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Experimental assessment of dynamic lateral resistance of railway concrete sleeper

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ABSTRACT

The *single tie (sleeper) push test* (STPT) is a common method to evaluate the lateral resistance of a railway track sleeper. This methodology evaluates the lateral resistance phenomenon in a static manner despite the fact that the majority of the exerted loads on a railway track have a dynamic nature. For this reason, a mass–spring–damper numerical model was created to investigate the dynamic lateral interaction between an isolated sleeper and ballast layer in the presence of various lateral impact loads. On the basis of the model outputs, a *pendulum loading test device* (PLTD) was designed and developed in the laboratory. In this regard, a cylindrical hammer with modifiable mass and triggering angle was installed on a steel frame for imposing lateral impact load on an instrumented concrete sleeper. The graphs of the sleeper–ballast interaction force versus the sleeper lateral displacement were extracted for different masses and triggering angles of the hammer. Considering a same condition for sleeper, the maximum value of this interaction force was called the *dynamic lateral resistance* (DLR) and static lateral resistance (SLR) respect to the dynamic and static states of lateral loading. Comparing the values of the sleeper DLRs and SLR indicated that unlike the constant SLR of 6.5 kN, the DLR was in the range 2–10.2 kN in the impact load domain of 3–40 kN. However, as a key finding, the average slopes of the DLR and SLR graphs were equivalent in the dynamic and static tests.

1. Introduction

Today with the increase of speed and axle load of trains, the amplitude of train lateral forces exerted on railway tracks has been increased which this issue highly affects the track lateral stability. Therefore, the track lateral resistance has become a topic of major concern for all railway transportation companies and institutes. Using various rolling stocks on different tracks (in a straight line, curved track, bridges, etc.), variable conditions of the track environment (temperature, wind, and earthquake) as well as the train accelerating and braking lead to numerous types of lateral forces.

The majority of the lateral forces which are generated at the wheel–rail interface have dynamic nature as the train passes the track. These forces can be determined by a Japanese technique namely *"New continuous method"* which calculates the lateral force for frequencies up to 100 Hz using a number of accelerometers attached on a train wheel [1]. Furthermore, the proposed theory of Klingel can be used to evaluate the lateral acceleration of a wheelset in a straight track. In this regard, sinusoidal lateral movement of a train will result in flanging and the subsequent hunting phenomenon in some cases [2].

The excessive centrifugal force in a railway curve possesses two components including a very short time impact force and a constant quasi-static force [3]. Moreover, sudden cross winds in comparison with constant cross winds have more considerable effects on the generated lateral forces [4]. In addition, aggressive acceleration and braking of trains produce large lateral forces which endanger the track lateral stability in weak track condition [5].

Consequently, it is important to make an accurate perception of the wheel–rail interaction and also a logical evaluation of lateral forces in a railway track. Naturally, the imprecise assessment of these forces for affording the associated lateral resistance of track will cause irrecoverable effects like train derailment. The derailment of a train can be categorized into four types of wheel flange climb, gauge widening, rail rollover, and track panel shift. The track panel shift derailment is often occurred in tracks with poor lateral resistance [5].

Alternatively, the concept of the lateral resistance of a railway track through the rail flexural action, fastener torsional resistance, and the sleeper–ballast interaction strength gives an assurance to keep the track geometry in horizontal plane particularly in curved tracks. In overall, the conducted researches in this field are divided into two classifications including the investigation of track lateral resistance and evaluating the applied lateral forces on track. First,

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the related fulfilled works on the track lateral resistance are introduced and then, the lateral forces generated in a ballasted railway track will be briefly reviewed.

1.1. Track lateral resistance

Generally speaking, the mobilized lateral resistance of a railway track against the exerted lateral forces is provided through the rails bending stiffness about their weak axes, torsional resistance of the fasteners, and the sleeper lateral resistance in contact with the ballast layer. It is obvious that the contact between the sleeper and ballast particles is a key parameter to supply the track lateral resistance. Therefore, the main characteristics of the sleeper including type (concrete, wooden, and steel), mass, dimensions, and spacing have much influences on this matter as well as the ballast properties such as type of mineral material, gradation, compaction, and the geometry of ballast section (e.g. shoulder ballast width) [6]. Moreover, in order to better understand the sleeper lateral resistance, the interaction zones of sleeper and ballast layer namely base, crib, and shoulder should be accurately evaluated. In order to determine the lateral resistance of a single sleeper or a track panel, several test methodologies have been introduced in the literature up to now.

STPT is the most useful and well-known method in which the lateral resistance of a single sleeper can be measured against its lateral displacement [7]. The lateral force corresponding to the lateral displacement of two millimeters is considered as the sleeper lateral resistance which leads to sleeper sliding [6]. STPT is a static evaluation of the sleeper lateral resistance which is suitable for static analyses such as the thermal buckling of ballasted tracks. This method certainly reflects nothing about the dynamic forces generated at the wheel–rail interface.

