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Analysis and Design of Pile Foundation for Viaduct

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***Abstract*: An efficient computational approach based on substructure methodology is proposed to analyze the viaduct–pile. The train–viaduct subsystem is solved using the dynamic stiffness integration method, and its accuracy is foundation–soil dynamic interaction under train loads. Verified by the existing analytical solution for a moving vehicle on a simply supported beam. For the pile foundation–soil sub system the geometric and material properties of piles and soils are assumed to be invariable along the azimuth direction. By introducing the equivalent stiffness of grouped piles, the governing equations of pile foundation–soil interaction are simplified based on Fourier decomposition method, so the three-dimensional problem is decomposed in to several two-dimensional axisymmetric finite element models. The pile foundation–soil interaction is verified by field measurements due to shaker loading at pile foundation top. In addition, these two substructures are coupled with the displacement compatibility condition at interface of pier bottom and pile foundation top. Finally, the proposed train–viaduct–pile foundation–soil interaction model was validated by field tests. The results show that the proposed model can predict vibrations of pile foundation and soil accurately, thereby providing a basis for the prediction of pile–soil foundation settlement.**

***Keywords*: Pile, soil structure, hardening soil, pile loading, STAAD analysis, metro tunnel, bridge pile, deformation of pile foundation, numerical calculation.**

1. Introduction

A pile foundation is an underground structure, which is excavated by different type of boring machine through the surrounding of soil/earth/rock. It is used where the bearing capacity of soil is low and heavy load structure like metro, fly-over , In today's world due to rapid urbanization in major cities, people from different places and background are getting attracted towards them, for job opportunities and better living standards and basic facilities which are not available in villages, this migration of people from small towns/villages to major cities making the cities over-crowded and due to which the vehicular movement also increasing, widening of roads has a limitation since the land is limited, hence traffic jams are occurring every days. So, utilization of underground space has become an important aspect and as a solution and it is becoming popular. Pile construction is one of the important and large infrastructure projects (like Underground Metro systems, cross passages, subways etc.), which are important for the development in the transportation networks, in major cities like Mumbai, Delhi Surat Metro, Patna metro Chennai and Bangalore etc. the structures, monitoring of deformation is very important aspect in the urban area tunnel construction process. Final lining is the concrete structure which comes in contact with the surrounding soil/rock and holds the different loads from surrounding. Finally, pile is designed for various forces, dead load, earth pressure, water pressure, surcharge loads, earthquake load, train and other services load, air pressure. Pile-supported viaducts are widely used in high-speed railways across soft soil deposited areas or densely populated urban areas. In China, viaducts are used in more than 70% of newly built high-speed railways. When trains pass through urban areas. The ground vibrations induced by trains running over viaducts transmit to the surrounding buildings due to the interaction between the soil and the structure, leading to serious noise interference and surrounding ground settlement, which brings detrimental effects to people's work and lives. There are many studies on the environmental noise problem; pile-supported viaducts are widely used in high-speed railways across soft soil deposited areas or densely populated urban areas.

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There are many studies on the environmental noise problem the environmental noise generated by trains passing through viaducts and discussed noise reduction measures. However, less attention was paid to the prediction and evaluation of settlement caused by ground vibrations due to trains running on viaducts. To this end, it is necessary to build a train–viaduct–pile foundation–soil interaction model to predict effectively the vibrations of pile foundation and soil.

2. 2D FEM Analysis by STAAD Pro

A two-dimensional Plane Frame Analyses is performed using the computer program from STAAD Pro. V8i. A near

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realistic 2Dmodel using beams bedded by radial springs are created and loads applied using STAAD command. Springs have been generated by using Staad command and reference are made to STAAD manual for further details. The bedding is modeled in such a way that the parts of the cross-sections where inward deformation occurs, i.e., where the springs would be subject to fixed at bottom. The material behavior of ground is generally assumed as being elastic. All forces are applied on the frame model in STAAD Pro and load combination are used for Ultimate Limit State (ULS) & Serviceability Limit State (SLS), and the Members are checked for the load combination for Ultimate Limit State (ULS) & Serviceability Limit State (SLS). The Normal force, bending moment and shear force for all members are taken from theStaad Pro and designed.

