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Analytical Study of High Speed Rail Bridge and Pile Foundation Subjected to Soil Structure Interaction Using Finite Element Software

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Abstract: High Speed Rail (HSR) was introduced in India in response to rising transport demand and reduced journey times. Pile foundation-supported piers are often used for elevated high-speed railways. The box-girder bridge and pile foundation embedded in multilayered soil have been analyzed for various critical conditions, viz. static condition, sudden brake conditions, derailment of train, and moving condition of train. In this type of complex problem, a theoretical approach to analyzing the pile foundation was insufficient. Thus, the Finite Element Method (FEM) based software, STAAD Pro. and PLAXIS 2D has been used. The main objective of this paper is to analyze the pile foundation under different conditions. Live loads on bridges are considered in Eurocode-1: Part 2. To perform the dynamic analysis, a 16 Hz frequency has been considered at a maximum 360 km/hr train speed. The results show that the moving condition and vibration effect increase the nodal displacement and in the case of derailment and sudden brake conditions, lateral load and moment have been increased, which changes the behavior of the pile foundation. According to IS 1343 code, a structure is safe as nodal displacement is within allowed limits in all cases. The combined effect of moving trains and vibrations increases nodal displacement by 10% when compared to the static condition. Hence, dynamic analysis is required. The lateral deflection of the pile increases in the case of sudden brake and derailment cases.

Keywords: High Speed Rail, STAAD Pro, PLAXIS 2D, Finite Element Method, Pile foundation

1. Introduction

1.1. Background

Over the last years, speeds of trains have been increasing significantly with increase in the travel demand, which bringing up new challenges in bridge and foundation conception. The current Ahmedabad-Mumbai high speed train passes through suburban and rural area, where the structure mainly comprises elevated high speed trains. The bridges and foundations are subjected to heavy impacts under high-speed loads. The Indian bullet train will run at a speed of 300 km/h, covering a distance of 509 km from Mumbai to Ahmedabad in approximately 2 hours. Substructures of high-speed rail (HSR) are typically rigid because they must satisfy strict longitudinal displacement limitations stated in most HSR design standards.

This paper presents the effect of sudden braking, derailment of train and a moving train on bridge and foundation. For this purpose, bridge has been modeled and analyze in STAAD Pro. software and pile foundation has been modeled and analyze in PLAXIS 2D. Bridge super structure, box girder is modelled by using plate element and pier and pier cap are modelled using beam element. The rail section is considered as per IRS specification and modelled as beam element. Piles are modelled as embedded beam raw element and pile cap is modelled as plate element below the ground level. The longitudinal displacement and vertical displacement observed at different location of bridge.

Geotechnical engineers commonly encounter two types of foundation problems in relations on the analysis and design namely (1) foundations subjected to static loads and (2) foundations subjected to dynamic loads. A static load has the property that the load carried by the foundation at any given time for a given structure is constant in magnitude and direction, e.g. the structure's dead weight. A dynamic load is distinguished by the fact that it changes over time. Machine operation, pile driving, fast moving traffic, and other factors can cause dynamic loads on foundations and engineered structures. Pure dynamic loads do not exist in nature. Loads are usually made up of both static and dynamic loads.

