NEW AUTOMATIC TRAIN STOPPING SYSTEM DURING EARTHQUAKE (II)

by

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SUMMARY

This paper describes a new anti-earthquake protection system which has been under development for the Tohoku SHINKANSEN to assure the safety of passengers on high-speed running trains in the event of an earthquake occurrence.

Conventional anti-earthquake protection systems have a serious defect that they have small time margin from earthquake-detection to principal motion-arrival. To secure a sufficient time margin, the new system employs the two methods.

The new system can also be used as an alarm system for important functions of large cities and industrial plants, etc.

INTRODUCTION

If the prediction of earthquake occurrence is possible, the safety of passengers on trains can be assured by stopping the train service at the predicted time. However, highly reliable prediction just before earthquake occurrence is impossible at the present stage, and no prospect of its realization exists in near future. Therefore, as the next best measure, a system is worked out to detect an earthquake as early as possible and to apply the emergency brakes to running trains, if necessary.

The simple, conventional anti-earthquake train protection system used for the Tokaido SHINKANSEN and Sanyo SHINKANSEN is the first realization of such an idea. It is outlined as follows: Seismoscopes are installed along the railway line at an interval of 20∿25km, and if a seismoscope detects horizontal motion of more than 40 gals, an emergency-stop-order is issued to the trains running within the range of 20∿25km from the seismoscope. However, experience shows that the time margin from the issue of the emergency-stop order to the arrival of principal motion is within several seconds and so considered not sufficient. It is apparent that a wider time margin is required for the improvement of the safety of passengers on high-speed running trains. Therefore, the new system employs the following two methods to secure a longer time margin.

1) To detect the initial motion of P-wave of an earthquake motion for estimating the location and magnitude of the earthquake.

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2) To set the earthquake detection points away from the railway line, pos- ssibly nearer to probable foci.

The method 2) requires knowledge of the probably focal region. Since most earthquakes which may cause serious damages to the Tohoku SHINKANSEN are known to have epicenters in the Pacific Ocean, the requirement 2) can be satisfied by setting the detection points along the coast of the Pacific Ocean. The time margin obtained by the new system consists of the S-P time provided by the method 1) and the propagation time of the principal motion between an earthquake detection point and the railway line, given by the method 2). A good time margin can be expected by the effective actions of 1) and 2) in all earthquakes except the ones which occure just under the earthquake observation network and therefore give little time margin due to short S-P time.

In the 6WCEE, the study about the method 1) was reported [1], showing that the magnitude of detected earthquakes can be assessed to some extent by the amplitude and period of their initial motions. Taking the result of study made after the 6WCEE also into consideration, an unmanned model system was installed in Miyako, a city located on the Pacific Ocean coast of the Tohoku district. In this paper, the function of the model system to estimate the location and magnitude of an earthquake is reported together with the estimation results.

OUTLINE OF THE MODEL SYSTEM

The purposes of the model system include a) automatic detection of earth- quake, b) estimation of the location and magnitude of the earthquake detected, c) verification of the algorism to automatically infer whether the detected earthquake is damaging or not, and d) confirmation of the possibility of the unmanned system operation. The item b) is principally described here.

Construction of Model System. The system consists of a tripartite earthquake observation network, a system to telemeter the obtained seismic data to a data processing center epuipped with a real-time and seismic data analysing system provided at the data processing center.

Table 1 shows the location of the 3 observation points. Fig. 1 repre- sents the plane arrangement of these observation points, showing a triangular network construction with each point being separated by 20∿25km. Table 2 gives the type and characteristic constants of the seismometers installed at these observation points. Most of them are velocity meters set on rock beds. The data processing center provided with seismic-data recording equipment and data processing equipment is located around the Miyako observation point. The seismic wave data obtained at the Kawai and Sotoyama observation points are transmitted to the processing center in digitals through the communica- tion link of the NTT (Nippon Telegraph and Telephone Public Corporation), and the data of the Miyako observation point is transmitted to the center in analogues by means of a private communication link.

