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DISCRETE ELEMENT MODELLING OF SLEEPER-BALLAST INTERACTION UNDER IMPACT LOADING

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Abstracts. Generally, track structure experience impact load (also called "shock load") due to the irregularities of either wheel or rail. The impact load, that may greatly exceed the static wheel load, are mainly caused by wheel/rail abnormalities such as poor weld geometry, rail corrugation, and rail defects like spalling, wheel burns and squats. Impact load is transient by nature which occurs over a short period with a high magnitude. This corresponds to the frequency range from 0 to 2000 Hz. In fact, ballast is a nonhomogeneous and discontinuities by nature. Based on literature, the conventional method, continuum modelling, cannot provide insight into the interaction of ballast particles. Hence, continuum modelling should be replaced by discrete element modelling (DEM) which has a finite number of ballast particles. The discrete element modelling is an approach to present the discontinuity of material. The ballast particles with various radii are modelled in LS-DYNA. The spherical shapes are modelled instead of polyhedral due to the lower cost of computational time and memory consumption. Even though the spherical model has limitation on the contact interlocking, this can be compensated by adopting the contact model. One bay ballasted track modelling has been conducted. The impact load associated with actual train load is applied on the rail. The interaction between sleeper and ballast are highlighted. Moreover, sleeper and ballast particle movement are presented. This study will provide greater insight into the ballast particle and the sleeper motion induced by impact load associated with actual train load.

1 INTRODUCTION

Railway ballast track, which has been widely used throughout the world, typically comprises rails, sleepers, fastening system, ballast, sub-ballast and subgrade. This type can be divided into two main components: superstructure and substructure. Superstructure, which is a multilayered construction supported by substructure, consists of rails, sleepers, fastening system and ballast. While, substructure includes sub-ballast and subgrade [1-2]. It is known that ballast is placed between superstructure and substructure. The duties of ballast are to transfer the load from superstructure to underlying structure, to provide stability of the track, to support sleepers uniformly, to absorb noise and vibration, to provide drainage system etc [3-6]. It is noted that ballast is one of the prone area to experience deteriorations which lead to track deterioration.

Previously, it was believed that the continuum method was capable to solve all the engineering problems [7]. However, it has been proven that this method cannot be used to solve some problems as this is only useful for solving homogeneous material [8-10]. By nature, the interactions among ballast aggregate particles are mostly discontinuous. Ballast shapes are sharp, angular, complex, and irregular. Since railway ballast normally consists of large particles of typical size approximately 40-60 mm, it is difficult to treat such a material as a continuum. It can be seen in many literatures that this approach could not perform the particle behaviour and difficult to highlight any significant phenomena such as particles interaction, ballast fouling, ballast breakage etc. Thus, discrete element modelling (DEM) is an alternative method, which was firstly introduced for rock and soil materials [11]. This approach is a numerical method for computing the motion and effect of a large number of small particles with its interactions in a granular assembly. The discontinuous behaviour can also be included. DEM can provide insight into the micro-mechanical behaviour of railway ballast.

Railway track is usually subjected to dynamic impact load. Such load is a large magnitude applied over a short period. This may induce damage in railway track. It is noted that the typical impact load varies between 100kN to 750kN. Based on field works and many literatures [12-20], it can be seen that the dynamic impact loads are caused by the irregularities of wheel or rail as well as the resonance effect produced among the track components [1]. It should be also noted that the impact capacity of sleepers can be reduced due to the modification of their cross section [21-24] and time-dependent behaviour [25-27].

A three dimensional finite element model was firstly conducted using ANSYS [28-30]. This model was validated by full-scale experiment based on the European standard [31]. The three-dimensional finite element software LS-DYNA was then used to analyze the dynamic responses of single bay ballasted track. The model has been validated against experimental drop impact tests [32-34]. This study presents the dynamic responses and sleeper-ballast interaction under impact loading. The outcome of this study can help improve the understanding of ballast movement of each particle under impact loading.