Pugasap K. [1] presented that High-speed rail (HSR) substructures are typically rigid, as they must fulfil strict longitudinal displacement limitations required in most HSR design standards. Numerical models were developed using CSiBridge. Dynamic studies of 36 different numerical models depicting a 20-span bridge supported by substructures with first horizontal frequencies of 0.566–3.706 Hz were used to evaluate the effects of substructure flexibility on relative displacements. Bhure H., et al. [2] investigates the dynamic response of a metro rail over-bridge, subjected to moving loads. The impacts of track irregularity and train inertia are not taken into account. In SAP2000, the superstructure, piers, and substructure of the bridge are modelled with shell elements, rails with frame elements, and the interaction between the bridge deck and the piers is simulated with link supports. The dynamic analysis is carried out using the finite element method, and the equations of motion are solved using the Newmark method. They observed the vertical deformation generated due to live loads are within permissible limit as per UIC guideline. Li., et al. [3] investigated a numerical solution for the dynamic response of a train–track–bridge coupled system, taking into account the influence of soil–structure interaction (SSI). Chen et al. [4] deduced the mapping relationship between pier settlement and rail deformation for different slab ballast-less track systems. Yau et al. [5] and Ju [6] analyzed dynamic responses of trains and bridges due to non-uniform settlement of a single pier. Yang et al. [7] did the investigations with focus on the deformation of railway bridge foundations due to soil consolidation and the dynamic load of trains. He et al. [8] found that the deformation of bridge foundations results in additional track irregularity, thereby affecting the running safety and riding comfort of high-speed trains.

Many different analytical approaches have been developed to deal with the problem of a laterally loaded pile, which can be characterized as computing pile deflection and bending moment as a function of depth below the ground surface. Due to the inability to provide single values to the requisite soil parameters, methods based on the theory of elasticity are not often relevant for design. When designing pile foundations that are subject to lateral loads and moments, requirements must be satisfied: 1) the soil should not be stressed beyond its capability, and 2) deflections should be kept to a minimum. Other literature said that the behavior of a pile subjected to lateral load is determined by the subsoil condition, the pile's sectional properties, the pile's top and bottom boundary conditions, and the structure's stiffness. the lateral load capacity of pile diameters ranging from 0.15 to 2.0 m in layered soil was determined using the finite element method (FEM). Researcher clearly mention that the Brom's method is based primarily on limiting values of soil resistance. Poulos and Davis [10] method is based on the theory of elasticity. These methods are applicable to only uniform layer of soil.

1.2. PLAXIS 2D – FEM Tool

PLAXIS 2D, a specialized tool for solving geotechnical engineering problems, has been used to perform the finite element modelling and analysis.

1.2.1. Soil Models

PLAXIS 2D has inbuilt soil models. The soil domain is generated by giving bore hole data at one or more locations. For the current work, the linearly elastic perfectly plastic, Mohr-Coulomb soil model was used. The Mohr-Coulomb model requires the parameters such as , E, , , C and as per [9].

1.2.2. Structural Element

Apart from soil, the other elements of PLAXIS can be defined using structural elements such as anchors, geo grid, plate, beam, and embedded pile. A beam element with embedded interface elements describes the interaction with the soil at the pile skin and pile base in an embedded pile. The material parameters of the embedded pile distinguish between beam parameters and skin resistance and end bearing parameters. The material property of pile is assigned to the beam element, which is specified as linear elastic.

2. Methodology

2.1. Modelling of Bridge

Table 1. *Cross-sectional properties of the various components of bridge.*

Component	Size (mm)	Depth (mm)
Box-girder		2500
Top width	12000	
Bottom width	6180	
Pier cap	7000 × 2500	3500
Pier	3000 × 4000	8000
Pile cap	9000 × 9000	2500
Pile diameter	1500	30000

The cross section details of simply supported 29.96 m span box girder bridge are shown in figure 1 and figure 2. Finite element modelling of structures (box girder, pier cap, pier) is done in STAAD Pro. Table 1 shows a cross-sectional properties of the various components of bridge. Rail section is modelled as per IRS specification by beam element. A bridge bearing is a bridge component that offers a resting surface between the bridge piers and the bridge deck. A bearing's aim is to allow for controlled movement and hence lessen the stresses involved. An elastomeric bearing was used in this study. The bearings are assigned as spring support and provide stiffness of it. The initial bridge model is same for all four conditions. In this study a total 120 m long span bridge is considered for analysis. A thickness of top slab, web section and bottom slab of box girder is 300 mm, 500mm and 300 mm respectively.

