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Key technologies of earthquake early warning system for China's high-speed railway

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Abstract

Purpose – The purpose of this study is to introduce the top-level design ideas and the overall architecture of earthquake early-warning system for high speed railways in China, which is based on P-wave earthquake early-warning and multiple ways of rapid treatment.

Design/methodology/approach – The paper describes the key technologies that are involved in the development of the system, such as P-wave identification and earthquake early-warning, multi-source seismic information fusion and earthquake emergency treatment technologies. The paper also presents the test results of the system, which show that it has complete functions and its major performance indicators meet the design requirements.

Findings – The study demonstrates that the high speed railways earthquake early-warning system serves as an important technical tool for high speed railways to cope with the threat of earthquake to the operation safety. The key technical indicators of the system have excellent performance: The first report time of the P-wave is less than three seconds. From the first arrival of P-wave to the beginning of train braking, the total delay of onboard emergency treatment is 3.63 seconds under 95% probability. The average total delay for power failures triggered by substations is 3.3 seconds.

Originality/value – The paper provides a valuable reference for the research and development of earthquake early-warning system for high speed railways in other countries and regions. It also contributes to the earthquake prevention and disaster reduction efforts.

Keywords Earthquake early-warning, High speed railway, China earthquake networks center (CENC), Earthquake emergency treatment

Paper type Technical paper

Earthquake early-warning is an important technical measure to improve the seismic safety of high speed railways (HSR). Countries operating HSRs, such as Japan, France, and South Korea, have established earthquake monitoring systems to prevent or lessen the harm of earthquakes to the operation-safety of HSRs (High-speed railway seismic safety technology research group, 2012).

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In 1965, the Japan Shinkansen earthquake warning and monitoring system was first deployed on the Tokkaido Shinkansen. Since its inception, the Japan Shinkansen earthquake warning and monitoring system can be divided into three development stages based on different alarm methods. First generation: Based on threshold alarm strategy, mechanical seismometers are installed in substations along the Shinkansen at intervals of about 20 km. When the seismometer detects that the horizontal acceleration value of seismic motion exceeds 40 gal, it automatically triggers the power outage of the traction substation, thereby triggering emergency braking of the train. Second generation: threshold warning that combines local alarms from seismometers along railway lines with remote alarms from seismometers along coastlines. Third generation: earthquake warning based on P-wave and S-wave, with access to earthquake warning information from the Japan Meteorological Agency.

China Railway attaches great importance to the impact of earthquake on the operation-safety of HSRs. In order to mitigate seismic risks, the introduction of foreign HSR earthquake early-warning systems was considered in the early stages of HSR construction. However, the HSR equipment technologies used by Japan and France, including OCS neutral-section passing technology, train operation control technology, and track circuit system significantly differ from those of China. Therefore, foreign technologies can only be used as references (Zhang, 2014).

To develop an earthquake early-warning system fit for the technical features and the actual operation needs of China's HSR, the former Ministry of Railways concluded a strategic cooperation agreement with the China Earthquake Administration in February 2012 to jointly promote the construction and technological breakthroughs in China's HSR earthquake early-warning system (Ministry of Railways & Seismic Bureau, 2012). Through a series of studies over 30 topics in five years, key technologies such as P-wave identification and warning, multi-source seismic information fusion, and earthquake emergency treatment have been developed. With constant improvement in system functions and performance indicators through special tests on the earthquake early-warning systems of Fujian-Xiamen Railway, Chengdu-Dujiangyan Railway and Datong-Xi'an PDL, the HSR earthquake early-warning system was successfully developed in December 2018 (China Academy of Railway Sciences Corporation Limited, 2018; Department of Science Technology and Information Technology of China State Railway Group Co., Ltd, 2018; Yan, 2017).

1. Key technologies for HSR earthquake early-warning

With the rapid development of China's HSRs, railway lines have taken on a network layout. Although the HSR lines are located as far away from the potential seismic risk zones as possible, some lines in the southwest and northwest regions inevitably approach or cross the active fault zones (China Earthquake Administration, 2019). Considering the distribution of active fault zones, potential seismic risk sources, and the layout of HSR lines in China, the "point-line-plane" combined earthquake early-warning strategy should be applied to China's HSR earthquake early-warning technology. The point means the earthquake hazards that might affect any point of HSR lines shall be addressed to improve warning accuracy; the line means the mutual warning function of adjacent lines in the railway network shall be used to improve the use efficiency of limited stations; plane means the early warning function of CENC shall be fully used to improve the scope, capability, timeliness, and accuracy of early warning. Both onsite warning and regional warning, i.e. hybrid warning (Ma, 2008), should be provided, which means, in case of an earthquake happening around a line, an onsite warning is given to the line and a regional warning is given to other lines nearby. In terms of HSR earthquake emergency treatment, it is necessary to fully consider the technical features of China's HSR, including its high speed, high density, and large-scale network-based operation, set different warning levels, formulate corresponding treatment strategies according to the degree of influence of earthquake intensities on HSR operation safety and operation order, and the technical approaches taken for rapid treatment of earthquake warnings, to rapidly and accurately treat earthquake warnings and reduce the impact on railroad traffic order.

In conclusion, two key technical issues need to be solved for HSR earthquake early-warning and treatment. One of them is the earthquake early-warning technology, and the other is the emergency treatment technology for HSR earthquake early-warnings.

1.1 Earthquake early-warning

Earthquake early-warning is to utilize the P wave, with its fast transmission speed and limited destructive potential, to send out timely alerts, allowing the area where the S wave is approaching to take disaster-reduction measures in advance. As for the realization of earthquake early-warning technology, the ground motion data is first collected to identify whether it is an earthquake. If it turns out to be an earthquake, the recorded data are used to estimate the location and magnitude of the earthquake, and then the ground motion distribution is inferred from the attenuation relationship.

1.1.1 Identification of earthquake events. As various kinds of vibration interference around earthquake monitoring stations will cause false triggering of monitoring equipment, it is necessary to judge whether it is a trigger event by establishing characteristic functions for the calculation of STA/LTA (Allen, 1978). For HSR earthquake monitoring stations, two three-component force-balance speed sensors of the same model are placed in the same station, but a few tens of meters apart. This is done so that errors in judgment won't happen when only one monitoring point is used. Through identification of the correlation of the output signals of the two sensors, false triggering of monitoring equipment is reduced or eliminated.

After the ground motion is identified by the P-wave picking algorithm, the similarity between the waveforms of the two sensors is arithmetically judged. The data similarity of two sensors, expressed in percentage, means that the time-frequency amplitude of the data recorded by the two sensors from the same channels over time is the same. When it reaches a certain value, it is considered a good similarity. The two sensors placed in one HSR earthquake monitoring station are usually over 40 m apart (National Railway Administration of the People's Republic of China, 2015). Since the interference wave attenuates quickly while the seismic wave attenuates slowly, the two sensors that are 40 m apart have obviously different interference waveforms and present poor consistency in waveforms. On the other hand, for seismic waves with a focal depth of over 10 km, the two sensors spaced 40 m apart can be regarded as the same observation point, presenting strongly consistent waveforms.

The similarity calculation method is as follows:

$$\mathrm{corr}(\mathrm{x}, \mathrm{y}) = \frac{E[(X - u_x)(Y - u_y)]}{\sigma_x \sigma_y} \tag{1}$$

where, u_x and u_y are the mean value of signals x and y, respectively, and σ_x and σ_y are the standard deviation of signals x and y, respectively. The waveform data of the two sensors is analyzed for similarity, and the correlation coefficients of the directions UD, NS, and EW are respectively calculated using 1 second data. When the calculated correlation coefficients of the three channels are above a certain value, it is thought to be an earthquake.

Figure 1 displays the signals that a HSR line's vibration interference caused in the monitoring station equipment. The signal envelopes recorded by the two sensors are similar in shape, according to the acquired time domain waveform. However, the correlation coefficients of directions UD, NS, and EW are 0.12, 0.02, and 0.00, respectively, showing no obvious correlation. This means the event was not an earthquake.

Figure 2 shows an earthquake of M4.9 with a focal depth of 15 km. It was recorded by an earthquake monitoring station about 160 km away from the epicenter. The amplitudes recorded by the collected sensor signals are very small, but the correlation coefficients of the three components UD, NS, and EW of the signals measured by the two sensors are 0.849, 0.965, and 0.912, respectively, showing obvious correlation among the three components. So, it can be judged as an earthquake event.