2 MODELLING

In this study, finite element package LS-Dyna is used to analyze the dynamic response of single span ballasted track. The sleeper and rails are modelled by solid element with eight nodes with three degree of freedom (translation). Truss element is used to model the prestressing wires by assuming perfect bond between prestressing wires and concrete. It should be noted that truss element cannot resist bending moment and shear force. The modulus of elasticity of concrete (f'_c) was estimated based on AS3600 [35]. The material properties of each element are shown in Table 1.

Table 1 Material properties of ballasted track.

Parameters	Characteristic value	Unit
Rail		
Modulus of elasticity	200000	MPa
Density	7870	Kg/m^3
Possion’s ratio	0.25	
Sleeper		
Concrete		
Modulus of elasticity	98000	MPa
Density	2400	Kg/m^3
Possion’s ratio	0.2	
Prestressing wire		
Modulus of elasticity	200000	MPa
Density	7850	Kg/m^3
Possion’s ratio	0.25	
Rail pad		
Modulus of elasticity	1250	MPa
Density	960	Kg/m^3
Possion’s ratio	0.42	
Ballast		
Layer thickness	30	cm
Modulus of elasticity	1000	MPa
Density	2600	Kg/m^3
Possion’s ratio	0.3	
Diameter	20-50	mm
Spring constant (Tangential)	1	
Spring constant (Normal)	0.3	
Damping constant (Tangential)	0.7	
Damping constant (Normal)	0.4	
Friction coefficient	1	
Rolling friction coefficient	0.3	

The extended finite element model was calibrated using vibration data [30, 36]. The updated finite element model was then transferred to LS-Dyna [33, 34], as shown in Figure 3. The simulation results were achieved by assigning the initial velocity to the drop mass to generate an impact event, similarly to the actual drop tests.

The ballast particles were firstly generated and packed into the cubic element. The contacts between each particle were assigned in terms of spring and damper by keyword *CONTROL_ DISCRETE_ELEMENT. The friction coefficient can be also applied. The contacts between each component were assigned using keywords *CONTACT_AUTOMATIC_SURFACE _ TO_ SURFACE and *CONTACT_AUTOMATIC_NODES_TO_SURFACE. The friction coefficient between rails and sleepers, sleeper and ballast, were 0.3 and 0.3, respectively. The contact interactions were defined using keywords *CONTROL_DISCRETE_ELEMENT. The contact parameters are shown in Table 1. The schematic contact between each particle is shown in Figure 1. It should be noted that the friction and rolling coefficient were applied into the contact between the ballast in order to compensate the disadvantage of spherical element.

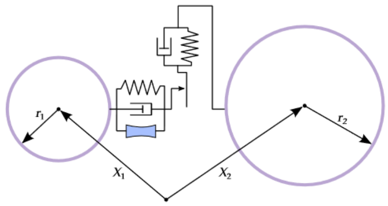


Figure 1 Schematic contact between each ballast particle [37].

It is noted that particle size varied between 20-50 mm were packed randomly into the concrete box, as shown in Figure 2. The gravity acceleration (9.81m/s^2) was applied to the ballast, sleeper and rails before applying the velocity to the impactor. It should be noted that ballast, sleeper and rails felt down freely without constraint in any directions. The velocity of impactor was 1.94 m/s which equivalent to the drop height 0.2 m the test rig [32-34]. The modeling has been validated against experiment. It was found that the finite element model was fairly sufficient for use in predicting impact responses. The trends of peak acceleration responses are quite close to the experiment obtained [32-34], although there is certain phase and pulse duration differences.

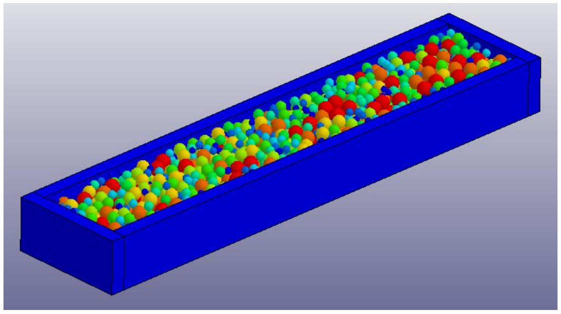


Figure 2 Various size of ballast packed into concrete box.

