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Management of the dynamic performance of earthworks for High-Speed Rail

Gestion de la performance dynamique des travaux de terrassement grandes lignes pour Train a Grande Vitesse

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ABSTRACT: The interaction of a high-speed train with the track system, and the response of the supporting ground can result in amplification of quasi-static track deflections as the train speed approaches a critical velocity. Numerous factors govern the development of this phenomenon, but of particular importance is the propagation of surface waves (Rayleigh waves) in the supporting ground. To avoid dynamic amplification, criteria for the design of earthwork structures are commonly specified as a minimum Rayleigh wave velocity as a function of train speed. Whilst this geo-dynamic phenomenon is recognised within the industry, there are no well-established guidelines or standards for assessing and mitigating this risk. This paper presents the approach used for contract C23 on Phase 1 of the HS2 project to assess and manage this risk, including the design of foundation treatment to improve the dynamic response of the earthwork structure.

RÉSUMÉ: L'interaction d'un train à grande vitesse avec le réseau de voies ferrées et la réponse du sol d'appui peuvent entraîner une amplification des déformations quasi statiques de la voie lorsque la vitesse du train s'approche d'une vitesse critique. De nombreux facteurs régissent le développement de ce phénomène, mais la propagation des ondes de surface (ondes de Rayleigh) dans le sol de support revêt une importance particulière. Pour éviter l'amplification dynamique, les critères de conception des ouvrages de terrassement sont généralement spécifiés comme une vitesse minimale de l'onde de Rayleigh en fonction de la vitesse du train. Bien que ce phénomène géodynamique soit reconnu au sein de l'industrie, il n'existe pas de lignes directrices ou de normes bien établies pour évaluer et atténuer ce risque. Cet article présente l'approche utilisée pour le contrat C23 de la phase 1 du projet HS2 afin d'évaluer et de gérer ce risque, y compris la conception du traitement des fondations afin d'améliorer la réponse dynamique de la structure de terrassement.

Keywords: High-speed rail; critical velocity effects; geo-dynamic performance; Rayleigh waves.

1 INTRODUCTION

1.1 Background

The HS2 project is a High-Speed railway line currently under construction in the UK. Phase 1 of HS2 runs between London and Birmingham and this paper focuses on an 80 km long open route section between Wendover in Buckinghamshire and Southam in Warwickshire (Contract C23).

High Speed 2 Ltd are the delivery authority for the project with Eiffage, Kier, Ferrovial Bam Joint Venture (EKFB) the appointed Contractor for C23 supported by an Arcadis, Setec, COWI Joint Venture (ASC) providing design services for the main civil engineering assets.

This section of the route will be constructed using track slab with a design speed of 360 km/hr which is significantly higher than traditional railways. At higher train speeds, there are additional engineering issues to consider, of particular importance is a form of resonance between the train and the supporting track-bed, termed Critical Velocity Effect, which is heavily influenced by the dynamic response of the underlying earthworks. Critical velocity effects have been recorded at various rail sites around the world (Woldringh et al 1999), with the phenomenon being linked to the proximity of the train speed to the site critical velocity (Madshus et al 2000).

There are no well-established design basis, guidelines and/or standards for assessing and mitigating the risks in routine design. This paper describes a simplified design approach developed for the design of HS2 earthworks to meet the dynamic performance criteria defined in HS2 Technical Standards for Earthworks (TS-E) (HS2, 2019a). The approach provides a robust and repeatable methodology for carrying out the design of earthworks and managing the associated uncertainty and risk.

The HS2 earthworks dynamic performance criteria were established based on precedent from past projects and the back analysis of problematic sections of existing track on other railways. The approach adopted by the TS-E does not establish wave amplitudes or particle velocities for the dynamic performance serviceability limit state of the track bed, but rather sets a minimum dynamic stiffness requirement for the earthwork, based on the design speed of the train, with the objective of ensuring that resonance is avoided.

1.2 Critical Velocity Effects

As a train travels over the ground, it creates a downward, deflection of the track bed due to the load of the wheels and bogies. In doing so, it generates surface waves that propagate through the track bed and supporting ground. At low train speeds, the surface waves travel faster than the train. As the train speed increases towards the speed of the propogating wave a critical velocity is reached at which resonance can occur, resulting in the dynamic amplification of the deflections.

The wave sources that are applicable for design of the earthwork structures are based on where there is likely to be significant variations in the magnitude of repetitive load applications. This is limited to the vertical load applied through the bogies and individual wheel axles of the train. (Arup, 2017). Each bogie and wheel axle act as a moving load that creates a downward deflection of the track along the railway line (Arup, 2017 & HS2, 2019b). As such, the loading at any given point is applied over a very short period (instantaneous) and at a frequency that is dependent upon the train speed.

