An open-source finite element approach complementary to a data-driven approach for assessment of line-infrastructure

Une méthode d'éléments finis open-source complémentaire a une approche basée sur l'analyse des données pour évaluer les infrastructures de ligne

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ABSTRACT: The correct assessment of the condition of line infrastructure is of vital importance for the modern society. Line infrastructure stimulates economic grow, enables trading operations and connects people. Disruptions on the services provided by line infrastructures (e.g. gas, water, telecommunication, transportation) can have a severe impact on its availability which can lead to significant economical and societal consequences. This paper proposes a hybrid methodology for the geotechnical assessment of line infrastructure, by combining an open-source finite element model with a data data-driven approach. This methodology is applied to a section of the Dutch railway network (120 km), in which the long-term displacement caused by train services is computed. The finite element model has been developed with a focus on computational performance, since a network analysis requires a large quantity of calculations. Axle acceleration measurements of a train are used to optimise the numerical results and improve the prediction of the long-term displacement, illustrating the added value of the proposed methodology. The proposed methodology can easily be adapted to study other line infrastructure applications.

RÉSUMÉ: La bonne évaluation de l'état de l'infrastructure de ligne est d'une importance vitale pour la société moderne. L'in frastructure de ligne stimule la croissance économique, permet des opérations commerciales et connecte les personnes. Des p erturbations sur les services fournis par les infrastructures de ligne (par exemple, le gaz, l'eau, les télécommunications, les tr ansports) peuvent avoir un impact sévère sur leur disponibilité, ce qui peut avoir des conséquences économiques et sociétale s importantes. Cet article propose une méthodologie hybride pour l'évaluation géotechnique des infrastructures de lignes, en combinant un modèle d'éléments finis open-source avec une approche basée sur l'analyse des données. Cette méthodologie a été appliquée à une section du réseau ferroviaire néerlandais (120 km), dans laquelle le déplacement de long terme causé pa r les services ferroviaires est calculé. Le modèle d'éléments finis a été développé en mettant l'accent sur sa performance de calcul, car une analyse de réseau nécessite une grande quantité de calculs. Les mesures d'accélération axial d'un train sont ut ilisées pour optimiser les résultats numériques et améliorer la prédiction du déplacement de long terme, illustrant la valeur aj outée de la méthodologie proposée. La méthodologie proposée peut facilement être adaptée pour étudier d'autres applications d'infrastructure de ligne.

KEYWORDS: open-source, finite-element, railways, data-driven, model-driven

1 INTRODUCTION.

Currently, the fourth industrial revolution is well on its way, computational power keeps increasing, automatisation of processes is getting more popular and the amount and accessibility of datasets grows. This also applies to the geotechnical field. In the Netherlands, thousands of cone penetration tests and borehole data are publicly available. Furthermore, geophysical datasets, geological models and digital information regarding the condition of line infrastructure is available.

Typically, either of two approaches are used to help network infrastructure managers with their operational activities; a model-driven approach or a data-driven approach. The model-driven approach is based on analytical and/or numerical models that describe the physical system whilst the data-driven approach uses sensor-data that monitors the infrastructure asset.

Although the amount of available data is increasing, the amount is not yet enough to make accurate predictions of the status of the entire infrastructure asset using data-driven approaches such as machine learning and data-fusion; therefore, a model-driven approach is often preferred. However, a model-driven approach is highly time consuming, and its parametrisation has the same limitations as the data-driven approach, since not enough data is available to accurately parametrise a model at network level. Furthermore, scalability is often a problem for model-driven approaches, due to the limited available computational power. In this paper a hybrid methodology is proposed where a data-driven approach and a model-driven approach are combined to enhance model predictions of line-infrastructure. All the models developed within the hybrid methodology are open-source and can be found in (Noordam & Zuada Coelho, 2021).

The proposed methodology can be used in several line-infrastructural applications such as: roads, railways and pipelines. In this paper the methodology is illustrated through a railway network analysis. In this application, the goal is to predict the permanent railway track displacement due to regular train traffic.

