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New Approach for the Assessment of Hydraulic Heave for the Deep Excavations in Layered Soils

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Abstract— Assessment of hydraulic heave for any deep excavations is very critical and appropriate suitable methods as well as good engineering practice shall be adopted for the assessment of hydraulic heave depending on the subsurface profile. Consideration of shear strength of cohesive soils plays an important role while estimation of hydraulic heave. This paper presents the assessment of hydraulic heave by analytical and finite element analysis for the deep excavation in layered soils.

Keywords* — *Shear Strength; Hydraulic Heave; Modulus of Elasticity; Poisson's Ratio; Permeability.

1. Introduction

Deep excavations can carry major risks to nearby structures, equipment's, and most important of all, persons. Furthermore, an excavation failure occurs very quickly, giving a worker virtually no time to escape. For this matter, extended studies are needed to assure that risks are minimized so major problems can be avoided and lives can be saved.

Due to space limitations in urban areas, deep excavations are often constructed in close proximity to surrounding buildings and services. In the design of deep excavations, the design of the retaining structure and support system plays a very important role. The design of deep excavations is often dominated by the problem of the water flow around the walls.

The present paper covers the new approach for the assessment of hydraulic heave in layered soils which can help in avoiding more complex treatments like ground improvement by jet grouting, deep dewatering systems. Analysis was carried out using elastic solutions, analytical methods and finite element analysis. Also, suitable monitoring system proposed to validate the estimated hydraulic heave and further assessment based on the monitoring data.

2. Description of the Project

Transtonnelstroy–AFCONS Joint Venture (TTAJV) has been engaged by Kolkata Metro Rail Corporation (KMRCL) for Kolkata East West Metro Contract UG1 Construction of Underground section from Howrah Maidan Station to end of New Mahakaran station in Kolkata. The scope of work includes project "Design and Construction works for Underground Stations at Howrah Maidan with Cross Over, Howrah with Subway, New Mahakaran with provision of Retrieval / Launching Shaft, Vent Shaft and associated Tunnels with Cross Passages till east end of New Mahakaran Station including Design Coordination as per Interfacing Requirements". The underground section has been shown in the following route map (Figure.1).

As a part of the project construction of vent shaft proposed between two stations of Howrah and New Mahakaran just besides the Hoogly river.

- Size of Excavation (between D wall to D wall): 11.30 m x 11.30 m
- Diameter of permanent lining: 10.30 m
- Natural Ground level: RL. 6.150 m
- RL of Bottom of Excavation: RL. -38.00 m
- RL of Bottom of clay layer below excavation: RL. -49.00 m
- Thickness, H, of clay layer below excavation: 11.00 m

Fig. 1: Route Map of Underground Section of East-West Metro (UG-01)

Geotechnical investigation carried out at the proposed vent shaft location and the following geological layers (Figure 2) derived based on field and laboratory test results;

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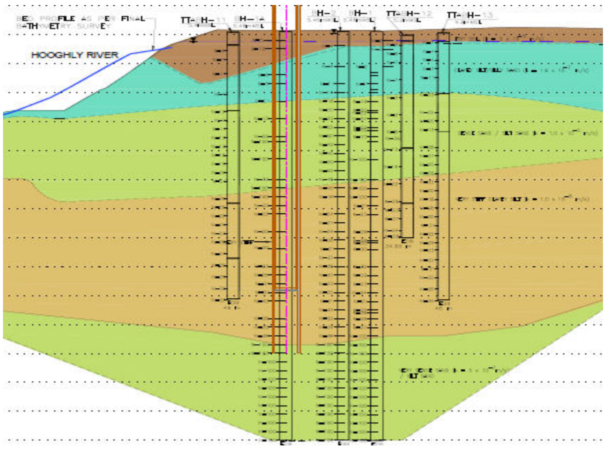

Fig. 2: Subsurface profile at vent shaft location

Table 1: Type of soil and its extent from the natural ground level

Stratum	Strata	Depth, m		Elevation (m, msl)	
		From	To	Top	Bottom
Made Ground	Unit 1	0	6.00	6.15	0.15
Silty Clay /Clayey Silt	Unit 2	6.00	12.50	0.15	-6.35
Silty Sand	Unit3b	12.50	30.00	-6.35	-23.85
Silty Clay /Clayey Silt	Unit3a	30.00	55.00	-23.85	-48.85
Silty Sand	Unit3b	55.00	70.00	-48.85	-63.85

The summary of physical and engineering parameters interpreted from field and laboratory test results and mentioned in Table 2.

