A Concept to Estimate the Life Cycle of the Railway Track Using Finite Element Modeling

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ABSTRACT

When a train is running on a railway track, its wheel-rail's dynamic and static forces exerts a vertical, longitudinal, and lateral load on the ground. A railroad track has two main parts which are superstructure which includes fastening systems, tie, and rail and substructure which includes fill material, bottom ballast, top ballast, subgrade, and sub ballast. Rail tracks that are ballasted get deformed with time in both lateral and vertical directions that lead to, in case of persistent traffic loading, deviations from the intended geometry. This study will develop a simulation of a complicated three-dimensional finite element model so that the ballast can detect the railway's life cycle. The simulation is created so that the railway track's cycle can be determined.

1. INTRODUCTION

Railway is one of the most commonly used mode of transport across the world, with trains being the primary transportation method in some countries. It should also be noted that ballast has been used to build railway tracks ever since railways have been conceptualised. The life cycle of tracks, however, began to deteriorate because of increased train speeds, axle loads, and traffic densities which led to higher maintenance cost. Such problems resulted in the slab track being used in the 1960s. The use of slab tracks has been evaluated by several researchers. Orel [12] compared ballasted track with slab track by considering economic and technical factors as well as their environmental effects. In addition, Blanco-Lorenzo et al. [2] used Multibody Systems (MBS) simulations and Finite Element Method (FEM) representation to develop a dynamic model of the train-track system for comparing various slab tracks with ballasted track.

Even though there are certain benefits of using slab track over the ballasted track, it major drawback is the higher cost of installation. Design engineers also tend to incline towards using ballast track based on their experience. There is thus greater emphasis on addressing ballast track's limitations such as increasing the track's life cycle and decreasing costs of maintenance. Hence, it is crucial to better understand ballast tracks' mechanical behaviour for which several approaches have been implemented including field tests, modelling, and large scale experimental tests.

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It should be noted that it is not easy to carry out field tests as it necessitates traffic to be stopped or data to be gathered during operational time which can become difficult to control or risky. Giannakos' [13] study, however, assessed the actions on sleepers for examining the pressures under the sleeper's seating surface that are imparted on the ballast. Further, Konon [22] explored ballast particles' vibrational acceleration by considering the train traffic having heavy axle loads. Equations have also been designed for identifying the inertial forces that are developed in soil media because of vibration dynamic affect.

In addition, researchers who had access to computational resources began modelling the ballast track's mechanical behaviour as per theoretical models that indicate the real behaviour. It is thus possible to appraise material behaviour in various conditions which can help save time and money. Various studies have focused on this subject. Kalliainen et al. [4] developed a non-linear 3D stress-strain behaviour by using FEM. Tutumluer et al. [9] used a DEM model for simulating ballast layers' mechanical behaviour having multiple aggregate gradation such as AREMA gradation. Gao [6] examined the 3D dynamic track's performance for evaluating how critical speed impacts ground-borne vibration. Aboud and Ibrahim [14] used a 3D FEM for examining the impact of ballast thickness, elasticity modulus, as well as mechanical properties of soft soil's undrained shear strength. Koch and Hudacsek [18] examined 3D dynamic effects resulting from a train passing over an area that has considerable support stiffness differences. Sun et al. [16] created a 3D track/ground FEM for assessing the ballasted railway track's dynamic response involving a rubber tire-reinforced capping layer. Hendry [21] presented an analytical method and FEM for identifying alternative methods' efficacy concerning stabilising the embankment of mainline railway track between Belfast and Dublin. Alabbasi and Hussein [1] compared the mechanical behaviour of ballast track under sinusoidal and realistic train loadings following 1000 cycles by using Discrete Element Method (DEM). De Miguel et al. [17] developed an MBS code that could estimate how accumulated track settlement would influence the train/track interaction. Moreover, Alabbasi and Hussein did a tremendous review that summarized the previous work done on modeling the ballast track problem [3]. Jiang and Nimbalkar [24] present a 2D FEM to examining beneficial aspects of geogrids in railway tracks. Their results shown the reliability of the support effect of the geogrids under flat and cyclic loads.

The simulation study conducted in this research of the railway track includes ballast track design, ballast material characterizations, dynamic loads, and train static. It also aims to examine the railway track's life cycle. The ballast's life cycle is thus assessed by conducting a complex simulation analysis as well as an appropriate model.

