Quantitative Evaluation of Damage Mitigation on Running Trains by Earthquake Early Warning

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SUMMARY:
In order to improve disaster prevention performance of railway systems against earthquake, besides hard countermeasures, a soft countermeasure is important which controls train operation just after an occurrence of earthquake by introducing an earthquake early warning (EEW) system. By making use of this system, train operation is expected to be properly controlled before the arrival of strong motion. In this paper, we propose a quantitative evaluation method to calculate damage-evaluation index of running trains by using train information, such as vehicle-braking performance and running speed, as well as EEW lead-time defined as time difference between receipt of warning information and arrival of strong quake. It is obvious that the lower damage-evaluation index indicates higher benefit of the EEW system. By applying this index to evaluation, we have obtained the following results quantitatively; 1) Damage-evaluation index is reduced with a longer lead-time and higher vehicle-braking performance. 2) Damage-evaluation index is reduced with lower running speed at receipt of warning information.

Keywords: Running trains, Earthquake Early Warning (EEW), Lead-time, Damage-evaluation index

1. INTRODUCTION

In order to improve disaster prevention performance of railway systems against earthquakes, besides hard countermeasures such as earthquake-resistant construction and reinforcement, a soft countermeasure is significantly important, which controls train operations just after an occurrence of earthquake by introducing an earthquake early warning (EEW) system. By applying the use of this system effectively, train operations are expected to be properly controlled before the arrival of strong motion.

Since the time difference between the receipt of warning information and arrival of strong quake (lead-time) is an essential index to evaluate the performance of the EEW system, the conventional evaluation method mainly uses lead-time, however other important train information such as vehicle-braking performance and running speed has not been considered. Though the present method using only lead-time is generally acceptable, introduction of train information makes the evaluation method more practical to quantify damage mitigation on running trains. In this paper, we propose a quantitative evaluation method by using train information as well as lead-time.

2. DEFINITION OF LEAD-TIME

The EEW system makes it possible to control trains during earthquakes before the arrival of strong motion. Accordingly, the time difference between receipt of warning information and the onset of strong motion is a significant index. In the present paper, this time difference is referred to as the lead-time. Fig. 2.1 shows the relationships between seismographs on railways and the hypocenter. The evaluation seismographs that directly control trains are located at the rail-side, and the warning seismographs are located closest to the hypocenter. Fig. 2.2 also highlights the concept of lead-time using P-wave and S-wave travel times.

Since the EEW system estimates earthquake parameters within a few seconds of P-wave arrival, estimation errors may be inevitable. However, the analysis outlined below was conducted assuming no earthquake estimation parameter errors for simplicity.

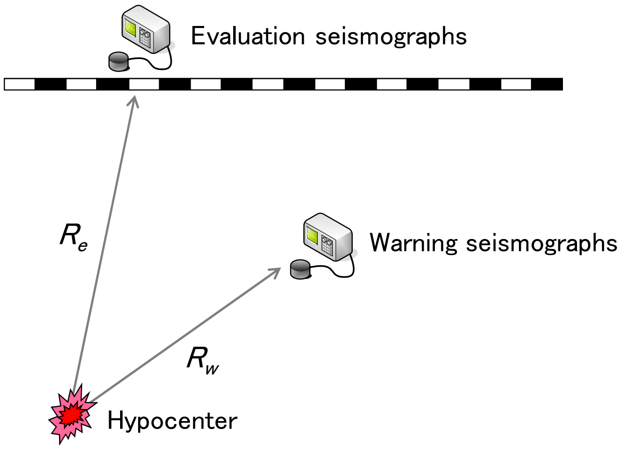


Figure 2.1. Relationships between the two types of seismographs and the hypocenter

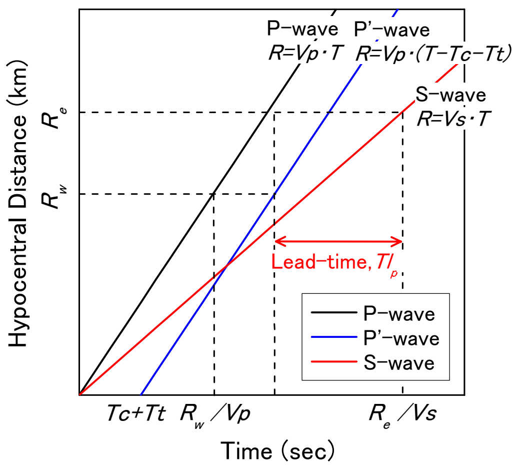


Figure 2.2. Outline of the concept of lead-time using P-wave and S-wave travel times

The lead-time with a P-wave warning is calculated using Eqn. 2.1.

$$Tl_p = \frac{R_e}{Vs} - \left(\frac{R_w}{Vp} + Tc + Tt\right) \tag{2.1}$$

where Tl_p is the lead-time with a P-wave warning, R_e is the hypocentral distance at the evaluation seismograph, R_w is the hypocentral distance at the warning seismograph, and Vs and Vp are the S-wave and P-wave velocity, respectively, Tc is the time taken to calculate the earthquake parameters, and Tt is the transmission time.In the same manner, the lead-time with a S-wave warning is given by Eqn. 2.2.