1.1.2 P-wave earthquake early-warning for parameter estimation. One of the core functions of P-wave earthquake early warning is to use information about the waves to directly predict basic seismic parameters (such as magnitude and hypocenter) so that more accurate estimates of the damage to the warning target can be made. For onsite warning, the basic seismic parameters are obtained through the analysis of the signals collected by a single sensor or multiple sensors at a close interval and using the seismic parameter prediction model.

(1) Single-station seismic parameter estimation

- Single-station magnitude estimation

The methods for predicting earthquake magnitude generally involve τ_c and P_d (Kanamori, Hauksson, & Heaton, 1997; Wu & Li, 2006; Wu, Kanamori, AIlen, & Hauksson, 2007). The τ_c method is to first calculate the seismic wave speed and displacement according to the data

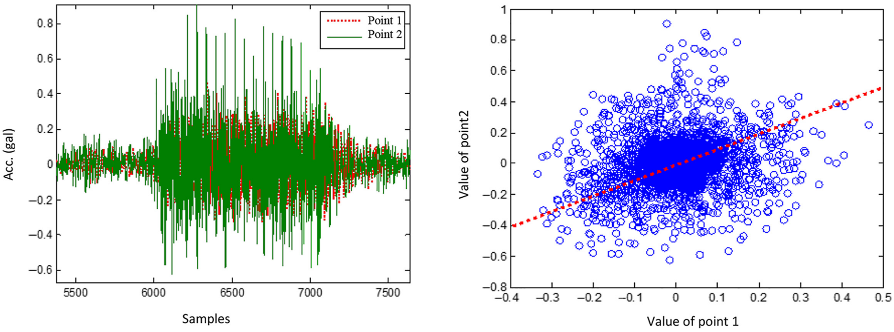

Figure 1.
Vibration waveforms measured by two sensors in UD direction and Their correlation

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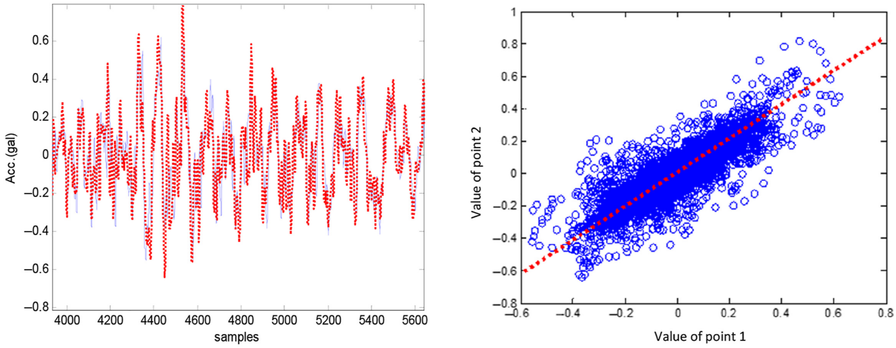

Figure 2.
Vibration waveforms measured by two sensors in UD direction and their correlation

Source(s): Authors' own work

collected after P wave arrives for several seconds, then obtain the predominant period of ground motion according to the integral ratio of speed to displacement, and finally obtain the magnitude using the magnitude calculation formula M. The formula of τ_c method of magnitude $(M)_{est}$ calculation is as follows:

$$(M)_{est} = C_1 * log\,\tau_c + C_2, \tau_c = \frac{2\pi}{\sqrt{r}}, r = \frac{\int_0^3 \dot{u}^2(t)dt}{\int_0^3 u^2(t)dt} \tag{2}$$

where, C_1 and C_2 are constant coefficients that are set according to the comprehensive analysis of geological conditions in different regions, $u(t)$ is displacement and $\dot{u}(t)$ is speed. The scale of fault fracture implied by P-wave frequency can be used to reflect the magnitude. τ_c is a refined and quantitative expression of such implicit information, which can be used to estimate the magnitude. The larger the τ_c, the greater the magnitude.

The P_d method is to calculate the earthquake magnitude using the amplitude of ground motion. P_d represents the recorded maximum displacement amplitude within 3 seconds after the P wave is triggered. The warning magnitude can be calculated through the analysis of the linear relationship between P_d and magnitude as well as the estimated epicentral distance. The formula for the P_d method for magnitude $(M)_{P_d}$ calculation is as follows:

$$\log(P_d) = a + b * (M)_{P_d} \tag{3}$$

where, a and b are constant coefficients. Through pre-processing of the seismic data, such as filtering and detrending, use of the historical seismic data in the earthquake-stricken areas, and further adjustment of the constant coefficients in the magnitude calculation formula, the earthquake estimation can be more accurate.

HSR earthquake early-warning makes full use of the results of different magnitude estimation methods, namely the linear combined characteristic period τ_c method and the P-wave vertical displacement amplitude P_d method, and comprehensive analysis to improve the accuracy of the single-station magnitude estimation.

$$M = a1 * (M)_{est} + a2 * (M)_{P_d} + a3 \tag{4}$$

where, a1, a2 and a3 are constant coefficients, which can be obtained from the historical magnitudes of the historical earthquake in stricken area.

Table 1 shows the difference in magnitudes obtained by τ_c method, P_d method and the combined τ_c and P_d method using 803 groups of historical seismic data. The results indicate that the combined method is better than the single method τ_c or P_d.

- Single-station epicenter positioning

In the estimation of epicentral distance for a single-station P-wave earthquake early-warning algorithm, this $B-\Delta$ method is frequently applied (Odaka, Ashiya, Tsukada, & Sato, 2003). This means that once the P wave is picked, the current position is used as the starting point to gather data for a few seconds in order to figure out the epicentral distance.

The epicentral distance and the trend of the seismic wave envelope are in a linear relationship. The seismic wave envelope can be simulated by $B-\Delta$ method (Figure 3), and its

Table 1. Comparison of magnitudes calculated by τ_c method, P_d method and $\tau_c + P_d$ method (deviation level ±1)

Data source | method	τ_c	P_d	$\tau_c + P_d +$
803 groups of simulation data	35%	32%	75%

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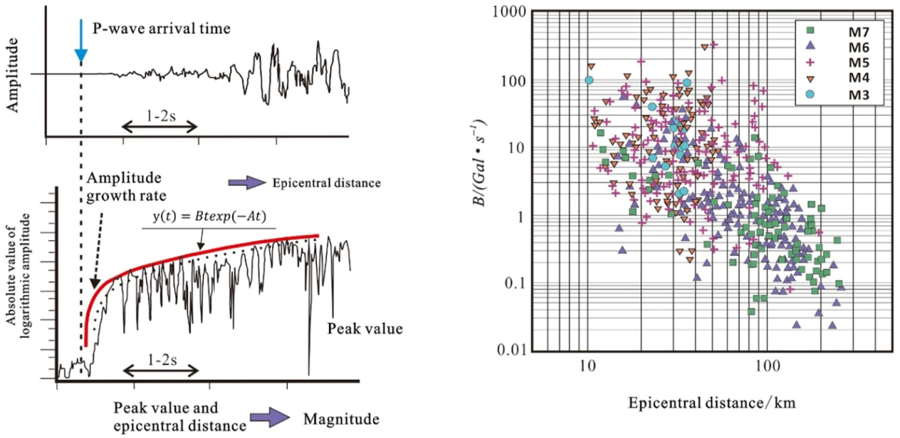

Figure 3. Schematic diagram $B - \Delta$: relationship between B and epicentral distance

Source(s): Authors' own work

fitting formula is: $y(t) = Bt * \exp(-At)$. The least squares of the data recorded a few seconds before the P wave arrives can be used to fit the waveform envelope for B, so as to determine the parameters B and A in the equation. The parameter A is related to the subsequent change in amplitude. The parameter B is related to the amplitude growth rate (i.e. the gradient of the envelope) of the initial P wave. After the parameter B is obtained, the formula for epicentral distance $\Delta (\Delta = a1 * logB + a2)$ can be applied, where $a1$ and $a2$ are the regression coefficients, which can be constantly adjusted according to the historical seismic records. Meanwhile, the method of making multiple fittings using the data of the P wave at different lengths before averaging is also effective for improving the results. Figure 4 shows the respective fitting results using the 2 s, 2.5 s, and 3 s data.

