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Dynamic performance of railway subgrade under high-speed train running using elaborate numerical simulation

Performance dynamique de la plate-forme ferroviaire sous train à grande vitesse en utilisant une simulation numérique élaborée

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ABSTRACT: The optimized matching of train and infrastructure plays an extremely important role in the design of high-speed train and railway subgrade. In this paper, the fully coupled elaborate three-dimensional train-track-subgrade-foundation model consisting of car body, bogie, wheelset, track, subgrade and foundation was established. All the components of the model were constructed with three dimensional solid element except the fastener simulated by spring and dashpot element. The material nonlinearity, the wheel-rail rolling contact nonlinearity and geometry nonlinearity were simultaneously taken into account in the analysis. The three dimensional static-dynamic unified viscoelastic artificial boundaries was introduced to model the infinite domain needed for the propagation of stress wave generated by the operation of the high-speed train. The construction procedure of the subgrade and track system were modeled following the generation of initial stress state in foundation soil. The train is modeled to accelerate from rest to the expected speed and then keeps running forward at this constant desired speed, the dynamic behaviours of the subgrade were then carefully investigated under this circumstance. It is expected that the stress waves due to wheel-rail rolling interaction propagate in all directions. The materials at different depth below the rail have different rate effect due to the impact of the wheels to the rails during the passage of the train, indicating that the materials experience repeated loading and unloading through their service period. This unique stress state may cause the materials to fatigue, and hence should be received enough attention in the design of the subgrade.

RÉSUMÉ: L'appariement optimal des trains et des infrastructures joue un rôle important dans la conception des trains à grande vitesse et de la plate - forme ferroviaire. Cet article établit un modèle tridimensionnel de fondation de la plate - forme de la voie ferrée, qui se compose de la carrosserie, du bogie, de l'essieu monté, de la voie, de la plate - forme et de la Fondation. Tous les composants du modèle ont été construits à l'aide d'éléments solides tridimensionnels, mais les attaches ont été simulées à l'aide d'éléments de ressort et de tampon. La non - linéarité du matériau, la non - linéarité du contact de roulement roue - rail et la non - linéarité géométrique sont prises en compte dans l'analyse. Une limite artificielle viscoélastique statique - dynamique unifiée tridimensionnelle est introduite pour simuler la région infinie nécessaire à la propagation des ondes de contrainte générées par l'exploitation des trains à grande vitesse. Le processus de construction de la plate - forme et du système de voie est modélisé en fonction de l'état de contrainte initial dans le sol de fondation. Le train est modélisé de façon à ce qu'il s'accélère de l'arrêt à la vitesse prévue, puis qu'il continue à cette vitesse constante prévue, puis qu'il étudie soigneusement les caractéristiques dynamiques de la plate - forme dans ce cas. On s'attend à ce que les ondes de contrainte dues à l'interaction roue - Rail se propagent dans toutes les directions. En raison de l'impact des roues sur le rail pendant le passage du train, les matériaux à différentes profondeurs sous le rail ont des effets de vitesse différents, ce qui indique qu'ils ont subi des charges et des déchargements répétés pendant leur utilisation. Cet état de contrainte unique peut entraîner une fatigue des matériaux, de sorte qu'une attention suffisante doit être accordée à la conception de la plate - forme.

KEYWORDS: Elaborate simulation; coupled train-track-subgrade; wheel-rail rolling contact; stress wave propagation; high-speed railway.

1 INTRODUCTION

High-speed railway is a fast and comfortable transportation mode in the world, it plays a significant role in modern life. The subgrade, which is filled and compacted layer by layer, serves as one of the infrastructures for railway line. During the passage of the train, the subgrade materials experience repeatedly loading and unloading. The materials can be caused to fatigue and gradually degrade after millions of train passage, so the efficient maintenance becomes more and more important. However, the maintenance measure should be conducted based on deep insight into the dynamic behaviors of the subgrade under train operation. The existing researches regarding the train-track-subgrade system (Bugár, 2015; Yang, et al. 2017; Zhai, et al. 2019; Lei, et al. 2017; Zhao, et al. 2018; and Mao, et al. 2021.) are demonstrated in Figure 1 and are based on these assumptions: (1) The dynamic responses are in vertical plane, and the lateral and longitudinal response are not considered; (2) The vehicle is a multi-body system composed of rigidity, mass point, spring, dashpot and beam element; (3) The wheel is treated as a point and the rail is regarded as a line modelled by beam element

(Euler–Bernoulli beam or Timoshenko Beam); (4) the vehicle is running at a constant speed and there is no acceleration process; (5) there is no stress state in the system before vehicle operation, et al. Under the above hypotheses, the wheel and the subgrade are regarded as a point, therefore, the wheel cannot roll on the rail because it has no volume, thus no traction force can be derived on wheel-rail contact area. Besides, no investigation can be conducted for the dynamic behavior of the subgrade because it is treated as a point without physical meaning.