Calculation of Spring Constants for soil:

The modeled as a beam bedded by springs. Multiple beam elements are created along centroidal axis of lining subtending angle of 50 to 100 representing linear 2D structure Beam model spring constants are derived from modulus of sub grade reaction Ks, which is calculated from: The Stiffness of Linear Elastic (Vertical) Springs for the Soils adjacent to Piles If you have a sub subsection, then copy and paste the sub subsection heading and modify the heading.

For Sand $$K_{tan} = D \times K_o \times \gamma \times X \times \tan\phi'$$

For Clay $$K_{tan} = D \times (1 - \sin\phi') \times \gamma \times X \times \tan\phi'$$

Where, D: Pile diameter; K_0: Coefficient of earth pressure at rest

γ: Unit weigth of soil; X: Depth below soil surface

ϕ': Internal friction angle

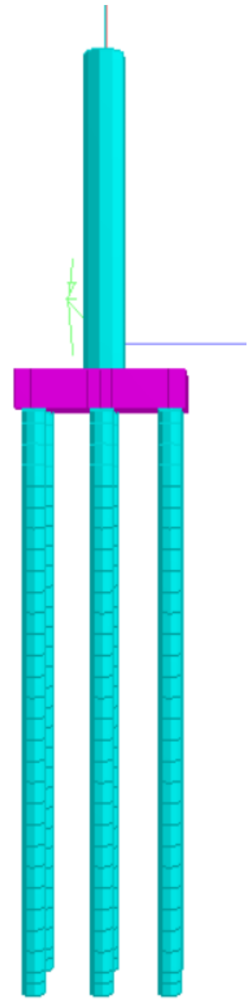

Fig. 2. 3D rendered view of model

Output diagram of STAAD file:

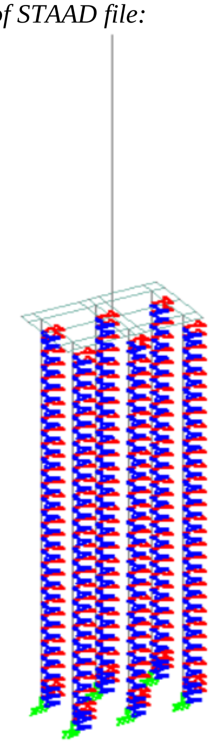

Fig. 1. Idealized model with spring supports

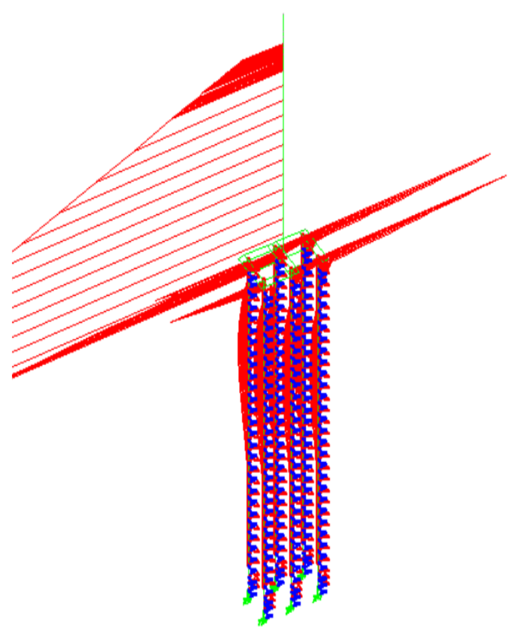

Fig. 3. Bending moment of pile

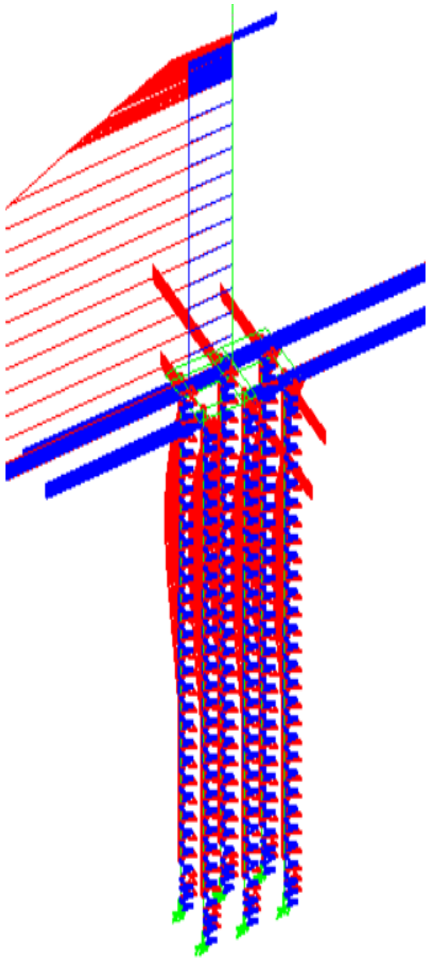

Fig. 4. Shear force of pile

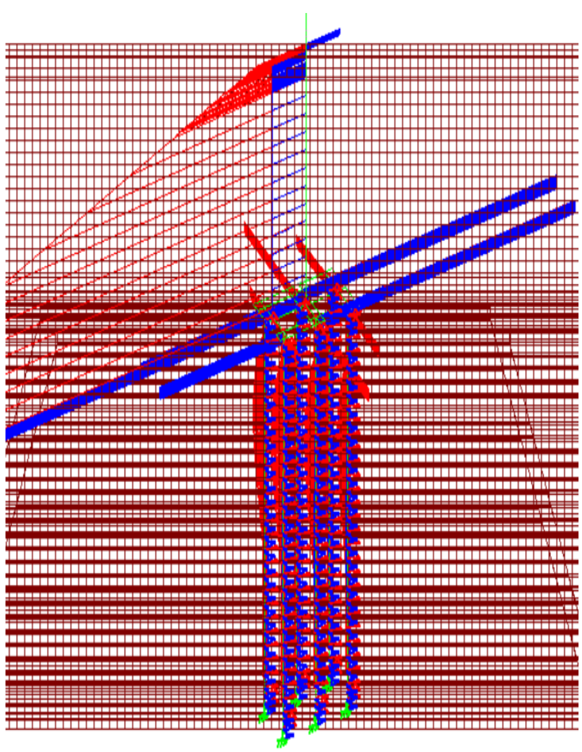

Fig. 5. Axial force of pile

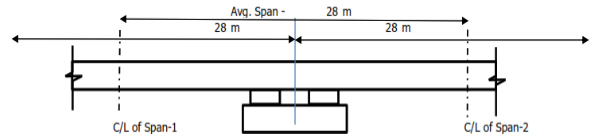

Fig. 6. Super structure elevation

3. 2D FEM Analysis by STAAD

Following assumptions are considered in while performing 2D analysis in RS2:

1. Plain strain condition is assumed; the geotechnical properties are considered assuming homogeneous, isotropic behavior of each layer.
2. The ground layers are modelled with the given properties, and the analyses are performed for drained condition.
3. Water table is assumed at surface.
4. Mohr-Coulomb failure criteria is considered; peak and residual value of shear strength parameters is defined.
5. External boundaries of model are assumed considering the size of tunnel, its cover from the surface and distance between two tubes, and theoretical influence zone. Boundary conditions are modelled as free top boundary (representing ground surface), fully fixed at bottom and vertical roller at the sides.
6. The segmental liner is simulated using structural monolithic elastic beam elements in 2-dimensional plane strain; main parameters defined are modulus of elasticity and moment of inertia. Effective moment of inertia is considered to take effect of joints in the precast segmental using Muir Wood's equation.

RS2 software used to simulate various ground layers and their lateral earth pressure coefficient, modeling the effect of twin tunnels and space between them and also the seismic condition or ordinary design and maximum design case.

Based on the understanding of ground conditions two cases are analyzed:

1. General Case – Having low soil cover and Basalt/Breccia of grade II at the tunnel level.
2. Worst case – Thick soil cover and grade III Tuff around the at the tunnel level.

Surface loading (Surcharge)

General case = 50kN/m^2

Worst case = 120kN/m^2

4. Geotechnical Design Methods

$R_t = R_s + W_p$

Where: $Q = R_c$ = the ultimate compression resistance of the pile.

