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Ballast Vibrations and Deformations due to Different Train Loading Scenarios Studied using the Discrete Element Method

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Abstract: This paper focuses on the effects of different dynamic train loading patterns on the vibration and permanent deformation accumulation trends of railroad ballast. As opposed to a continuous sinusoidal load pulse often applied in cyclic triaxial tests, the actual dynamic train loading may have loading patterns of varying pulse shapes with rest periods. A validated ballast model, based on the Discrete Element Method and imaging based aggregate size/shape characterization, was used to simulate both continuous sinusoidal and moving wheel loading patterns of different train loading speeds or frequencies with and without rest periods between load pulses. The continuous sinusoidal loading resulted in larger ballast layer settlements in DEM simulations when compared to a more realistic moving wheel dynamic loading pattern that considered rest periods.

Keywords: Railroad Track, Dynamic Loading, Ballast, Vibration, Permanent Deformation, Discrete Element Method

1 Introduction

Ballast is an essential layer of the railroad track structure, and provides primarily drainage and load distribution. Understanding railroad ballast vibrations and deformation behavior is important for an adequate design, construction, and maintenance of the track structure. Although ballast materials are commonly specified as uniformly graded in size with angular particle shapes and crushed faces, ballast engineering properties, such as aggregate type and gradation, particle shape, texture and angularity, and particle hardness and abrasion resistance, can vary within certain specifications to influence the overall track behavior and performance. Other major factors affecting the behavior of ballast under repeated train loading include compaction state during installation, loading amplitude and frequency (or load pulse shape, duration and rest period) influenced by train speed, number of load cycles, stress history, and confining pressure.

Large-scale triaxial tests are traditionally performed in the laboratory to evaluate the individual effects on the ballast vibrations and deformation behavior (Suiker et al. 2005, Anderson and Fair 2008, Aursudkij et al. 2009, Indraratna et al. 2010). Ballast aggregates tend to harden and become stiffer under cyclic loading with the elastic or resilient modulus increasing gradually as the number of load cycles increases (Suiker et al. 2005, Lackenby et al. 2007). Most commonly a continuous sinusoidal load pulse is applied on the ballast samples in triaxial tests and the permanent deformation behavior or ballast settlement is evaluated at different frequencies to represent different train speeds. This approach is often deemed sufficient since in-situ measurements indicate greater ballast settlement is observed as the train speed increases, say from 150 km/h to 300 km/h as in the study by Kempfert and Hu (1999). Related modeling research using the Discrete Element Method (DEM) focuses on conducting numerical simulations of the tested samples as aggregate particle assemblies to investigate ballast behavior under continuous cyclic loading patterns (Indraratna et al. 2010, Lu and McDowell 2010). Note that as opposed to a continuous sinusoidal load pulse often applied in cyclic triaxial tests, the actual dynamic loading may have different loading patterns of varying pulse shapes with rest periods, according to axle spacings and car lengths, which may directly affect the vibration and deformation trends caused by a moving train at low, intermediate and high speeds (Huang et al. 2009).

This paper investigates effects of different dynamic train loading patterns on the vibration and permanent deformation accumulation trends of railroad ballast using a validated DEM modeling and simulation approach. The results from the dynamic, repeated train loading DEM simulations are intended to emphasize the need for utilizing realistic, similar to field experienced loading patterns to accurately predict the trends and magnitudes of vibrations caused and the permanent deformations accumulated in the railroad track substructure including ballast, subballast and subgrade.

2 Ballast discrete element model

With the objective to provide better engineering insight into the design of ballasted track, current ongoing research at the University of Illinois has developed a ballast performance model based on the DEM which uses rigid but random shaped “blocks” as the basic elements to realistically simulate interactions such as interlock/contact of actual aggregate particles (Tutumluer et al. 2007 and 2009, Huang et al. 2009). The ballast DEM model requires as input imaging based aggregate size and shape quantifications (see Figure 1). Among the various particle shape/morphological indices, the flat and elongated (F&E) ratio, the angularity index (AI), and the surface texture (ST) index, all developed using University of Illinois Aggregate Image Analyzer (UIAIA), are key indices (Rao et al. 2002, Pan et al. 2006). The image-aided DEM approach creates three-dimensional (3D) aggregate shapes as individual discrete elements based on the UIAIA scanned images. Using the technique, Figure 2 shows typical particles generated and used in the ballast DEM model. The ballast DEM model was calibrated in early research efforts with laboratory direct shear (shear box) strength test results and more recently validated with settlement measurements from full-scale test track (Huang et al. 2009; Tutumluer et al. 2011).