2 MODEL DESCRIPTION.

In this section the numerical and data-driven models are described. The numerical model consists of two parts; the dynamic train-track interaction model and the long-term cumulative settlement model.

2.1 *Dynamic train-track interaction model*

The dynamic train-track interaction model is based on the model described in Zhai & Sun (1994). A schematic representation of the model is shown in Figure 1.

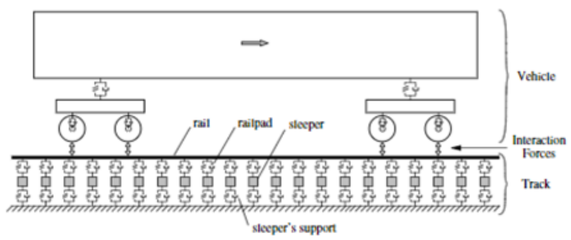

Figure 1. Schematisation of the dynamic train track interaction model (Zuada Coelho *et al.*, 2021).

The dynamic train-track interaction model consists of two separate systems: a train system and a track and subsoil system. The train system is a model which consists of masses and linear springs and dampers. In Figure 1 the train model is shown which consists of one wagon, which is modelled as a moving mass. The wagon is connected with springs and dampers to two bogies, which are also modelled as moving masses. The bogies are connected with springs and dampers to the wheels which are modelled as moving masses. Note that the configuration of the vehicle is not limited to the one as shown in Figure 1, but it can be extended to take into account different axle configurations.

The track and subsoil system consist of a two dimensional finite element system. As the numerical model is to be used at network level, it needs to be computationally efficient. Therefore the finite element system solely consists of rod elements, Timoshenko beam elements and masses. The rail is modelled with Timoshenko beam elements. At every 0.6 m, the rail elements are connected to railpads. The railpads are connected to the sleepers and the sleepers are connected to the sleeper's support, both by rod elements. The sleeper's support represents a combination of ballast bed and subsoil and is modelled as a spring damper element.

The dynamic stiffness and damping of the sleeper's support are determined by the cone-model based on one-dimensional wave propagation (Wolf & Deeks, 2004). The calculated dynamic stiffness and damping for railway loading depend on the subsoil layering and geomechanical properties and train velocity (Zuada Coelho *et al.* 2021).

As the full system consists of two dynamic sub-systems, the system is solved with a customised incremental Newmark solver. At each time step, interaction forces between the train system and the track system are calculated using Hertzian contact theory (Eq. 1 and Eq. 2) (Zhai & Sun, 1994).

$$F_{w,i} = k_c \delta_i^{3/2} \quad (1)$$
$$\delta_i = u_{v,i} - u_{t,i} - \eta_i \quad (2)$$

where $F_{w,i}$ is the contact force at wheel i; k_c is the generalised stiffness coefficient; δ_i is the indentation at wheel i; $u_{v,i}$ is the displacement of wheel i; $u_{t,i}$ is the displacement of the rail at the location of wheel i; η_i is the irregularity of the rail at the location of wheel i.

2.2 *Cumulative settlement model*

Results of the dynamic train track interaction model are used as input for the cumulative settlement model. The used cumulative settlement model is described in detail in Varandas *et al.* (2014). This model is a semi empirical explicit settlement model for the ballast, which is a function of the number of load cycles and the amplitude of the applied force in the ballast. Below the complete formulation is written:

$$u_n = \frac{\gamma}{M_{\alpha\beta}} \int_0^{\bar{F}_n} F^\alpha \left(\frac{1}{h(F)+1}\right)^\beta dF \quad (3)$$
$$S_N = \sum_{n=1}^{N} u_n \quad (4)$$

where u_n is the permanent deformation after one loading cycle; α, β and γ are ballast material parameters; F is the force; $\bar{F}_n$ is the amplitude of the force from the sleeper to ballast at loading cycle n; $h(F)$ is the history of the load. Each deformation u_n is summed to calculate the total permanent deformation S_n. The parameter $M_{\alpha\beta}$ is a normalisation parameter and is calculated by:

$$M_{\alpha\beta} = \frac{F_0^{\alpha+1}}{\alpha+1} \sum_{n=1}^{N_0} \left(\frac{1}{n}\right)^\beta \quad (5)$$

where F_0 is the reference load amplitude and N_0 is the reference number of cycles.