The earthquake monitoring stations of HSR have an approximately linear distribution. In order to further improve the positioning accuracy, the regular fitting formula $B - \Delta$ is improved by the further introduction of the predominant period τ_{pmax} and the maximum peak of P wave band P_d in addition to considering the relationship between epicentral distance Δ and B. The fitting formula is as follows:

$$log_{10} R = a1 * log_{10} \tau_{pmax} + a2 * log_{10} P_d + a3 * log_{10} B + a4 \quad (5)$$

where, $a1$, $a2$, $a3$ and $a4$ are the regression coefficients obtained from historical earthquake records.

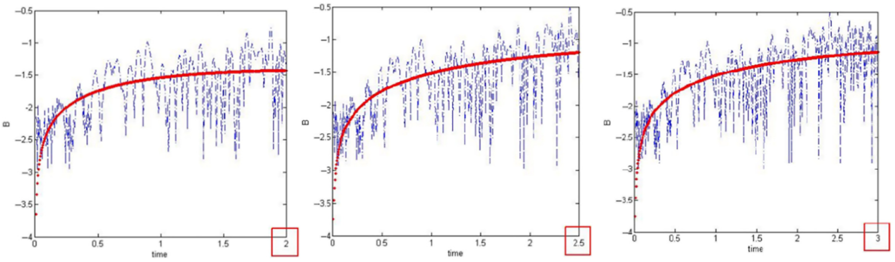

Figure 4. $B - \Delta$ fitting results using the data of different durations

Source(s): Authors' own work

- Single-station azimuth calculation

In the estimation of epicenter azimuth for single-station P-wave earthquake early-warning, the polarization analysis method is applied (Flinn, 1965; Lockman & Allen, 2005). Polarization analysis is a common method for the calculation of epicenter azimuth, and it is not affected by the signal-to-noise ratio of seismic signals. This technique is appropriate for HSR earthquake monitoring stations that are frequently interfered with non-earthquake events, when attempting to determine the azimuth of the epicenter.

The calculation of seismic azimuth is mainly based on the polarization property of the P wave. Using a digital seismograph to record the three components, we can form a 3*3 variance matrix: M.

$$M = \begin{bmatrix} Var(x) & Cov(x,y) & Cov(x,z) \\ Cov(x,y) & Var(y) & Cov(y,z) \\ Cov(x,z) & Cov(y,z) & Var(z) \end{bmatrix} \tag{6}$$

where, x, y and z represent the recorded three components, respectively (directions EW, NS and UD). The covariance matrix of the components x and y is defined below:

$$Cov(x,y) = \frac{1}{N}\sum_{i=1}^{N}[(x(i) - u_x)(y(i) - u_y)] \tag{7}$$

where, u_x and u_y are the average value of recorded data in x and y directions, respectively. Suppose the characteristic roots obtained from the matrix M are $\lambda_1, \lambda_2, \lambda_3$ and the corresponding orthogonal eigenvectors are $\varepsilon_1, \varepsilon_2, \varepsilon_3$, then the square matrix formed by the coordinates $\varepsilon_1, \varepsilon_2, \varepsilon_3$ is considered to be the solving matrix. Based on the projection of the maximum eigenvector corresponding to the maximum eigenvalue on the horizontal plane, the seismic azimuth is determined. Suppose the eigenvector corresponding to the maximum eigenvalue is $\varepsilon_1 = (mn, me, mz)^T$. The azimuth of an earthquake relative to the station is determined according to the symbols mn, me, mz and the relative magnitude and the symbol of the value. The calculation methods are listed below:

With the epicentral distance Δ and the azimuth $\boldsymbol{\theta}$, in combination with the longitude and latitude of the station, the longitude and latitude of the hypocenter can be inferred.

(2) Multi-station seismic parameter estimation

The limitations of single-station P-wave earthquake early-warning in magnitude and epicenter positioning result in a large deviation from the true value. Therefore, using the information of the arrival time difference and station location of two or more stations can give more accurate magnitude and epicenter positioning in the monitoring areas formed by multiple stations.

- Multi-station magnitude estimation

The magnitude parameters are continuously estimated by using an artificial neural network, comprehensively applying a variety of magnitude indicators in each second section (1–3 s) of the limited P wave band, and simulating the multi-band and multi-type (acceleration, speed, and displacement) records in real time.

In the case of known and unknown epicentral distance, multiple parameters are extracted from the data of the first 3 seconds after the P wave arrives and used for the training and verification of artificial neural network. The parameter, energy ratio of vibration channel, peak acceleration PGA, peak speed PGV, peak displacement PGD, cumulative absolute speed CAV, A and B, effective P pulse width, predominant period τ_c, maximum predominant period τ_{pmax}, maximum displacement of P wave P_d, where, τ_c and τ_{pmax} are defined below:

$$\tau_c = 2\pi \Big/ \sqrt{\left[\int_0^{t0} \dot{u}^2(t)dt\right] \Big/ \left[\int_0^{t0} u^2(t)dt\right]} \tag{8}$$

$$\tau_{pmax} = \max\left(2\pi\sqrt{X_i/D_i}\right. \tag{9}$$

where, $u(t)$ is the displacement time history, t_0 is the time window length based on integral calculation, $X_i = aX_{i-1} + x_i^2, D_i = aD_{i-1} + (dx/dy)_i^2$, x is the speed, and the smooth factor a is set to 0.99.

In the ANN toolbox of Matlab, the BP method is used to train the network. In the hidden layer, there are 55 neurons, and tansig is used as the transfer function, while in the output layer, the transfer function is linear function. Its structure is shown in Figure 5.

In the case of using an artificial neural network to estimate magnitude and the epicentral distance, the standard deviation σ is 0.38 JMA magnitude units. The error distribution and regression results are shown in Figure 6. If the epicentral distance is unknown, the standard deviation σ is 0.50 JMA magnitude units. The error histogram and regression results are shown in Figure 7. When the epicentral distance is known, the error in the estimate is not too high.

- Multi-station epicenter positioning

Earthquake early-warning has high requirements for real-time performance. Usually, the P-wave arrival time collected by a few triggered stations is used to locate the epicenter. The Master Station method is a widely applied algorithm (Zhou, 1994). The Master station method does not depend on the original time of the earthquake. The arrival times of two different seismic phases at the same station or the arrival times of the same seismic phases at two different sites can be used to get an equal differential time surface (EDT surface). The

Figure 5.
Design neural network structure

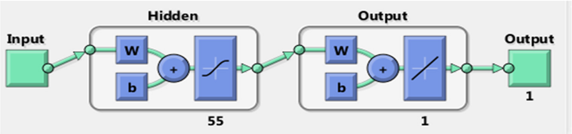

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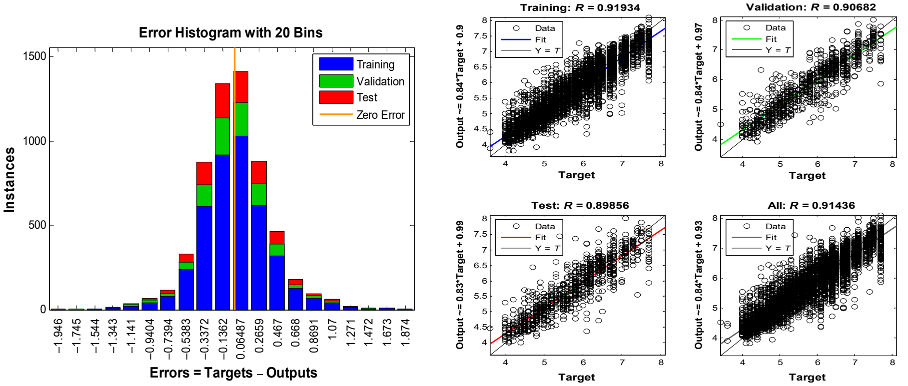
Figure 6.
Error histogram and regression results (epicentral distance is known)



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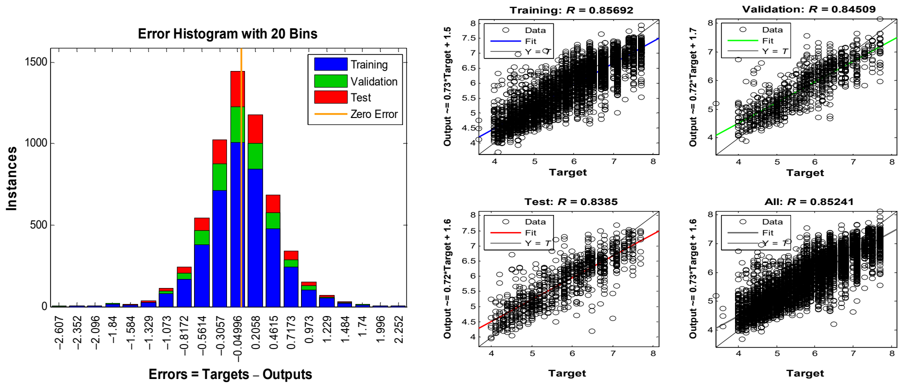

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Figure 7. Error histogram and regression results (epicentral distance is unknown)

epicenter is located in the area where most of the EDT surfaces pass, and the difference between the observed arrival time and the theoretical arrival time is the smallest. The EDT surface is essentially a hyperbolical surface obtained through the calculation of different arrival time information.

