Evaluating Train Vehicle Running Safety on a Bridge in the Event of an Earthquake

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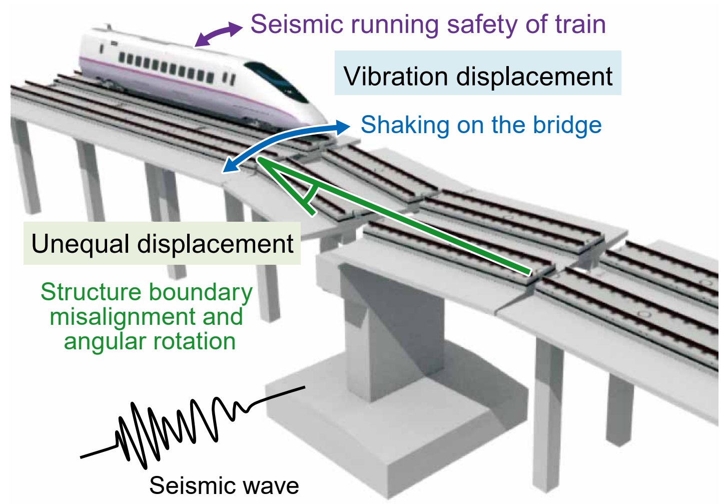
The 2004 Niigata Prefecture Chuetsu Earthquake, the 2011 off the pacific coast of Tohoku earthquake, and the 2015 Kumamoto earthquakes caused railway vehicle derailments (Shinkansen train derailed by the 2004 Niigata Prefecture Chuetsu Earthquake). Multifaceted measures are being promoted throughout the railway system to prevent derailments in future earthquakes. Vehicle derailment behavior is affected not only by the magnitude and characteristics of earthquake motion, but also by the effects of structures, tracks, and vehicle vibration characteristics. Thus, evaluating it accurately requires a cross disciplinary outlook. After outlining the technology to simulate the vehicle derailment behavior considering these effects, this paper introduces a newly proposed, simple evaluation method for seismic running safety on a bridge that takes into account the nonlinear behavior of structures.

Shinkansen train derailed by the 2004 Niigata Prefecture Chuetsu Earthquake

(Source: "The Railway Accidents Analysis Report" (Japan Transport Safety Board) (http://www.mlit.go.jp/jtsb/railway/rep-acci/RA2007-8-1.pdf; as of October 13, 2021))



Vibration displacement and unequal displacement

Introduction

Vehicle derailment behavior in an earthquake, influenced by many factors, presents a complex mechanism. Nonetheless, thanks to vigorous R&D since the 2004 Niigata Prefecture Chuetsu Earthquake, simulation technology has been advanced, and causes of these derailments have been individually elucidated and the behavior has been quantified.

Most vehicle derailments during earthquakes so far have occurred on bridges and viaducts. It is known that derailment is greatly affected by vibration amplification and unequal displacement; the former of which is caused by the bridge shaking more than the ground surface, hence, amplification and the latter of which is caused by misalignment against the adjacent bridge due to the different earthquake shaking (Vibration displacement and unequal displacement)[1].

