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Ground reinforcement design to enhance critical speed through a simplified approach

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Abstract

In recent years, there have been significant advances in the railway sector, with a substantial increase in train speed, resulting in new challenges for the technical community in terms of infrastructure performance. When the supporting soil of the railway track is soft, the train speed can approach the speed of wave propagation in the track-ground system, giving rise to the so-called critical speed effect. This effect is characterized by the great amplification of the track response with dramatic consequences in terms of safety, ground-borne vibrations and maintenance costs. This well-known issue can be mitigated in several ways, one of them based on the reinforcement of the soil with columns. Bearing that in mind, the present paper aims to study the enhancement in the critical speed of the railway system achieved by a soil reinforcement with jet grouting columns, for a homogeneous and layered ground. Furthermore, a simplified methodology capable of accurately predicting the critical speed for reinforced grounds is proposed.

Keywords: traffic-induced vibrations; critical velocity; ground reinforcement; simplified methodology.

1 Introduction

Nowadays, a large investment is needed in the development of an efficient transportation network in which rail transport takes precedence over other options, in an attempt to significantly reduce CO2 emissions. The achievement of such goal is strongly conditioned by the implementation, improvement and expansion of new railway projects in metropolitan areas and by the interconnection between urban agglomerations. However, such expansion and improvement brings new geotechnical challenges, both in terms of safety and environmental impact, as well as in ground-borne noise and vibrations. In what concerns railway projects to overcome long distances, the operating speed of the vehicles has increased over the last years. This condition has consequences in the railway design process, namely due to the significant levels of displacement induced on the track, which can compromise the safety and stability of the infrastructure [1, 2].

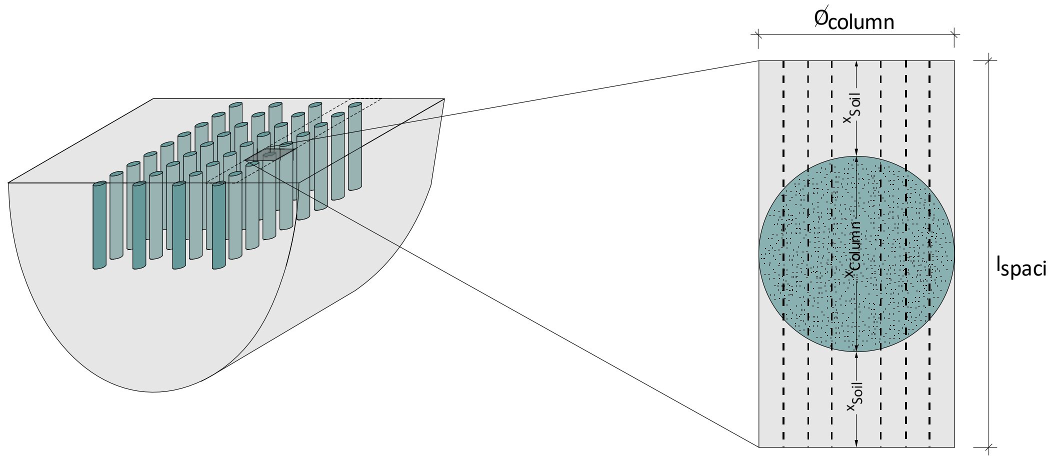
From a theoretical point of view, the effects of dynamic amplification on the surface response of an elastic solid due to a moving load have been the subject of research in recent decades [3]. The minimum velocity of the moving and non-oscillatory load that gives rise to the propagation of seismic waves in the medium, i.e., the velocity that leads to a maximum amplification of the dynamic response, is usually defined as the critical speed of the system. In railway systems, it is clear that the critical speed is completely dominated by the bending wave propagation in the track and the properties of wave propagation in the ground system [4, 5]. When the train operating speed reaches the critical velocity of the field several problems arise regarding the global safety, track degradation rate as well as the vibration field generated. In fact, Connolly et al. [6] suggests that in order to avoid such problems the train speed must limit to 50% of the critical speed computed. However, when the train speed must increase in order to make a railway line economically viable, mitigation measures needs to be applied to the ground which allows a safety increase in the operating speed [7].

Based on such perspective, the present article proposed a simplified methodology to predict the critical speed of reinforced geotechnical with discrete columns being further validated using 3D numerical modelling. The impact that a soil reinforcement with jet-grouting columns (with distinct embedded depths) has on the critical speed of the system for a layered ground is also evaluated.

2 Methods

Numerically assess the critical speed of a railway tracks requires the adoption of robust numerical models which, in most cases, are time-consuming. Once the critical speed is obtained when the wavelength propagated along the track is the same as the wavelength in the surrounding soil, it is possible, for simple scenarios, to obtain the critical speed using analytical formulations. As easily perceived computing the critical speed of a railway track using analytical methodologies allows a clearer physical perception of the problem with an excellent computational efficiency, since it does not require the numerical solution of a huge system of equations.