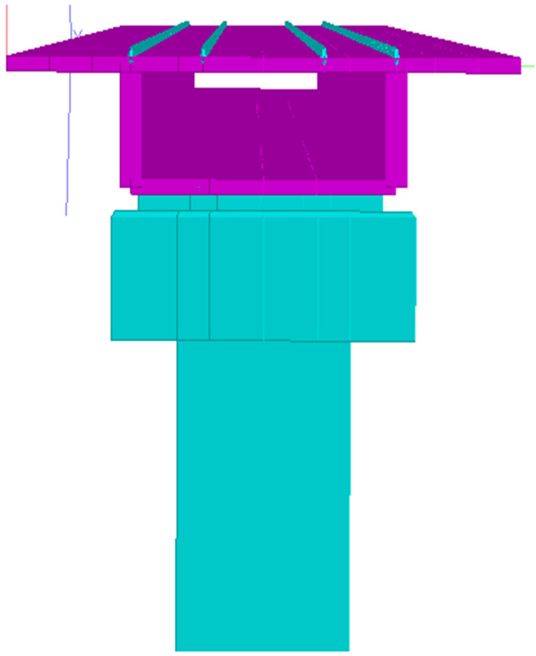


Figure 1. *3D view of Bridge.*

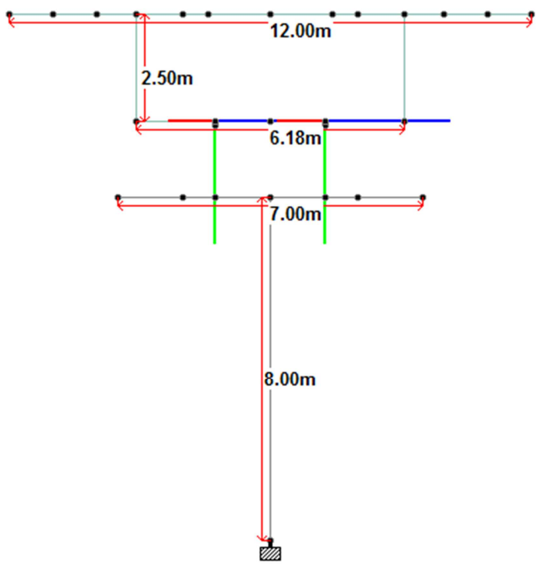
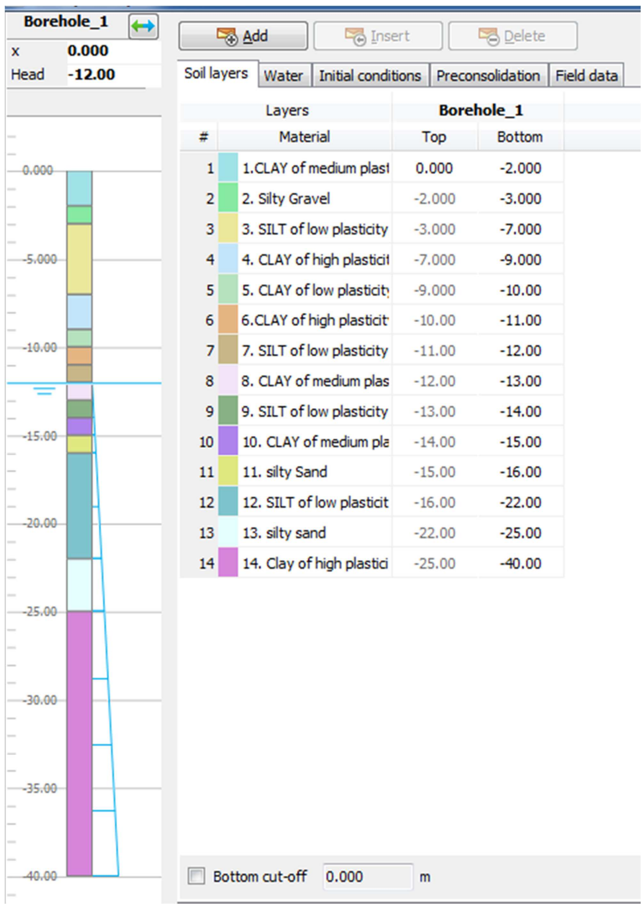