Table 2: Physical and Engineering Parameters of Various Soil Layers

Strata	Unit Weight (γb)	Poisson's Ratio (ν')	Angle of Friction (ϕ')	Cohesion (c')	Undrained Shear Strength (c_u)	Drained Young's Modulus (E')	Undrained Young's Modulus (E_u)	Unit Skin Friction (fs)	Permeability (k)	Earth Pressure at Rest (K_0)
	kN/m³	-	deg	kPa	kPa	MPa	MPa	kPa	m/s	
Unit 1	18	0.3	28	0	N/A	10	-		5×10^{-5}	0.53
Unit 2	18	0.25	25	0	50	10	1.25E'	50	1×10^{-7}	0.58
Unit 3b (above -13.5 mMSL)	19	0.2	30	0	N/A	10	N/A	σ_{vo}' (K_s tanδ)	1×10^{-5}	0.47
Unit 3b (below -13.5 mMSL)	19	0.2	34	0	N/A	100	N/A	σ_{vo}' (K_s tanδ)	1×10^{-5}	1.0
Unit 3a	19	0.2	30	0	-4.77 * z - 19.32	-z +11	1.25E'	$\alpha * c_u$	1×10^{-7}	0.5
Unit 3b (Deep)	20	0.2	34	0	N/A	100	N/A	σ_{vo}' (K_s tanδ)	1×10^{-5}	0.8

2. Preliminary Proposal for Mitigation of Hydraulic Heave

The assessment for hydraulic heave estimated by considering only the dead weight soil mass above the interface where hydraulic pressures develops and concluded as unsafe. To make it safe for excavation and construction of permanent structure, deep dewatering system proposed at inside of the vent shaft. The following are the constraints to adopt the deep dewatering system for the proposed vent shaft location;

- The permeable soils at the base of clay layer is in artesian conditions high discharge submersible pumps needed which may suck fine soil particles along with the water and it can lead to undermining.
- The proposed structure is very close to the river, it was very difficult to lower the water levels to the required levels as suggested in the design.
- Proposed deep dewatering system leads to increase in effective stresses due to lowering of water level. This increase in effective stresses leads to more ground settlements and create an unsafe condition for nearby existing infrastructure.
- Disposal of water collected from dewatering system is involves a lot of protocols which may difficult in sometimes.

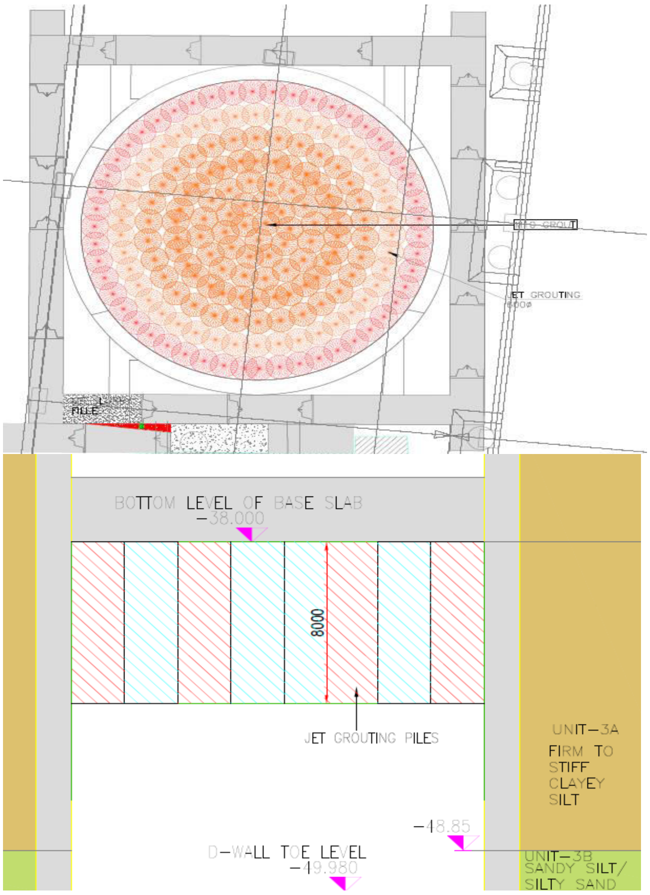

Fig.3: Proposed Layout section for Jet Grouted Columns at Vent Shaft

The target shear strength of treated zone achieved considered as 1 MPa which is reasonably achievable, and the targeted permeability of soil is around 1×10^{-7} m/s. The resulted outcome of the quantities for the said treatment is as follows;