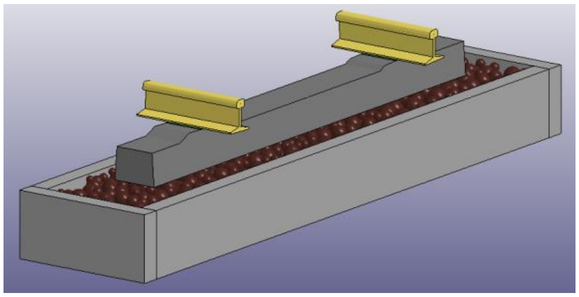
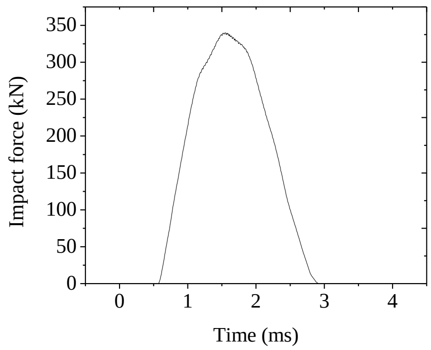


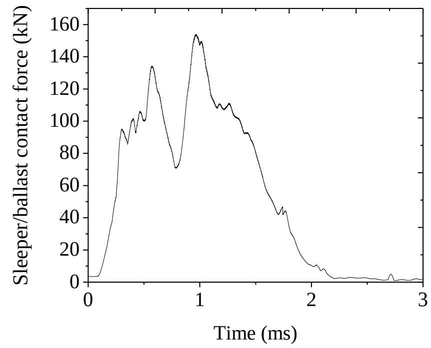
Figure 3 Finite element modelling of railway ballast track.

3 RESULTS AND DISCUSSIONS

The contact force between sleeper and ballast is shown in figure 4a. It is observed that about 340 kN is the contact force between sleeper and ballast due to the applied velocities of drop mass of 1.94 m/s. It is also noted the pulse durations is about 2.6ms. While, the maximum sleeper/ballast contact force is about 150 kN, as seen in figure 4b.



a) Impact force



b) Sleeper/ballast contact force

Figure 4 Contact force between sleeper and ballast.

Figure 5 presents the displacement contour at time of 0.64s and the displacement time history of sleeper at rail seat and mid-span. It should be noted that all components are in equilibrium within 0.5s after applying gravity acceleration. The result shows that the positive displacement is observed so that there is a slight uplift of sleeper at rail seat during unloading. The permanent displacement is also observed after all components are in equilibrium at about 0.9s due to the settlement and packing of ballast. The displacement of sleeper at rail seat (loaded side) is larger than that at mid span and another rail seat.