The recording system performs magnetic recording after delaying the transmitted data by 30 sec with a delay memory. The data processing system processes the received data on real-time basis.

The unmanned operation of the model system has caused no particular problem up to now except the occurrence of some line errors and power failures. It has been confirmed that the unmanned operation is satisfactory provided a communication line is leveled up and a continuous power-supply is assured.

Earthquake Detection. Detection of seismic waves is performed when the output of the seismometers exceeds a threshold noise level. This detection time is used for inferring the location of an earthquake. Since the model system estimates the magnitude of an earthquake based on the initial motion of P-waves, it is necessary to know whether the detected seismic wave is P-wave or not. Otherwise, if the principal motion of large amplitude is regarded as P-wave, the magnitude may be overestimated causing malfunction of the system. Two methods are available for the discrimination of P-wave.

1) Discrimination by apparent propagation velocity (used in the model system).

2) Discrimination by polarity-change of the product of horizontal and vertical components of the seismic wave.

Estimation of Epicentral Location, Direction of Incoming Seismic Wave and Apparent Propagation Velocity. To locate the focal only from the arrival time of a seismic wave, arrival times at least 5 points are required. From 5 arrival times, 5 unknown values i.e. spatial coordinates (X,Y,Z) of a focus, apparent propagation velocity V and earthquake origin time T_o can be determined. Since the model system has only 3observation points, 2 unknown value are to be assumed. Suppose that the locations of the observation points are Miyako (X_1, Y_1), Kawai (X_2, Y_2) and Sotoyama (X_3, Y_3). From Fig.2,

$$(X - X_i)^2 + (Y - Y_i)^2 + Z^2 = V^2(T_i - T_o)^2, \qquad i = 1,2,3 \qquad (1)$$

where T_1, T_2, T_3 are seismic wave arrival times at Miyako, Kawai, Sotoyama respectively. In the model system, X and Y are determined by assuming that the apparent P-wave velocity of the detected wave is V = 6.0km/s and the depth is Z = 40km. V is, as can be seen from Fig. 2, the mean wave propagation velocity between the focus and the detection points.

To calculate the direction of incoming seismic wave θ and apparent propagation velocity V, suppose that a plane wave is propagated from the epicentral direction (θ). From Fig. 3,

$$(X_i - X_j)\sin\theta + (Y_i - Y_j)\cos\theta = V(T_j - T_i), \qquad i.j = 1,2,3 \qquad (2)$$

θ and V can be calculated from this equation. θ can also be obtained from X and Y in another calculation.

Estimation of Magnitude.

It is necessary to estimate the magnitude from the initial motion of P-wave. According to Gutenberg-Richter, magnitude can be obtained from the maximum double amplitude (vertical motion, A μ) of P-wave by the use of following equation:

$$m = \log (A/T + \alpha)$$

$$M = 1.59m - 3.97$$

where T is the period of max.-portion of the wave, α is a function of focal depth Z and epicentral distance Δ. For example, α is 5.3 when $Z = 0 \sim 100$km and $\Delta = 2°$ ($\fallingdotseq$ 222km). Since A/T has the dimension of velocity, this portion is replaced by the velocity amplitude of vertical motion and, further, by the single amplitude ν of the rising portion of P-wave. If mkine is used as the unit of ν, $A/T = \omega A/2\pi = 2(10\nu)/2\pi = 10\nu/\pi$. Let ν be ν_o at $\Delta = \Delta_o$ and ν at $\Delta = \Delta$km on the assumption that a wave propagates in 3 dimensions:

$$\nu = \Delta_o \nu_o / \Delta \qquad \therefore \ \nu_o = (\Delta/\Delta_o)\nu$$

If m is calculated at $\Delta = \Delta_o$,

$$\begin{aligned} m &= \log(10\nu_o/\pi) + \alpha_{\Delta=\Delta_o} \\ &= \log(10\Delta\nu/222\pi) + 5.3 \quad (\Delta_o = 222\text{km}) \end{aligned}$$

$$\begin{aligned} M &= 1.59m - 3.97 \\ &= 1.59\ (\log\nu + \log\Delta) + 1.53 \end{aligned} \tag{3}$$

Since 3 values of ν are obtained from 3 observation points, the mean value νm of these values is adopted as ν in Eq. (3).