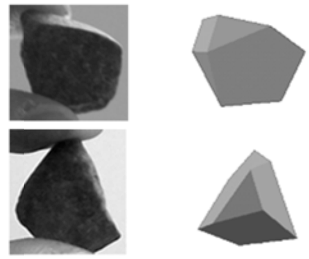


Fig. 1 Rigid polyhedron blocks used in the University of Illinois ballast DEM model

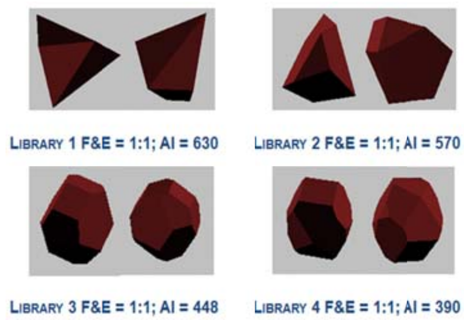


Fig. 2 Typical particle libraries used in the University of Illinois ballast DEM model

The validated ballast DEM model was used in this study to simulate loading patterns of different train speeds and/or repeated loading frequencies both with and without rest periods between the load pulses. Figure 3 shows the front view of a half-track model established for this purpose to predict ballast settlement under repeated train loadings. One half of a tangent track cross-section was used in the simulation to reduce the number of ballast particles and hence the computation time by taking advantage of the symmetry in both loading and geometry. Totally 4,609 particles were used to form a 45-cm thick ballast layer with one side having fixed boundary and the other side forming a 2:1 slope at the shoulder. The crosstie was a typical size used in the United States (US): 20.3-cm wide, 17.8-cm deep, and 259.1-cm long.

The aggregate gradation used in the ballast layer DEM simulation is shown in Figure 4. The particle shape indices quantified by UIAIA were representative of crushed stone ballast materials with an AI of 584 and an F&E ratio of 2.2. The ballast layer was compacted to a target void ratio of 37% as the initial condition.

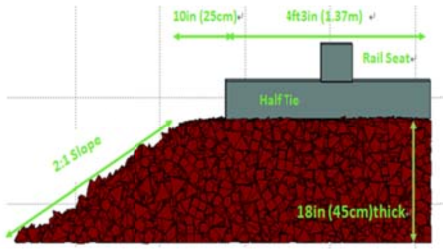


Fig. 3 Front view of half-track model

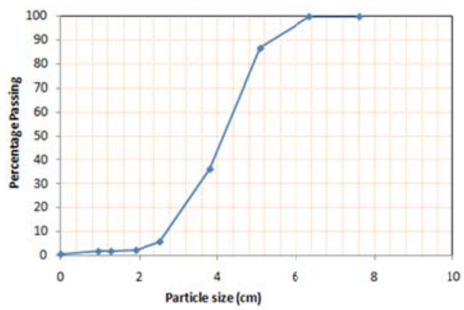


Fig. 4 Ballast material gradation used in the half-track DEM model

Totally six different loading patterns were studied for their effects on predicted settlements in the ballast layer DEM simulations as depicted in Figure 5. Continuous sinusoidal load pulses were applied first as train loading by means of different load frequencies to simulate different train speeds as suggested by Indraratna et al. (2010). The details about the sinusoidal loads can be found in Table 1 and Figures 5a and 5b. The minimum sinusoidal pulse was set to 45 kPa to represent the unloaded state of the tie, and the maximum ballast pulses are listed in Table 1.