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- Diameter of Jet Grouted Column: 600 mm to 800 mm
- Length of Jet Grouted Column in Clay Layer: 8.00 m (from RL. -38.00 m to RL. -46.00 m)
- Number of Jet Grouted Columns: 318 Nos

4. Estimation of hydraulic heave by Analytical Method

The hydraulic heave due to water pressure for the deep excavation carried out using geotechnical engineering principles [1] as such as considering weight of soil as well as the shear strength of Soil. The schematic view of the present condition shown below Figure 4;

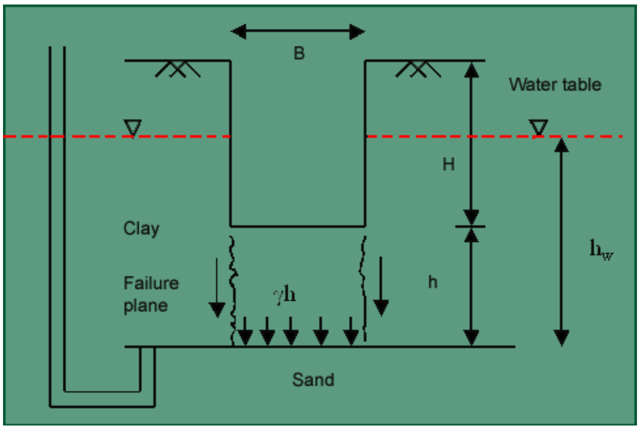

Fig. 4: Schematic View of Deep Excavation (Cross Section)

Hence alternative proposal of ground improvement of soil by jet grouting methods considered. As the base slab, bottom level proposed at RL. -38.00 m, jet grouted columns of 600 mm – 800 mm diameter proposed from RL. -38.00 m to RL. -46.00 m to improve the shear strength of soil which further helps in resistance against hydraulic heave due to uplift pressure.

The factor of safety against hydraulic heave / Clay Bursting, FS =$[\gamma_s.h+2\alpha c_u(h/B)/\gamma_w.h_w]$
Where,
γ_s = Saturated Unit weight of the Clay layer of Below Excavation Level
h = Thickness of Clay Layer below Excavation Level
α = Adhesion Factor
c_u = Undrained Cohesion of Clay Layer of Below Excavation Level
B = Width of the Excavation
γ_w = Unit Weight of Water
h_w = Height of Water table on the outside of the excavation

The ground water level is monitored and recorded by installing 4 (four) numbers of standpipe piezometers. These standpipe Piezometers were penetrated up to RL – 50.0 m. Results of the ground water level recorded data presented in table 3 and figure 5.

Table 3: Water Level Monitoring Data at various Standpipe Piezometers

Date	Water Level in msl (m)			
	Standpipe (L-01)	Standpipe (L-02)	Standpipe (L-03)	Standpipe (L-04)
10-04-2019	-10.40	-13.89	-14.44	-14.35
11-04-2019	-10.25	-13.88	-14.46	-14.53
12-04-2019	-9.96	-14.26	-14.47	-14.55
13-04-2019	-9.83	-14.40	-14.45	-14.87
14-04-2019	-9.64	-14.28	-14.37	-14.46
15-04-2019	-9.57	-14.25	-14.36	-14.25
16-04-2019	-9.57	-14.20	-14.39	-14.07
17-04-2019	-9.54	-14.09	-14.38	-14.48
18-04-2019	-9.47	-14.14	-14.41	-14.70
19-04-2019	-9.44	-14.36	-14.58	-14.24
20-04-2019	-9.39	-14.37	-14.59	-14.40
23-04-2019	-9.35	-14.41	-14.56	-14.22
24-04-2019	-9.34	-14.49	-14.59	-14.78
25-04-2019	-9.35	-14.49	-14.56	-14.22

