5	0	0.329	0.000	328.9	
29	3	9	0.5	0.434	0.015	449.2	
30	6	7.5	0	0.288	0.000	288.4	
31	4.5	9	0	0.376	0.000	376.2	
32	4.5	9	0	0.376	0.000	376.2	
33	6	6	1.5	0.241	0.040	281.2	
34	7.5	3	3.5	0.116	0.092	208.3	
35	6	6	1	0.241	0.027	268.2	

Table 4b: Settlement of the existing road along the monorail alignment (Contd..)

Bore Hole No	Thickness of			Settlement of (mm)		Total settlement (mm)	Remarks
	Fill (m)	Soft clay(m)	Stiff clay (m)	Soft clay (m)	Stiff clay (m)		
36	4.5	6	4.5	0.277	0.123	399.3	Bore hole locations are shown in map1. Bore-log data taken from DPR reports (FUGRO Geotech Pvt. Ltd, Navi
37	4.5	6	4.5	0.277	0.123	399.3	
38	7.5	6.5	3.5	0.228	0.079	307.5	
38	6	3	6	0.132	0.163	295.7	

40	4.5	11	0	0.433	0.000	432.8	Mumbai, India)
41	4	6.5	1.5	0.310	0.045	355.0	
42	4.5	6	4.5	0.277	0.123	399.3	
-	3.5	4	9	0.222	0.255	476.9	Anik – wadala
-	3	8	4.1	0.401	0.114	514.5	Anik – wadala
-	2.3	3.7	2.6	0.244	0.105	348.7	near Bakti park
-	2.3	3.65	3.05	0.241	0.121	362.3	Anik – wadala
-	2.35	3.6	2.05	0.237	0.085	321.7	Anik to Mysore colony
-	2.1	8.4	0	0.458	0.000	458.4	Madhuban
-	2.2	12.5	0	0.578	0.000	578.0	Bakti Park
-	4.5	0	5.5	0.000	0.205	204.6	between pier 32 - 33
-	3	7	0	0.364	0.000	364.4	between pier 24 - 25
-	3	0	7	0.000	0.285	284.8	between pier 19 - 20
-	7	0	10.5	0.000	0.271	271.2	between pier 76 - 77

DESIGN OF REMEDIAL MEASURES

The existing level difference between the concrete slabs near the monorail piers and the slabs away from piers has created a safety hazard for traffic movement. All most all slabs near the pier show distress in the form of multiple cracks. Hence, such slabs need to be replaced immediately. For replacing these slabs, various options like reconstruction of PQC slabs, Interlocking Concrete Block Pavement and Flexible pavement are available. It may be noted from tables 4a and 4b that, at different locations the amount of settlement / level difference is varying but after repairs, the road top level for repaired locations and existing slabs should match. This means that thickness of pavement to be reconstructed after dismantling distressed PQC slabs near the piers varies. Further, there should not be any drainage problems due to percolation of water from repaired locations. Looking into these aspects, it is recommended that the PQC slabs which are severely affected near the piers and away from the piers should be dismantled and the whole pavement can be reconstructed using flexible pavement. The thickness of pavement in such case can be designed based on IRC: 37-2012. Since the sub-soil comprises of marine clay and subgarde is made of selected soil (filled up soil), there would be significant difference between the CBRs of the selected subgrade and foundation soils. As per IRC: 37 - 2012, in such a scenario, effective CBR is to be considered for pavement design. Assuming CBR of soft marine clay as 2 per cent, CBR value of filled up material to be 6 per cent, the effective CBR for subgrade would be 5 per cent.

The design of flexible pavement has been carried out based on IRC: 37- 2102. Data assumed for the design is as follows:

Effective CBR of the subgrade = 5 %
Traffic in terms of million standard axles considered for the Main road (Anik - Wadala Road) = 150 msa
The traffic in terms of million standard axles considered for Sion - Koliwada road (Wadala monorail station and behind the station) = 30 msa

To prevent differential settlement and to improve the bearing capacity and drainage of fill material, non-woven geotextile and bi-axial geogrid of ultimate tensile strength 100 kN/m are proposed to be used.

Based on the above data the proposed pavement cross sections of the road for long term measures (reconstruction of affected stretch) is given in Figure 5 and Figure 6 for Anik - Wadla road and Wadala station to main roads respectively. Finally the proposed cross section road level should be matched with existing finished road top levels of the other lane which is stable and not showing any sign of distress. The typical sketch shows the finished road level after implementation of remedial measures is indicated in figure 7.

Construction Procedure

The identified PQC slabs which have developed distress and other pavement layer below the PQC slabs should be removed and the soil should be excavated up to a depth of 780 mm for Anik - Wadala Road (Northern connector road) and 740 mm for Wadala station to Main road (Wadala station and Sion – Koliwada road behind the Wadala Monorail station). The depth mentioned here is from the existing finished road top level (FRL).

- The loose soil in the excavated pit should be compacted by a vibratory roller / plate compactor
- Non woven geotextile layer should be cut to required dimensions and placed inside the excavated portion. The geogrid and geotextile should conform to Section 700 of MORTH Specifications for Road and Bridge Works (Fifth revision - 2013).
- The sand layer should be spread on the top of the geotextile layer and compacted using plate vibrator. Sand should conform IS 383 (Grading Zone III or coarser).
- The construction sequence of different pavement layers as shown in Fig 5 and 6 should be taken up sequentially.
- The pavement layers (GSB, WMM, DBM and BC) shall be constructed as per MoRTH (Ministry of Road Transport and Highways) Specifications for Road and Bridge Works (Fifth revision - 2013).

