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Dynamic Analysis of Pile Foundation of a Railway Bridge: A Review

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***Abstract*— In this paper, therefore, there is a dynamic analysis of pile foundations of the railway bridges. We examine the efforts of the existing literature on Soil Structure Interaction (SSI), and point out the direction of the field of research out of the old assumptions of fixed-base to the dynamic models of BDWF and FEM. We too criticize such approach in use, particularly the functions of impedance used by Novak, to discover where the gaps are in the design of high-speed rail foundations.**

***Index Terms*— Soil-Structure Interaction (SSI); Dynamic Analysis; Pile Foundations; Railway bridges; High-Speed Rail (HSR); Impedance Functions; Kinematic and Inertial Interaction; Liquefaction and Scour.**

I. INTRODUCTION

A. The Necessity of Soil-Structure Interaction (SSI)

In fact, the existing design guidelines, such as the IRS Bridge Rules [1] and RDSO Guidelines for Seismic Design of Railway Bridges [2] BIS. (2016). IS 1893 (Part 1) [3] and the IRC:78[50], IS 2911[4] and Eurocode 8[5] are based on pseudo-static approaches and involve a Coefficient of Dynamic Augment (CDA). Although that appears to be fine with rigid foundations [6],[7], such techniques completely fail with flexible pile foundations since they do not take into consideration inertial effects. With you fast loading, say a train at 300km/h, the system of piles-soil actually strikes upon dynamic resonances, telling you that the old-fashioned assumptions you are used to are merely obsolete [8],[9],[10],[11].

II. NEED FOR DYNAMIC ANALYSIS OF RAILWAY PILE FOUNDATIONS

A. Constraints of Fixed Design Approaches

Current design standards, such as the IRS Bridge Rules and IRC:78, rely on pseudo-static methods that use a Coefficient of Dynamic Augment (CDA) to account for live loads [1],[3]. While this works fine for short-span girders on rigid bases, it completely breaks down for flexible pile foundations [12],[13],[14]. Static methods assume loads are applied slowly enough to safely ignore inertia [15], [16].

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In reality, a train passing at 300 km/h creates a rapid loading rate that directly triggers the natural dynamic frequencies of the pile-soil system, making these older approaches invalid [17],[18],[19][20].

B. The Integrated Train-Track-Bridge-Soil System

Through civil engineering studies, it is important that analysis of a railway bridge is done as a complex of a complete train railway-track bridge-soil [17],[11],[21],[22]. In the lecture, it was stated that older traditional uncoupled models tend to underestimate the dislocation of the pile on the basis of not taking into account the continuous interaction of forces of these subsystems.[23]. We further discussed the fact that Indian soil characteristics in the region bring about certain geotechnical problems which provide the need of fully coupled dynamic evaluation in the proper foundation design [24],[25].

III. Soil–Structure Interaction Mechanisms

A. Kinematic Interaction

Kinematic interaction, therefore, occurs when a rigid base alters the movement of the ground during an earthquake, where the piles bend themselves and not based on the weight of the superstructure [26],[27],[28]. We must be able to capture such behavior of bending with special consideration of the fact that the stiffness is different in the layered soils [29],[30][31].

B. Inertial Interaction

Inertial interaction is influenced by the mass of the superstructure. As the bridge vibrates, it produces inertial forces F=ma that are transferred to the foundation, leading to translation and rotation of the pile cap [32],[33]. this adaptability extends the natural period of the bridge, often resulting in increased spectral displacements within displacement-based design frameworks.[34],[6]

C. Effects of Pile Groups

Piles in railway bridges are seldom independent. The behavior of a pile group is distinct from that of an individual pile because of Pile-Soil-Pile Interaction (PSPI)[35], [27], [36], [37], [38].

Dynamic Interaction Factors: Makris and Gazetas (1992) [26] showed that the movement of a "source" pile creates stress waves that travel to "receiver" piles. At specific frequencies, these waves can interfere constructively, resulting in resonance [39], [27], [36], [40], [19].

Shadowing Effect: For large-strain loading, Brown et al. (2001) in NCHRP Report 461 quantified the "shadowing effect," where leading piles shield trailing piles [40], [41], [42]. They proposed p-multipliers(Pm≈0.4−0.9) to reduce the stiffness of trailing piles in FEM models [43], [44].

IV. Mathematical Modeling of Pile–Soil Systems

A. Beam on Dynamic Winkler Foundation (BDWF)

The pile is modeled as a Euler-Bernoulli beam resting on a viscoelastic medium [45],[46],[47].

The governing differential equation of motion for a pile subjected to a dynamic load $P(x,t)$ is given by Hetenyi (1946) [48]:

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + m_p\frac{\partial^2 w(x,t)}{\partial t^2} + F_s(x,t) = P(x,t). \qquad (1)$$

Therefore, EI is a mere flexural rigidity, m_p is the mass of the piles per unit length, and $F_s(x,t)$ is the soil reaction.

Figure 1 the mathematical model of piles-soil. The pile is modelled as an Euler Bernoulli beam, and the soil surrounding it is treated through the use of independent viscoelastic modules each of which has three major components.

Nonlinear Spring (K) Reflects the elastic stiffness and soil subgrade response, representing the static load-deflection characteristics (p-y curves) [49],[50],[51].

- Viscous Dashpot (C): Positioned in parallel to the spring, this element mimics energy dissipation processes, particularly radiation damping (wave propagation) and hysteretic material damping [47],[52].
- Participating Mass (m_f): A Mass component is added to consider the inertia of the oscillating soil block, which is essential to avoid underestimating dynamic magnification at elevated speeds [53],[54].

