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3D analysis of high-speed trains moving on bridges with foundation settlements

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Abstract This paper investigates the derailment of trains moving on multi-span simply supported bridges with foundation settlements or rotations. Rail irregularities, train–track–bridge interactions, and wheel/rail separations were considered in the three-dimensional nonlinear finite element analysis. A moving spring-mass with separation and contact modes was used to validate the proposed finite element model. In the parametric study, finite element results indicate that foundation settlements or rotations cause sharp displacements between two simply supported girders, which generate large train derailment coefficients. The train derailment coefficients rise with increased train speed, and they greatly increase at a critical speed. The time history displacements of a train obviously contain a jump when it passes a location with foundation settlements or rotations, so a warning system can be established using this measurement.

Keywords Derailment · Finite element analysis · High-speed train · Moving wheel element · Rail irregularities · Settlement ·

1 Introduction

High-speed rail systems are mainly used for passenger transport, so safety and comfort are the most important requirements. However, when high-speed trains travel on a railway with foundation settlements, their safety becomes a serious problem. For this reason, finding the relationship between foundation settlements and train derailments is more and more important, but the related investigations are limited in the literature. Mauer [1] presented a dynamic settlement model to simulate track settlement behavior under rail traffic, and simulations of track settlement under various conditions were described and discussed. Dahlberg [2] used the finite element program LS-DYNA to simulate the long-term behavior of the track. He used the elastic-plastic analysis and found that settlement will occur if the element stresses near the rail exceed the material yield limit. In addition, ‘hanging sleepers’ may be modeled and obtained as a result of track settlement. Liang et al. [3] indicated that track damage involves not only the failure in strength of components but also overdeformation or intolerable settlement of the system below the track. They investigated the interactions between the vehicle vibration and the subgrade design parameters. Vostroukhov et al. [4] studied the possibility of detecting the derailment of trains by measuring vibrations of the rails under the locomotive. Both theoretical and experimental studies have been carried out. Lundqvist and Dahlberg [5] presented a computer model by which the dynamic train/track interaction can be simulated and examined the influence of one or several voided sleepers on the train/track interaction force and on the track dynamics, as well as the issue of track settlement due to hanging sleepers. Wong et al. [6] measured the settlement and formation of piping holes on surfaces along a rail embankment subject to normal traffic load. Piezometers installed in the native peat and soil underneath the embankment...
inside and outside problematic areas were used to measure the pore pressure responses during train traffic. Saussine et al. [7] used a discrete element simulation to study behaviors related to the alteration in railway ballast after repeated train passing, and the numerical results for the settlement of a track submitted to 20,000 loading cycles or more were presented. Yau [8] presented an incremental-iterative procedure to investigate the influence of ground settlement on the dynamic interactions of a train–bridge system and indicated that the inclusion of ground settlement is generally small on the bridge response, but it can drastically amplify the vertical response of a moving train, especially with a concave-up settlement profile. Yau [9] investigated the dynamic response of a Maglev vehicle traveling over a series of guideway girders undergoing ground support settlement and indicated that the increase in levitation gap for a Maglev vehicle may result in a larger vehicle response, but the response with a smaller gap will be significantly amplified at higher speeds once ground settlement appears at the guideway supports. Ju [10] investigated the derailment of high-speed trains moving on this bridge type with foundation settlements. In this paper, the acceleration of elevated bridge girders may be significantly magnified during the seismic load; moreover, gaps between simply supported girders will produce large derailment coefficients.

Since multi-span simply supported bridges are often built in city areas for high-speed trains, this study used a three-dimensional (3D) nonlinear finite element model modified from a linear one [11] to determine the derailment of high-speed trains moving on this bridge type with foundation settlements. In this paper, the nonlinear finite element model is first introduced, and it is then validated using a theoretical solution with contact and separation modes. Finally, the parametric studies of the derailment of trains moving on multi-span simply supported bridges were investigated. Train–track–bridge interactions and nonlinear wheel–rail separations are considered in the numerical analysis, so that the finite element model is realistic enough to determine an accurate derailment coefficient due to the loading sources of foundation settlements and rail irregularities.

### 2 Derailment coefficient and rail irregularities

The maximum wheel derailment coefficient \(Q/P\) from all the train wheelsets is calculated as follows [12]:

\[
Q/P = \operatorname{Max}(Q_i/P_i), \quad i = 1, n
\]

where \(Q_i\) and \(P_i\) are the horizontal and vertical forces of the \(i\)th wheelset, and \(n\) means the total number of wheelsets for the train. In this study, the Western Europe standard was used, since the finite element analysis requires a specific average movement distance to calculate the train derailment coefficient. The specification standard for derailment prevention in Western Europe is \(Q/P < 0.8\), where the average movement distance of \(Q/P\) is set to 2 m.

Rail irregularities may enlarge the train derailment effect during foundation settlements, so this paper also investigates train derailment due to rail irregularities with a sample function \(r_n(X)\) [13] as follows:

\[
r_n(X) = \sum_{k=1}^{N} a_k \cos(\omega_k X + \phi_k)
\]

where \(a_k\) is the amplitude, \(\omega_k\) is a frequency (rad/s) within the upper and lower limits of the frequency \([\omega_l, \omega_u]\), \(\phi_k\) is a random phase angle in the interval \([0, 2\pi]\). \(X\) is the global coordinate in the rail direction, and \(N\) is the total number of terms. The parameters \(a_k\) and \(\omega_k\) are computed by:

\[
a_k = 2\sqrt{G_{rr}(\omega_k)\Delta \omega}, \quad \omega_k = \omega_1 + (k - 1/2)\Delta \omega, \quad \text{and} \quad \Delta \omega = (\omega_u - \omega_l)/N, \quad k = 1, 2, \ldots, N
\]

where \(G_{rr}(\omega)\) is a power spectral density (PSD) function, \(A_r\) is the roughness coefficient, and \(\omega_1\) and \(\omega_2\) are frequencies that change the shape of \(G_{rr}(\omega)\). The frequency \(\omega_1\) is set to zero in this study, so Eq. (4) is the same as the PSD function in reference [14]. The rail irregularity had an amplitude of 2 mm per 20 m of the rail in the vertical and transverse directions of the rail, and the irregularity parameters are shown in Table 1.