APPLICATION OF THE BEZGIN METHOD TO ESTIMATE DYNAMIC IMPACT FORCES AND JUDGE THE CONDITIONS FOR BALLAST PULVERIZATION AND SLAB CRACKING DUE TO ABRUPT AND RAPID CHANGES IN RAILWAY TRACK PROFILE

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Abstract

Dynamic impact forces occur on railway tracks due to the presence of roughness of the track and the wheel and relate to the train speed and the rate of change of roughness. Variations in track profile and track stiffness and variations in wheel circularity are the causes of roughness. Quantification of the dynamic impact forces is not an easy task due to the complexity of the mechanics of the rolling stock interaction with the railway track. A number of experimental studies have led to an understanding of the dynamic impact forces, yielding a set of conservative and case-specific empirical equations. There are also many calculation-intensive numerical techniques, relying on iterative calculations seeking to converge to a state of temporary equilibrium for the analyzed structural domain within small-time increments. These techniques provide detailed and valuable information for the stresses that develop within the many components of the railway track. However, such numerical techniques rely on expensive computational tools that require experienced users to apply and interpret their results. The sheer amount of representative structural and material data input required to define the analyzed structural domain of the railway track properly is also an important task to accomplish in order to conduct a meaningful analysis. The second author developed a simple analytical method that can provide an accurate analysis for the dynamic impact forces on any railway track relying on track stiffness as the only mechanical railway track parameter. This paper introduces an ongoing study led by the second author and provides an insight into how a designer or a track maintainer can apply the Bezgin Method to estimate dynamic impact forces that may occur in rail-ends and within turnouts. This paper will also discuss how one can judge the conditions for ballast pulverization or slab cracking should these conditions exist.

Keywords: Bezgin Method, dynamic impact forces, rail-ends, turnouts

1 Introduction

Railway vehicles may transfer dynamic impact forces to the railway tracks that are higher than their static loads due to wheel-rail interface irregularities that occur for various reasons related to both track and/or railway vehicle itself. While track profile varies abruptly in the occurrence of insulated, bolted, welded rail joints, and singular rail surface defects [1,2], it changes rapidly along a specific length of the track in turnouts where the train must pass over discrete elements [3-5] such as a switch, crossing, and closure panels. Abrupt and rapid changes in the track profile cause significant dynamic impact forces and dynamic excitation.

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The abruptness of the profile variation influences vibration levels and usually higher defects causes an increased level of vibration [6]. Especially corrugation resulting passing frequencies are likely to damage the slab in ballastless tracks and sleepers in the ballasted tracks. Therefore, structural damage related to P_2 dynamic impact forces must be minimized. American Railway Engineering and Maintenance-of-Way Association (AREMA) limits the dynamic impact factor to 200 percent and continuously reinforced concrete slab crack width to 0.3 mm in slab tracks [7].

Higher dynamic forces also damage the ballast layer in abrupt profile changes. The impact attenuation capacity may become inadequate due to excessive bearing pressure, causing ballast pulverization [6]. This damage decreases the structural resistance, drainage capability, service life and requires maintenance tasks which form a significant proportion of the lifecycle expenses. AREMA allows a maximum of 586 kPa (85 psi) ballast pressure under concrete tie for new constructions with high-quality ballast. It also recommends a 448 kPa (65 psi) limit which is more suitable for existing lines [8]. In order to satisfy these limits, dynamic forces should be estimated properly and geometrical variations should be limited accordingly.

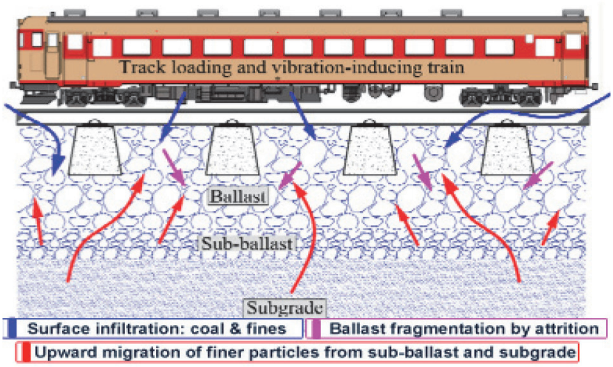

Figure 1 Ballast deterioration and sleeper damage due to dynamic loading [9]

There are some simple empirical equations that take train speed and wheel diameter as an input as well as some experiment-based case-specific relationships to quantify dynamic impact forces. In order to get more realistic results, track engineers and researchers mostly use complex numerical modeling or advanced track instrumentations that may be costly, time-consuming, and requires specialization. In this work, the previously introduced Bezgin Method [10] which is a cost-effective analytical method which takes track stiffness into consideration will be used to estimate dynamic impact forces and evaluate the conditions of railway components at turnouts and rail ends. Further advancements on the estimation of dynamic impact forces due to profile variation, stiffness change, and wheel flats using the Bezgin Method can be found in the relevant resources [11-13].