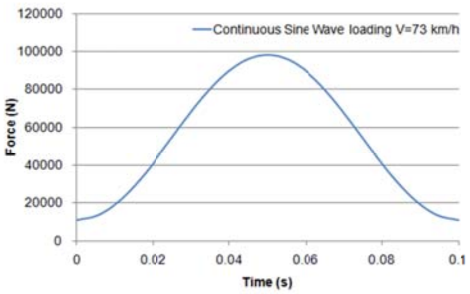
Table 1 Train loading at various speeds applied by means of continuous sinusoidal loads (after Indraratna et al. 2010)

Frequency (Hz)	Maximum Vertical Ballast Pressure (kPa)	Train Speed (km/h)
10	374	73
40	536	291

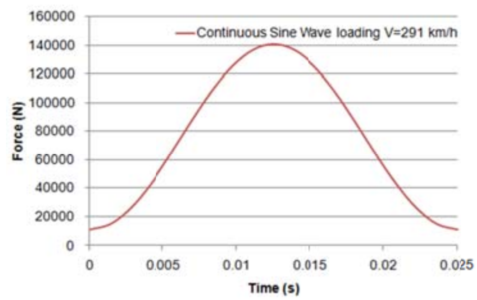
To evaluate the effect of any rest period that might exist between load pulses on accumulated permanent deformations, two half sine or haversine type single load pulses with rest periods were also considered following an approach similar to the one adopted for highway materials resilient modulus testing and characterization, e.g. AASHTO T307. The details about this approach of applying only one haversine load in 1-second with the load pulse duration and rest period changing according to the train speed is depicted in detail in Figures 5c and 5d. In addition, moving wheel loads and their realistic dynamic loading patterns from standard US railcar configurations were recently studied by Huang et al. (2009) in a proposed track "sandwich model" for the train speeds indicated in Table 1 using the DEM model. These two loading patterns fully consider the interactions between different axles and axle spacings. Accordingly, the faster the train travels the more independent the effects of the different axle loadings become. These realistic load pulses and the rest periods computed by the "sandwich model" are also shown in Figures 5e and 5f for the train speeds listed in Table 1.

3 Numerical simulation results

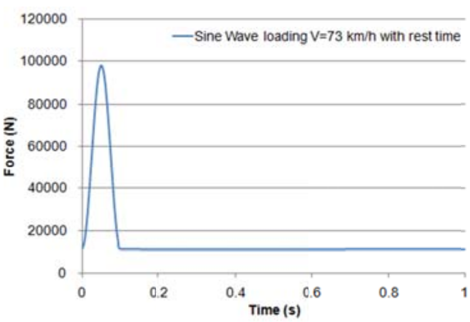
Because of the significantly high number of aggregate particle contact forces computed and checked for global equilibrium of the granular assembly at each iterative time step, the DEM simulations could not be conducted for up to as many cycles as the laboratory cyclic triaxial tests often apply loads on the ballast specimens. Accordingly, Figure 6 shows the predicted settlements of the track when experienced up to 1,000 cycles of both the continuous sinusoidal load pulses (see Figures 5a & 5b) and the repeated haversine load pulses with rest periods (see Figures 5c & 5d) at different train speeds. Note that the 1,000 cycles took exactly 1,000 seconds for the haversine pulses applied with rest periods whereas the 1,000 cycles of the continuous sinusoidal loads took much less according to the loading frequencies and train speeds considered. Nevertheless, for the equal 1,000 load cycles applied, the track simulations for the continuous sinusoidal loading yielded more settlement than the ones that sustained repeated haversine loads with rest periods. Therefore, having a rest period between load pulses indeed influences the settlement behavior of the ballast layer. The higher frequency loading of 40 Hz (train speed of 291 km/h) also resulted in a slightly more settlement after 1,000 cycles. This is due to the fact that at the higher speed not only a higher number of loads the track experiences in a certain amount of time, but also the magnitude of the loading is larger.