It is conspicuous that the above-mentioned assumptions violate the fundamental laws of mechanics, the model is far away from reality. Field measurements conducted on high-speed railway also show that the dynamic response caused by train running are essentially three-dimensional. Therefore, the multi-rigid body model shown in Figure 1 is not suitable for simulating vehicle running on railway line. In this dilemma, it is urgent to perform the research on subgrade dynamics in more detail.

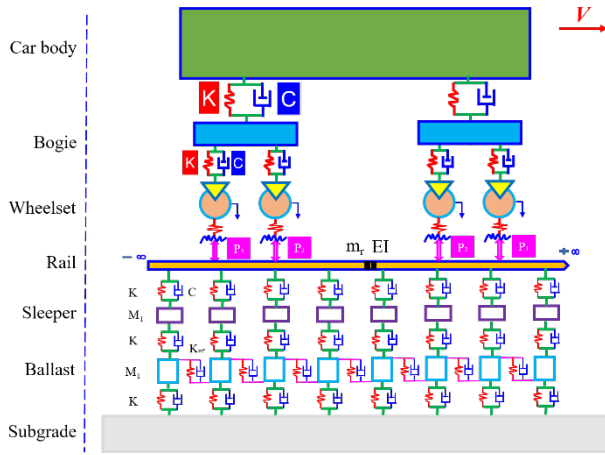


Figure 1. The widely used multi-rigid body model for coupled vehicle-track-subgrade system.

2 MODEL ESTABLISHMENT

2.1 Overview of the model

It is assumed that the railway line is straight in this analysis, the Chinese Code for design of high-speed railway (TB 10621-2014) is referred for developing the elaborate numerical model. There are four parts in the model, namely the vehicle part, the track part, the subgrade art and the foundation. Except the foundation, there are sub-part for other three parts, as illustrated in Figure 2.

2.2 Materials used in the analysis

2.2.1 Vehicle system parameter

The parameters used for vehicle are listed in Table 1.

Table 1. Vehicle parameters

Name	Unit weight kN·m ⁻³	Elastic modulus GPa	Poisson's ratio	Damping ratio	
			-	α/s^{-1}	β/s
Car body	28.0	71.0	0.33	0.106	0.0009
Bogie	78.0	206.0	0.28	0.106	0.0009
Wheel	78.0	206.0	0.30	0.106	0.0009
Axle	78.0	206.0	0.30	0.106	0.0009

2.2.2 Track system parameter

The parameters used for track system are listed in Table 2.

Table 2. Track system parameters

Name	Unit weight kN·m ⁻³	Elastic modulus GPa	Poisson's ratio	Damping ratio	
			-	α/s^{-1}	β/s
Rail	78.0	206.0	0.3	0.106	0.0009
Sleeper	24.0	30.0	0.3	0.317	0.0027
Slab	24.0	35.5	0.1	0.317	0.0027
CA Mortar	18.0	0.10	0.4	0.528	0.0044
Concrete base	24.0	30.0	0.1	0.317	0.0027
Fastener system		Dynamic stiffness: 46 kN/mm, Damping coefficient: kN·s/m			

2.2.3 Subgrade and foundation parameters

The main parameters for subgrade and foundation are listed in Table 3, some parameters are not included due to space limitation.

Boundary and initial conditions

The stress waves induced by wheel-rail rolling contact propagate in vehicle, track, subgrade and foundation, so the wave transmission boundary should be dealt with correctly. In this analysis, the verified three dimensional viscoelastic static-

dynamic unified artificial boundary with high precision and robustness is adopted to model the infinite domain (Xue et al., 2014).