Figure 2. *Section of bridge.*

2.2. Modelling of Pile

Pile is modelled as embedded beam raw element and pile cap is modelled as plate element. Because pile-soil interaction is a strongly 3D process, modelling piles in a 2D finite element model has limits. Pile-soil interaction is challenging to model, and classic approaches that model pile rows as plates or node-to-node anchors have obvious limitations. PLAXIS 2D has an embedded beam row that can be used to simulate a row of piles in the out-of-plane direction. In comparison to other approaches, it is expected to produce a more realistic pile-soil interaction behavior. Plates has significant flexural rigidity and normal stiffness. The required material properties of plate elements are bending stiffness (EI) and axial stiffness (EA). From these two parameter the equivalent plate thickness is automatically calculated. The modulus of subgrade reaction is considered as per IS 2911 part-1 section 2 [13] for every one meter of soil depth. All the properties are assigned as per borelog data and the value of E and   are considered as per [11]. Figure 3 shows a borelog profile input in PLAXIS 2D.

Meshing: The 15-node triangular element or the 6-node triangular element is the most basic sort of element in a mesh. A geometry model made of points, lines, and clusters is essential input for the mesh generator. Meshing model is shown in figure 5.



#	Layers Material	Borehole_1 Top	Bottom
1	1.CLAY of medium plast	0.000	-2.000
2	2. Silty Gravel	-2.000	-3.000
3	3. SILT of low plasticity	-3.000	-7.000
4	4. CLAY of high plasticit	-7.000	-9.000
5	5. CLAY of low plasticity	-9.000	-10.00
6	6.CLAY of high plasticit	-10.00	-11.00
7	7. SILT of low plasticity	-11.00	-12.00
8	8. CLAY of medium plas	-12.00	-13.00
9	9. SILT of low plasticity	-13.00	-14.00
10	10. CLAY of medium pla	-14.00	-15.00
11	11. silty Sand	-15.00	-16.00
12	12. SILT of low plasticit	-16.00	-22.00
13	13. silty sand	-22.00	-25.00
14	14. Clay of high plastici	-25.00	-40.00

Figure 3. *Borelog data in PLAXIS 2D.*

3. Load Characteristic

The live load is considered as per Eurocode-1: Actions on structures – part 2: Traffic loads on bridge. The total number of cars in train is 6 with the length of each car as 25 m. Each car consists of four axles and load of each axle is 250 kN. The distance between two axles is 2.5 m. The moving load is directly applied in STAAD by using vehicle definition which changes the location of point of load.

Braking force and derailment loads are considered as per Eurocode-1: Actions on structures – part 2: Traffic loads on bridge. Wind load is considered as per Eurocode-1: Actions on structures - Part 1-4: General actions - Wind actions. The total wind load 0.9 kN/m^2 is applied in Z direction. Code of practice for plain, reinforced & prestressed concrete for general bridge construction" [12] (Concrete bridge code) is followed to apply all possible load combinations as shown in table 2.

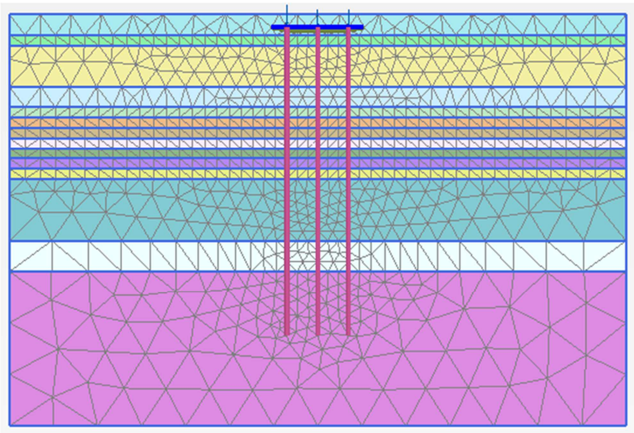


Figure 4. *Meshing.*

Table 2. *Load combinations as per IRS.*

Load Combinations
1 DL + 1.2 LL
1 DL + 1.2 LL +1 WL
1 DL + 1.2 LL + 1 EQX
1 DL + 1.2 LL + 1 EQZ