RESULT OF PROCESSING BY THE MODEL SYSTEM AND CONSIDERATION

The model system started operation at the site in March, 1979. Table 3 shows the earthquakes whose epicenters, etc., were calculated from the seismic data processed by the model system at the site. Table 4 gives the earthquakes whose epicenters, etc., were calculated by inputting the seismic data recorded at the site before the model system is installed. Table 3 also shows the results of processing.

The result of location of epicentrers is described first. Fig. 4 represents the comparison of the location of epicenteres done by on-site processing with that announced by the Japan Meteorological Agency (JMA). Fig. 5 shows the location of epicenters performed with respect to the earthquakes listed in Table 4. These results indicate that the calculated epicenters are located in the same direction as announced by JMA but are located considerably near to the detection points when compared with the announced epicenters. The errors in epicentral distance calculation originated from two possible causes, a) errors in reading seismic wave arrival time, b) improper values assumed for V and Z.

Fig. 6 represents the change in calculated epicentral locations when the values for V and Z are varied. It also gives the results of correction applied to the P-wave arrival time. These results indicate that the epicentral distance increases with the increase in the value of V or Z. However, the calculated epicentral location do not coincide with the true location for any values of V and Z because of the error in reading the P-wave arrival time.

The results of calculation to obtain the epicentral direction θ and apparent propagation velocity V based on Eq. (2) are described next. The values of θ for the earthquakes processed on the site are shown in Fig. 4. These results are generally found inferior in accuracy compared with those obtained from X and Y, and naturally the accuracy becomes worse as the epicenter is located nearer to the detection point. The values of apparent propagation velocity V for the processed-earthquakes at site are given in Table 3. The calculated values of V are greater than 7 km/s, lying within the range of P-wave propagation velocity except some abnormally large values. Since no example has been given in which the S-wave portion is detected first and processed, it is not clear whether P-wave discrimination is possible or not by the value of V.

Lastly, the calculation result of magnitude is described.

The magnitudes of the earthquakes given in Table 3 and Table 4 were calculated by the use of Eq. (3). Two values of epicentral distance Δ were used: one is Δ_J obtained from the JMA-announced epicenter, and the other is Δ_m calculated by the model system. The mean value of the three observation points was adopted as mean amplitude of velocity of earthquake motion. Let M_1 be the magnitude obtained from Δ_J and ν_m, and M_2 from Δ_m and ν_m. Fig. 7 shows comparison M_1 of and M_2 with the magnitude M_J announced by JMA. According to Fig. 7, M_2 using Δ_m compared fairly well with JMA up to a value of approx. 5, whereas M_1 using Δ_J mostly lies within ± 0.5, of the true value. The values of M_1 corresponding to $M_J = 7$ and 7.7 are underestimated, which is supposed to be due to the face that the epicentral distances were more than 600km. The reason why M_2 does not give good results is that the estimation of Δ_m has a large error. If Δ_m is estimated accurately, magnitude can be obtained with high accuracy, as can be seen from the calculation results of M_1.

The error in estimating Δ_m originates from the errors in reading the P-wave arrival time and in assuming focal depth Z and apparent propagation velocity V.

