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Evaluation train induced ground vibration boom with Vibtrain

Évaluation du “boom des vibrations du sol” induit par les trains avec VibTrain.

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ABSTRACT: The Swedish Transport Administration is planning new high-speed railway lines that will connect Stockholm, Gothenburg, and Malmö, with operating speeds from 250 to 320 km/h. However, at such high speeds in soft soil areas, can result in significant amplification of ground vibrations, a "ground vibration boom." This phenomenon was first observed in Sweden in 1997, leading to extensive research, during which the NGI developed the VibTrain tool for train-induced ground vibration analysis. There are still various challenges associated with train speeds exceeding 200 km/h on soft ground. To achieve optimized and sustainable ground improvement, a better understanding of its dynamic and cyclic behavior, as well as the validation of design tools and construction techniques, is needed. This paper presents a revival and re-evaluation of VibTrain for assessing the risk of the ground vibration boom for planning of new lines. The tool was compared with previous analyses of the Ledsgård case and extended with a parametric study of both the load model HSLM-A and ground improvement using lime cement stabilization. Additionally, VibTrain was compared with the results from Tyrens (2016) for the Järna location in East link. The analysis indicates that VibTrain is well-suited for initial assessments of the risk associated with the ground vibration boom. However, for the detailed design of soil improvement, more sophisticated calculation models are required. Results indicate importance of the train load description and of well characterized dynamic properties of track and subsoil. Validation of numerical models with field test at speeds above 300 km/h are recommended.

RÉSUMÉ: La Direction suédoise des transports prévoit de nouvelles lignes ferroviaires à grande vitesse reliant Stockholm, Göteborg et Malmö, avec des vitesses de 250 à 320 km/h. Cependant, à de telles vitesses dans des zones de sol mou, des vibrations importantes du sol, appelées "boom des vibrations du sol", peuvent se produire. Ce phénomène, observé en Suède en 1997, a conduit à des recherches approfondies. L'Institut norvégien de géotechnique a développé VibTrain, un outil d'analyse des vibrations du sol induites par les trains. Des défis subsistent pour les vitesses dépassant 200 km/h sur sol mou. Une compréhension approfondie du comportement dynamique et cyclique du sol, la validation des outils de conception et des techniques de construction sont nécessaires pour une amélioration optimisée et durable du sol. Cet article présente une réévaluation de VibTrain pour évaluer le risque du "boom des vibrations du sol" dans la planification des nouvelles lignes. L'outil a été comparé à des analyses antérieures et étendu avec une étude paramétrique de l'amélioration du sol par stabilisation au ciment de chaux. VibTrain a été comparé aux résultats de Tyrens (2016) pour l'emplacement de Järnaslätten dans l'Ostlänken. L'analyse suggère que VibTrain convient bien aux évaluations initiales du risque lié au "boom des vibrations du sol", mais des modèles de calcul plus sophistiqués sont nécessaires pour la conception détaillée de l'amélioration du sol en raison de divergences observées dans des conditions de sous-grade améliorées.

Keywords: Train vibrations, Vibtrain, Lime cement, Train load model

1 INTRODUCTION

The Swedish Transport Administration (STA) is planning for new railway lines with higher speeds (250–320 km/h) than the existing ones (maximum 200 km/h). The increased speed poses several technical challenges for the infrastructure design with respect to soft soil settlement, ground vibrations and need for optimizing (Ekström & Hallingberg, 2012) the track design with respect to material use and CO2-footprint. One challenge is the so called ground vibration boom (Krylov, 2017), during which the train speed approaches the wave speed (critical speed) in the underlying track-foundation system. This phenomenon can cause significant train and ground vibrations and is essential to avoid (STA, 2023). It was observed when the X2000 train was introduced in late 1990s in Sweden with a new track at Ledsgård on very soft ground containing organic clay and vibration levels became 10 times larger than previously experienced (Madshus & Kaynia, 2000). Extensive underground reinforcement was necessary to increase the critical speed and reduce the track and ground vibrations (Holm et. al. 2002, Hall et. al. 2023). There is a need for better understanding of the long-term static and dynamic behaviour of lime cement stabilized subsoil to optimize the railway foundations, therefore STA have taken initiative to several related studies (e.g. Hall et. al. 2022). Here the Vibtrain software has been applied to study the effect on the critical speed of the train load model, and the subsoil lime cement reinforcement.