4. Dynamic Analysis

Due to the train passing at a very high speed, it creates additional vibration and displacement in the structure. Thus, additional dynamic analysis of the bridge structure is required. In this study, the maximum speed of a train is considered to be 360 km/hr. The total length of the train is 150 m. So, the time taken to pass the whole train from one particular point is 1.5 sec. So, the frequency of train at speed 360 km/hr is 16 Hz. Which mean, 16 load points were passed from a one particular rail point (node). To complete a 1 cycle of wave, 0.0625 seconds required i.e., time required for passing one train wheel from a particular point is 0.0625 seconds. Harmonic wave is applied to perform the dynamic analysis and amplitude of wave 125 kN is considered.

5. Load Conversion

After the analyses have been done in STAAD, the support reactions are applied to the pile cap in PLAXIS 2D. But we are unable to apply that same load and moment as we modelled the pile in the two-dimensional software. In actual conditions, all that load acts at the center of the pile cap, which transfers the load to all the piles.

Total vertical load on single pile, Q = Total load at bottom of pier, (Q_y) / No. of piles.

$$\text{Load due to moment, } Q_m = \pm \frac{M_x \times x}{\Sigma x^2} \pm \frac{M_y \times y}{\Sigma y^2} \quad (1)$$

$$\text{Total load acting on single pile} = Q \pm Q_m \quad (2)$$

The additional horizontal load is acted on the pile due to the shear force generated because of the moment in the Y direction. After find out all the possible combinations of loads on section of pile foundation. Only, a critical section is analyzed and verify the results with IRC 78 [14] and Indian Railway Standard specification code for lateral deflection of pile and vertical settlement of pile.

6. Results and Discussion

This section summarises and discusses the results obtained from numerical modelling for all four different cases. A nodal vertical and longitudinal displacement at top of girder, bottom of girder, at pier cap and bottom of girder were outputted from each cases. Support reactions and moment in central pier was considered for further analysis of pile foundation. The permissible limit for displacement as per IS 1343 is equal to minimum of span/350 or 20 mm (= Min. (85.7 or 20 mm)) and maximum longitudinal displacement as per Eurocode-1 part 2 is 5 mm (in the direction of moving train).

As per HSR design standard require that longitudinal displacements between two successive decks be controlled because too much displacements can lead to structural damage. It was observed that the maximum longitudinal and vertical displacement in derailment case. The vertical nodal displacement is reduced as load transfer from top to bottom. Thus, maximum displacement observed at top of girder.

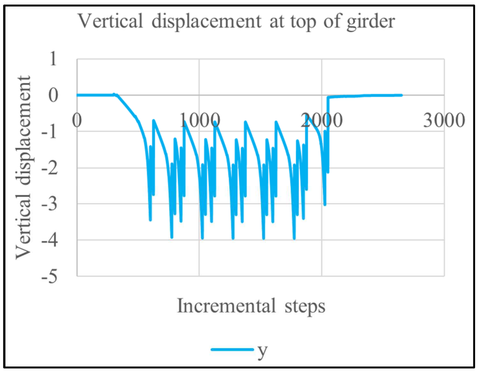


Figure 5. *Maximum displacement at top of girder subjected to moving train.*

Table 3. *Summary of all cases.*

Case	Vertical Displacement (mm)	Vertical load (kN)	Lateral load (kN)
Static	10.2	9275.6	334
Moving	12	9275.6	341
Sudden brake	10.3	9286	591.1
Derailment	10.5	9941	586.7

In the case of moving train condition which produce 16 Hz frequency vibrations, it was observed that the displacement was increased compared to static condition. Figure 5 shows a displacement corresponding to the moving train at top of girder. The natural frequency of structure was found and the results was satisfied the criteria given in Eurocode-1 part-2. Thus, the further dynamic factor was not required in design criteria. Table 3 shows a summary of results for all cases.