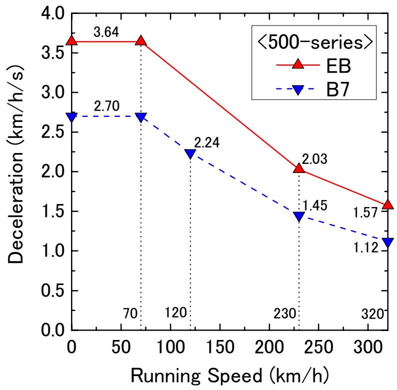
$$Tl_s = \frac{R_e}{Vs} - \left(\frac{R_w}{Vs} + Tt\right) \tag{2.2}$$

where Tl_s is the lead-time with a S-wave warning.
In this paper, the parameters of calculating lead-time are taken where Vp is 6.0 km/sec, Vs is 3.5 km/sec, Tc is 2.0 sec and Tt is 1.0 sec.

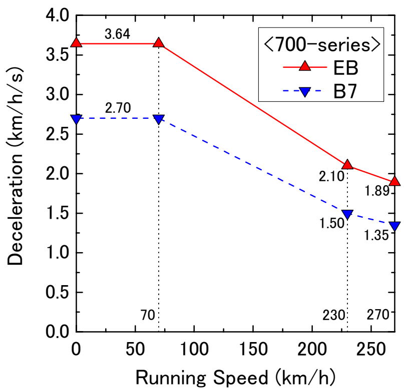
3. QUANTITATIVE EVALUATION OF DAMAGE MITIGATION

3.1 Train information of vehicle-braking performance

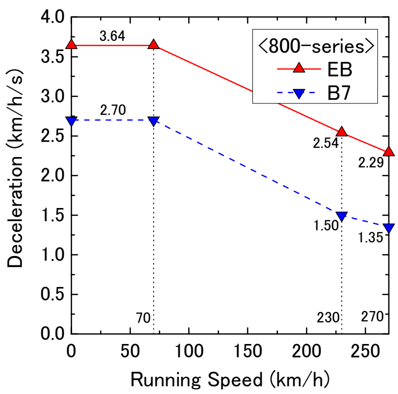
It is more effective to introduce the EEW information, obtaining lead-time, for the sake of train-controls just after an occurrence of earthquake. However, it has not discussed quantitatively on the benefit of increasing lead-time. Here we suggest the quantitative evaluation of damage mitigation on running trains by introducing the information of vehicle-braking performance and running speed.



(a) 500-series



(b) 700-series



(c) 800-series

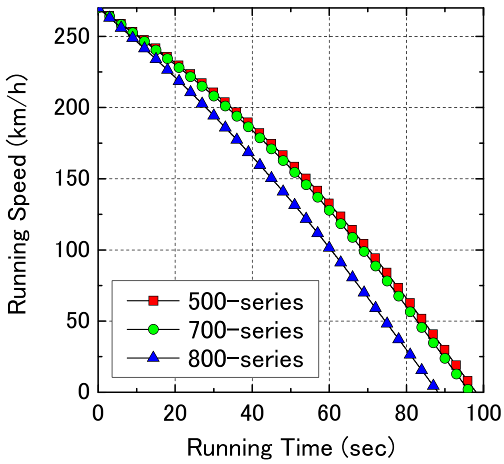
Figure 3.1. The relationship of running speed and deceleration each Shinkansen

Fig. 3.1 shows the relationship of running speed and deceleration in 500-series, 700-series and 800-series Shinkansen. In these figures, EB shows the emergency-braking characteristics of each vehicle, and B7 is the most powerful deceleration in normal-braking ones. These vehicle-braking performance is expressed a differential equation as Eqn. 3.1.