Load-deflection responses of total and incomplete track panels are measured by the continuous track lateral pull test (TLPT) and the discrete cut panel pull test respectively. Several sleepers contribute in this response and hence, it is not possible to calculate the lateral resistance of an isolated sleeper [7]. In the mechanical track displacement test, some instruments are installed on a tamping machine and the lateral resistance of a whole track is determined using lining and lifting cylinders [8].

Moreover, the method of using a derailment wagon needs a special test vehicle and related measurement equipment on both wagon and track. However, the outputs of this test are the most accurate assessments of the real condition of the track lateral resistance [6]. In the continuous dynamic measurement test using dynamic track stabilizer (DTS), the sleeper–ballast friction is correlated with the lateral resistance of sleeper [6].

1.2. Literature review on STPT

In the field of research work on the determination of the lateral resistance of a single sleeper, numerous efforts have been made in the field or laboratory circumstances. In this regard, Prud'homme and Weber [9] carried out one of the first researches on the lateral resistance of wooden sleepers resulted in a formula for critical lateral force. A coefficient was then added to this formula by Ahlbeck and Harrison [10] considering the effects of radius and temperature of curved tracks.

Moreover, Gallego and Gomez-Rey [11] performed a number of field tests on concrete sleepers in three buckled curves at 60 °C for evaluation of the values of various track parameters in order to validate their finite element (FE) model of the lateral track buckling analysis. Furthermore, several field tests were conducted by the European Rail Research Institute (ERRI) [12,13] on concrete sleepers. Their tests outputs were given as force–displacement graphs for strong track (trafficked), medium track (just tamped–undisturbed), and weak track (loose tamped/relay) conditions.

In addition, Sussmann et al. [14] carried out about 125 STPTs on concrete sleepers in different track conditions including prior to surfacing, after surfacing/before stabilization, after stabilization, and after traffic. To ensure whether further tests were required or not, the mean, range, and the standard deviation were calculated usually after 10 tests. The results of their research were given in form of force–displacement diagrams.

Moreover, an analytic-empirical model was introduced by the US railroads, the US DOT's Volpe Center, and the Association of American Railroads (AAR) by performing over 500 STPTs to determine the lateral resistance of sleeper [15]. The effects of shoulder ballast width, quantity of crib ballast and the ballast compaction were assessed for both concrete and wooden sleepers located inside the granite ballast layer. Moreover, a great deal of concentration was allocated to determining the impacts of the maintenance and following restoration of the lateral resistance through the dynamic track stabilization (DTS) and accumulative traffic [7].

In a parametric study on the lateral ballast resistance, Kabo [16] developed a 3D elasto-plastic FE model to investigate the effects of ballast geometry, vertical and lateral loading, and the friction between ballast and sleeper on the lateral resistance of a concrete sleeper. Furthermore, Zakeri et al. [17] investigated the lateral resistance of various sleepers by conducting several STPTs in the field and laboratory conditions.

Le Pen and Powrie [18] conducted both theoretical and experimental works to evaluate the contribution of the base, crib, and shoulder ballast in the total lateral resistance from a geotechnical perspective. In addition, Zakeri et al. [19] performed some laboratory and field tests on frictional (B70-F) and conventional (B70) concrete sleepers. They concluded that using a frictional sleeper makes an increase of 64% (in lab condition) and 68% (in field condition) in the lateral resistance of the sleeper.

Moreover, Le Pen et al. [20] utilized image processing and limit equilibrium calculations to investigate the effects of geometrical dimensions of the shoulder ballast on the lateral resistance of a scaled G44 concrete sleeper. They also compared the shoulder resistance of adjacent sleepers with an isolated sleeper. In another experimental study, Koike et al. [21] conducted a series of laboratory tests on different kinds of 1/5-scale concrete sleepers concentrating on the sleeper shape, spacing, and the number of sleepers. They also proposed a numerical method for determination of the sleeper lateral resistance. Furthermore, Zakeri et al. [22] developed a FE numerical model to investigate the lateral resistance of a frictional sleeper. In comparison with conventional concrete sleeper, frictional sleepers increased the lateral resistance up to 63–70% in the model. A summary of mentioned research works and studies on STPT is presented in Table 1.

Noting to Table 1, it can be found except the references [9], [10], and [15] which have presented semi-analytical equations for assessing the lateral resistance, all other references proposed a definite range in this matter based on their experimental and numerical studies. Although depending on their consumptions, the suggested values in this table are not in the same range but in the present study, a comparison will be made between the *dynamic lateral resistance* (DLR) of sleeper and the relevant laboratory works.

1.3. Research methodology

Regardless of the continuous dynamic measurement and derailment wagon test methods, all of mentioned methods and research works have been performed in a static way yielding the static lateral resistance of a ballasted railway track. Whereas in real condition, the exerted lateral force on track majorly has dynamic nature with a particular magnitude and frequency. Furthermore, the dynamic behavior of the ballast layer has an important influence on the lateral resistance. In order to obviate this shortage in