Table 3. Vehicle parameters

Name	Unit weight kN·m ⁻³	Compressive modulus MPa	Poisson's ratio	Damping ratio	
			-	α/s^{-1}	β/s
Upper formation	19.5	190.0	0.3	0.844	0.0071
Lower formation	19.0	100.0	0.3	0.739	0.0062
Embankment	18.5	85.0	0.28	1.055	0.0088
Clay-1	18.0	9.2	0.3	0.844	0.0071
Clay-2	18.6	11.3	0.28	0.739	0.0062
Silty clay	19.3	13.2	0.29	0.689	0.0057
Silt	19.8	16.5	0.25	0.580	0.0049

2.2.4

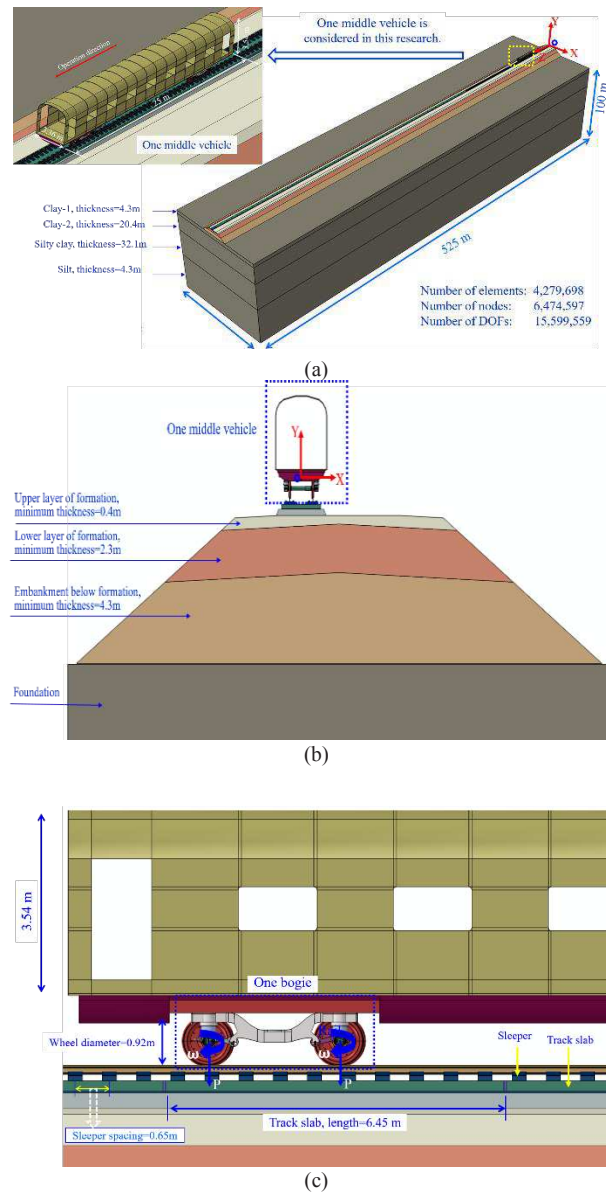


Figure 2. Elaborate model for coupled vehicle-track-subgrade-foundation. (a) Overview of the three-dimensional model; (b) Front view of the coupled system and (c) Close-up view of the bogie and track.

The stress state is generated in subgrade and track system due to gravity prior to vehicle operation, this state plays a crucial

role in following dynamic computation, so the generation of initial stress state is performed before vehicle running.

3 RESULTS AND DISCUSSIONS

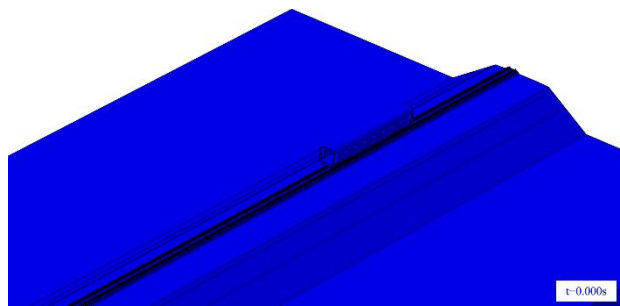
3.1 Development and propagation of stress wave

The stress waves field generated by wheel-rail rolling contact propagating in infrastructure are plotted in Figure 3, the wheel-rail interaction causes the strongest wave field near the bogies, but the intensity of stress wave is different around the front and rear bogie.