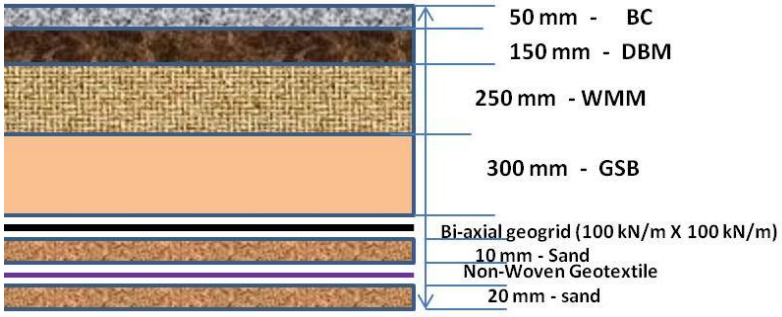

Figure 5 Proposed cross section for Anik - Wadala road (Northern connector road)

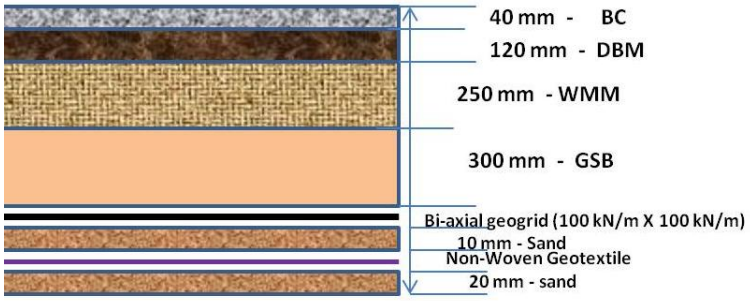

Figure 6 Proposed cross section from Wadala station to Main road(Wadala station and Sion – Koliwada road behind the Wadala Monorail station)

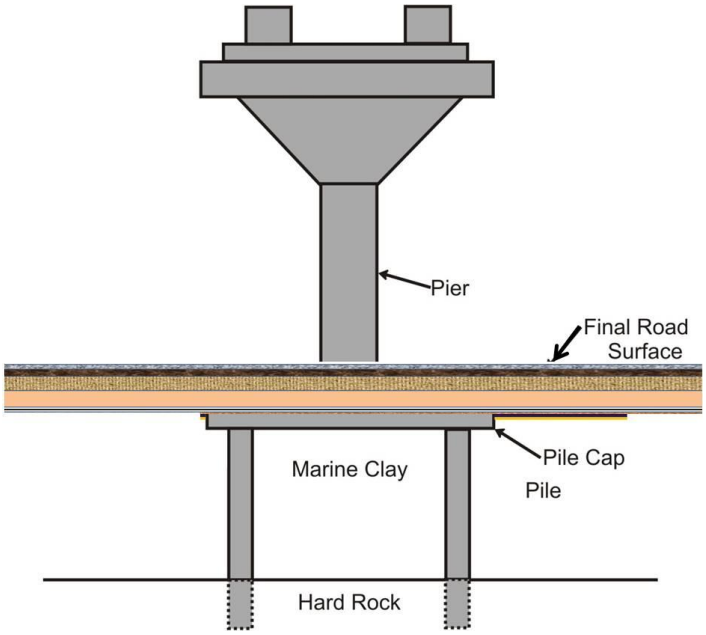

Figure 7 Typical sketch showing the FRL after implementation of remedial measures

CONCLUSIONS

The cement concrete pavement near the monorail piers is severely distressed and cracked, while the concrete panels away from the piers are intact. From the settlement analysis it was observed that the distress and cracking of cement concrete pavement is due to consolidation (settlement) of soft marine clay sub-soil.

The observed level difference (from surveying) between the concrete slabs near the monorail piers and the slabs away from piers (varies from 250 to 550 mm) are matching with the current settlement analysis.

It was noted from observed settlements in the field and the settlements estimated based on sub-soil properties, about 85 per cent of the degree of consolidation has already been occurred in the field. Hence, further settlements would be minimal.

Since the sub-soil comprises of soft marine clay and subgarde is made of filled up soil, effective CBR is considered for pavement design. The design of flexible pavement has been carried out based on IRC: 37- 2102.

To prevent differential settlement and to improve the bearing capacity bi-axial geogrid are proposed as a basal reinforcement.

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REFERENCES

CSIR – CRRI report (2015). “Design of remedial measures for upheaval of PQC panels adjacent to piers of monorail in Mumbai”, New Delhi.

IRC: 37 (2012). “Tentative guidelines for design of flexible pavements”

IS 383 (1970). "Specification for coarse and fine aggregates from natural sources for concrete (Second revision)"

IS 15284 (2003). Design and construction for ground improvement-Guidelines. Part 1: Stone columns. 267-290.

MoRTH (Ministry of Road Transport and Highways)(2013). “Specifications for Road and Bridge Works (Fifth revision)”