2. DESCRIPTION OF THE MECHANICAL PROBLEM

The railway track's life cycle simulation can be regarded as a multiphysics problem because of various factors outlined by railway industries that are given below:

1. Every track component has to perform a particular task.
2. The model's every component has diverse stress-strain dependencies.
3. The rails are linked in series via bolts and fish plates.
4. The rails function as beams so that the wheel load can be transferred to the sleepers.
5. Different components have nonlinear behaviour interactions.
6. Through sleepers, the rails are held in their proper positions, the load is transmitted to the ballast, and an accurate gauge is provided through fittings and fastenings.
7. The total load of the moving trains as well as the track is on the construction.

The train running over the railway track exerts a load from vertical, lateral and longitudinal directions to the ground through the wheel-rail combining the static and dynamic forces. The main parts of the railroad track can be classified as superstructure which include rail, fastening systems, and tie (sleepers) and substructure which include top ballast, bottom ballast, sub ballast, fill material and subgrade as described in Figure 1.

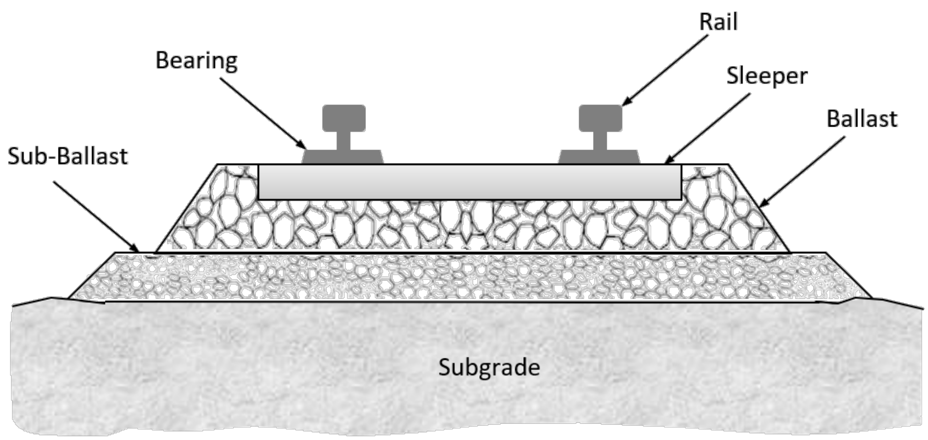

Figure 1: Main components of railroad track

Generally, a ballasted track is utilised to ensure stability as well as levelling for the track's load bearing capacity, easier maintenance of economic considerations, and rapid drainage. It forms the railroad's primary structural part that disseminates the train loads effectively to the underlying support structure. Various materials can be used to construct a ballasted track such as gravel, basalt, slag, and granite. The construction materials' chemical and mechanical compositions impact the ballast structure's performance. Ballast constitutes coarse aggregate that is uniformly graded and placed immediately beneath and between the sleeper. To ensure the ballast stability and strength, superior ballast aggregate shape properties are required. With time, ballasted rail tracks are deformed in lateral and vertical directions that in case of repeated traffic loading can lead to deviations from the intended geometry. Angular sharp corners breaking because of cyclic loading can further deteriorate ballast and accelerate track settlement. A track's differential settlement can decrease the track's safety and create considerable risk to trains.

Ballasts are often replaced for addressing faults in geometry. It is commonly seen that ballast layer can get contaminated because of fouling agents including internal particle breakage and upward clay migration. This can result in rapid deterioration in settlements along with the lateral spread because of reduced lateral restraints. Thus, to avoid repeated maintenance, a standard ballast is crucial. Figure 2 presents the upward clay migration's contamination of the ballast layer.

Railway ballast is filled under the train rails' sleeper and is linked with the capping layer subgrade, offering a consistent support layer. Further, ballast is filled between the rail and sleepers for withstanding the trains' high loads. Hence, rail ballast aggregate properties are crucial for the rail structure's effective load carrying capacity as well as its life cycle. It is, therefore, necessary for decent ballast to be strong, stable, hard-wearing, easy to clean, drain easily, and deformation underload resistant. When constructing a railway track, the rock-on-rock movement interaction are significant characteristics. In construction, rock supply depends on durability and size.

Figure 2: Ballast layer is contaminated by upward clay migration

2.1. CONSTITUTIVE MODEL AND MATERIAL PROPERTIES

The system can be classified into sleeper, subgrade, ballast, and sub-ballast. While the modelling of the sleeper considers linear elastic, that of the ballast and sub-ballast considers hardening soil model involving small strain-stiffness (HS small) and takes into account the stiffness degradation with strain. For the subgrade modelling, Mohr–Coulomb is used in which subsection has strength while stiffness parameters are gathered from laboratory tests.