2.3 *Data-driven model*

The data driven model consists of an inverse analysis where the numerical results are optimised with experimental results. The inverse analysis is performed using the Levenberg Marquardt method (More 1977), which is a method to solve non-linear least square problems.

3 CASE STUDY: RAILWAY NETWORK

3.1 *Site description*

The studied railway track is located between Amsterdam and Eindhoven in the Netherlands. This track has a length of approximately 120 km. The track is used by different kind of passenger trains and cargo trains.

The railway line presently consists of a double track railway with standard gauge, and it is loaded every service hour with four intercity trains (Double Decker) and four local trains (Sprinters) in each direction, 16 hours per day. It is assumed that 27 cargo trains (with 10 wagons) pass per day. Each train has a different configuration and mass, stiffness and damping parameters. It is assumed that the travelling speed of all trains is 140 km/h.

The track is divided in 90 segments which are chosen following a stochastic subsoil schematisation (Hijma *et al.*, 2015). as proposed in Zuada Coelho *et al.*, (2021). Each segment represents a section of the railway track railway where the subsurface had a similar formation process.

Within each segment, an average of 5 different subsoil scenarios are presented, resulting in a total of 433 scenarios for the studied network section. The soil parameters are estimated based on geotechnical site investigations tests. These are the input for the calculation for the dynamic stiffness and damping for the sleeper's support, as described in Section 2.1.

3.2 *Data description*

Along the track, multiple datasets are available which can be used to improve the numerical model: Interferometric synthetic aperture radar (InSAR) which can be used to map height changes, loaded track deformation measurements and axle accelerations of a moving train. While each dataset can be used to make better predictions, this paper focus on the use of axle acceleration measurements to improve the dynamic train-track interaction model.

Figure 2 presents data measured with an accelerometer on the front axle of a moving train along one segment of the railway track. The top figure shows the velocity of the train and the bottom figure shows the acceleration of the front axle.

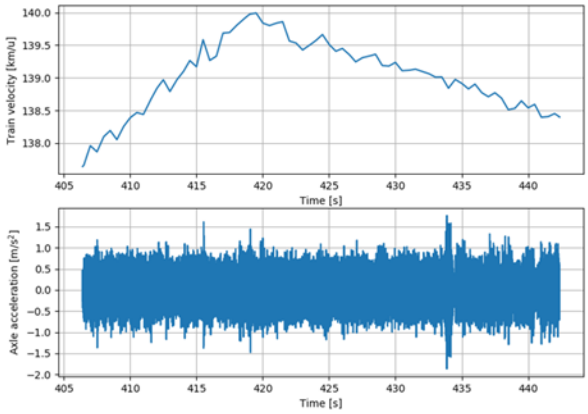

Figure 2. Time history of: (top) train velocity and (bottom) axle acceleration measurements.

4 ASSESSMENT OF RAILWAY TRACK SETTLEMENT

4.1 *Model-driven results*

The dynamic response of the three types of trains is calculated for each of the 433 scenarios, making a total of 1299 computations with the dynamic train-track interaction model, presented in Section 2.1. The dynamic responses following each train type are combined in the cumulative settlement model per scenario, i.e. 433 calculations are performed with the cumulative settlement model, presented in Section 2.2. For each segment, the cumulative settlement resulting from each scenario is used to calculate the mean and the standard deviation of the cumulative settlement after one year of train traffic within the segment.

Figure 3 shows the cumulative settlement after one year of train traffic along the railway track. The solid line represents the mean cumulative settlement resulting from passenger trains; the dotted line represents the mean cumulative settlement resulting from passengers and cargo trains. The transparent shading around the mean cumulative settlement represent the 95 % confidence interval. A distance of 0 km corresponds to city Amsterdam, whilst a distance of 120 km corresponds to the city of Eindhoven.