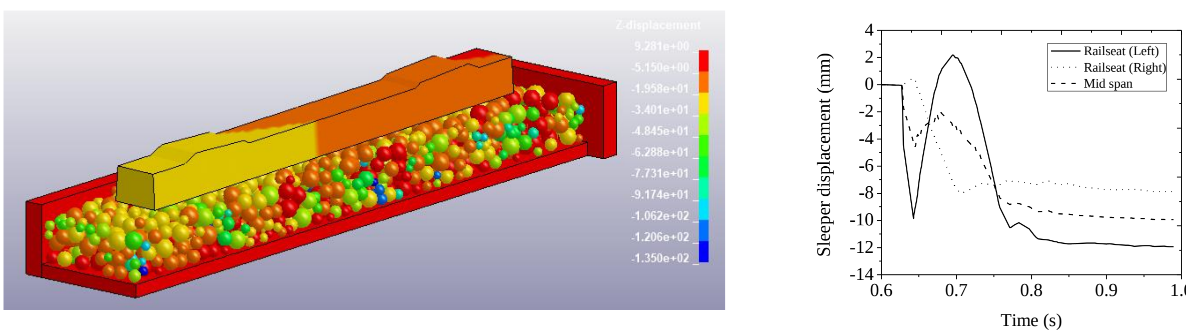
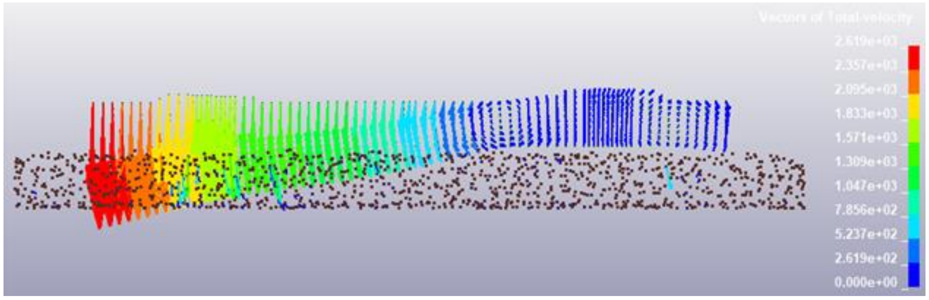
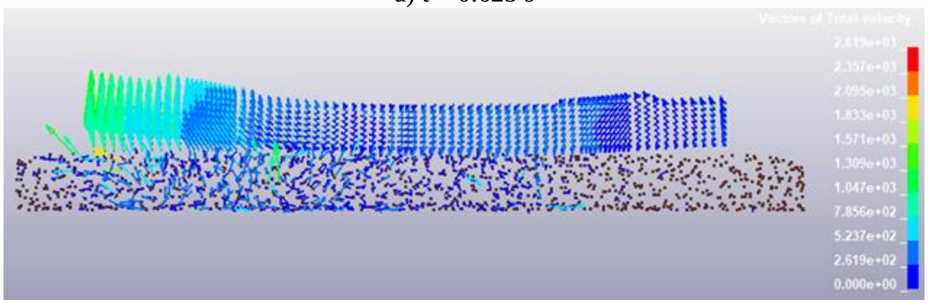


Figure 5 Vertical displacement contour and sleeper displacement time history.

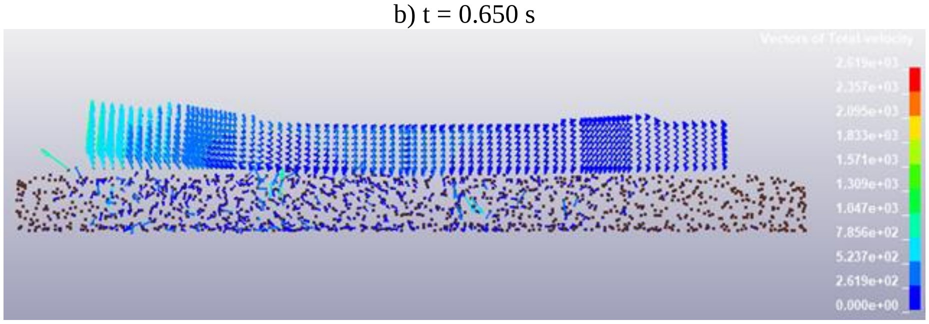
The movements of ballast particles and sleeper at each node are presented in terms of displacement vectors as shown in figure 6. Figure 6a displays the ballast and sleeper responses at the initial stage under gravity. Figure 6b-d shows the responses of ballast and sleeper under impact loading at each time step. It should be noted that the displacements contour and vector are cumulatively presented from the starting of applied gravity acceleration so that the displacements displayed are not due to only impact loading but also gravity at the first stage. Hence, figure 6 illustrate the node vector velocities of ballast and sleeper instead of displacement as it can show the behaviour at particular time. It is clearly seen that sleeper and ballast on loaded side moves down significantly and tends to lift up when unloading as previously describe. It is finally seen that ballast has a permanent settlement which lead to the permanent settlement of sleeper. These can be compared to the time history response obtained in figure 5.