Table 5 shows the difference of results between visual and automatic readings of the P-wave arrival time from the recorded waves. With all such large errors, the epicentral direction coincides with the true values with the small errors as shown in Fig. 4 and Fig. 5. From these results, accuracy of estimating epicentral distance is expected to become high, if appropriate assumption is made for Z and V. Since the earthquakes of $Z > 100$km are not supposed to cause damages, it is not so remarkably unreasonable to assume $Z = 40$km for the earthquakes of $Z < 100$km. As for the assumption of V it is difficult to uniformly assume it for earthquakes of all possible epicentral directions in the vicinity of Japan having a complicated crustal structure, because V in Eq. (3) is the mean velocity of propagation between an epicenter and 3 detection points. Therefore, the following method can be used as a solution.

• An approximate value of epicentral direction is tentatively calculated first, and then recalculation is performed by assuming the seismic wave velocity depending on the epicentral direction.

To improve the detection accuracy of seismic wave arrival time, reduction of ground noise and clarification of wave generation are required. For this purpose, application of filters will be effective.

If the epicentral location and magnitude are accurately estimated, the judgement of whether an earthquake is damaging or not can be replaced by the determination of object area to be given an alarm. Supposing that the alarm object area is the one which will suffer a small damage and, that this area is a circle with the epicenter being its center, the alarm object area can be determined from the results of study [2] about the relationship between its radius and magnitude.

CONCLUSION

The fundamental function of the captioned system, to estimate the epicentral location and magnitude by the use of the data at the initial stage of earthquakes, has been studied with the consideration being centered on the result of automatic processing of the model system. The result has shown that the epicentral direction can be determined almost accurately even if some errors are present in reading the P-wave arrival time, whereas the result of epicentral distance calculation has a large error. This error causes the error in estimating magnitude to become large, but an accurate magnitude has been found to be obtainable if the accuracy of epicentral distance estimation increases. Improvement of the accuracy of epicentral distance estimation requires the assumption of an appropriate value for the apparent propagation velocity and the increase in the accuracy of reading the P-wave arrival time. Attempts have been made to solve these problems by the use of other methods for earthquake detection and epicentral calculation in addition to the improvement of accuracy by the above-mentioned method.

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2) Katsumata, M., 1978, The Relation ship among Earthquake Magnitude and Distance where Damage Reaches, and Area in which Severe Damage Extends, KENSHIN-JIHO Vol. 42, No. 3∿4 p.p. 73∿76.

Table 1. Station List

Station	Lat.	Y northward	Long.	X eastward	Height
Miyako	39°39'32.0"	0.0 km	141°56'41.5"	0.0 km	250 m
Kawai	39°36'38.9"	-5.31	141°42' 2.1"	-20.98	340
Sotoyama	39°25'42.5"	-25.58	141°54'53.1"	-2.59	125

Table 2. Type of Characteristics of Seismometer Used in Earthquake Observation

Station	Type	Number of Components	Natural Frequency	Damping Factor
Miyako	D	3	0.1 Hz	0.5
	V	3	0.3	40
	A	3	0.5	100
Kawai	V	3	0.3	40
Sotoyama	V	3	0.3	40

A,V and D show accelerometer, velocity meter and displcement meter, respectively.

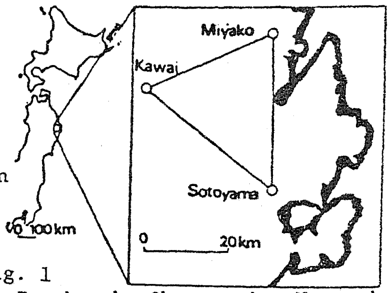


Fig. 1 Earthquake Observation Netwark for the Model System

Table 3. List of Earthquakes Processing On-line at the Site and the Results of Processing

Origin Time	λ	ψ	M	λ	ψ	M_2	θ(°)	V(km/s.)
1979. 4. 3, 2:26	142°12'E	38°30'N	5.3	142°04'E	39°07'N	3.5	158.5	7.4
1979. 6.21, 19:48	141°58'E	39°38'N	4.0	142°04'E	39°36'N	3.4	78.0	14.4
1979. 6.21, 23:06	139°57'E	43°39'N	5.3	141°38'E	40°12'N	4.1		6.9
1979. 7. 4, 15:08	146°39'E	43°46'N	5.9	142°24'E	39°48'N	3.2	62.2	7.4
1979.10. 2, 8:37	141°53'E	39°56'N	5.0	141°54'E	39°46'N	3.6	12.9	11.8

V_p=6km/sec., Z=40km.