The design of the earthwork structure needs to consider how the waves propagate longitudinally within the track bed-earthworks system and continue to interact with the moving train. It has been shown that the site critical velocity is governed by the minimum phase velocity of the fundamental Rayleigh wave mode of the foundation and embankment profile at the site (Madshus et al, 2000).

According to studies on the soil structure interaction between slab track and supporting earthwork (Arup, 2017), there are two wave velocities that may affect the overall performance of a track-earthworks systems:

- Track slab 'Winkler Beam' bending wave speed; and
- Rayleigh wave velocity of the earthworks structure.

One conclusion of the study is that the bending stiffness of the track slab does not affect the critical Rayleigh wave velocity of the earthworks but may reduce the displacements with stiffer track bed elements. This enables the stiffness requirement of the earthworks structure to be decoupled and designed for separately to the rail system (i.e. track bed) once the overall system performance and earthworks design criteria have been established.

Figure 1 summarises the terminology that defines and groups the track bed and earthworks components. This paper covers the earthwork structure and foundation located below the Protection Layer.

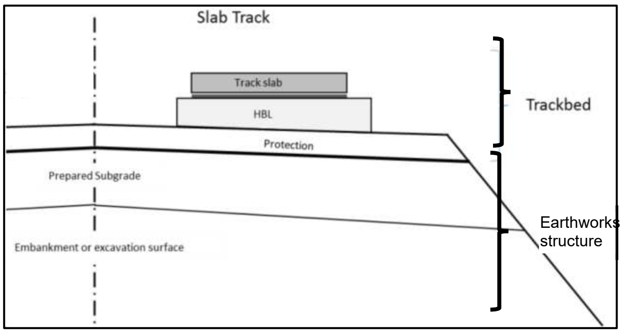

Figure 1. Schematic section illustrating track-earthworks system terminologies (adapted from HS2, 2019a).

2 FUNDAMENTALS OF RAYLEIGH WAVE PROPOGATION

The theoretical Rayleigh wave velocity for an elastic half space can be estimated using Poisson's ratio (ν), Youngs Modulus (E) and density (ρ), as the governing parameters:

$$V_{R} = \left(\frac{0.87 + 1.12\nu}{1+\nu}\right)\sqrt{\frac{E}{2\rho(1+\nu)}} \quad (1)$$

The waves are characterised by an anti-clockwise particle motion relative to the direction of travel as shown in Figure 2 below.

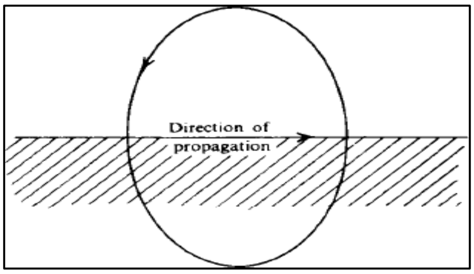

Figure 2. Particle motion on the surface during the passage of Rayleigh wave in an elastic homogenous half space (from Richard et al., 1970).

The frequency or wavelength affects the depth of influence beneath the surface. Lower frequencies with a longer wavelength excite particles to a deeper depth. This geometrical zone of influence normalised to wavelength is illustrated in Figure 3 below.

Reflecting on this zone of influence, a common ground profile with increasing stiffness with depth will have a higher Rayleigh wave velocity at lower wave frequencies (longer wavelength) and lower wave velocities at high frequencies.

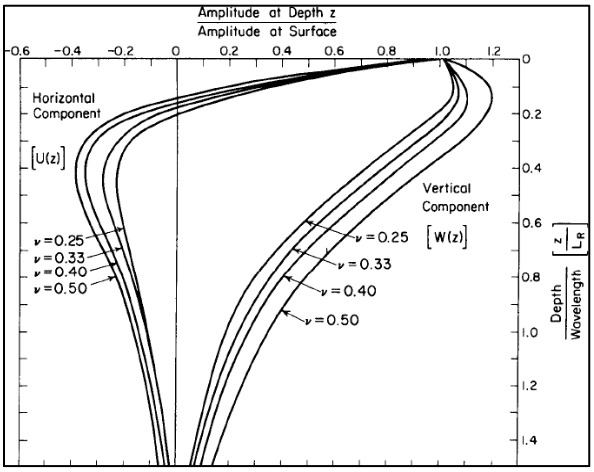

Figure 3. Amplitude ratio vs dimensionless depth for Rayleigh waves in a homogenous half space (from Richard et al., 1970).