2 Dynamic impact factor estimation due to abrupt and rapid changes in track profile

This chapter focuses on the application of the Bezgin Method to estimate dynamic impact forces in special locations where profile changes rapidly such as rail-ends and turnouts. Fig. 2 illustrates the passage of a wheel over two different rails with vertical alignment difference (h). In the figure, wheel diameter is 920 mm (3 ft) and rails are type 60E1 with a depth of 172 mm (6.8 in).

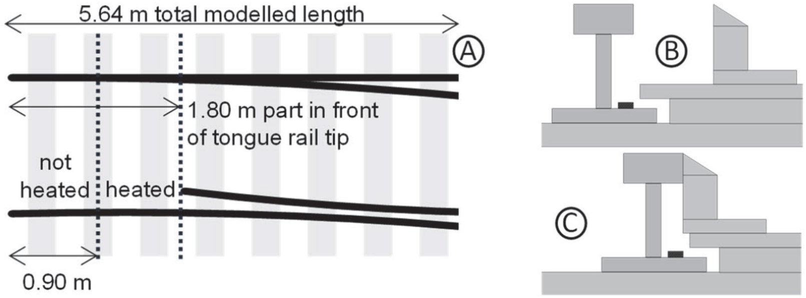

Figure 2 a) Depiction of wheels' passage over a rapidly decreasing profile and b) close-up views

While "g" denotes the horizontal distance between the rails, "h" is the vertical rail elevation and "L" denotes the contact length between the two spots where rail leaves the left rail (A) and drops onto the right rail (B). One can easily measure the track length (L) where vertical elevation (h) occurs in a turnout. However, this is not an easy task for rail-ends. Equation 1 and 2 correlates rail elevation (h) and contact length (L) with the wheel diameter (r) for rail-ends.

$$h = r\left(1 - \cos\varphi\right) \tag{1}$$

$$l = 2r \cdot \sin\frac{\varphi}{2} \tag{2}$$

One can estimate the dynamic impact forces via sets of equations provided by the Bezgin Method using equivalent stiffness of the rolling stock and railway track as an input. Bezgin Method yielded seven equations for cases of track profile and stiffness variations, and wheel flats. In this paper, "The Extended Bezgin Equation for descending track profile (K'B,d)" will be used to estimate the dynamic impact factors in abrupt changes. Equation 3 presents K'B,d where equivalent system deflection is a', impact reduction factor is f, and system damping is s. Equation 4 is the impact reduction factor which relates the free-fall time from "h" track irregularity to the time to pass the irregularity along a transition length (L).

$$K_{B,d}^{'} = 1 + \sqrt{\frac{2h}{a'}\left(1 - f - s\right)} \tag{3}$$

$$f = 1 - \frac{t_{fall}}{t_{pass}} = 1 - \frac{\sqrt{2.h/g}}{L/V} = 1 - \frac{V}{L}.\sqrt{\frac{2h}{g}} \tag{4}$$

Fig. 3 presents dynamic impact forces for abrupt changes at rail ends with h = 5 mm elevation for varying wheel diameter (D), static wheel load (F_S), train speed (V), and equivalent system stiffness (k_{eq}) that is a combination of the stiffness of rolling stock and the railway track. It is seen that the dynamic impact factor increases with decreasing wheel diameter, decreasing static wheel load, and increasing speed.

Fig. 4 presents dynamic impact forces for turnouts with h = 5 mm rail elevation where elevation occurs in limited lengths of L = 30 cm (1 ft) and L = 60 cm (2 ft). In addition to the finding of Fig. 3, it is seen that dynamic factor increases with decreasing transition length (L). The same scale is used in Fig. 3 and 4 to compare the dynamic impact factors of rail ends and turnouts with the same height of profile variation.