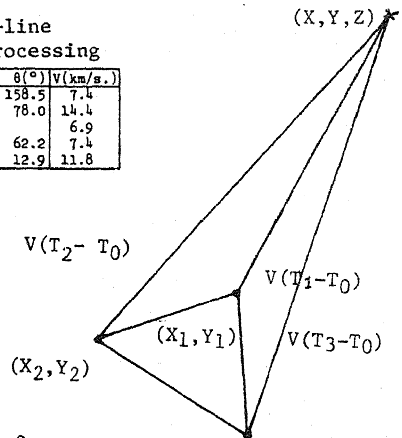


Fig. 2 Relationship between Epicenter and Observation Point Locations

Table 4. List of Earthquakes Processed Off-line

Origin Time	λ	ψ	Z	M
1977. 5.13, 10:26	141°53'E	38°15'N	50 km	5.0
11.17, 4:36	142°15'E	41°55'N	70	5.3
11.21, 23:28	142°00'E	39°36'N	60	4.4
12.17, 0:17	141°05'E	36°35'N	50	5.6
12.24, 7:10	143°36'E	39°04'N	40	5.1
12.24, 8:07	143°28'E	39°08'N	20	5.0
12.26, 3:07	143°41'E	39°10'N	30	4.8
1978. 1. 3, 21:27	143°39'E	39°06'N	20	4.7
1. 4, 9:57	142°10'E	42°36'N	120	5.2
1. 7, 4:42	142°02'E	41°28'N	60	4.9
1.11, 22:29	143°17'E	39°09'N	30	4.9
1.14, 12:24	139°15'E	34°46'N	0	7.0
1.16, 14:32	143°29'E	39°05'N	20	4.9
2.19, 2:33	142°48'E	38°07'N	40	5.3
2.20, 13:53	142°01'E	38°39'N	40	4.9
2.20, 14:00	142°05'E	38°47'N	60	4.7
3. 7, 0:11	134°07'E	38°14'N	440	5.7
3. 7, 11:49	137°45'E	32°09'N	440	7.7
3.13, 2:59	142°00'E	38°45'N	60	5.0
3.16, 7:06	141°04'E	26°35'N	280	6.7
4. 6, 17:40	142°34'E	41°32'N	50	5.1
4. 6, 22:54	142°01'E	38°48'N	60	4.5
4.10, 0:34	143°36'E	39°03'N	10	4.5
4.10, 23:27	141°54'E	40°10'N	100	4.4
7.16, 2:45	142°39'E	41°51'N	60	5.3
7.23, 23:47	121°27'E	22°11'N	20	7.1
7.27, 2:12	143°33'E	39°37'N	20	4.5
9.24, 7:43	143°23'E	38°23'N	30	5.4
10.19, 8:30	144°11'E	41°11'N	60	5.3
10.20, 3:20	142°31'E	38°52'N	30	4.7

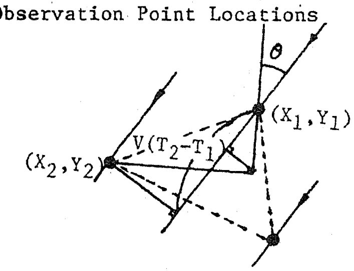


Fig. 3 Relationship between Wave Propagation Direction and Observation Point Location