This type of profile is known as normally dispersive. A profile that has decreasing stiffness with depth is known as inversely dispersive and will result in lower Rayleigh wave velocities for lower wave frequencies. This concept is graphically presented in Figure 4 below.

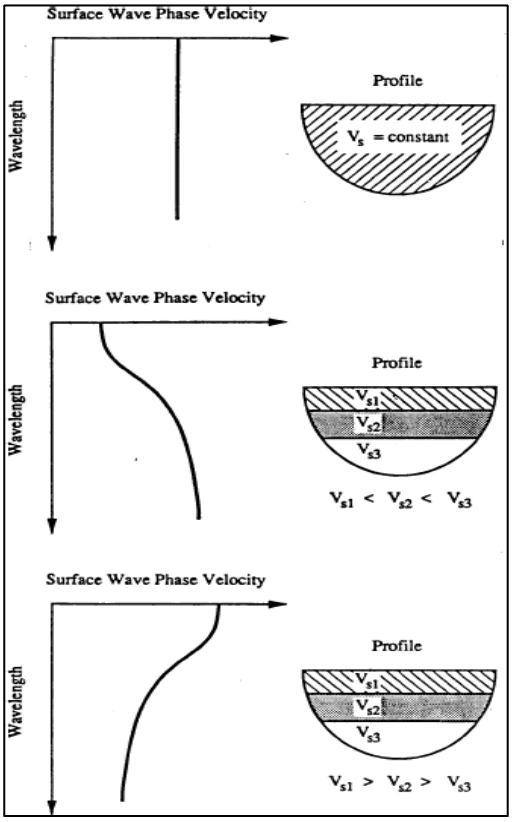

Figure 4. Example of non-dispersive (homogenous half space), normally dispersive and inversely dispersive profile (from Rix, 1988).

Surface waves will decay as the distance from the source increases. This decay is partly caused by the geometrical attenuation as the wave front spreads. This phenomenon is illustrated in Figure 5.

There is also hysteretic damping within the soil that dissipates energy due to straining of the soil, referred to as material damping. While geometric and material damping rapidly attenuates the wave energy, they do not affect the fundamental Rayleigh wave velocity of the system and the potential for amplification to occur.

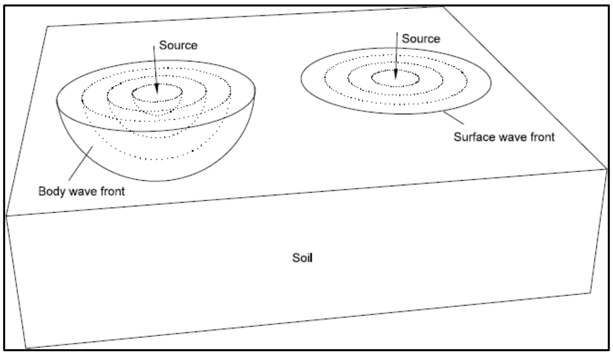

Figure 5. Geometrical attenuation of vibrations.

3 DYNAMIC PERFORMANCE CRITERIA AND REQUIREMENTS

The TS-E (HS2, 2019a) defines the earthworks dynamic stiffness as the *"transient stiffness of the earthwork at any defined level in response to dynamic loading"*. The same TS-E (Table 4.2/1) specifies the performance criteria to be satisfied by the earthworks design and construction verification testing as a limiting Rayleigh wave velocity (V_R), measured at Formation Level:

$$V_R \geq 1.6 \times DS \tag{2}$$

where DS is the design speed which for HS2 Contract C23 has been set at 360 km/hr (100 m/s). The standard requires that the dynamic performance is demonstrated by design and validated by construction verification testing. This has been achieved through verification by calculation in design, supported by the undertaking of demonstration field trials, and by end product testing of the completed earthworks.

4 DYNAMIC PERFORMANCE DESIGN APPROACH

4.1 Risk assessment method

Initially, a qualitative screening was used to determine sections of subgrade of potentially low stiffness that were at risk of requiring foundation treatment to achieve the specified minimum Rayleigh wave velocity criteria. A risk rating process was followed to focus risk mitigation activities at the different stages of the design and construction.

The first step was to identify areas along the route where the in-situ ground may have low stiffness. The risk levels were derived from assessment of predicted shear wave velocity profiles based on the geological model and published data. The risk categories applied in the early stages of design development are summarised in Table 1. The shear wave velocity for individual layers within a layered deposit is more familiar to design engineers and is a useful indicator of the expected Rayleigh wave response. This was therefore used as part of the screening exercise. Based on the initial mapping, various areas along the route were categorised as being at high risk of requiring foundation treatment to achieve the HS2 dynamic performance criteria, notably:

- Shallow/at grade embankments and shallow cuttings;
- Faulted zones and dissolution features (soft infill/voids);
- Transitions between cuttings and embankments.