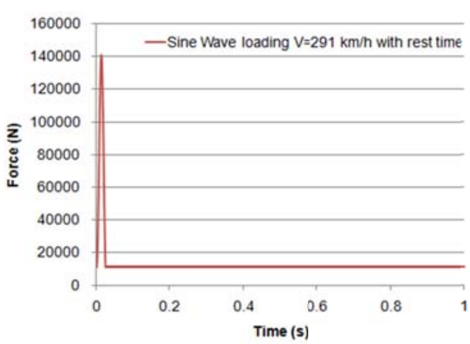
(a) Continuous sinusoidal, 73 km/h



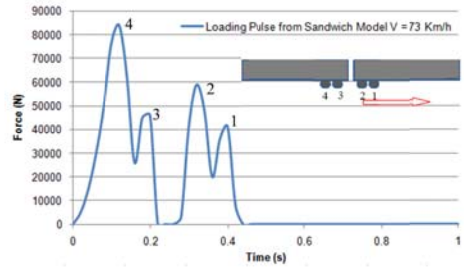
(b) Continuous sinusoidal, 291 km/h



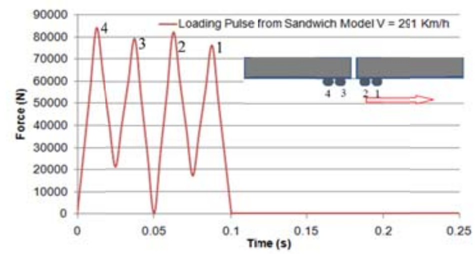
(c) Haversine with rest period, 73 km/h



(d) Haversine with rest period, 291 km/h



(e) Sandwich model, 73km/h (Huang et al. 2009)



(f) Sandwich model, 291 km/h (Huang et al. 2009)

Fig. 5 Different loading patterns studied using the half-track ballast DEM model

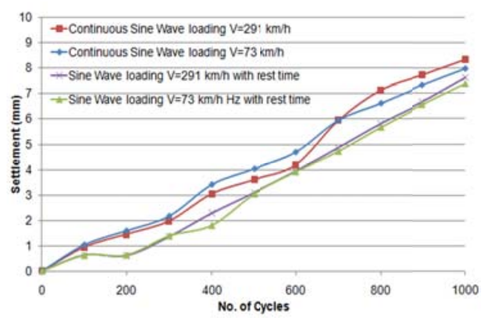


Fig. 6 DEM model settlement predictions for continuous sinusoidal loading and haversine loading with rest period

A deficiency of the ballast DEM model currently being improved upon is that individual aggregate particles as DEM elements cannot break under repeated train loads as opposed to the known ballast breakdown and degradation that commonly take place in an actual railroad track. Beyond this limitation, how the settlement prediction trends in Figure 6 would change with increased load cycles was still a topic of investigation. Figure 7 presents the results for ballast settlement predictions for up to 4,000 cycles of the continuous sinusoidal loads obtained at the train speeds of 73 and 291 km/h, respectively. The settlements under both train loadings accumulated rapidly almost in a linear fashion with the increasing load cycles. When the load cycle reached around 3,000, the ballast layer under the train traveling at 73 km/h did not accumulate any further settlement for a certain number of load cycles, and then started to settle again (see Figure 7). The same phenomenon was also repeated when the load cycle reached 4,000. This is probably due to the non-deformed, unbreakable DEM particles used in the DEM simulations. As the load cycle increased in the simulations, certain particles may have suddenly rotated and displaced causing the surrounding particles to rearrange in local areas. If this phenomenon could happen with aggregate particles chipping and breaking sharp edges, a "stable zone" often observed in experimental studies (Indraratna et al. 2010) would also be reached in the numerical simulations.

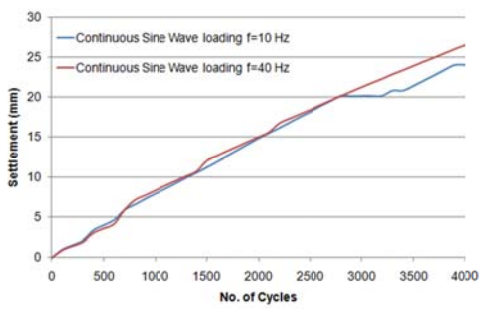


Fig. 7 Continuous sinusoidal loading settlement predictions for up to 4,000 cycles

The realistic dynamic load pulses and the rest periods computed by the "sandwich model" (Huang et al. 2009) were also applied on top of the tie due to the passing of railcar bogies (see Figures 5e and 5f). One car pass therefore consists of two axles of the front car and another two axles from the adjacent car behind. This loading pattern considers the different material properties of the track, i.e., dynamic response of the structure, wheel load interaction, and a rest period caused by axle spacing and car lengths. Accordingly, it is more realistic when compared to the sinusoidal loads. The dynamic pulses from the sandwich model (see Figures 5e and 5f) were employed next in the DEM simulations. Note that such a loading pattern was recently used to successfully predict measured field settlements in different ballast sections tested at the Transportation Technology Center, Inc. (TTCI) FAST track facility in Pueblo, Colorado (Tutumluer et al. 2011).