Since soil reinforcement solutions are materialized by adopting discrete solutions and the analytical methods assume horizontal invariant layers a homogenization process is required. The main concept behind the homogenization process is to determine the average propagating speed of S and P waves for the reinforced longitudinal alignment, depicted in Figure 1 a). As shown in Figure 1 b), the section used for the homogenization comprises the spacing between the columns in the longitudinal direction and the diameter of the columns in the transverse direction.



a) b)

Figure 1 – Schematic representation of the reinforcement: a) Overview; b) Detailed view.

Taking into account the geometry depicted in Figure 1 b), it is possible to compute the average velocity of S and P waves taking into consideration the length of soil and the column crossed:

$$c^* = \frac{l_{spacing}}{\dfrac{2x_{soil}}{c_{soil}} + \dfrac{x_{column}}{c_{column}}} \tag{1}$$

where c^* refers to the homogenized property (Cs, Cp); $l_{spacing}$ is the longitudinal spacing of the columns; x_{column} and x_{soil} correspond to the column and soil length of each sub-alignment, respectively; c_{soil} and c_{column} stand for the properties of the soil and columns, respectively.

Since the columns geometry is circular, the homogenization process must be computed for several alignments of the soil-column cell presented in Figure 1 b). Such alignments are represented by dashed lines. Thus, a different value of x_{soil} and x_{column} is found. Finally, the homogenized properties (Cs and Cp) is the average of all those values. Therefore, the dispersion curve of the reinforced scenario is computed by assuming the thickness of the reinforcement soil as a homogeneous layer with the propagating properties derived from the homogenization procedure previously shown.

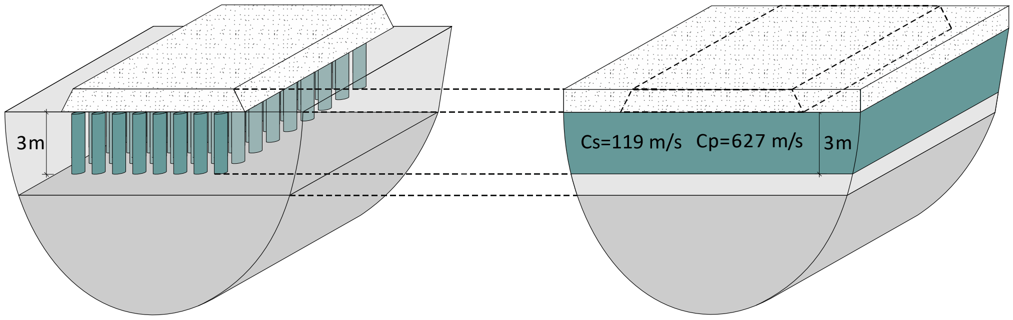
As proposed by the authors [4], the critical speed can be predicted by the intersection point between the soil and track dispersion curves. Once the railway track adopted in the present article is a simple reinforced concrete slab, the dispersion curve can be easily obtained by solving the Bernoulli-Euler beam in free field conditions:

$$k_1 = \sqrt[4]{\frac{\omega^2 m_{slab}}{EI_{slab}}} \tag{2}$$

where k_1 is the wavenumber in rad/m, ω is the loading frequency in rad/s, m_{slab} is the linear weight of the concrete beam and EI_{slab} is the bending stiffness

3 Results

To clarify how the simplified prediction methodology works, an application example is presented. The main objective is to predict the critical speed for the scenario with 3 m deep jet grouting columns for a layered ground expressed in Figure 2 a).



a) b)

Figure 2 – Schematic illustration of: a) reinforced ground and embankment scenario; b) simplified section assumed for the analytical analysis.

Element	E (MPa)	ν (-)	ξ (-)	ρ (kN/m³)
Embankment	251.68	0.3	0.03	2000
Soft soil	32.4	0.49	0.03	1700
Stiff soil	216	0.35	0.03	2000
Jet grouting	1e3	0.25	0.01	2200

Table 1 – Mechanical properties used.

All the material properties used in the present article are expressed in Table 1, given rise to shear wave velocities of 80 m/s and 200 m/s for the shallow and deep soil, respectively. For the jet-grouting reinforcement it was adopted columns with 80 cm of diameter spaced of 1.6 m in both directions. As easily perceived Figure 2 b) shows how the real reinforced scenario is simplified to compute the analytical soil dispersion curve. By applying the homogenization process to the reinforced scenario expressed in Figure 2 a) the following properties are derived: i) longitudinal wave velocity (Cp) of 627 m/s; ii) shear wave velocity (Cs) of 119 m/s. Finally, by computing the soil and track dispersion relationship, it is possible to determine the critical speed through the intersection point of these analytical curves, expressed in Figure 3. In order to validate the simplified methodology a comparison must be establish with a realistic numerical model. In this sense, the scenario expressed in Figure 2 a) was additionally solve using a 3D FEM-PML numerical model [8] being computed the dynamic amplification curve and presented in Figure 4.