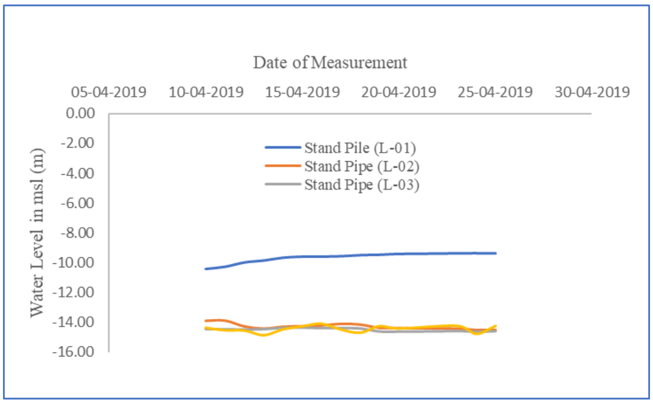

Fig. 5: Ground Water Table Variation

Based on the monitoring data, it was observed that the ground water table varying between RL -14.00 m to RL. -15.00 m. Hence the ground water table considered at RL. -14.00 m for the analysis presented here. In this case the design parameters are as follows;
γ_s = Saturated Unit weight of the Clay layer of Below Excavation Level = 20kN/m^3
h = Thickness of Clay Layer below Excavation Level = 11.00 m (Excavation Level is RL. -38.00 m and Clay layer bottom level is RL. -49.00 m)
c_u = Undrained Cohesion of Clay Layer of Below Excavation Level = 200 kPa
B = Diameter of Vent Shaft = 10.30 m
γ_w = Unit Weight of Water = 9.81 kN/m^3
h_w = Height of Water head = 35.00 m (RL. -14.00 m)

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Based on above parameters, the factor of safety against hydraulic heave estimated as 1.30 which is acceptable considering the temporary stage construction [4]. The hydraulic heave (upward movement) of the soil at the base slab level due to removal of overburden soil is estimated based on linear elastic continuum approach as:

- Deformation Modulus, E_s, of Clayey Soil in Compression = 100 MPa
- Ratio β, of Deformation Modulus on unloading to that for Loading (since soil is inelastic) = 5-10.
- Deformation Modulus for Unloading, $E_u = \beta.E_s$ = 500 MPa with β = 5.
- Poissons Ratio, υ = 0.20
- Stress released (=Overburden Pressure removed), q = (38+6.15) *20 = 883 kN/m^2
- Width of Excavation, B = 11.30 m
- Shape Factor, I = 1.13
- Deformation/relaxation of soil, $\delta = qB\,(1-\upsilon^2)/E_u.I$ = 21.6 mm

5. Estimation of Hydraulic Heave using Elastic Solutions

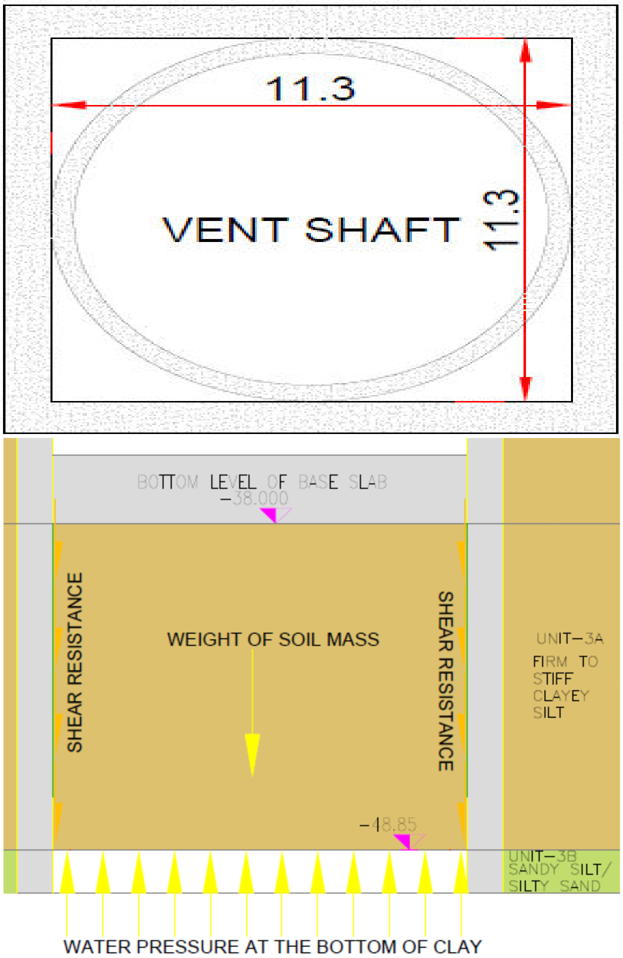

Fig. 6: Plan and Sectional view at bottom of Vent shaft

The assessment for hydraulic heave estimated by analytical method that considering plain strain condition and which is more appropriate for the length of excavations of larger than the width of excavations. As the size of excavation is 11.30 x 11.30 m, estimation of hydraulic heave by considering plain strain condition is too conservative. Hence the hydraulic heave estimated by considering three-dimensional effect [3] and presented here. The plan and section shown in Figure 6 considered in the analysis.