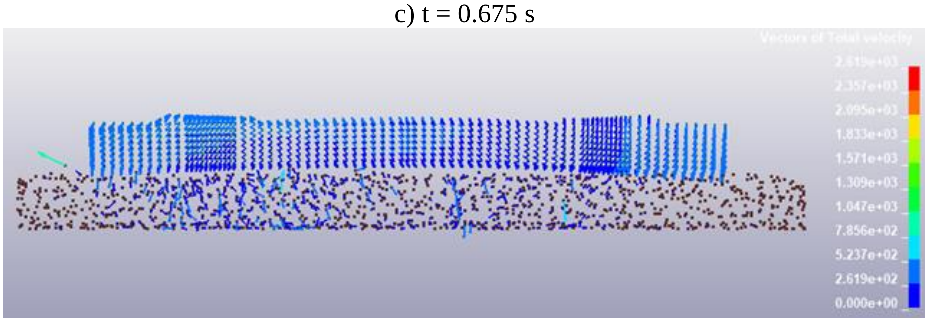
a) t = 0.625 s



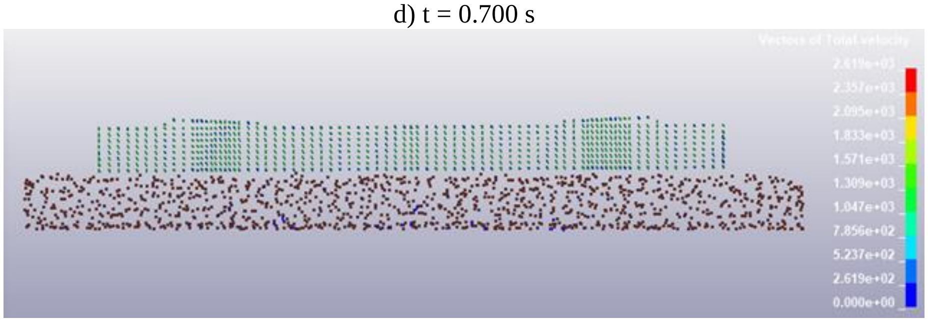
b) t = 0.650 s



c) t = 0.675 s



d) t = 0.700 s



e) t = 0.100 s

Figure 6 Velocity vectors of ballast and sleeper at each time.

It should be noted again that this study did not consider the lateral resistance of sleeper as we only consider the vertical movement. However, due to the random placement of various size of ballast, sleeper was not completely flatly placed on ballast bed. Also, in fact, longitudinal rail and fastening system can considerably constrain the movement of sleeper in longitudinal and transverse directions and they may also help reduce uplift effect.

4 CONCLUSIONS

Discrete element modelling (DEM) is an alternative method to take into account the nature of granular and heterogeneous materials. This method has been firstly used for granular material and then adapted to railway ballast. This method is very useful and powerful as it provides the multi scale mechanic behaviour and the movement of each ballast particle. A commercial finite element package, LS-Dyna, has been employed to extend the model for impact analysis and it has been validated against experimental drop impact tests. The spherical particle was employed since it can provide a better computational time and memory consumption than polyhedral. Although the simple spherical cannot provide insight into the real shape and particle contact, this can be fitted by adapting the proper contact coefficient between each particle. In fact, railway track normally experiences impact load, which is a shock load applied in short duration, due to the irregularities of either wheel or rail. It should be noted that the magnitude is much higher than static load. Thus, the vertical velocity of drop mass of 1.94 m/s associated with actual train loads was applied to the rail. It should be noted that this equivalents to about 340 kN. The results show that the maximum displacement occurred at rail seat under impact load while the displacement on another side of rail seat is lower than that at mid-span. The permanent deformation of sleeper is also observed. This is because ballast particles are packed and settled and then sleeper is pressed down into the ballast bed. Moreover, it is noted that uplift of the sleeper is observed during unloading. It should be noted that the relative uplifts of the sleepers tend to cause deteriorations of railway tracks over time, such as ballast breakage, excessive dilation and densification, which can cause further track differential settlements. In fact, ballast can be broken and crushed due to the impact load which leads to severe track degradation. However, this study did not consider ballast breakage. Hence, it is recommended to take into account the spherical cluster particle and ballast breakage under impact loading for further study.

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