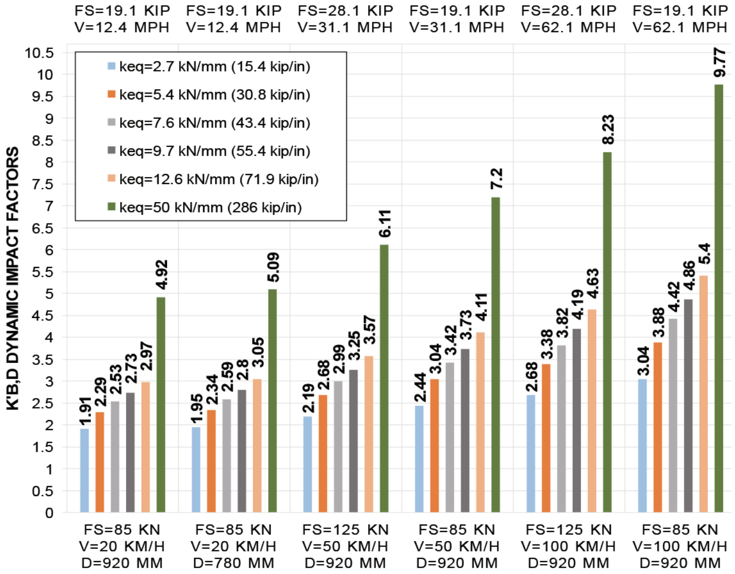

Figure 3 K’$_{B,d}$ impact factors for abrupt changes at rail ends with 5 mm rail elevation

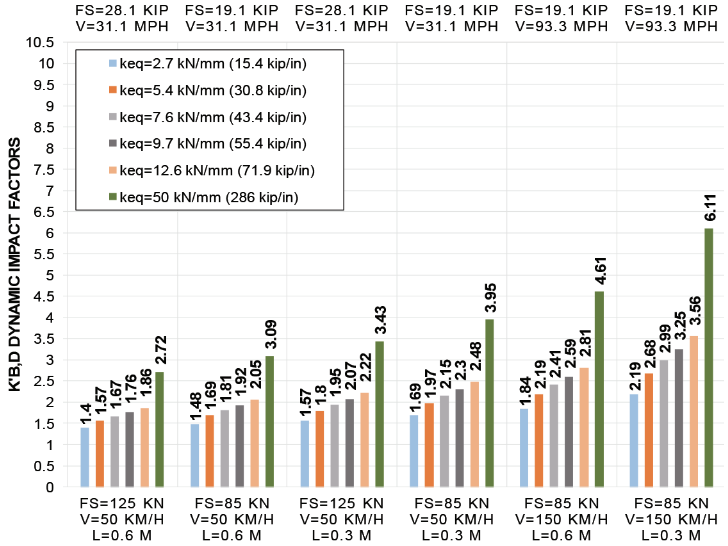

Figure 4 K’$_{B,d}$ impact factors for rapid changes at turnouts with 5 mm rail elevation

3 Evaluation of slab, tie and ballast condition under dynamic impact forces

The last chapter shows that dynamic impact forces may reach approximately up to 10-fold of the static wheel load for the assessed conditions. The quantity of the dynamic impact forces determines the average and maximum contact pressure in the wheel-rail interface, rail base (sleeper) pressure, and sleeper base (ballast) pressure. A 10-fold increase in the wheel forces means a 10-fold increase in the pressure on the bearing elements which may cause the exceedance of bearing stress limits and thus; plastification of the rail, cracking of the sleeper or slab, and pulverization of the ballast. Loss of the ballast material and/or local defects in the rail surface increases dynamic impact forces further and accelerates the deterioration of the track geometry. Therefore, track engineers must evaluate the condition of the bearing elements by comparing the stress levels of the track layers with allowable stress limits set by relevant standards. Fig. 5 and 6 shows the change of maximum sleeper bearing pressure and rail bottom pressure with dynamic impact factors for three different static wheel loads and two sleeper types (B320 and B58) with different base areas. It is assumed that the effective base area of the sleeper is %75 and %50 of the axle force is distributed to the sleeper under the wheel. 1st allowable limit in Fig. 5 refers to maximum allowable pressure on the ballast layer for newly constructed sites with high resistance ballast (0.59 MPa) and 2nd allowable limit is for existing tracks (0.45 MPa), specified by AREMA. The maximum allowable limit of Fig. 6 refers to the allowable concrete stress limit of 32 MPa [14].