Stability against hydraulic heave estimated as follows;

- Hydrostatic Pressure at the bottom of Clay layer = (49-14) *10 = 350 kN/m^2
- Perimeter, p, of Excavation = 4*11.3 = 45.20 m
- Total Surface Area, S (= p.H) (D Wall & Clay Soil), S = 45.20*11= 497.20 m^2
- Total Uplift Force at the bottom of Clay Layer, P_u = 11.3*11.3*350 = 44691.50 kN
- Total dead weight of clay soil below base slab, P_d = 11.3*11.3*11*20 = 28091.80 kN
- Total Shear Resistance along the D Wall, $P_s = S x \alpha x c_u$ = 497.20*0.5*200 = 49720.00 kN
- Factor of Safety against Failure, FoS = $(P_d + P_s)/P_u$ = 1.74

Thus because of the three-dimensional effect in considering the square shape the Factor of Safety against uplift failure increases from 1.30 (plane strain) to 1.74 (square). The Settlement estimated based on the Nishida (1996) [2] which consists the parameters of total depth of excavation and excavation depth at each stage. The results presented in Table 4.

$$\rho z = \frac{p(1+\upsilon)}{4E(1-\upsilon)}\Big[(3-4\upsilon)\{\sqrt{a2+(z-c)2}-(z-c)\}\big)+(5-12\upsilon+8\upsilon2)\{\sqrt{a2+(z+c)2}-(z+c)\} + (z-c) - \frac{(z-c)2}{\sqrt{a2+(z-c)2}} + \frac{(3-4\upsilon)(z+c)2-2cz}{z+c} + \frac{2cz\,(z+c)2}{(\sqrt{a2+(z+c)2})3} + \frac{2cz}{z+c} + \frac{(3-4\upsilon)(z+c)-2cz}{\sqrt{a2+(z+c)2}}$$

Table 4: Hydraulic Heave at each stage of excavation

S.No	Excavation Level, RL	Vertical Displacement, δz in mm	Cumulative Displacement, mm
1	6.15		
2	1.15	2.79	2.79
3	-3.85	2.88	5.67
4	-8.85	3.01	8.68
5	-13.85	3.23	11.92
6	-18.85	3.60	15.52
7	-23.85	4.25	19.77
8	-28.85	5.46	25.23
9	-33.85	7.86	33.09
10	-38	9.16	42.25

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6. Estimation of Hydraulic Heave by Finite Element Analysis

Since it is a deep excavation, finite element analysis is carried by using Plaxis 2D software [5] considering elastic-plastic behavior of soil and with Mohr-Coulomb failure criterion. Excavation and construction for each lift of 1.50 m is considered for each stage of construction with the lining modeled as strut. Soil layers created as per the Table 1 and physical and engineering parameters considered as per Table 2. Hydraulic heave measured at each stage of excavation and graphical representations of initial condition shown in Figure 7 and Final Stage of excavation shown in Figure 8.