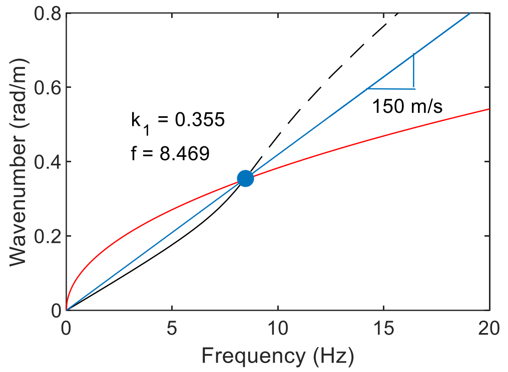


Figure 3 – Analitical dispersion curves for the 3 m column scenario (black line –soil; red line –track).

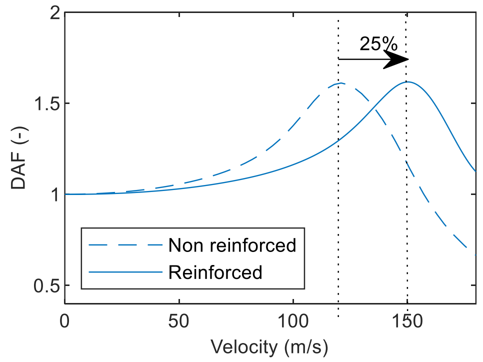


Figure 4 – Dynamic amplification factor for the 3 m columns scenario.

The critical speed predicted by the analytical methodology, in which the soil dispersion relationship is obtained for a homogenized reinforced scenario, is practically the same as the critical speed computed numerically (Figure 4). From the results, it can be concluded that using the simplified analytical methodology allows to accurately predict the behaviour of grounds reinforced with discrete solutions and, consequently, their critical speed.

The study was extended for a different columns embedded depth in order to evaluate the impact that resting the columns toe's in the stiffer layer produces. For that, a new scenario was modelled using both the simplified methodology and the 3D FEM-PML periodic model, where the columns embedded depth was assumed as 4 m coinciding with the boundary between soils. The results achieved can be found in Figure 5 and Figure 6 where it can be seen, once more, a accurately prediction of the critical speed for the reinforced ground by the simplified methodology. It also must be highlighted that resting the columns in a stiffer soil leads to a higher critical speed of the system, as expected.

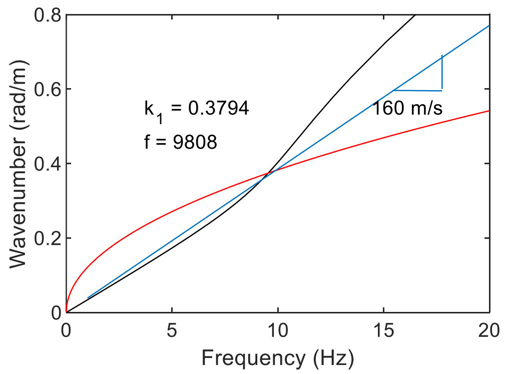


Figure 5 – Analitical dispersion curves for the 4 m column scenario (black line –soil; red line –track).

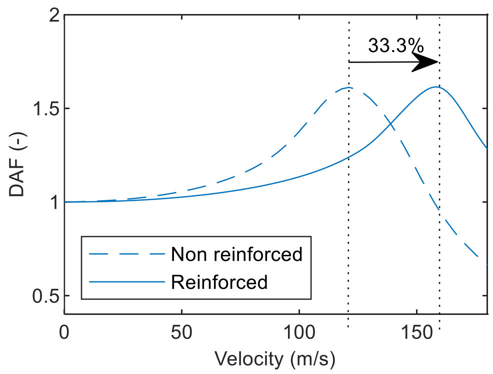


Figure 6 – Dynamic amplification factor for the 4 m column scenario.

4 Conclusions and Contributions

The article presented a simplified analytical methodology for predicting critical speed in reinforced geotechnical scenarios. To analytically determine the dispersive behavior of such scenarios, the thickness of the reinforced soil is converted into a fictitious one, with propagation properties computed from the presented homogenization procedure. Therefore, the critical speed can be estimated by the intersection between the dispersion relationship curves of the reinforced soil and the railway track. The accuracy of the simplified methodology was verified for different numerically analyzed scenarios, showing a good agreement between the analytical and numerical critical speeds.

Secondly a brief parametric study was conducted assuming two distinct scenarios of reinforcement embedded depth. Since one of the cases assumed the columns toe's coincident with the border between soil layers it was possible to assess the impact produced by the support conditions of the columns toe's. As expected the scenario that rested the reinforcement columns in the stiffer layer is the most optimized one, however the relative increase is not so expressive, with a difference around 10 m/s.

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