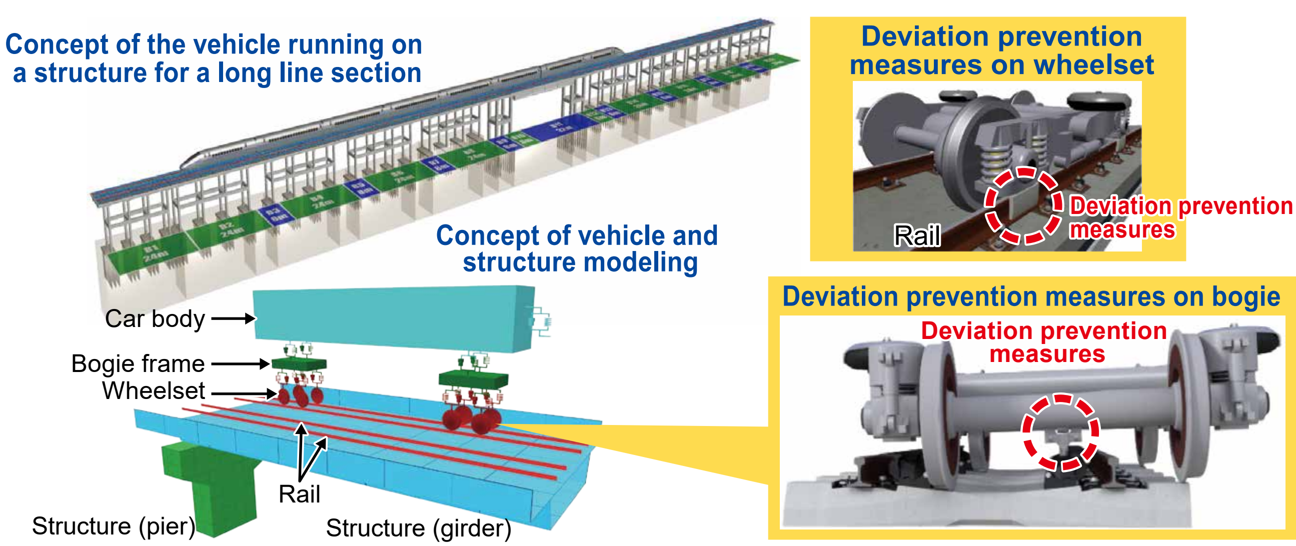
It is known that embankment sections and tunnel sections have a low possibility of derailing a train during an earthquake. This is because embankments and tunnels have less amplification of earthquake shaking than on bridges. In addition, they have an advantage over bridge sections in that they have less track misalignment.

Evaluating seismic running safety in an earthquake by dynamic simulation of a vehicle/bridge

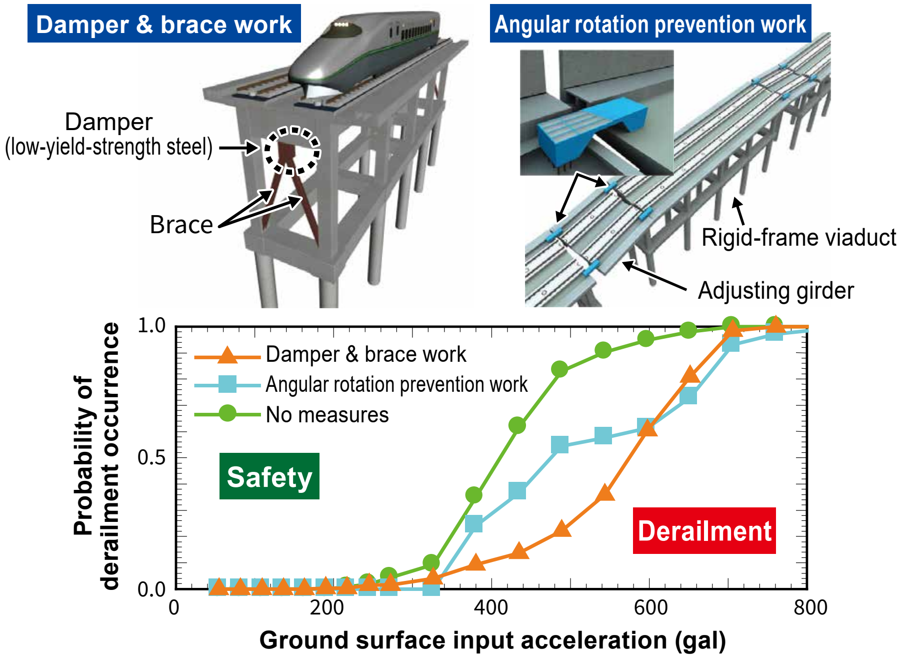
To elucidate the derailment behavior of railway vehicles running on bridges in earthquakes, we need to perform detailed numerical simulations using a computer. To do this, we need to consider not only vehicles but all the dynamic behavior of track surfaces and bridges on which the vehicles run.

RTRI has been developing the dynamic interaction analysis program DIASTARS for vehicles and structures (Dynamic interaction analysis program considering the vehicle-structure dynamic interaction)[2]. It can simulate the behavior of vehicles and structures, taking into account the interaction forces between wheels and rails. As in Dynamic interaction analysis program considering the vehicle-structure interaction, DIASTARS is used for vehicle running analysis in an earthquake for long line sections and for the performance evaluation of deviation prevention measures following the derailment.