Table 1. Risk Categories relative to HS2 Rayleigh Wave Performance criteria and equivalent shear wave velocity.

Parameter	**Low Risk** (1)	**Medium Risk** (1)	**High Risk**
Rayleigh Wave Velocity V_R (m/s)	>200	$160<V_R<200$ and where there are local heterogeneities (<50m)	<160
Shear Wave Velocity V_S (m/s)	>210	$170<V_S\leq210$ and where there are local heterogeneities (<50m)	<170

(1) – For V_R, the boundary between Medium and Low Risk is defined as $(1.6\times DS)\times1.25$

In the initial categorisation of risks and development of the scheme design, a partial factor of 1.25 was adopted to reflect uncertainty in the ground investigation data that was available and the potential effectivness of proposed mitigation measures. In addition, field trials were initiated to better define the dynamic properties of the proposed fill material and investigate the improvement in dynamic response achieved by the proposed foundationt treatment methods.

4.2 Design methodology

The HS2 project involved developing a Scheme Design followed by a Detailed Design for the earthworks. At each stage, the risk assessment was updated based on the latest information. Two methods for predicting the dynamic performance of the completed earthworks by calculation were developed, starting from the simplest form:

- Direct comparison of shear wave velocity profiles for each layer in the earth structure to ensure that all layers are greater than 1.7 x the design speed using a simplified relationship between shear wave velocity and Rayleigh wave velocity (Richart et al 1970)
- Forward modelling, 1D analysis method to establish the anticipated performance of the entire layered Earth Structure.

To forward predict the performance of the earthwork using a 1D analysis method, a weighted average velocity forward modelling approach has been used to estimate the Rayleigh wave dispersion curve for a layered deposit (Leong *et al*., 2012 & 2013). The method enables the rapid assessment of multi-layered systems, including; in situ strata and the engineered earthwork structure, and provides the resulting estimated Rayleigh Wave velocity (V_R) dispersion curve at formation level. The modelling requires the Shear wave velocity (V_S) and the Poisson's ratio (ν) of each layer for the ground profile representing an earthwork asset. The analysis can be rerun to establish the depth of treatment needed to improve the stiffness of the layered system to ensure that the dynamic performance criteria are achieved.

This method allows individual, low stiffness layers to be assessed as being acceptable due to the compensating response of stiffer layers within the profile. The 1D analysis method was used to develop standard look up charts for the design of foundation treatment which were used as an intermediate step in the design process. The design process followed for the design of the earthworks is given in Figure 6.

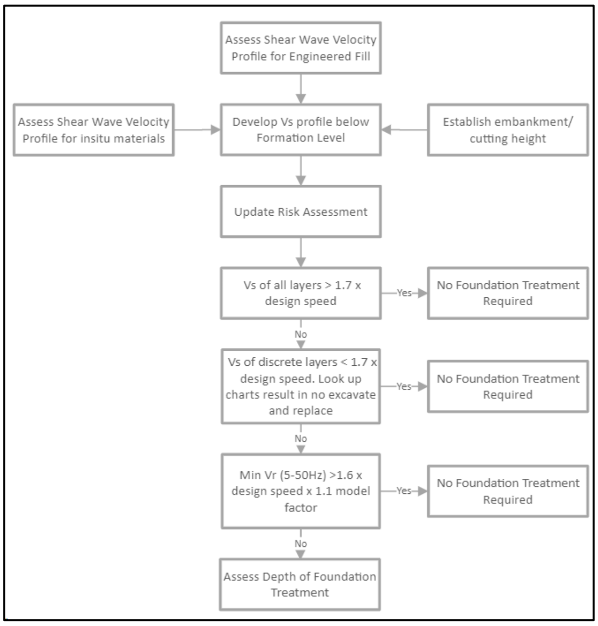

Figure 6. Design process for dynamic performance risk assessment and foundation treatment design.

For engineered fill forming the earthworks, the Shear wave velocity (V_S) was conservatively assumed as 250 m/s through Scheme Design with the same shear wave velocity value being assigned to the foundation replacement fill. This value was investigated as part of Detailed Design field trials which subsequently allowed an increase in the design value to 300 m/s to reflect increased confidence in the performance of the specified fill materials to be placed within the high-speed rail earthworks.