The total calculation time for the entire section of network was 360 minutes, using a i7500CPU 32GB RAM, which illustrates the good computational performance of the model.

From Figure 3, it follows that the cargo trains have a large influence on the long-term cumulative settlement of the railway track. That is because cargo trains are heavier than the passenger trains, and because the cargo trains have more wagons, therefore transmit more loading cycles to the track.

Furthermore, it can be seen that the 95% confidence interval around the mean settlements are relatively narrow compared to the total value. That is because the calculated subsoil scenarios per segment vary in layering but not in the soil parameters per layer. The shown confidence interval does not take into account the local spatial variability of the subsoil parameters. In order to get more certainty regarding the settlement prediction, the numerical model needs to include local information about the soil parameters. This can be achieved by incorporating additional datasets, e.g., from measured InSAR data and loaded track deformation data.

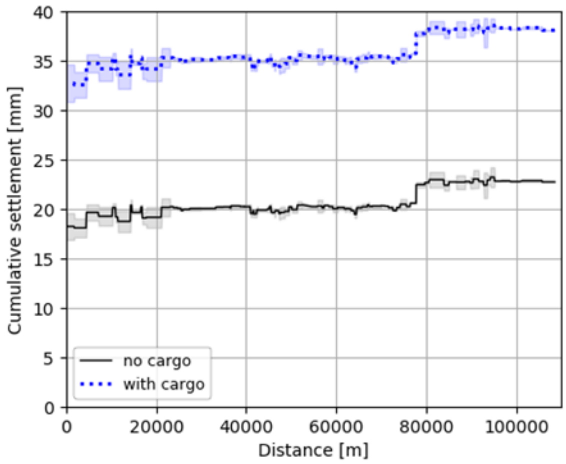

Figure 3. Cumulative settlement of the train track versus distance. The shading represents the 95% confidence interval within the segment due to the stochastic subsoil characterisation.

4.2 *Data-driven results*

The acceleration data contains energy in frequencies up to 250 Hz. The high frequency content results from the irregularities in the contact between wheel and rail, which have not yet been contemplated in the current model.

The object of the current study is to model the interaction between the track and subsoil, through the sleeper support force. Therefore, the relevant frequency is the frequency in which the sleeper is maximally loaded, i.e. the frequency of the front wheel driving over a sleeper. The sleepers are located 0.6 m from each other and the average train velocity within the analysed segment is 139 km/h (see Figure 2). This results in a dominant frequency for this segment of 64 Hz.

The acceleration data is integrated to a velocity signal, and the signal is smoothed over a wavelength of 10 m. These operations facilitate the numerical optimisation procedure. The force in the sleeper support is back calculated from the amplitude of the axle velocity signal at the sleeper passing frequency: 64 Hz. In order to retrieve this amplitude from the velocity signal, a Fast Fourier Transformation is performed. Figure 4 shows the velocity amplitude in the frequency domain.

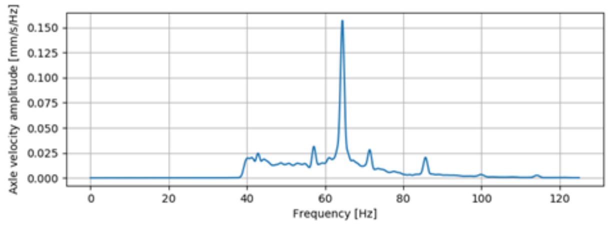

Figure 4. Axle velocity in the frequency domain.

From Figure 4 it can be seen that at a frequency of 64 Hz, the axle velocity amplitude is 0.16 mm/s/Hz. This approach has been reproduced for the remaining segments of the railway track.

4.3 *Hybrid model results*

The hybrid model results from the combination of the model-driven with the data-drive results. These models are combined my means of the inverse analysis as described in Section 2.3.

For the inverse analysis, the sleeper support stiffness is iteratively optimised. The target of the inverse analysis is the front axle velocity amplitude at the sleeper passing frequency which for the segment in analysis corresponds to an amplitude of

0.16 mm/s/Hz at the frequency of 64 Hz. Figure 5 shows the converging pathway of the solution.