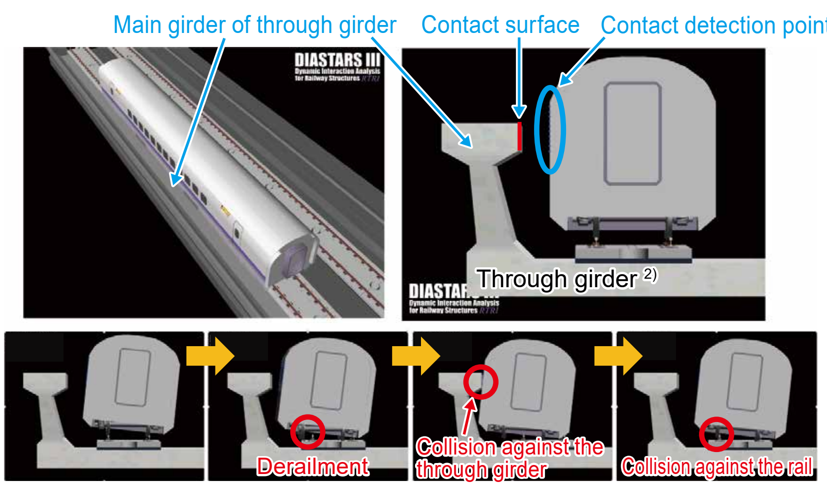
Probability of derailment occurrence shows an example of performance



Dynamic interaction analysis program considering the vehicle-structure dynamic interaction



Probability of derailment occurrence



Contact analysis of vehicle-structure interaction

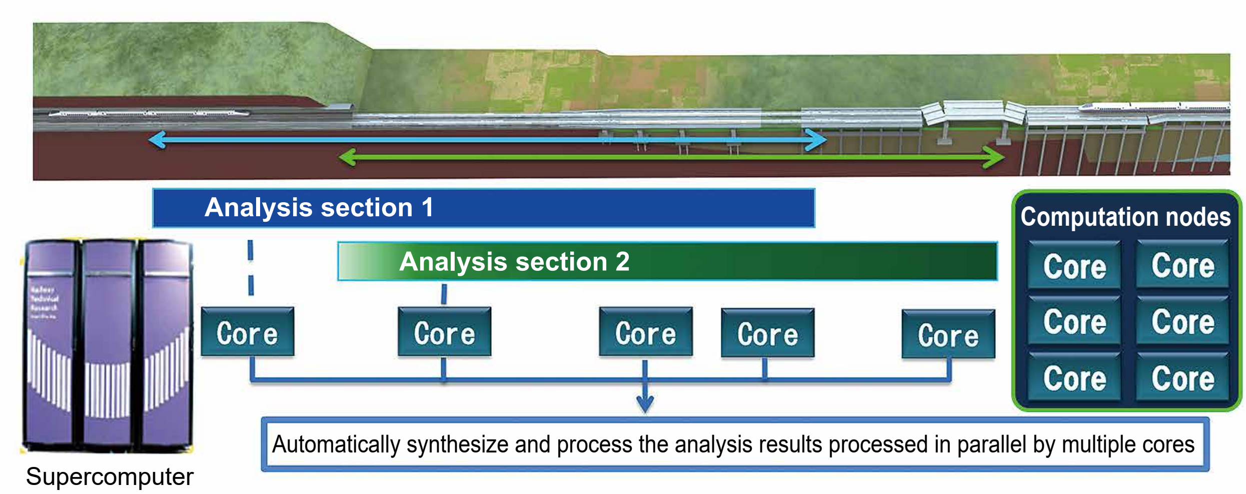
evaluation for damper & brace work and angular rotation prevention work, which are countermeasures to reduce the probability of derailment during earthquakes. Damper & brace work is a construction method that reduces the response in an earthquake by placing steel materials diagonally, like braces, to increase stiffness and combining dampers, which are members absorbing the earthquake motion energy. Angular rotation prevention work is a construction method that reduces the deviation at the boundary by connecting the viaduct in the track direction. In this example, note the 400 gals (≈ 0.4 times the gravitational acceleration) point of the ground surface input acceleration (*1) on the horizontal axis in the figure. With no prevention measures, the probability of derailment damage (*2) was approx. 45%, whereas with the introduction of angular rotation prevention work, it decreased to approximately 30% and, with the further introduction of damper & brace work, it decreased to approximately 10%. (*1: maximum acceleration on the surface of the earth due to the earthquake; *2: percentage of the wheelsets that derailed in series of trains running in the line section.)