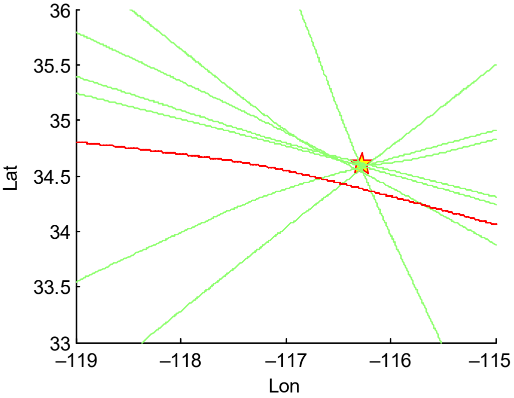
The EDT method uses the arrival time difference of seismic phases to locate the epicenter. Using the arrival time difference of the same seismic phase at different stations or that of the different seismic phases at the same station can obtain more accurate positioning results. In earthquake early-warning, the automatic picking of the P-phase provides the most accurate and timely results. The difference in arrival time of the P wave at different stations is most commonly used. Assuming that the P-wave speed is constant, after the arrival time of the same seismic phase at two stations is obtained, the location of the epicenter satisfies the following hyperbolic relationship:

$$\left(\sqrt{r_1^2+z^2} - \sqrt{r_2^2+z^2}\right) - V_p\Delta T = 0 \tag{10}$$

where, r_1 is the distance from the epicenter to one of the stations, r_2 is the distance from the epicenter to the other station, Z is the focal depth, V_p is the P-wave speed, and ΔT is the arrival time difference of P phase at two stations.

If the arrival time difference of two stations, average wave speed, and focal depth are known, the hyperbolic curve for epicenter positioning can be determined. When N stations are triggered, $N(N-1)/2$ hyperbolic curves can be drawn, which often form an overdetermined equation set. Adding up the hyperbolic equations, the residual's spatial distribution for the right part of the above equation can be obtained. Establish a relationship $W_R = 1/(\sqrt{2\pi}\,\sigma_{Res}).\exp(-Res^2/(2\sigma_{Res}^2))$ between the residual Res and the weight W_R with the normal distribution (σ_{Res} is the standard deviation of the residual and set to 0.1 from experience) and minimize the residual of the equation to obtain a better result. Figure 8 shows eight hyperbolic curves plotted using the P-wave arrival time difference of the first triggered station and eight other stations in the Hector mine earthquake. Of these hyperbolic curves, there is abnormal one (red). Even with abnormal data, good results can also be obtained after the residual of the equation is minimized.

1.1.3 Ground motion attenuation model. After seismic magnitude and epicentral distance are determined, it is necessary to estimate the ground motion-affected scope with a ground motion attenuation model and then take appropriate emergency treatment measures according to the magnitude of the ground motion along HSR lines.



Note(s): The star is the epicenter and the red hyperbolic curve is the abnormal one
Source(s): Authors’ own work

Figure 8.
Positioning results from P-wave arrival time difference of multiple stations in hector mine earthquake

There are three most common models for ground motion attenuation relationships (Yu, Li, & Xiao, 2013):

$$\text{Model 1}: \ln Y = c_1 + c_2M + c_4\ln[R + C] \tag{11}$$

$$\text{Model 2}: \ln Y = c_1 + c_2M + c_4\ln[R + R_0], R_0 = C_5\exp(C_6M) \tag{12}$$

$$\text{Model 3}: \ln Y = c_1 + c_2M + c_3M^2 + c_4\ln[R + R_0], R_0 = C_5\exp(C_6M) \tag{13}$$

Among them, Model 1 is an early attenuation model, which is not as good as Model 2 and Model 3 in focal dimension and is not in line with the records of measured strong earthquakes, so Model 1 is not chosen. The selection is mainly based on the comparative analysis of Model 2 and Model 3. Select the horizontal acceleration attenuation relationship in western China given in Table 2 and substitute it into Model 2 and Model 3 for comparative analysis, and the results are shown in Figure 9. Take M = 8.0 and R = 1.1 km as an example. In the major axis

Table 2.
List of calculation methods

mz	*Mn*	*me*	Azimuth (θ)
Negative	Positive	Positive	$arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Negative	Negative	Positive	$\pi - arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Negative	Negative	Negative	$\pi + arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Negative	Positive	Negative	$2\pi - arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Positive	Positive	Positive	$\pi + arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Positive	Negative	Positive	$2\pi - arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Positive	Negative	Negative	$arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$
Positive	Positive	Negative	$\pi - arctan\left(\frac{\lvert me\rvert}{\lvert mn\rvert}\right)$

Source(s): Authors’ own work

direction, the ground motion value at the epicenter obtained from the attenuation relationship of Model 2 is 1,236 gal, and the result of Model 3 is 933 gal. The ratio of the two results is as high as 1.3 times. In the 2008 Wenchuan (M8.0) earthquake, the maximum horizontal acceleration recorded at Sichuan Wolong Station, 1.1 km away from the southern end of the seismogenic fault, was 957 gal. The measured data was closer to the results of Model 3. Therefore, the attenuation formula of Model 3 was selected (Table 3).

The ground motion attenuation relationship actually adopted for HSR earthquake early-warning is as follows:

$$\ln Y = c_1 + c_2 M + c_3 M^2 + c_4 \text{In}\left[\mathrm{R} + c_5 \exp(c_6 M)\right] \tag{14}$$

where, Y is the peak acceleration (cm/s^2), M is the magnitude, R is the epicentral distance (km), and c_1, c_2, c_3, c_4, c_5, c_6 are the regression coefficients, as shown in Table 4.

1.2 Earthquake emergency treatment

In foreign countries, the control over the operating trains imposed by the HSR earthquake emergency treatment system upon the receipt of earthquake warnings mainly involves two modes. One of them is the train control system control mode represented by the French

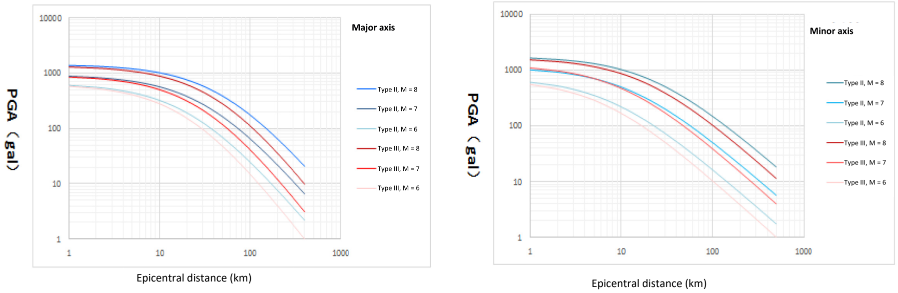


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Figure 9.
Comparison of two ground motion attenuation models

Attenuation relationship	Direction	c_1	c_2	c_3	c_4	c_5	c_6	σ
Class II site	Major axis	2.026	0.532	0.000	−1.954	2.018	0.406	0.240
	Minor axis	1.010	0.501	0.000	−1.441	0.340	0.521	0.240
Class III site	Major axis	0.537	1.167	−0.051	−2.170	2.170	0.383	0.232
	Minor axis	−0.760	1.068	−0.046	−1.490	0.264	0.530	0.232