Figure 8 shows the predicted settlements from the DEM simulations for up to 2,000 car passes of the 4-peak dynamic loading patterns applied. Although similar magnitude settlements were predicted within the first 500 passes of the initial shakedown, as the number of passes increased, the ballast layer loaded by the faster train exhibited a higher rate of accumulation yielding an approximate settlement of 26-mm when compared to the 16-mm permanent deformation caused by the 73-km/h train.

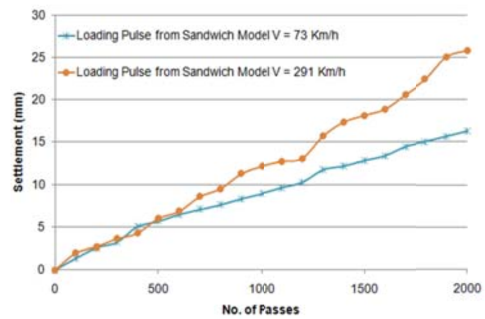


Fig. 8 DEM model settlement predictions for the moving wheel dynamic loading patterns from Figures 5e and 5f

Considering that four peaks or axle loads resulted in a car pass, one can compare the settlements predicted due to the moving wheel loading patterns to the predicted ballast settlements due to continuous sinusoidal loads if the tracks experienced equal number of axle loadings. Figure 9 presents such a comparison where the predicted settlements from the different tracks were due to these two loading patterns applied at different train speeds, respectively. Note that each car pass corresponds to four axles or load cycles and the settlements predicted from the continuous sinusoidal loadings were significantly larger than the settlements from the moving wheel loading patterns (see Figure 9). Although the magnitudes of the continuous sinusoidal loads were somewhat higher, the sandwich model moving wheel load pulses were much more realistic for the same weight of an individual car considered in both cases. Therefore, the moving wheel loading patterns are clearly more realistic since rest periods are properly considered according to the specific axle spacing and car lengths as opposed to a continuous sinusoidal load pulse often applied in cyclic triaxial tests. As a result, the continuous sinusoidal loading pattern, which caused more settlements in the DEM simulations, can give more conservative results when used in cyclic/repeated load triaxial testing and evaluation of the permanent deformation behavior of ballast aggregates. Although no comparative data are available at this time, the moving wheel load dynamic pulses are also believed to simulate more realistically the field vibration trends due to a passing train.

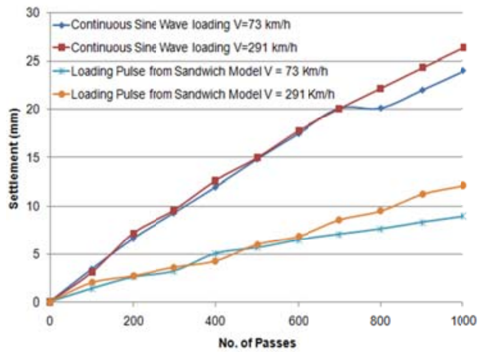


Fig. 9 Comparisons of settlement predictions for the various dynamic loading patterns

4 Conclusions

This paper investigated different dynamic loading patterns that may affect ballast layer vibration and settlement trends with the aid of a realistic ballast numerical model developed at the University of Illinois based on the Discrete Element Method (DEM) and imaging based aggregate particle size/shape characterization. The following conclusions can be drawn from this study:

1. Continuous sinusoidal load pulses caused larger ballast layer settlements to be predicted in DEM track simulations when compared to a more realistic moving wheel dynamic loading pattern that considered rest periods according to the characteristics of the track, individual car axle spacing, car length, multiple wheel load interaction and train speed.
2. A higher speed train also had higher dynamic load frequencies and magnitudes to cause greater predicted settlements.
3. Rest time between dynamic load pulses had a major influence on ballast settlement.
4. Future work will need to validate both the dynamic loading patterns and the predicted vibration and settlement trends with full-scale field testing and measurement.

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