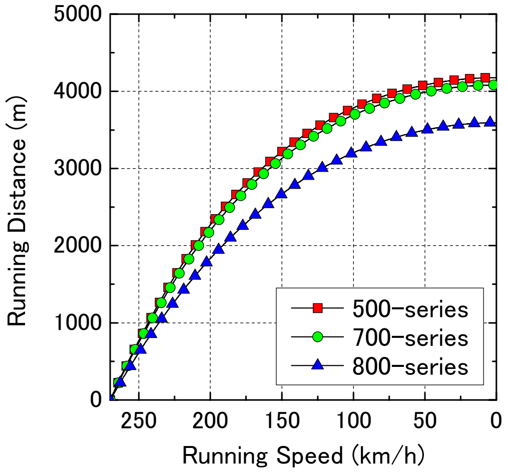
$$\frac{d^2x}{dt^2} = -\alpha \cdot \frac{dx}{dt} - \beta \tag{3.1}$$

where t is the running time, x is the running distance, α and β are optional constants of the vehicle-braking performance.

The vehicle-braking performance, running time, running speed and running distance of the train, are obtained as integral calculus by Fig. 3.1 and Eqn. 3.1. Fig. 3.2 (a) shows the relationship running time and running speed, and Fig. 3.2 (b) illustrates the relationship running speed and running distance of each Shinkansen. Fig. 3.2 (a) demonstrates that 500-series and 700-series Shinkansen that running at 270 km/h need braking-time approximately 95 seconds to stop trains, and 800-series Shinkansen needs braking-time approximately 90seconds. Besides Fig. 3.2 (b) shows 500-series and 700-series Shinkansen running at 270 km/h need braking distance about 4000 m and 800-series Shinkansen needs approximately 3500 m. Because of each vehicle-braking performance is not identical, braking-time and braking-distance from same initial running speed are different respectively.



(a) The relationship between running time and running speed



(b) The relationship between running speed and running distance
Figure 3.2. Vehicle-braking performance of each Shinkansen

3.2 Quantitative evaluation of damage mitigation on running trains

By applying the vehicle-braking performance in Fig. 3.1, we studied the relationship of running train risk and lead-time at an occurrence of earthquake by introducing EEW information. Fig. 3.3 shows a concept of the evaluation that is a start point of vehicle-braking action at reception of P-wave and S-wave warning. To begin with, P-wave warning braking action to make the use of P-wave arrival information is as defined as train running state between the P-wave warning time and the vehicle-stop time. In the next place, S-wave warning braking action is defined as train running state between the S-wave arrival time and the vehicle-stop time in case P-wave arrival information is not made use of.

In this paper, the damage-evaluation index is defined that using the S-wave warning braking at standard running speed V_{std} and the P-wave warning braking at initial running speed V_0. The running trains, that are received P-wave warning, are able to stop shorter distance, because of braking faster than receiving conventional S-wave warning. It is conceivable that "running-distance ratio", which is a ratio of running distance in P-wave warning braking action to that is S-wave braking action, is proportional to the probability that the running train encounter a damaged structure. In addition, a square of "running-speed ratio", which is a ratio of average running speed in P-wave braking action to that in S-wave braking action, is proportional to the kinetic energy that is corresponding to impact of the vehicle into a damaged structure. Since it is difficult to estimate in advance when a running train encounters damaged structure, running speed is averaged from warning time to the vehicle-stop time is used in this evaluation. Accordingly "damage-evaluation index" is defined as a product of running-distance ratio and square of running-speed ratio. This relation is formulated as Eqn. 3.2.

$$Rp(Tl) \propto \left(\frac{Dpv_0}{Dsv_{std}} \right) \cdot \left(\frac{\overline{Vpv_0}}{\overline{Vsv_{std}}} \right)^2 \qquad (3.2)$$

where *Rp (Tl)* is a damage-evaluation index by introducing P-wave warning information against the conventional S-wave warning, Dsv_{std} is a running distance at a standard running speed V_{std} on receiving S-wave warning. Dpv_0 is an initial running distance V_0 on receiving P-wave warning. $\overline{Vsv_{std}}$ is an averaged running speed in case of the standard running speed V_{std} on receiving S-wave warning and $\overline{Vpv_0}$ is averaged running speed in case of the initial running speed V_0 on receiving P-wave warning.