Source(s): Authors' own work

Table 3.
Attenuation relationship for horizontal acceleration in Western China

		c_1	c_2	c_3	c_4	c_5	c_6	σ
Major axis	Western China	2.026	0.532	0.000	−1.954	2.018	0.406	0.240
	Eastern China	2.027	0.548	0.000	−1.902	1.700	0.425	2.027
Minor axis	Western China	1.010	0.501	0.000	−1.441	0.340	0.521	0.240
	Eastern China	1.035	0.519	0.000	−1.465	0.381	0.525	1.035

Source(s): Authors' own work

Table 4.
Regression coefficient (c) and statistical standard deviation (σ) in acceleration attenuation relationship of Bedrocks in Eastern and Western China

Mediterranean High Speed Line (Li, 2004). Upon receipt of warnings, the train control system is manually operated to send out a control signal to stop the train. The other one is the traction power supply system control mode represented by the Japanese Shinkansen (Beijing-Shanghai High Speed Railway Technology Research Group, 2000; Nakamura, 1988). Upon the receipt of warnings, the traction substation stops supplying power to OCS, and the onboard device automatically activates emergency braking right after detecting OCS power-off.

Learning from the earthquake emergency treatment technologies of foreign HSRs, we propose an earthquake emergency treatment method that combines the multi-level treatment strategy and the ground system interlocking treatment with the dedicated onboard device-controlled emergency treatment (China State Railway Group Co., Ltd, 2018a, b). Upon the receipt of earthquake early-warning information from along HSR lines, the signal interface, communication interface, and traction power supply interface on the ground jointly trigger the traction power supply system and the communication and signaling system of HSR for automatic treatment. At the same time, the onboard earthquake emergency treatment device takes automatic actions to effectively control the operating trains, thus reducing seismic secondary disasters.

1.2.1 Earthquake emergency treatment mode. Given that the P-wave earthquake early-warning technology has such issues as deviation in epicenter positioning and magnitude as well as false alarm, a multi-level treatment strategy (I, II, and III) is employed for China's HSR earthquake emergency treatment, that is, speed-limited operation at low warning threshold (I) and stop at high warning threshold (II and III). Considering the technical characteristics of EMUs, the communication signaling system, and traction power supply system of China's HSR, multiple fast control measures are adopted, including automatic train control by onboard earthquake emergency treatment devices, train control system-triggered control, and OCS power-off. These three modes are independent of each other, as shown in Figure 10.

Mode 1: Automatic train control by onboard device. The onboard earthquake emergency treatment device is installed on high-speed trains, consisting of an onboard seismic host and onboard seismic terminals. It realizes train-ground information transmission through the railway digital mobile communication system GSM-R .The onboard seismic host is connected with the train braking system through an interface, and the onboard seismic terminals are installed in driver's cabs at both ends of the train. For Level-I treatment, the onboard seismic terminal gives audible prompts to the driver for speed-limited operation. For Level-II and Level-III treatment, the onboard seismic host automatically triggers the train braking system to stop operation; meanwhile, the onboard seismic terminal gives voice prompts.

Mode 2: Train control system - triggered. For Level-II and Level-III earthquake early-warning, the earthquake early-warning central system automatically sends the earthquake emergency treatment information to the railway signal interfaces distributed in BTSs, relay stations, and train stations along the railway line. Then, the railway signal interfaces trigger the linkage operation control system for linkage actions, so that all high-speed trains within the emergency treatment range automatically stop.

Mode 3: OCS power-off. For Level-III earthquake early-warning, the earthquake early-warning central system automatically transmits the earthquake emergency treatment information to the traction substation interfaces distributed in traction substations along the railway lines. The traction substation interfaces trigger the connected traction power supply system to power off, so that all high-speed trains within the emergency treatment range automatically stop due to power failure.

The earthquake early-warning threshold is determined mainly by the bearing capacity of HSR bridges, tunnels, and OCS, as well as the safety and comfort parameters of high-speed trains. Earthquake early-warning is divided into three levels, from low to high, by peak ground acceleration (see Table 5). The corresponding emergency treatment rules are as

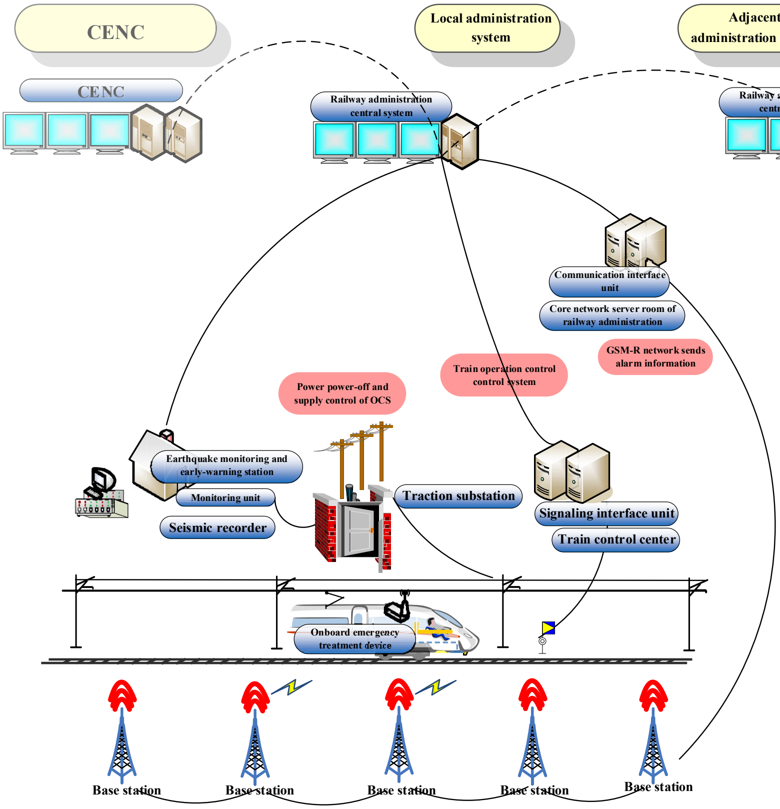

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Figure 10.
Earthquake emergency treatment mode

Table 5.
Rules for emergency treatment of earthquake early-warning

Level of warning	Warning threshold A (gal)	Rules for emergency treatment of earthquake early-warning
Level I	$40 \le A < 80$	Operation under speed limit
Level II	$80 \le A < 120$	Train control system and onboard earthquake emergency treatment device activate emergency braking
Level III	$120 \le A$	Traction power supply system is powered off Train control system and onboard earthquake emergency treatment device activate emergency braking

Source(s): Authors' own work

follows: For Level-I treatment, the earthquake early-warning central system transmits the Level-I warning information to the onboard earthquake emergency treatment device, which then gives audible prompts to the driver to manually slow down the train to below 160 km/h. For Level-II treatment, the earthquake early-warning central system transmits the Level-II warning information to the train control system, and the onboard earthquake emergency treatment device, which then activate the emergency braking of the train; For Level-III treatment, the earthquake early-warning central system transmits the Level-III warning information to the train control system, the traction power supply system and the onboard earthquake emergency treatment device. The train control system and the onboard earthquake emergency treatment device activate the emergency braking of the train while the OCS is powered off.

1.2.2 Ground earthquake emergency treatment. Ground earthquake emergency treatment is realized by the signal interface unit, communication interface unit, GSM-R network, and earthquake early-warning central system.

(1) Train operation control by train control system

The warning information is transmitted by the earthquake early-warning central system to the signal interface, which then sends information to the train operation control system. The system then activates emergency braking for the trains in the earthquake-affected area and prevents the trains in the non-earthquake-affected area from entering the earthquake-stricken area. Upon receipt of false alarm release and post-earthquake train operation recovery information, the signal interface automatically restores the device to its original status.

(2) OCS power-off

The earthquake monitoring information is sent by stations. After identifying and confirming the information, the earthquake early-warning central system sends a power-off command to the earthquake monitoring stations near the traction substation in the corresponding area within the earthquake-affected scope. Under the control of the traction power supply interface, the traction substation OCS is powered off, thus realizing the power-off control of OCS within the earthquake-affected scope. Upon receipt of false alarm release and post-earthquake train operation recovery information, the traction power supply interface automatically restores the device to its original status.

