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ScienceDirect

Procedia Engineering 189 (2017) 2 – 10

Procedia Engineering

www.elsevier.com/locate/procedia

Transportation Geotechnics and Geoecology, TGG 2017, 17-19 May 2017, Saint Petersburg, Russia

Development of a new and an explicit analytical equation that estimates the vertical dynamic impact loads of a moving train

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Abstract

One can only estimate the dynamic vertical impact loads under motion, since there are many effective parameters some of which are unrepresented in an equation and since the values of the considered parameters are not deterministic but estimations. Many empirical and semi-empirical equations in the literature correlate dynamic impact loads to train speed and measurable aspects of train and track components. These aspects frequently relate to track and train geometry and track stiffness. However, the development of these equations relies on load and deflection measurements from particular in-service tracks or especially set-up test tracks. The constants that frequently appear in these equations are particular to the conditions that generated them. Therefore, one lacks an explicit understanding of these equations unless one takes the time to investigate in detail the particular study and the particular set of data that generated these equations. Train speed limits also bound the applicability of these equations. This paper concentrates on the development of an explicit mathematical equation aimed to provide an explicit analytical estimate for the dynamic impact loads that develop on any railway track by the axles of a moving train. This paper introduces the concept of impact reduction factor and introduces a new equation that relies on the principle of conservation of energy and kinematic principles along with the impact reduction factor to estimate the impact loads generated by a moving train. The introduced equation analytically relates the dynamic impact load factor to train speed, track stiffness and vertical irregularity development along the track horizontal alignment.

Peer-review under responsibility of the scientific committee of the International conference on Transportation Geotechnics and Geoecology

Keywords: Train speed; track stiffness; track deformation; impact reduction factor; dynamic impact load factor; dynamic impact load.

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Peer-review under responsibility of the scientific committee of the International conference on Transportation Geotechnics and Geoecology
doi:10.1016/j.proeng.2017.05.002

1. Introduction

Mechanical design of a railway track requires the determination of the maximum impact load imposed by the railway vehicle considered in the railway track design. The vertical loads of a moving vehicle are greater than their values at-rest, unless mathematical perfection exists in the geometry of the interacting components of the vehicle and the supporting structure and unless perfect homogeneity exists in the supporting structural stiffness along the structural length. However, such perfections are practically unlikely and therefore vehicular motion generates vertical loads that are higher than their values at-rest. The increased vertical loads due to vehicular motion vary in time and vibrate the supporting structure during and after their occurrence. They may also act within a finite amount of time, resulting in an instantaneous increase on the supporting structure. Therefore, these increased loads are dynamic impact loads.

The impact load directly relates to the maximum static axle load and the design speed of the train. Speed of passenger trains on ballasted tracks or slab tracks in service today extend to up to 350 km/h with static axle loads that reach 190 kN. Speed of freight trains reach 120 km/h with static axle loads reaching 250 kN, excluding dedicated freight tracks for mining and other heavy haulage lines [1].

Along with the train speed and the static axle load, condition of track alignment, track stiffness, damping and stiffness aspects of the rolling stock wheel-bogie and frame configuration also affect the impact load values. Existing literature presents an array of useful equations that correlate the impact loads factors to the mentioned parameters above [2]. All of these equations are empirical in nature, correlating the physically related parameters through numerical constants.

This paper presents the development of an analytical equation based on classical mechanics. The contributing physical principle to the development of the equation is energy conservation through the storage of the kinetic energy of an impacting rigid body on a structure as the stored potential energy in the elastically deformed supporting structure. The contributing field in the development of the equation is kinematics.

2. Vertical impact force of a falling mass exerted on a stiff supporting structure

Let us assume a mass (m) dropped from a height (h) on an elastic spring with stiffness (k). Compared to the deformation (x_s) caused when this mass gently places on the spring by an external agent, the mass dropped on the spring causes a higher deformation (x_i) and thus generates a higher force in the spring. Equation 1correlates the displacement caused by the mass impact (x_i) to the displacement caused by the mass placement (x_s). Details of this development exist in the literature [3]. The term in the parenthesis is the impact displacement ratio showing that the ratio of the impact displacement to static displacement caused by a mass on to a structure increases with increasing structural stiffness (k) that causes a decreasing static displacement (x_s) and increasing height (h). Multiplication of both sides of Equation 1 by the stiffness (k) of the supporting structure results in Equation 2 that relates the impact force (F_i) to the static force (F_s). In this case, the term in the parenthesis is the impact force constant (K) that amplifies the static force to yield the impact force.

$$x_i = x_s\left(1+\sqrt{{}^{2h}/_{x_s}+1}\right), \text{where } K = 1+\sqrt{{}^{2h}/_{x_s}+1} \tag{1}$$

$$F_i = k.x_i = k.x_s\left(1+\sqrt{{}^{2h}/_{x_s}+1}\right) = F_s.\left(1+\sqrt{{}^{2h}/_{x_s}+1}\right) \tag{2}$$

These simple equations are very informative. For instance, one can clearly see that the impact force is at least double the static force for h=0 as the mass freely places on a structure at its undeformed position. One can also see that as the stiffness of the impacted structure increases, so does the impact force that occurs on the supporting structure.

The idea used in the development of the equations above partly helps the development of an analytical equation that estimates the vertical impact force of a laterally moving train at a certain speed (v) over a track with stiffness (k). The following section introduces this approach and the new equation developed by the author.