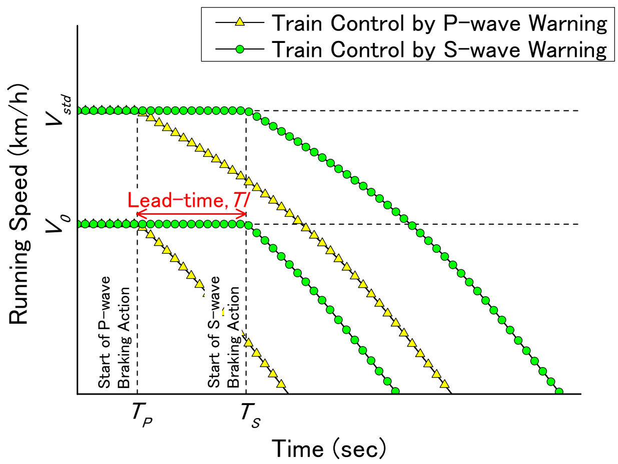
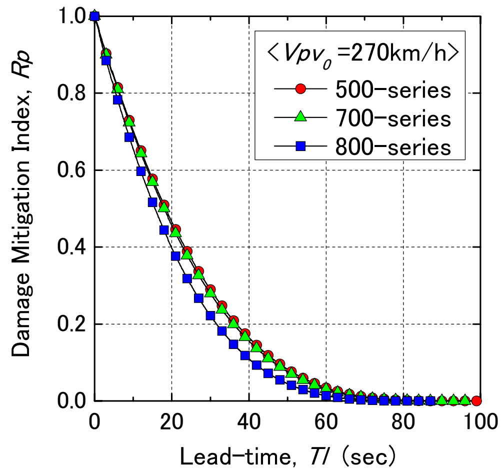


Figure 3.3. Concept of lead-time and running speed by P-wave and S-wave warning

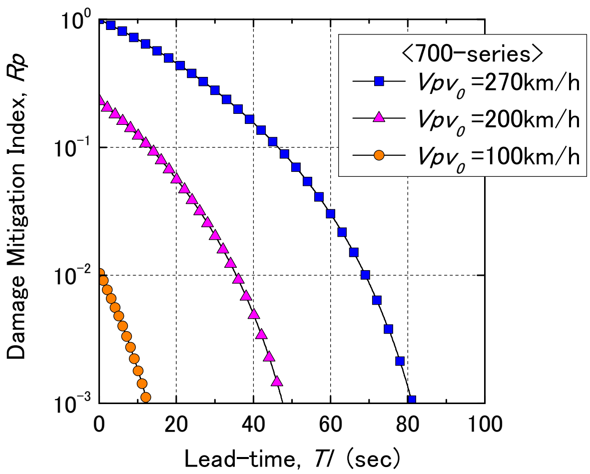
Fig. 3.4 (a) shows a damage-evaluation index against lead-time at 500-series, 700-series and 800-series Shinkansen. In this analysis, Vsv_{std} is 270 km/h and Vpv_0 is 270km/h. Focusing on 700-series Shinkansen, lead-time becomes approximately 20 seconds where the damage-evaluation index of running train at 270 km/h is 0.5. Therefore, it was conceivable that the running train risk will be mitigated by a half on running trains for the benefit of 20 seconds lead-time obtained by the EEW system just after an occurrence of earthquake. Moreover, picking up the difference of each vehicle in the same figure, 800-series Shinkansen has the largest damage-evaluation index with the same lead-time, because 800-series Shinkansen has the highest braking performance than other Shinkansens. Using the proposed method, we can evaluate the damage mitigation on braking performance difference. The above results indicate that for the sake of progress the running train safety, improving of vehicle-braking performance is important as well as the increasing lead-time.

When the initial running speed is faster, the running distance is longer that makes trains encounter with damaged structures more frequently. Therefore, the running speed at strong motion arrival thought to be another important factor to evaluate a risk by the P-wave warning against S-wave warning. Fig. 3.4 (b) shows a damage-evaluation index on the standard running speed of 270 km/h in case of the initial running speed of 100 km/h, 200 km/h and 270 km/h.

Since the running speed is slower, the deceleration of vehicle braking is larger as shown in Fig. 3.1, that follows the damage-evaluation index smaller. In case of 10 seconds lead-time, the-evaluation mitigation index is 0.70 in the initial running speed of 270 km/h, 0.12 in that of 200 km/h and 0.0018 in that of 100 km/h. Therefore, as to evaluate the running train risk during earthquakes, it is obvious the running speed on arrival of seismic strong motion is a principal factor.



(a) Evaluation of braking performance for 270 km/h of initial running speed



(b) Evaluation of running speed in an occurrence of earthquake for 700-series

Figure 3.4. Evaluation of damage-evaluation index for 270 km/h of standard running speed

4. CONCLUSION

In this paper, we evaluated the damage-evaluation index against the lead-time by introducing train information such as vehicle-braking performance and running speed. The damage-evaluation index is defined as a product of running-distance ratio and a square of running-speed ratio by P-wave warning comparing with the conventional S-wave warning.

Applying such a suggested method to parametric study, we confirmed quantitatively that damage index decreases in case of longer lead-time and higher vehicle-braking performance. Moreover we evaluate the risk difference of running speed at the time of receiving EEW information. Accordingly we have obtained the following results quantitatively; 1) Damage-evaluation index is reduced with longer lead-time and higher vehicle-braking performance. 2) Damage-evaluation on index is reduced with a lower running speed at the receipt of warning information.

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