(3) Transmission of warning information through GSM-R network

Through the communication interface and the GSM-R network, the earthquake early-warning central system transmits warning, false alarm release, and post-earthquake train operation recovery information to the onboard emergency treatment device on the train that is operating in the earthquake-affected area.

(4) Dispatching the command system

Upon receipt of warning information, the HSR dispatching system promptly gives an alarm to the dispatcher, showing the epicenter location, seismic magnitude, and earthquake-affected scope in real time. After receiving false alarm release and post-earthquake train operation recovery information, the dispatching system issues a dispatching command to restore normal operation.

(5) Automatic false alarm release and train operation recovery

The earthquake early-warning central system confirms the warning information through CENC and sends false alarm release information to signal interface, communication interface, traction power supply interface, and dispatching system if the information is confirmed as a false alarm.

1.2.3 Onboard emergency treatment. In order to further shorten the earthquake early-warning and alarm treatment time and timely control the operating status of high-speed trains, a scheme of GSM-R transmission-based onboard emergency treatment devices are further proposed. This is based on the experience from the emergency treatment technology of the onboard equipment on the Japanese Shinkansen that can trigger the signaling system and the traction power supply system for emergency treatment during an earthquake. Specifically, it means the development of a dedicated onboard emergency treatment device installed on high speed trains, mainly consisting of a host (incorporating a GSM-R communication unit and a control unit) and a display terminal. The host control unit and the train braking system are hardwired, and the terminal is installed at the driver's console.

The onboard emergency treatment device receives real-time earthquake early-warning information released through the GSM-R network and takes corresponding rapid actions to control trains according to different warning levels. It prompts the driver to resume operation in accordance with relevant regulations after receiving earthquake early-warning release and train operation recovery information. The treatment process is as follows:

> For Level-I train control mode, the display unit gives an audible (voice) visual alarm to the driver and displays the current status on the display terminal, and the driver manually controls the train to operate at a limited speed based on the alarm information.
>
> For Level-II and Level-III train control modes, the control unit automatically controls the emergency relay through hard wires to disconnect the safety loop, thus applying emergency braking.

2. HSR earthquake early-warning system

The HSR earthquake early-warning system is used to determine the earthquake-affected scope and the warning level according to the ground motion parameters measured by seismic stations in real time and the basic seismic parameters quickly estimated on the basis of the earthquake first-arrival information. It then sends out earthquake emergency treatment information for local and regional railways in the earthquake-affected scope, jointly triggers the relevant systems to take effective emergency treatment actions for trains in operation, identifies the authenticity of the warning information, and automatically releases the false alarm off information or enables manual earthquake alarm off before the destructive seismic wave arrives.

The HSR earthquake early-warning system is composed of the earthquake early-warning and monitoring system (ground) and the onboard emergency treatment device (onboard). The earthquake early-warning and monitoring system consists of earthquake monitoring stations, signal interfaces, and the railway administration's earthquake monitoring and warning central system. The earthquake monitoring and warning stations and the railway administration's central system are networked with the earthquake monitoring and warning systems of adjacent railway administrations. This lets the earthquake department's seismic network realize the release of earthquake early-warning information to the related railway systems in the earthquake-affected areas. The railway administration's central system is set in the railway administration, and the field monitoring device is set along railway lines. After receiving the earthquake early-warning information, the onboard emergency treatment device takes effective emergency treatment measures for trains in operation, thus realizing the control of train operation. The railway administration's central system is interconnected with the CENC information center to realize joint warning.

The architecture of earthquake early-warning system is shown in Figure 11.

2.1 Earthquake early-warning and monitoring system

Field monitoring devices collect real-time data on ground motion in earthquake-affected areas from nearby railway lines and along the lines. They also get information from the earthquake departments and early warning systems of nearby railway administrations. This

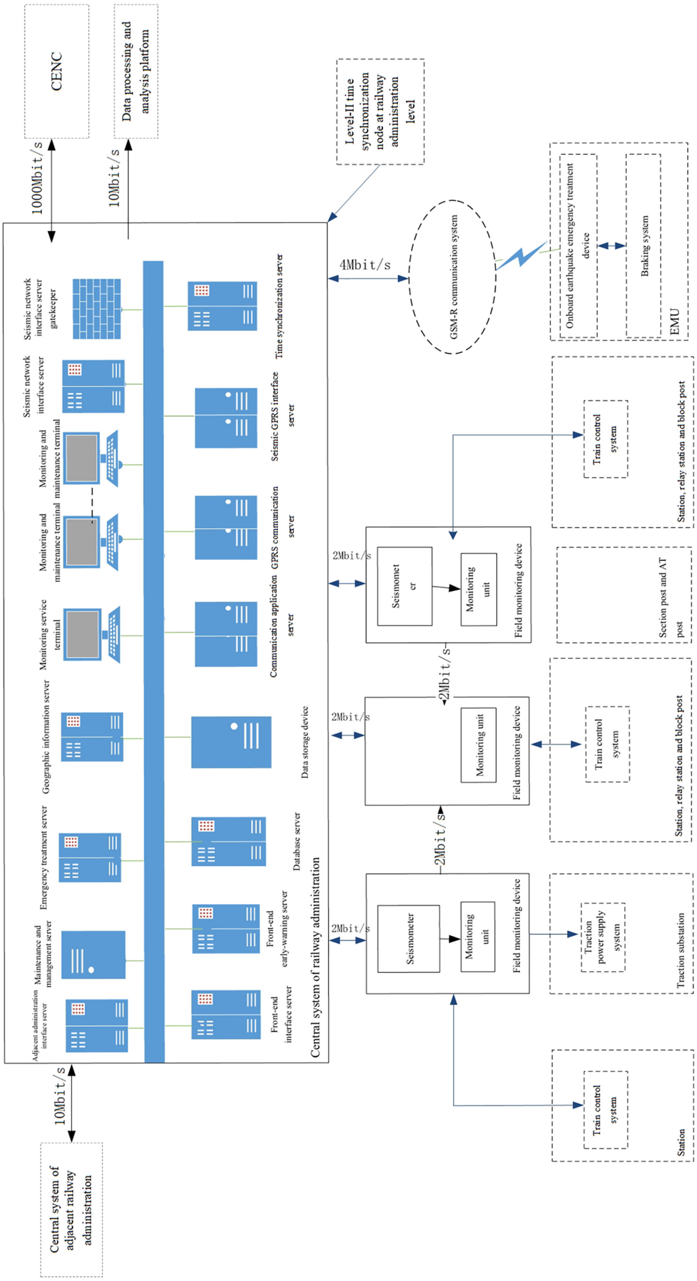

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Figure 11.
Architecture of HSR earthquake early-warning system

system then analyzes and processes this data to give trains effective, accurate, and reliable earthquake monitoring and warning information and controls the trains in operation through the joint action of the onboard emergency treatment device, HSR wireless communication system, and traction power supply system, signaling system and dispatching system.

The earthquake early-warning and monitoring system has a two-level architecture. The first level is the railway administration's central system, and the second level is the field monitoring device.

(1) Field monitoring device

According to the *Technical Specification for Earthquake Early-warning and Monitoring System of High-speed Railway*, earthquake monitoring stations should be built along HSR lines, in the section where the ground motion peak acceleration is 0.1 gn or above, at a distance of about 25 km, mainly in traction substations, section posts, AT posts, and communication relay stations along railway lines.

The field monitoring device consists of a seismometer and monitoring unit, and the monitoring unit includes a data acquisition unit, monitoring host, traction substation interface, signaling interface, power supply, network and disconnector, lightning protection module, etc. (Figure 12).