Because it can also continuously analyze the dynamic behavior before and after the derailment, in recent years DIASTARS has also been used for R&D aimed at elucidating the behavior of vehicles after a derailment and evaluating the performance of countermeasure work to prevent deviation. For example, it enables performing numerical analysis in consideration of contact between deviation prevention measures installed on the bogie or wheelset of the vehicle and the track structure (Dynamic interaction analysis program considering the vehicle-structure interaction) and contact between the car body and track structure. Contact analysis of vehicle-structure interaction shows an example of an analysis of how the vehicle derails due to shaking by earthquake motion and the car body collides with the main girder of the through girders located on the side of the track.

For configuring the computation process, as in Dynamic interaction analysis of long line section by parallel computation of supercomputer, the analysis section is divided into multiple smaller sections, and the running analyses of the respective sections are concurrently processed on multiple processors in a supercomputer to significantly speed up the process. This allows us to exhaustively capture the effects of various parameters such as vehicle speed, running position, and magnitude of earthquake motion, enabling us to consider the whole of a long line section and detailed phenomenon elucidation.

New Evaluation Method for Seismic Running Safety for Large Scale Earthquakes

RTRI has proposed a new evaluation method for seismic running safety, considering the nonlinear behavior of bridges in large scale earthquakes (Evaluation method of seismic running safety considering the nonlinear behavior

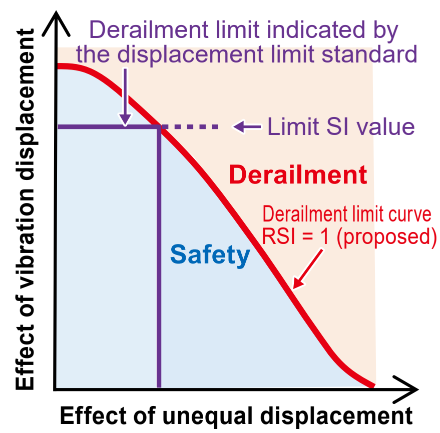


Dynamic interaction analysis of long line section by parallel computation of supercomputer

of the bridge)[3]. This method determines the possibility of vehicle derailment by calculating the running safety index (RSI), which is an index that takes into account the effects of vibration displacement and unequal displacement. Specifically, if RSI > 1, it determines that the possibility of the derailment is high, and RSI < 1 it determines that the vehicle running is safe. RSI evaluates seismic running safety by focusing on the effect of vibration displacement on the vertical axis, independently of the effect of unequal displacement indicated on the horizontal axis. The proposed RSI is an index that simultaneously considers the effect of vibration displacement focusing on the acceleration of the top of the structure and the effect of unequal displacement due to angular rotation of the bridge boundary. The effectiveness of the RSI index and the derailment limit curve as shown above was found by performing the precise simulation of vehicle running in an earthquake for several hundred thousand cases that assume a wide range of conditions, by using DIASTARS on a supercomputer as described above. The RSI values (the range below the red curve in Evaluation method of seismic running safety considering the nonlinear behavior of the bridge) are effective also for nonlinear responses in large scale earthquakes and, therefore, can be applied to a wider range than displacement limiting standards that require the assumption of linear responses (the purple line range in Evaluation method of seismic running safety considering the nonlinear behavior of the bridge). In addition, the validity of the RSI was validated for multiple long line sections after it was verified that the result of simulation by DIASTARS and the result of the evaluation by RSI matched with each other regarding the derailment position and the derailment limit.

Conclusion

We think that if we can develop a bridge that does not let vehicles derail in an earthquake, it will be the ideal form of a railway bridge, but to realize this would require future technological development.



Evaluation method of seismic running safety considering the nonlinear behavior of the bridge

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2) Wakui, H., Matsumoto, N., and Tanabe, M., "A Study on Dynamic Interaction Analysis for Railway Vehicles and Structures - Mechanical model and practical analysis method -," Quarterly Report of RTRI, Vol.35, No.2, pp.96-104, 1994

3) Tokunaga, M., Narita, K., and Goto, K., "Simplified Evaluation Method for Running Safety of Railway Structures in Consideration of Nonlinear Behavior," Quarterly Report of RTRI, Vol.62, No.2, pp.137-142, 2021