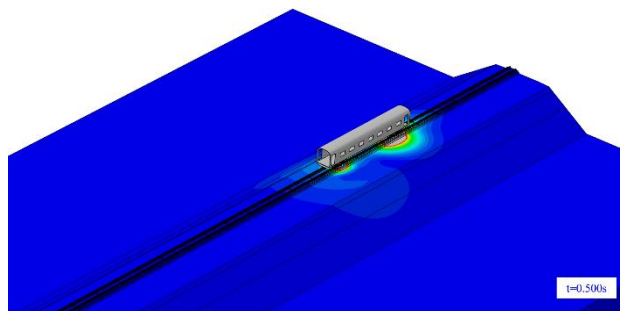
It should be emphasized that the intensity of stress is much higher in wheel-rail contact area than other position, so the stress intensity is limited to lower level in order to ensure the visibility of the wave field in subgrade and foundation.

Figure 3 shows the generation and evolution of stress waves propagating in all directions in subgrade and foundation. The intensities of wheel-rail interactions are different during the vehicle running process, causing different influence range in infrastructure.

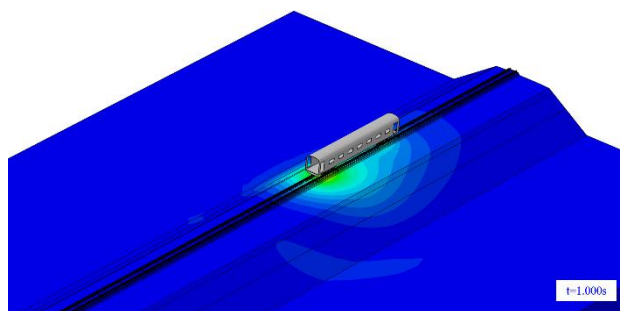
The influenced zone varies due to the changing of wave intensity. The stress waves propagate in front of the vehicle owing to the wave speed is faster than the operation speed of the vehicle (maximum speed is approximately 14 m/s in this analysis). The wave field is much stronger around the bogies all the time.



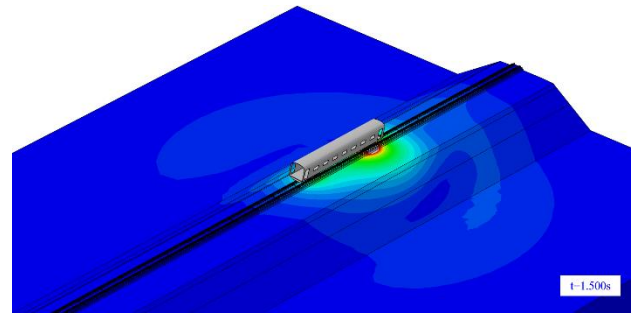
(a)



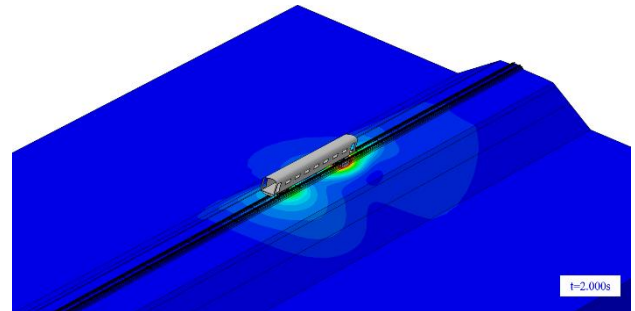
(b)



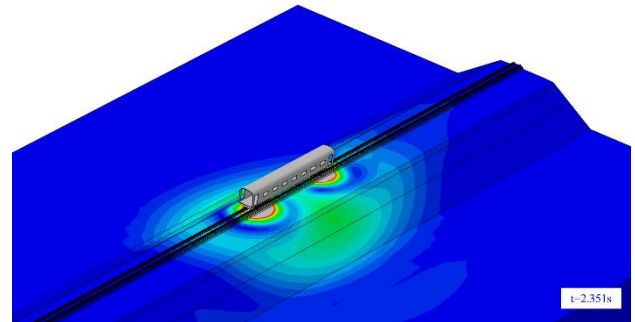
(c)



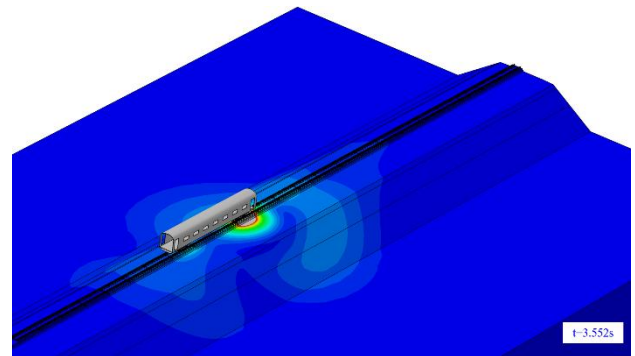
(d)



(e)



(f)



(g)

Figure 3. Development and propagation of stress wave in coupled vehicle-track-subgrade-foundation at different events. (a) 0.000s; (b) 0.500s; (c) 1.000s; (d) 1.500s; (e) 2.000s; (f) 2.351s and (g) 3.552s.