The field monitoring device can quickly estimate parameters, such as earthquake magnitude and acceleration, according to the real-time measured ground motion parameters, and timely transmit the earthquake alarm information. Its main functions are as follows: realizing real-time monitoring of ground motion, effectively filtering out interference signals, accurately identifying earthquake events, and transmitting the monitoring information to the railway administration central system in real time; quickly carrying out P-wave identification, earthquake location, magnitude estimation, ground motion intensity prediction, and early-warning level identification; and sending earthquake early-warning information to the railway administration central system. The action of the traction power supply system will be triggered when it detects that the peak ground motion (threshold alarm) has reached the Level III alarm threshold or when it receives the Level III treatment information from the railway administration central system. When it receives the Level II and Level III alarm information or receives the Level II and Level III treatment information released by the railway administration central system, the action of the train control system interface relay will be triggered. By detecting the subsequent waveform, it will release false alarm off information to the railway administration central system in case of any false alarm. When receiving the false alarm-off information released by the railway administration

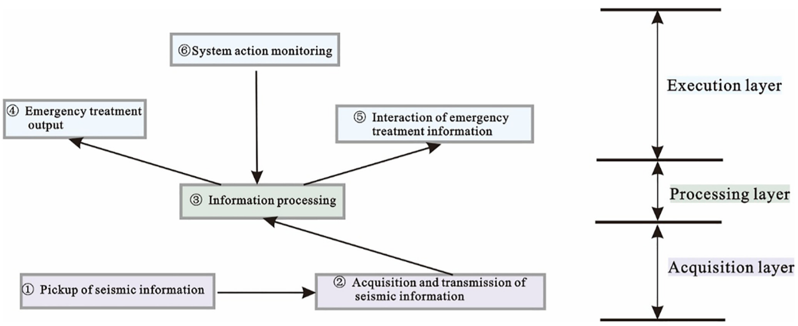

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Figure 12.
Structural diagram of field monitoring device

central system, it will automatically restore the device status. Dynamically monitor the working status of each main component in real time and send it to the railway administration central system in real time. It has a disconnector, which can be manually operated as required to realize isolation from the traction power supply system and train control system. It has functions such as device self-testing, software upgrading, data downloading, and data backup.

(2) Railway administration central system

According to the standard of Q/CR 633–2018, each railway administration is equipped with a railway administration central system, which can realize the interoperability of seismic information in 18 railway administration central systems through the dedicated railway network. When the railway administration central system receives the earthquake warning or quick report information from the adjacent railway administration central system or seismic network center, it will send emergency treatment instructions for high speed trains and field monitoring devices entering the train control scope of the railway administration. This will make it possible for the regional linkage train control treatment to happen.

The railway administration central system consists of an earthquake early-warning and monitoring information system and communication interface, which are set up in the information server room of the railway administration (Figure 13). The hardware equipment includes database server, application server, interface server, storage device, network device, safety device, maintenance terminal, train operation dispatching terminal, power supply dispatching terminal, track engineering dispatching terminal, communication and signaling dispatching terminal, etc. The software system includes application software for the railway administration central systems, as well as system software such as operating systems, database management, middleware platforms, system security management, geographic information management, and storage management. The communication interface consists of a seismic information processing application server, a packet data communication server, a cell broadcast communication server, and network equipment. The communication interface software includes application software such as seismic information processing, location management of onboard earthquake treatment devices, packet data communication management, and interface management, as well as system software such as operating systems and database management.

The railway administration central system can integrate and process the earthquake early-warning information and alarm information generated by field monitoring devices. It can quickly calculate the scope of HSR affected by the earthquake according to the ground motion acceleration and magnitude, determine the earthquake emergency treatment level, display on the train operation dispatching terminal and maintenance terminal in the form of dynamic graphics and audible and visual alarms, and dynamically adjust the magnitude and

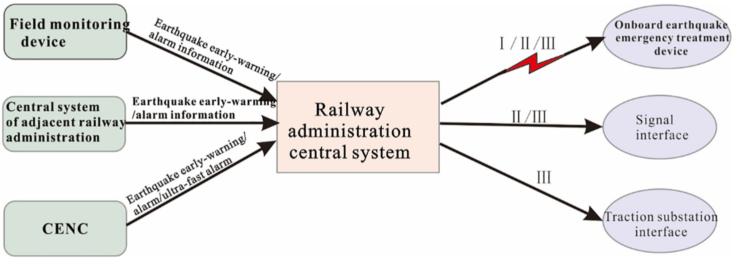

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Figure 13.
Schematic diagram for main functions of railway administration central system

treatment range with the update of multi-station earthquake early-warning information. This enables the system to provide detailed railway mileage information for emergency rescue and post-earthquake recovery operations after an earthquake. Its main functions are as follows: realizing the collection, analysis and, processing of information such as ground motion monitoring, P-wave earthquake early-warning and threshold earthquake alarm within the jurisdiction; carrying out multi-station P-wave earthquake early-warning, calculating emergency treatment level and impact scope, releasing emergency treatment the information, false alarm, alarm off, and post-earthquake recovery information, information interaction with the seismic network and adjacent railway administration; device status monitoring and surveillance; maintenance management; and other functions. It has the function of interconnecting with the GSM-R communication system, sending emergency treatment information to onboard earthquake detection devices within the scope of Level I, Level II, and Level III emergency treatment through GPRS, training control systems within the scope of Level II and Level III emergency treatment through a monitoring unit, and traction power supply systems within the scope of Level III emergency treatment. It is responsible for dynamically monitoring the trains within the jurisdiction and sending earthquake emergency treatment information to the onboard earthquake emergency treatment device. The central system receives the monitoring information, alarm information and device status information of the field monitoring device within the jurisdiction in real time; receiving the status information of the onboard earthquake detection device in real time; receiving the alarm information from the central system of the adjacent railway administration in real time; and the monitoring information, early-warning information and quick report information from the CENC in real time. The monitoring service terminal displays the alarm information and treatment information in real time, and the monitoring and maintenance terminal displays the contents of the monitoring service terminal, as well as the working status and isolation status information of system equipment, in real time, and has the functions of alarm off and post-earthquake system recovery information sending.

(3) Joint warning of seismic network

In view of the fact that HSR route selection is as far away from fault zones as possible, seismic monitoring stations are arranged along the line, and monitoring points are sparse. In comparison, CENC has a high-density network layout and is set close to fault zones. Combining with the CENC can further improve the timeliness and accuracy of HSR earthquake early-warning and realize regional warning. Therefore, data exchange platforms for CENCs (mutual backup) are set up in Beijing and Guangzhou to realize earthquake information interaction with the CENC in a “headquarters-to-headquarters” manner (Yang, Liu, Zhang, & Hu, 2019) and forward them to each railway administration central system (Figure 14).

The main functions of a data exchange platform are as follows: data receiving, data distribution, and data processing. The data receiving function receives earthquake event waveform data, earthquake early-warning, alarm, quick report, ground motion parameters, alarm cancellation, and other information sent by the seismic network information system in real time. It also receives earthquake event waveform data, peak acceleration, early-warning, alarm, device working status, and other information sent by the railway administration central system in real time. The data distribution and processing function analyzes and processes the received earthquake event waveform data, early-warning, alarm, quick report, ground motion parameters, alarm cancellation, and other information from the seismic network. It then sends this information in real time to the central system for railway administration, which creates emergency treatment instructions.

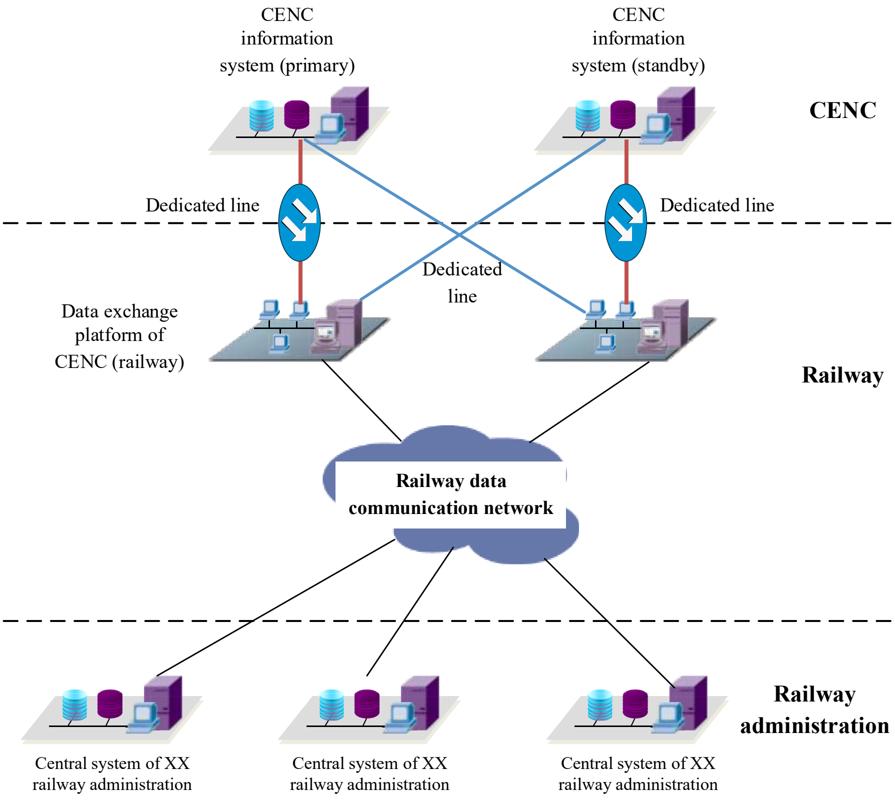

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Figure 14.
Overall architecture of data exchange platform