All the Moment acting on pile foundation was converted in to equivalent load. The lateral deflection was observed for pile foundation for all four cases. The maximum permissible limit for lateral deflection as per IRC 78 is one percentage diameter of the pile. A maximum displacement has been observed for static, moving rail condition, sudden brake condition and derailment of train was 2.48 mm, 2.52 mm, 6.52 mm and 10.1 mm respectively. Thus the maximum deflection was observed in derailment case. Figure 6 shows a deflection profile of pile which observed in PLAXIS 2D.

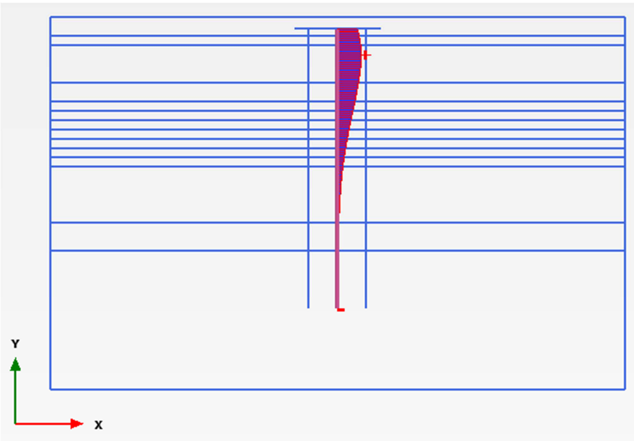


Figure 6. *Deflection of pile.*

7. Conclusion

Due to the availability of various modelling and computational techniques, an attempt should be done to model a given complex structure very close to a real structure. The influences of four different cases on HSR bridge and foundation were investigated through STAAD Pro. and PLAXIS 2D. The longitudinal displacement and vertical displacement were investigated at different location of bridge. The lateral deflection of pile foundation was carried out from PLAXIS 2D. The results of this study revealed that derailment of train is not only a significant problem for superstructure but also substructure (pile foundation) in the sudden brake condition and derailment conditions. It is required to considered the dynamic effect (moving condition of train) as displacement results observed more.

Nodal displacement is within allowed limits in all cases, according to IS 1343 code. As a result, the structure is safe. When a train is moving, the displacement of one particular spot increases and then decreases as train's wheel passes by it. According to the study, the lateral reaction at the bottom of the pier increases in the case of breaking and derailment. Which also affects pile foundation behavior. Due to vibration effects of moving train, displacement of node is increased by 10 percentages compare to static condition. Hence, dynamic analysis with respect to moving condition is required. High-speed rail (HSR) substructures are typically rigid, as they must fulfil strict longitudinal displacement limitations required in most High speed rail design standards.

The pile foundation was successfully designed in multi layered soil under simultaneous lateral, axial and moment loads using FEM based software. For the homogeneous soil layer, all theoretical methods are more accurate. Deflection, pile capacity, bending moment, and other parameters are difficult to determine in combinations of multilayer soil, with N number of piles/pile group using these theoretical approaches. Therefore, to discover a solution for a complex problem, we use finite element method based software, which allows us to incorporate all the complexity in one model.

The effect of modulus of subgrade reaction (Soil Structure Interaction) reduce the deflection of pile which reduce the required diameter of pile compare to conventional study. In all cases, the lateral displacement of the pile is within allowable limit, i.e., less than 1% of the pile diameter (=15 mm). The lateral displacement of the pile increases when sudden brakes is applied and the train derails (collision condition). The vertical settlement of pile group foundation has within permissible limit (<25mm) as per Indian Railway Standard specification

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