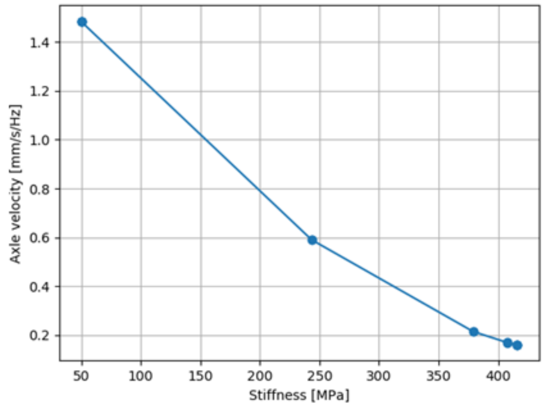

Figure 5. Inverse analysis converging pathway, Axle velocity versus stiffness.

From Figure 5, it can be seen that within 5 iterations, convergency occurs for the dynamic stiffness, at 416 MPa. The resultant dynamic stiffness of 416 MPa is applied to the sleeper support in the dynamic train-track interaction model. The cumulative settlement model is then used to recalculate the cumulative settlement after one year, while taking into account both passenger trains as cargo trains. Figure 6 presents the comparison between the initial predicted and the updated long-term cumulative settlement for the segment in analysis.

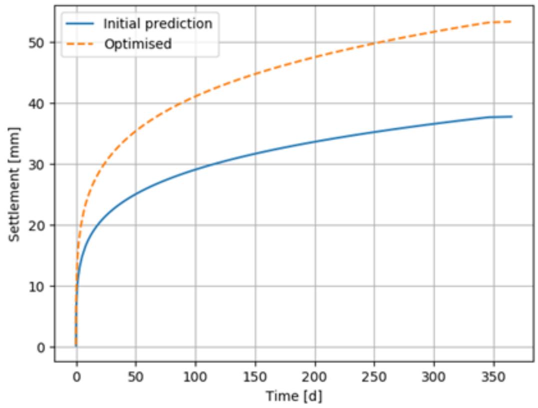

Figure 6. Time history of the cumulative settlement. Comparison between the initial prediction of the dynamic stiffness and the optimised dynamic stiffness.

From Figure 6 it follows that the optimised dynamic stiffness has significant influence on the cumulative settlement after one year of train traffic. Where using the first guess of the dynamic stiffness results in a settlement after one year of 38 mm, using the optimised dynamic stiffness results in a total settlement of 53 mm.

5 CONCLUSIONS

This paper presents an open-source hybrid model for the assessment of line infrastructure (Noordam & Zuada Coelho, 2021). This model combines a model-driven (finite element model) with a data-driven approach where experimental data is used to improve the model results. The applicability of the hybrid model is illustrated through a case study regarding the assessment of a railway track settlement. In this case study, the cumulative settlements after one year of train traffic are calculated along a section of 120 km of rail track.

The proposed hybrid model has shown to be valuable for network analysis where many calculations need to be performed. In the presented case study, 1299 dynamic finite element calculations were performed in 360 minutes, which illustrates the applicability of the model to assess infrastructure at network level.

In order to improve the prediction of the cumulative settlement after one year of train traffic, the numerical model is combined with axle acceleration data. This data is used to optimise the dynamic stiffness along the railway track, which in turn is used to compute the updated cumulative settlement. This was illustrated for a segment of the network, where it was found that the new estimation of cumulative settlement is 40% higher, in respect to the initial guess.

This paper shows that it is feasible to assess the state of infrastructure at network level, taking into account the spatial variability along the infrastructure. The results of such analysis can help infrastructure managers to improve their operational activities and provide insight into the current and future state of their infrastructure asset.

At the moment, the cumulative model only takes into account the ballast deformation. In the future a model incorporating subsoil deformation, that accounts for the cyclic subsoil deformation, will be added to the hybrid model. Moreover, additional datasets will be added to the data driven approach in order to improve the long-term prediction of the cumulative settlement.

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