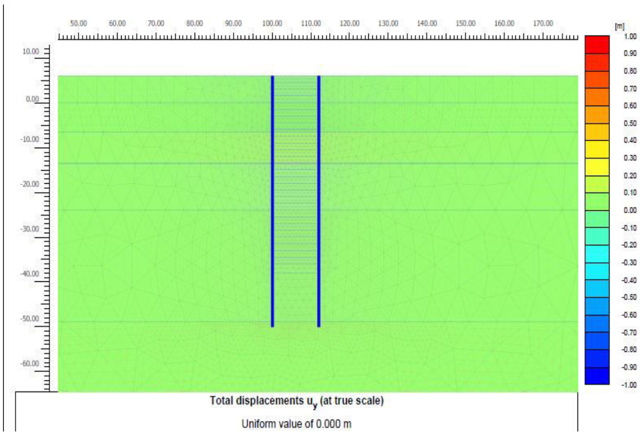

Fig. 7: Hydraulic Heave at Initial Condition

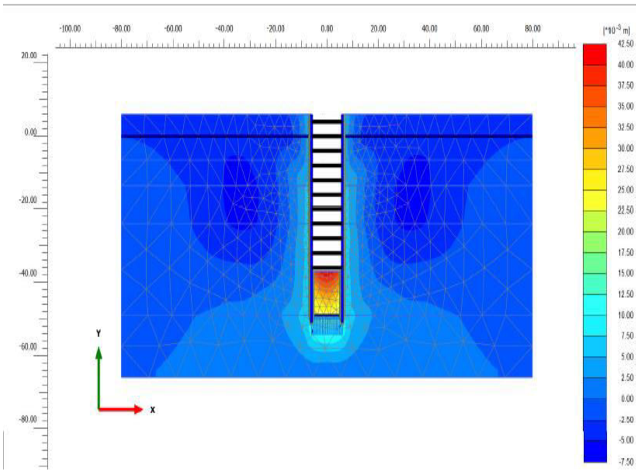

Fig. 8: Hydraulic Heave at the end of excavation

Total heave at the end of excavation could be of the order of 42.50 mm. However, since excavation is carried out gradually, heave would get mobilized gradually and increase with depth excavation. The final heave that is likely to occur over the last phase of excavation would be very small. The hydraulic leave at each stage of excavation is estimated and the results shown in figure 9.

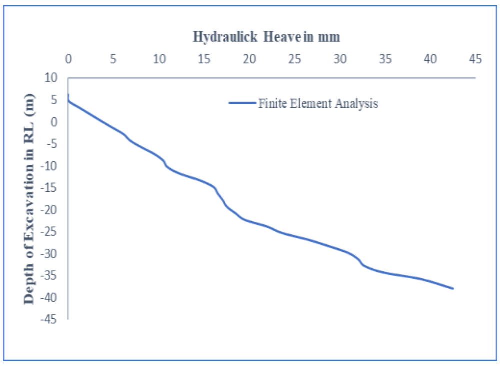

Fig. 9: Variation of Hydraulic Heave with respect to depth of excavation

From the finite element analysis, the factor of safety against hydraulic heave estimated as 1.568. The results of assessment of hydraulic heave by analytical method, elastic solution and finite element method indicate that the factor of safety against hydraulic leave is more than 1.30 and hence no ground improvement required against hydraulic heave failure.

7. Project Cost and Time Savings

Cost analysis and savings in time are estimated when compared with the proposal of jet grouted columns and presented below;

- Number of jet grouted columns required inside of the vent shaft: 318 Nos
- Length of Boring required: 15582 m
- Total length of jet grouted columns required for ground improvement: 3180 m
- Total cost for the construction of jet grouted columns: 1.41 Crores
- Total time required for construction of jet grouted columns: 90 Days (4 Nos per day)
- Total time required for construction of jet grouted columns:160 Days (2 Nos per day)

From the above assessment, it may conclude that total cost savings is around 1.41 crores and approximate time savings will be around 90 days to 160 days.

8. Conclusion

Estimation of hydraulic heave considering appropriate methods helps in avoid of complex mitigation measures and saves cost and time for project. Careful attention shall be given when the deep excavations carry in layered soils. The estimation of factor of safety against hydraulic heave carried out for a deep excavation of around 44 m considering analytical, elastic solutions and finite element methods. The factor of safety against hydraulic heave estimated by analytical method, elastic solutions and finite

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element methods are 1.30, 1.74, and 1.568 respectively. The total hydraulic heave estimated considering elastic solutions and finite element methods are 42.25 mm and 42.50 mm respectively. The variation of hydraulic heave by elastic solutions and finite element method are presented in figure 10.

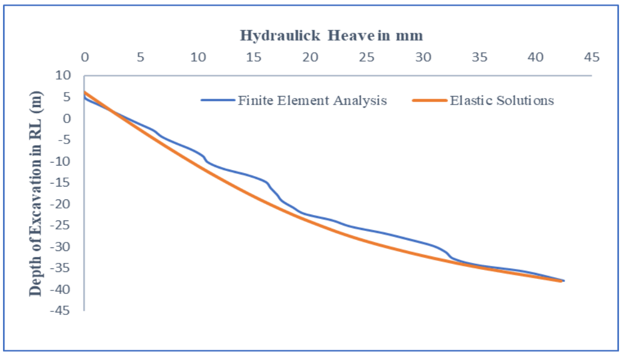

Fig.10: Variation of Hydraulic Heave with respect to depth of excavation

Estimation of hydraulic heave by both elastic solutions and finite element analysis shows similar variation and compatible each. The analysis carried out with different methods such as analytical methods, elastic solutions and finite element methods results no ground improvement required and available thickness of clay below the excavation level is enough to resists the generated hydraulic heave during excavation.

Total time savings estimated as 90 to 160 days depending on the number of jet grouted columns installation per day and approximate cost saving is around 1.41 crores.

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