For simulating the model, various material properties are considered. Some of these properties are shape, rock density, durability, crushed particles, grain size distribution, shape, angularity, texture, crushing and abrasion resistance, bulk-specific gravity, sulphate soundness, absorption, ballast aggregate specifications, ballast fouling, and ballast layer behaviour such as strength and deformation parameters.

2.2. LOADING

Stress can be divided into geostatic stress (weight of subgrade soil), stresses caused by wheel loading, and stress caused by weight of ballast and sub-ballast. In the first step, the modelling of geostatic stress is carried out. In the second step, the activation of ballast, sub-ballast, and sleeper is done and their weights and interface surfaces are taken into account. Various dynamic steps at diverse several dynamic time intervals are implemented. During these steps, wheel loading is also taken into consideration. Wheel loading can be indicated by the operation frequency and loading magnitude as shown in Figure 3.

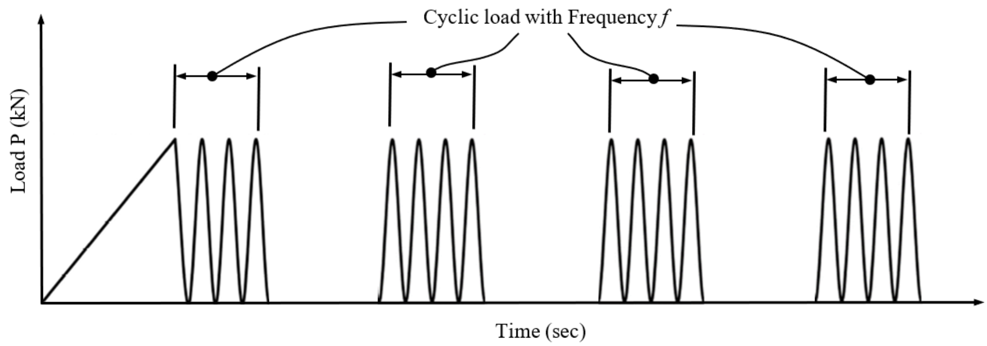

Figure 3: Description of the cyclic loading

3. FINITE ELEMENT MODEL AND BOUNDARY CONDITIONS

A computer-aided engineering (CAE) software as well as a suitable 3D model will be used to conduct the finite element model. Further, the horizontal dimension is increased to a minimum of 10 times the subgrade formation width for decreasing the boundary's impact on the finite element analysis. Moreover, the model's depth is increased to a minimum of 10 times the ballast and subgrade formation thickness (See Figure 4). For rail and sleeper, beam element is applied. The reflected stress wave's impact caused by load will also be considered. This technique is presented in [25] and [26], and has been successfully used for different academic and industrial applications.

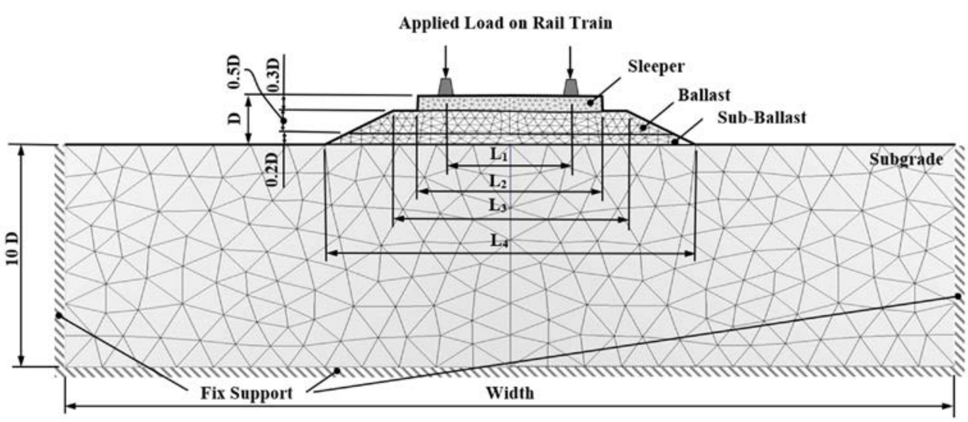

Figure 4: Cross sectional area for Finite Element Model and Boundary conditions

4. NUMERICAL SIMULATION AND RESULTS

Figure 6 illustrates a typical railway construction cross-section. The sleeper is modelled with ballast, rail, and subgrade formation primarily to determine the effectiveness of the construction design of subgrade, ballast, and sub-ballast formation beneath service load (dynamic loading caused by train) for which the lateral and vertical deformation as well as stress is established at particular points (A, B, and C) (see Figure 5).