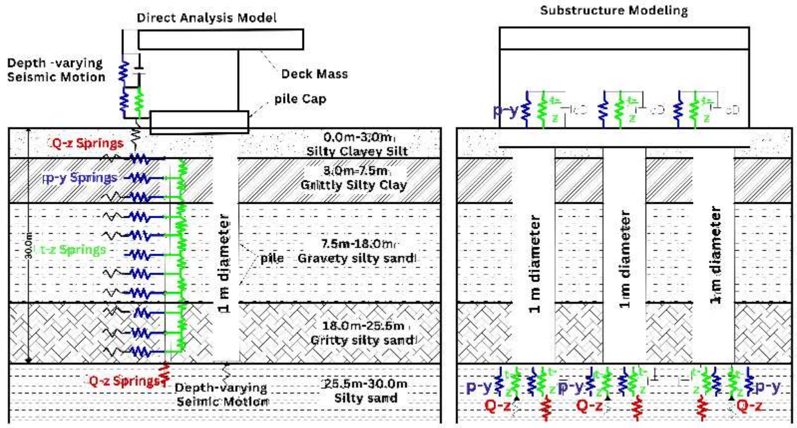

Figure 1. The BDWF model represents the interrelation between the soil and the pile and uses the depth-dependent springs (K), the viscous dashpots (C), and the near-field soil inertia.

B. Nonlinear Dynamic Foundation with Mass

Recent research of high-speed dynamics, the standard massless spring model is insufficient.[53],[45]. They formulated a Nonlinear Dynamic Foundation Model that includes the inertia of the soil.

$$F_s(x,t) = k_{eff} w(x,t) + c_f \frac{\partial w(x,t)}{\partial t} + m_f \frac{\partial^2 w(x,t)}{\partial t^2} - k_s \nabla^2 w(x,t) \qquad (2)$$

Where m_f represents the foundation mass and k_{eff} captures the nonlinear stiffness. The dynamic magnification factor [53] is underestimated by the ignoring of m_f.

C. Impedance Functions (Novak's Formulation)

In case you are attempting to think about the energy radiation in the semi-infinite soil media, Novak (1974) basically introduced complex-valued impedance functions [47],[55],[56],[29],[57]. The dynamic stiffness is characterized.

$$\mathfrak{K} = k_{static}(1 + i2D) \qquad (3)$$

The equation shows that the stiffness of piles is determined by the frequency ($a_0 = \omega r / V_s$) thus requiring the use of frequency-dependent springs in the process of calculating HSR, as is the case in MIDAS Civil [55],[23],[58].

D. Analytical Solution for Moving Loads

Assuming a moving railway load, a frequency-domain answer, actually, double fourier transforms [59],[60].

$$\tilde{y}(\xi,\omega) = \frac{2\pi P \delta(\omega + v\xi)}{EI\xi^4 + k - m\omega^2} \qquad (4)$$

This is an analysis model that we normally rely on to verify FEM results. It happens that the deflection curves are symmetric, however, the shear forces are slightly unbalanced under moving loads [59], [61], [62], [63].

V. Review of Fem and Midas Civil-Based Studies

A. Modelling Strategies

SSI analysis into two main techniques applicable in MIDAS Civil [34], [23], [14]:

- Direct Method: Simultaneously modelling the structure and soil with Winkler springs
- Substructure Method: Examining the foundation independently to create impedance matrices, which are subsequently utilized on the pier bases

B. Numerical Findings on Dynamic Response

- Velocity Effects: So, I traced the work of Hayir (2010) in which he considered beams on Winkler foundations - essentially the way they bend under moving loads. He discovered that the faster the load, the greater the bend of the beam. However, the most important lesson was that, in case the grounding is firm enough, it can contain that additional deflection and make the entire system stable [59], [64], [65], [66].

- Foundation Mass Importance: FEM to demonstrate that the foundation mass parameter (m_f) significantly influences the Dynamic Magnification Factor (DMF). Their research found that conventional models that overlook soil inertia are non-conservative in high-speed situations [53]
- Group Efficiency: the SMiRT-23 conference indicating that conventional spring models need to be adjusted by an efficiency factor ($\alpha < 1.0$) to incorporate group interaction in seismic assessments [66], [42].

VI. SEISMIC SSI: LIQUEFACTION AND SCOUR

A. Liquefaction-Induced Lateral Spreading

In liquefiable soils, p-y curves need to be adjusted according to the excess pore water pressure ratio, (r_u) [67], [68], [69], [70]. They proposed a degradation formula $p_{liq} = p_{static}(1 - r_u)$, which suggests that in completely liquefied soil, the pile functions as a column without support that may be prone to buckling [71], [72], [73].

B. Scour Effects

The pile gets all messed out by scour. According to the knowledge we got during our structural engineering course [74], [75]. scour essentially extends the effective length of the pile and compromises its buckling strength, as well as changes the natural frequency. That is to say that in case of an earthquake it may even hit a resonance zone, and that is a bit frightening.[76], [77], [38], [41].

VII. CONCLUSIONS

Drawing from a thorough examination of the literature and theoretical models, the subsequent conclusions are reached:

- Inertia is Critical: The assumption that a foundation is massless is outdated for HSR dynamics; the mass term of the foundation(m_f) notably affects the response [53], [10], [12].
- Frequency Dependence: Static stiffness models cannot adequately address contemporary railway loads; intricate impedance functions (Novak impedance functions) are necessary to account for radiation damping [77], [29].
- Group Effects: For 25T axle loads, "p-multipliers" are crucial for considering the shadowing impact in pile groups.
- Modelling Efficacy: MIDAS Civil is essentially a good utility in these analyses, provided you do the stringent SSI formulas of the parameters of the Pile Soil Support, you see [23], [77], [59].

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