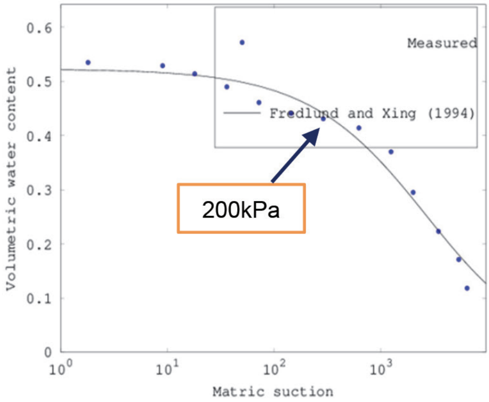

Figure 5 Variation of maximum sleeper bearing pressure with dynamic impact forces for different static axle loads and sleeper types

Studies show that deterioration of the ballast layer is directly connected to the pressure on the ballast layer, without an influence from the seating surface [15]. However, the wider base area of the B320 sleeper type (0,78 m^2) considerably reduced the pressure compared to B58 2.4 sleeper type with the narrower base area (0.61 m^2) for a constant static wheel load. The difference between the two sleepers increased with increasing dynamic impact factors. It is seen that a flawless track riding conditions without any track or wheel roughness does not generate dynamic impact forces and pressures on the track layers are far from the limits and one would not expect ballast deterioration and slab cracking. As the dynamic impact factor goes up, sleeper bearing and rail bottom pressures approach to limits causing increasing loss of friction at inter-particle contact points of ballast material and cracking of the concrete layer. Permanent settlement due to deterioration of track components/layers accelerates the development of impact forces.

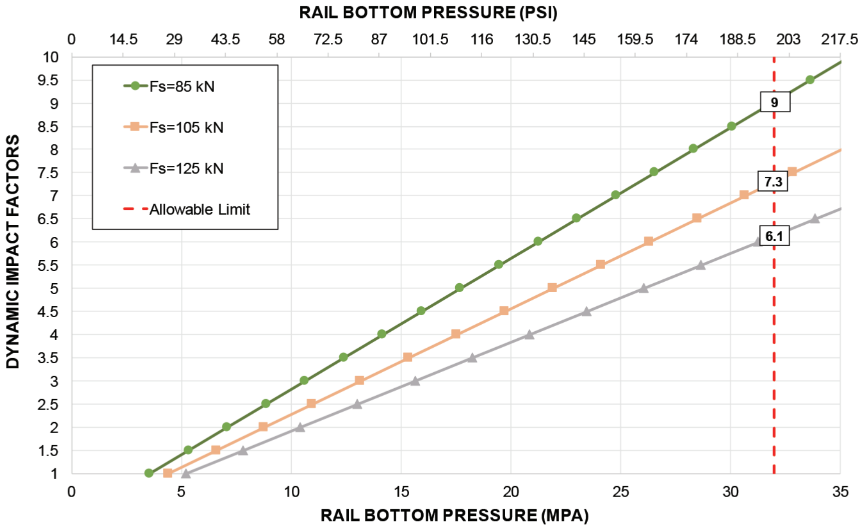

Figure 6 Variation of rail bottom pressure with dynamic impact forces for different static axle loads

Maximum sleeper bearing pressure reaches the allowable sleeper bearing pressure when dynamic impact forces are between 2.2 and 3.9 in newly constructed lines and 1.7 and 3 in existing lines. The same dynamic impact factor becomes riskier when static wheel load is heavier and sleeper base area is narrower. Pressures at the bottom of the rail, on the other hand, require higher magnitudes of dynamic impact factors to reach intolerable limits. However, it is showed in the previous chapter that dynamic impact factors may reach excessive values especially when bogie and wheel suspensions are excluded and abrupt changes occur at rail-ends.

4 Conclusion

In order to maintain track safety, one must be able to estimate dynamic impact forces efficiently so that he or she can compare the effective pressures with allowable limits and judge the conditions of track elements. This paper presented the application of the Extended Bezgin Equation for decreasing track profile developed by the Bezgin Method to estimate dynamic impact forces and judge the condition of ballast, sleeper, and slab when there are rapid and abrupt changes in track profile.

While it is relatively easy to measure the track length in which profile variation exists in turnouts, it may be difficult for rail ends. The paper presented the correlations between profile variation, contact length, and wheel diameter so that one can apply Bezgin Method to the assessment of dynamic impact forces at abrupt changes. Calculations showed that lower static wheel load, wheel diameter, and contact length, and higher train speeds increase dynamic impact forces. factors are found to be up to approximately 6-fold at turnouts and 10-fold at rail ends for given input parameters.

Dynamic impact forces acting on a track directly affects the pressure on the sleeper and ballast layer. Excessive wheel forces may lead to various damages for different track elements such as rail plastification, sleeper cracking, and ballast fouling. The second part of the paper examines the relationship between static wheel force, sleeper base area, dynamic impact factor, and resulting pressures on the track elements. The maximum dynamic impact factor to prevent ballast failure is found to be 3.9 for newly constructed lines and 3 for existing lines for given input parameters. The maximum dynamic impact factor to avoid sleeper failure is found as 9 for given input parameters.

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