Hence, this research assesses and compared the stress history and deformation at particular points A, B, and C as well as measure the strain and stresses at every subsection point (ballast and sub-ballast) at various time increments, while computing the stiffness at every point and average stiffness at different times for measuring the ballast and sub-ballast's service life.

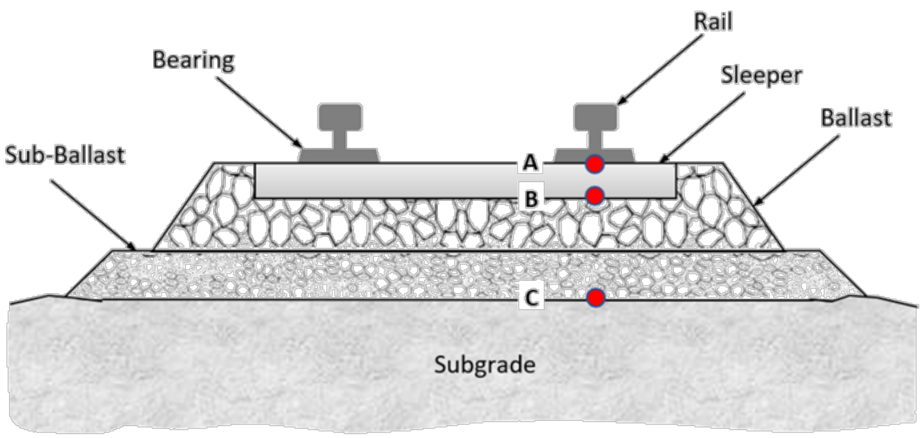

Figure 5: Typical cross section if railroad construction

Using standard dimensions and material properties of railway industries [3,13,16], an estimated primary result of the numerical analysis shows that at the start of the first hundred cycles, the settlement goes quickly (Figure 6), and then goes slowly and has a steady state value. Studies have shown that the number of load applications has a non-linear relationship with settlement of ballast. This may be connected to the number of load cycles using a semi-logarithmic relationship as:

$$\delta_N = \delta_1(1 + k \log N) \tag{1}$$

where δ_N indicates the ballast settlement at N load cycles, δ1 indicates the first cycle settlement, and k indicates an empirical constant based on the initial compaction, reinforcement type, saturation degree, and ballast type.

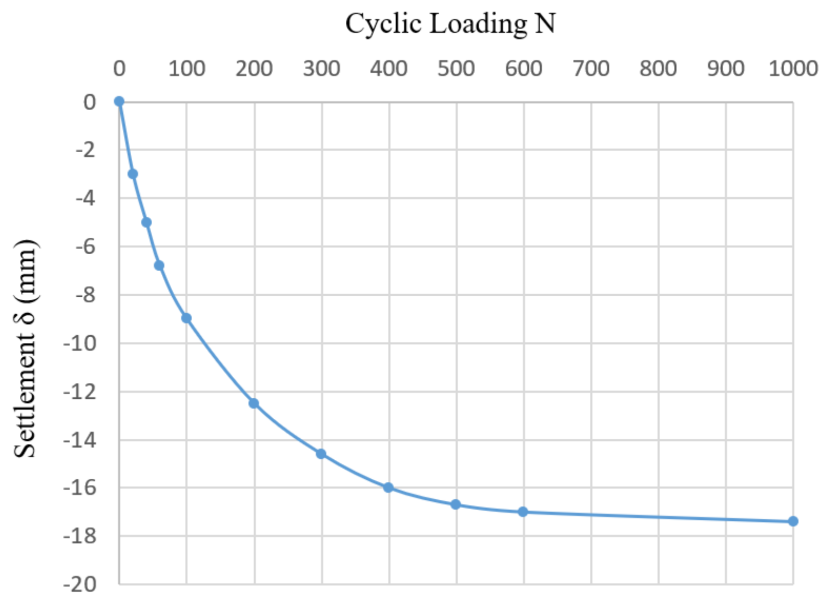

Figure 6: Estimated variation of settlement of ballast under cyclic loading

5. CONCLUSION

This paper outlines the major aspects of a railroad track. As per a first trial numerical study, ballasted rail tracks tend to deform with time in lateral and vertical directions and leads to deviations from the intended geometry in case of consistent traffic loading. Further, in the beginning of life cycles, the settlement goes quickly. Hence, it is necessary to standardise the used ballast so that maintenance is not required constantly.

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