2 VIBTRAIN

Vibtrain was developed by NGI (Madshus Kaynia) to try to understand the first observations of the high speed phenomenon at Ledsgård in 1998. Vibtrain consists of a beam on a horizontally layered halfspace with the vertical train loads are modelled as moving point loads (Krylov). Stiffness matrices for the beam and are combined with ones for the half space (Kausell). Further details are given in Håård (2022) and Norén-Cosgriff (2017). The recompiled version of Vibtrain was satisfactorily verified by comparing with the earlier results (Madshus/Kaynia 2000).

3 EFFECT OF LOAD MODEL (HSLM-A)

The critical speed phenomenon was investigated in a parametric load study with the HSLM-A load model of the EN 1991-2, which has 10 train sets (A1-A10) with different lengths, axle loads and axle distances. The track and subgrade were modelled with the same parameter values as reported in Madshus & Kaynia (1999) for all train load models. Figure 1 shows the effect of load model on variation of the "critical speed". The variation depends on the on the match between the load frequency (ratio of train speed to the vehicle length, the boogie or the axle spacing) and the response frequency corresponding to the critical speed. It is important that the load model encompasses a range of frequencies as to detect the critical speed and the larges track deflection which is dependent on the specific numerical model and its input parameters.

For design and comparison of different remedial measures, where the critical speed is higher than the allowable train speed, it necessary to have some other criteria as allowable vibration or deflection level, e.g. in STA (2023) the requirement of a maximum deflection 2 mm is used.

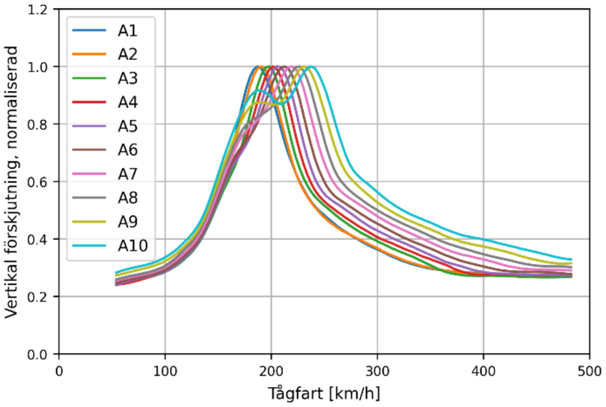

Figure 1. Effect of train load model on critical speed.

4 EFFECT OF LIME CEMENT REINFORCEMENT COMPARISON WITH FE-ANALYSIS

To study the effect on the critical speed of an increased subsoil stiffness in VibTrain, an equivalent modulus is used, assuming the entire soil mass has an homogenously increased stiffness, proportional to the reinforced volume fraction (η-factor) and the elastic modulus increase due to soil reinforcement (γ-factor) (Håård, 2022). We consider a specific case for the Järna plain some 50 km south-west of Stockholm (se also Müller et. al. 2020) with 2 m high embankment over soft clay. Three reinforcement cases were considered, 1) singular lime cement columns (LCC) 0.6m diameter and 20 m deep, placed in a regular grid with c-c distance of 1.1 m; 2) Two 10 m deep lime cement "walls" along the track, one beneath each rail, with 1.5 m separation in the transverse direction. The walls consist of overlapping columns with a c-c distance of 0.5m; and 3) a combination of the above singular columns and walls. The three cases have reinforcement volume fraction of 0.27, 0.21 and 0.46 respectively. Further details about incorporating design recommendations given by STA (2023) when establishing geometry, soil and lime cement properties are given in Håård (2022).

Below Vibtrain results are compared with the ones from the finite element software (ωFE-N) used in the design (Müller et. al. 2020). In ωFE-N the ground reinforcement is modelled explicitly as 3D columns inside the soil volume, thus smearing of properties is avoided. However, the ωFE-N uses Abaqus for creating geometries and the resulting stiffness matrices with millions of degrees of freedoms are solved in the frequency domain with a parallell computer at KTH to resulting in computing times of few seconds for one train passage.

Figure 2 shows for different train speeds "peak-to-peak" deflection, the sum of the maximum downward and upward deflection during the each train passage. The three subfigures clearly show the effect of reinforcement increasing the critical speed from some 300+ km/h for the unreinforced to over 400 km/h for the case with for case with most reinforcement. The results (not shown) indicate in general Vibtrain and ωFE-N have similar vibration frequencies, while Vibtrain gives larger deflections for most cases and train speeds. Possible reasons for discrepancy in deflection could be the simplified modelling of the embankment in Vibtrain and/or the use of first order tetrahedra elements in the FE-analysis. Such elements are known to give overly stiff response for nearly incompressible material such as clay (see e.g. Frâncu 2021, Hall 2022).