4.3 Foundation Treatment Design

4.3.1 Treatment options

The foundation treatment options focussed on achieving a homogenous improvement in the foundation to the high-speed rail earthworks. This was necessary due to the need to verify the minimum Rayleigh wave velocity of the completed earthwork using in-situ testing of end-product performance. Solutions that consist of locally stiffened elements such as rigid inclusions would not enable these construction stage verifications to be readily completed. The excavate and replace solution using a combination of imported engineered and stabilised site won fill was selected as the preferred solution. This in effect, modifies the 1D layered model by replacing a low velocity layer with a higher velocity layer to provide an increase in the overall dynamic performance of the earthwork.

The performance of the layered soil system was verified by a series of field trials carried out on earthworks constructed with replacement fill material to confirm the overall Rayleigh wave velocity as detailed in Section 5.

4.3.2 Target design criteria and construction verification testing

Following the results of the earthworks field trials the additional safety factor of 1.25 applied in Scheme Design was subsequently removed, but a model factor of 1.1 was adopted in the 1D analysis to recognise the uncertainty inherent in the forward modelling method and its relationship to field measurements.

To reflect the discrete extent of ground investigations and the variable nature of the natural materials, additional construction risk management controls are specified in the design to ensure that the completed earthworks meet the end product testing requirements. To account for potential variability of each fill material type demonstration areas are required during the works for each unique source of fill, construction team (workmanship), and/or unique subgrade strata.

Measurement of compacted fill density and E_{V2} stiffness will be used for earthworks quality control to ensure the engineered fill achieves the minimum shear wave velocity required to improve the overall Rayleigh Wave performance. Surface geophysical testing in advance of foundation treatment will also be used to manage potential variability in natural ground conditions for higher risk areas.

Ultimately, the completed earthwork structure is required to be verified using an end product test in accordance with the Technical Standard. Continuous Surface Wave (CSW) geophysical testing is proposed to be utilised at final earthworks formation level for this field verification. This is following the sucessful demonstration during the Detailed Design field trials and calbration during cosntruction stage demonstration areas for each fill type.

5 DETAILED DESIGN FIELD TRIALS

Six earthworks field trials have been undertaken on site to date to assess the static and dynamic performance of different fill types as well as their suitability for use in earthworks' construction including as replacement fill for foundation treatment. Material types used in the trials comprised granular fill (imported and site won), stabilised glacial tills, and both stabilised and unstabilised Chalk. Embankments up to 3.6m high were constructed and tested before construction, during fill placement and after construction to validate key design assumptions.

For the dynamic performance, geophysical testing was performed at various stages during construction and after completion of the earthworks. The results obtained demonstrated the improved dynamic performance of the earthwork due to increased stiffness of the replacement fill adopted for foundation treatment.

In addition to the improvement with increasing depth of replacement fill material, the results also validated the suitability of the 1D weighted velocity forward modelling method and Figure 7 shows a comparative example of Rayleigh wave velocity dispersion curves predicted from the 1D analysis and those obtained from the field specific trial for that tested location. A good agreement between the two sets is observed.

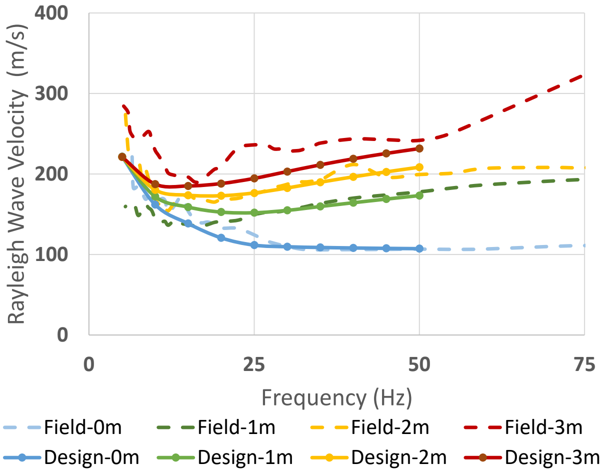

Figure 7. Typical Example of comparative Rayleigh Wave velocities dispersion curves obtained from the design forward analytical tool and from field trials.

6 CONCLUSIONS

The risk management-based design approach adopted for assessing the dynamic performance of the earthwork structures, and the design of foundations treatment has been found to be reliable in demonstrating compliance with dynamic performance criteria and requirements specified for the HS2 earthworks structures.

The use of a relatively simple, 1D wave propagation forward modelling method has enabled a more efficient design to be developed that considers the improvements obtained from stiffer layers of earthworks constructed over less stiff in-situ foundation materials.

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