$Q_b = R_b$ = base resistance

$Q_s = R_s$ = shaft resistance

W_p = weight of the pile

R_t = tensile resistance of pile

In terms of soil mechanics theory, the ultimate skin friction on the pile shaft is related to the horizontal effective stress acting on the shaft and the effective remoulded angle of friction between the pile and the clay and the ultimate shaft resistance

R_s can be evaluated by integration of the pile-soil shear strength t_a over the surface area of the shaft:

$t_a = C_a + s\,n \cdot \tan\upsilon\ a$

Where: $s\,n = Ks \cdot s\,v$ (refer geotechnical notes)

$\therefore t_a = C_a + KS \cdot s\,v \cdot \tan\upsilon\ a$

5. Pile Spacing and Pile Arrangement

In certain types of soil, especially in sensitive clays, the capacity of individual piles within a closely spaced group may be lower than for equivalent isolated pile.

However, because of its insignificant effect, this may be ignored in design. Instead, the main worry has been that the block capacity of the group may be less than the sum of the individual pile's capacities. As a thumb rule, if spacing is more than 2 - 3 pile diameter, then block failure is most unlikely.

It is vital importance that pile group in friction and cohesive soil arranged that even distribution of load in greater area is achieved. Large concentration of piles under the centre of the pile cap should be avoided. This could lead to load concentration resulting in local settlement and failure the pile cap. Varying length of piles in the same pile group may have similar effect. For pile load up to 300kN, the minimum distance to the pile cap should be 100mm for load higher than 300kN, this distance should be more than 150 mm.

In general, the following formula may be used in pile spacing

End-bearing and friction piles: $S = 2.5 \cdot (d) + 0.02.\ L$

Cohesion piles: $S = 3.5 \cdot (d) + 0.02 \cdot L$

where:

d = assumed pile diameter

L = assumed pile length

S = pile centre to centre distance (spacing)

There are following four cases are critical.

Table 1

LOAD CASE	Rb	Rc	V. LOAD (t)	LONG. MOMENT (t-m)	TRANS. MOMENT DUE TO (t-m)			
					Load Due to Vertical LL reactions (V*tcc/2)	Due to Curvature Eccentricity ($P^*e_{curvature}$)	Ecc. Betw. C/L Align. & C/L Pier (P^*e_{trans})	Total
LOAD CASE 1 : Both Span Both Tracks	125.1	50.9	176.0	52.0	0.0	0	0.0	0
LOAD CASE 2 : ONE SPAN, BOTH TRACK LOADED	104.7	0.0	104.7	73.30	0.0	0	0.0	0
LOAD CASE 3 : BOTH SPAN, ONE TRACK LOADED	62.6	25.4	88.0	26.0	221.3	0.1	0.0	221.4
LOAD CASE 4 : One SPAN, ONE TRACK LOADED	52.4	0.0	52.4	36.7	131.7	0.0	0.0	131.7

LOAD CASE	HORIZ. LOAD, H_L (t)	FORCE @ R.L (m) (i.e. Brg Level)
LOAD CASE 1 : MAXIMUM REACTION CASE :	35.5	65.878
LOAD CASE 2 : MAXIMUM LONG. MOMENT CASE :	19.4	65.878
LOAD CASE 3 : MAX. TRANSVERSE MOMENT CASE :	18.7	65.878
LOAD CASE 4 : ONE SPAN ONE TRACK	10.2	65.878

Table 2

Summary of results

Pile	Unit	Tender bore hole		NCC bore hole	
		Normal	Seismic	Normal	Seismic
Vertical Pile Load	t	271	368.60	271.00	369.00
Vertical Pile Capacity	t	310	399.33	378	485.00
Horizontal Pile Load	t	7.410		7.60	
Horizontal Pile Capacity	t	34		39	
Provided Reinf.	%	0.44		0.44	
Crack width value	mm	0.0000		0.000	
Stress in Reinf.	MPa	232.00		230.70	
Stress in Concrete	MPa	6.81		6.73	
M/Mu		0.68		0.68	
Allowable Interaction Ratio	1.00				

6. Conclusion

The method of FEM analysis (STAAD Pro) are used to study the behaviour of soil/rock mass surrounding the pile. The FEM method made the study of soil/rock masses behaviour much easier and simplified the design of segment for the bored tunnel. Different forces are applied in the model and with the help of possible load combinations the segment is designed for normal and worse load cases. The study of surrounding soil/rock masses the settlement and deformation in the existing adjacent building or any other structure can be anticipated in well advance and which will help the designer to provide additional supports at that particular location to avoid excess settlement.

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