5 DISCUSSION

The difference in the numerical analysis methods indicate a difficulty in comparing different methods for evaluating the effects of and optimizing subsoil reinforcements. To evaluate the effect of reinforcement layouts, e.g. a percentage increase in critical speed or rather percentage decrease in deflection could be used for evaluating the effect of different reinforcement solutions (e.g. Müller et. al. 2020, Norén-Cosgriff 2019).

To optimize subsoil reinforcement extensive research is required both with respect to improve the evaluation of in-situ static, dynamic, and long-term properties of LCC, achieve desired field properties, and advance numerical modeling for specific column configurations. E.g. there is no standardized procedure for evaluating the in-situ stiffness of LCC (Helle et. al 2022, Dannewits 2005) and thus actual dynamic properties of lime cement reinforcement which can have substantial spatial variation (e.g. Larsson et. al. 2005) is difficult to characterize. E.g. there are very few reported studies of the dynamic interaction between track, soil and LCC in which individual columns are modelled (Müller et. al 2020). Therefore validation with field tests are vital to improve the tools used in railway design.

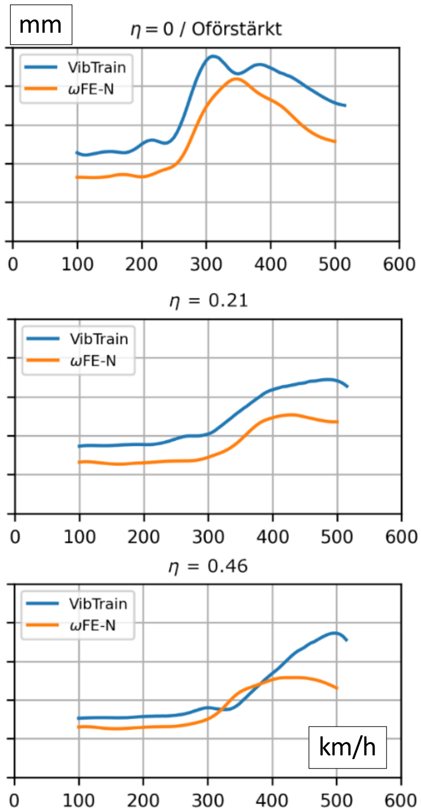

Figure 2 Maximum sum of downward and upward deflection "peak-to-peak" (mm) during the each train passage for different train speeds. Upper: unreinforced soil, Middle: ,case 2) walls along track, Lower: case 3) walls along track + singular columns.

6 CONCLUSIONS AND OUTLOOK

The study showed the recompiled 20+ year old VibTrain tool runs very fast on modern computers, yielding in about a minute, critical speed results consistent with original Ledsgård investigations.

Vibtrain can function as a fast calculation kernel in a screening tool for the highspeed phenomenon giving more detailed result then the simple shear wave speed criteria in the current STA regulations. However, detailed design of geotechnical remedial measures should be performed with more advanced tools which can account for more complicated soil and reinforcement geometry and bedrock depth variation.

In VibTrain, modeling geotechnical measures like soil reinforcement with lime-cement columns via the equivalent modulus method aligns with expected behavior, indicating that an increased equivalent modulus reduces displacement and raises the critical train speed.

Comparing Vibtrain results with ωFE-N (Ülker-Kaustell 2016) for the Ostlänken case, there is good agreement for unreinforced subsoil cases, but differences arise for reinforced subsoil due to inclusion of individual lime cement columns in the ωFE-N model and the use of the equivalent stiffness modulus in VibTrain.

The study shows the importance a realistic description of the track and subgrade properties and also the need for developing a load description capturing the main features of the planned train types for the new railways in Sweden.

In addition to the vertical load there is also need for a demand metric for irregular rail induced horizontal and vertical motions which can affect the long term behaviour of the track and subgrade response, and environmental vibrations.

Finally we emphasize the urgent need for new field tests ("Ledsgård 2.0") at speeds over 300 km/h for evaluating the accuracy of modern analysis tools and more importantly our geodynamical knowledge.

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