3.2 Rate effect analysis

The element in upper formation located below one of the rails is selected to analyze the stress response over time and the rate effect. For three-dimensional analysis, there are six stress time histories including three normal stress time histories and three shear stress time histories. Due to page limitation, only the vertical dynamic stress and its rate effect are analyzed in this paper, as shown in Figure 4.

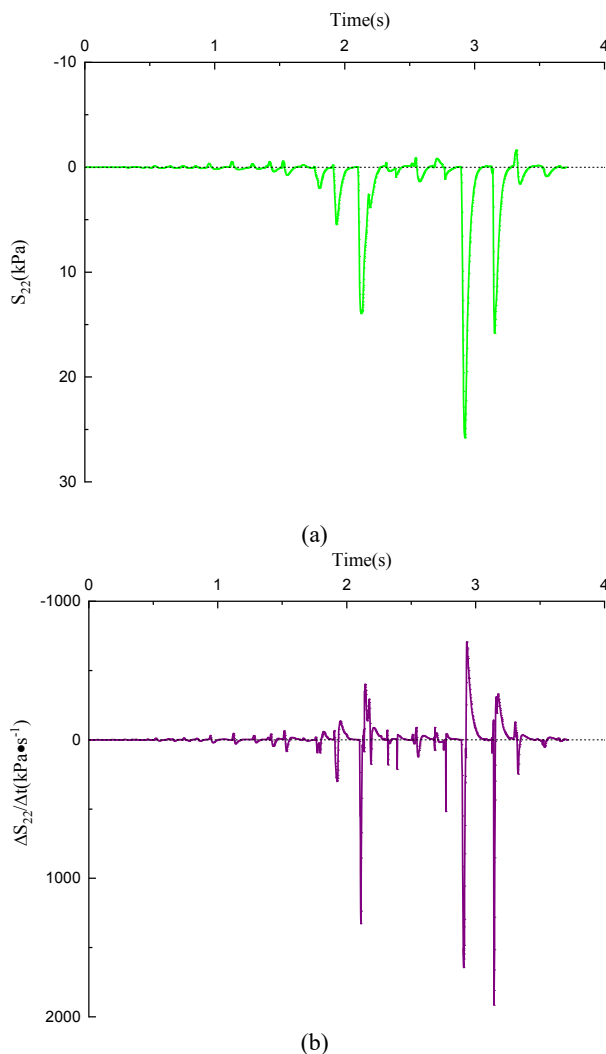


Figure 4. Stress response and rate effect. (a) vertical dynamic stress time history; and (b) rate effect of the corresponding element.

In Figure 4, the vertical dynamic stress demonstrates four peaks in the time history plot, corresponding to the four wheelsets of the vehicle. The peak values are different and are between 10 to 25 kPa, the value is consistent with the measured data in Chinese railway line (China academy of railway science, et al, 2011), indicating the correctness of the calculation

The rate effect of stress can be defined as the ratio of changes of stress in a given increment to the duration of the corresponding increment. For the selected element in upper formation, although the absolute value of vertical dynamic stress is small with maximum of 25 kPa, its stress rate effect is much higher with the maximum of 2000 kPa/s, showing the material experiences an intensive loading and unloading process. The repeated loading and unloading can cause material to fatigue. With the coupled temperature and moisture effects, the material can be caused to degradation gradually.

4 CONCLUSIONS

This study aims to investigate the three-dimensional dynamic behavior of subgrade under vehicle operation using elaborate numerical analysis. With nonlinearly-coupled vehicle-track-subgrade-foundation model and large scale computation, the main findings of this study include:

- The stress waves induced by the wheel-rail rolling contact propagate in all directions, and the wave field is much

stronger near the two bogies, the influence zone of wheel-rail impact is limited.

- The vertical dynamic stress in upper formation is at relative low level, but its rate effect can be very high. The repeated loading and unloading can cause infrastructure material to fatigue and even degradation.

5 ACKNOWLEDGEMENTS

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