The railway administration central system receives real-time information such as seismic network early-warning, alarms and quick reports. It's also forwarded by the data exchange platform, as well as real-time local alarm information such as P-wave earthquake early-warning and threshold earthquake alarms sent by self-built stations along the railway. Through comprehensive analysis and fusion processing of the information, it calculates the scope of HSR affected by the earthquake, generates emergency treatment information, and sends to the corresponding affected scope. Because information like seismic network early-warning and quick report is very accurate and usually better than early-warning information from stations along the HSR, the earthquake early-warning data will be processed in order when they were received, following the rules for alarm upgrading and prioritizing the use of CENC information.

2.2 Onboard earthquake emergency treatment device

The onboard earthquake emergency treatment device is designed to periodically send status reports to the communication interface of the ground center system, including information about the GSM-R cell where the onboard device is located and equipment working status information. The communication interface receives the earthquake alarm information sent by the earthquake early-warning communication application server and calculates the cell corresponding to the earthquake impact scope according to the longitude, latitude, or kilometrage information in the alarm information. The communication interface judges all onboard receiving devices within the alarm range and sends earthquake early-warning information to the onboard receiving devices within the specified range in GPRS mode through the GSM-R network. After the onboard device completes the corresponding treatment, it sends a control output receipt to the communication interface unit, which sends this receipt information to the earthquake monitoring and early-warning information system. The overall architecture is shown in Figure 15.

Functions of onboard earthquake emergency treatment device are as follows: it has a GSM-R wireless data transmitting-receiving function based on GPRS to realize the reception and response of emergency treatment information. After receiving the emergency treatment information, it notifies the driver to apply maximum service brake or automatically trigger emergency brake according to different emergency treatment levels, and has functions such as brake control release, relay status recovery, device isolation and device isolation status recovery. At the same time, it has functions such as voice display alarm, release of voice display alarm, event voice prompt, function setting, parameter input, log recording and query, system information viewing, document management, event data storage and export, system reset and self-test.

2.3 Key performance indicators of earthquake early-warning system

From 2013 to 2018, the HSR earthquake early-warning system has been tested, verified, and applied on the Fuzhou-Xiamen HSR, Chengdu-Dujiangyan Railway, and Datong-Xi'an HSR successively as pilot projects. Through field tests (Wang, Dai, Xi, & Wei, 2019; China Academy of Railway Sciences Corporation Limited, 2020), the functions and key performance indicators of the earthquake early-warning, monitoring system, and onboard earthquake detection device have been comprehensively and scientifically verified. The key technical indicators of the system have excellent performance: The first report time of the P-wave is less than 3 seconds, accounting for more than 90%. Within the epicentral distance of 100 km, the deviation is less than 20 km, accounting for more than 70%. The magnitude deviation of earthquakes with magnitudes of 5 to 7 is less than 1, accounting for more than 80%. From the first arrival of P-wave to the beginning of train braking, the total delay of onboard emergency treatment is 3.63 s under 95% probability. The average total delay for emergency treatment of the CTCS-2 train control system is 5.5 s, and that of the CTCS-3 train control system is 6.5 s. The average total delay for power failures triggered by substations is 3.3 seconds (Figure 16).

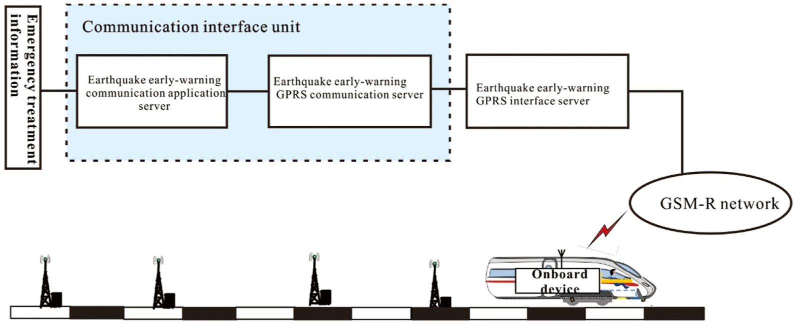

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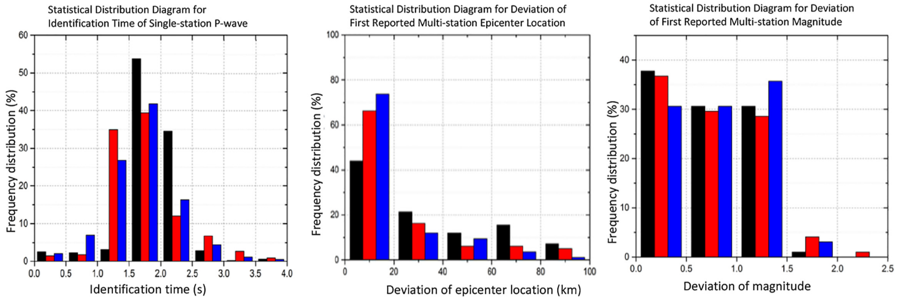
Figure 15. Schematic diagram of overall architecture for emergency treatment of onboard earthquake detection device

Figure 16.
Test verification of P-wave earthquake early-warning parameters



First report *t*≤3s, exceeding 90%

Deviation of epicentral distance ≤20km, exceeding 70%

Deviation of magnitude 5~7 ≤±1, exceeding 80%

Source(s): Authors' own work

3. Conclusion

The HSR earthquake early-warning system has realized a number of innovations in China's HSR technology system.

(1) We have innovatively proposed and, for the first time, enabled local and remote multi-source early-warning, multi-level earthquake alarm treatment strategy and multiple fast control measures. The developed onboard earthquake emergency treatment device has realized rapid and reliable treatment of onboard earthquake emergency treatment information for the first time, effectively reducing the time of HSR earthquake emergency treatment.

(2) From 2013 to 2018, the HSR earthquake early-warning system has been tested, verified, and applied on the Fuzhou-Xiamen HSR, Chengdu-Dujiangyan Railway, and Datong-Xi'an HSR successively as pilot projects. The key technical indicators of the system have excellent performance: The first report time of the P-wave is less than 3 seconds. From the first arrival of P-wave to the beginning of train braking, the total delay of onboard emergency treatment is 3.63 seconds under 95% probability. The average total delay for power failures triggered by substations is 3.3 seconds.

(3) The HSR earthquake early-warning system serves as an important technical tool for HSR to cope with earthquakes, and fills the gap in automatic emergency treatment of HSR in earthquake scenarios.

However, it should be noticed that China's HSR earthquake early-warning technology needs to be continuously optimized and improved. Especially when the seismic parameters are estimated by using the first few seconds of arrival waves from a single or a few stations, there is great uncertainty in the estimated seismic parameters and ground motion magnitude. The joint warning with integrated monitoring information from CENC can better make up for the deficiency, and further application research and tests need to be strengthened. The deterministic method is adopted in the calculation process of treatment scope of the HSR earthquake early-warning system, which is different from the actual earthquake intensity release. The probability-based research theory on earthquake impact scope carried out by relevant countries is worthy of reference for China's HSR earthquake early-warning. In addition, with the promotion and application of the HSR earthquake early-warning system, it is necessary to further strengthen the research on post-earthquake emergency response plans and post-earthquake operation recovery strategies for HSRs. Sequentially, this can form a full chain of technical support from earthquake early-warning, earthquake occurrence, emergency treatment, emergency rescue, and post-earthquake recovery, providing more complete technical support for HSRs to cope with natural disasters.

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