Table 5. Error in Automatic reading of P-wave Arrival Time

	Miyako		Kawai		Sotoyama	
Seismic Intencity at Miyako	Error in Automatic Reading of P [sec.] (Number of Earthquakes)	Number of Earthquakes Impossible to be Evaluated	Error in Automatic Reading of P [sec.] (Number of Earthquakes)	Number of Earthquakes Impossible to be Evaluated	Error in Automatic Reading of P [sec.] (Number of Earthquakes)	Number of Earthquakes Impossible to be Evaluated
0	0.08 ± 0.25 (13)	7	0.06 ± 0.11 (15)	4	0.15 ± 0.41 (15)	4
I	0.06 ± 0.10 (9)	6	0.23 ± 0.41 (8)	7	0.40 ± 0.59 (9)	5
II	0.22 ± 0.16 (3)	2	0.14 ± 0.17 (4)	1	0.32 ± 0.32 (4)	1
III	0.27 ± 0.31 (3)	0	0.42 ± 0.50 (3)	0	0.27 (1)	1

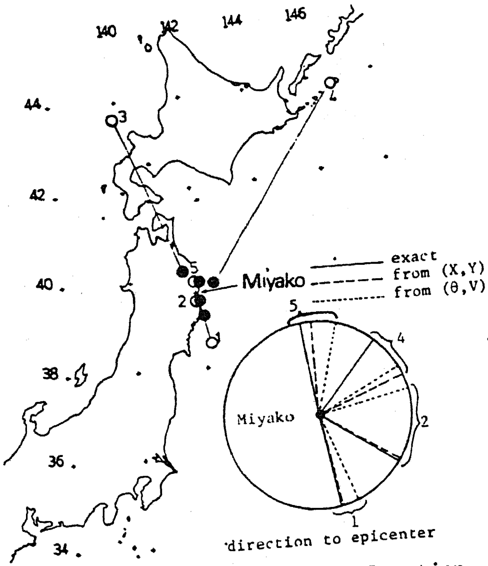


Fig. 4 Results of Epicentral Location Calculation (On-line Processing)

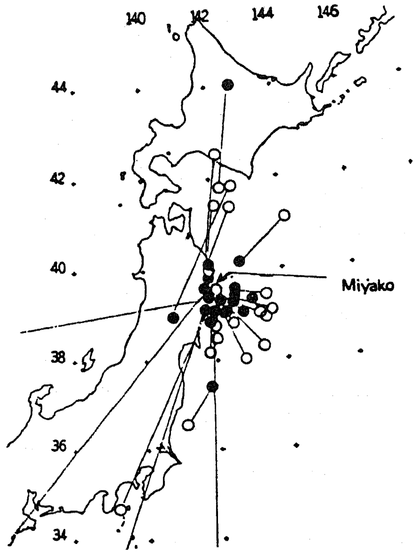


Fig. 5 Results of Epicentral Location Calculation (Off-line Processing)

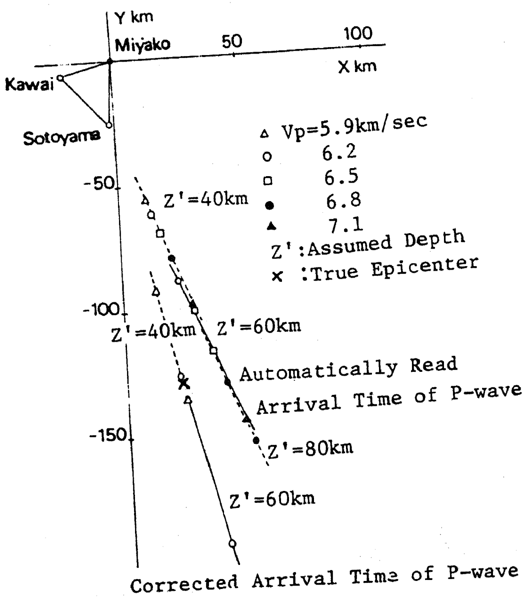
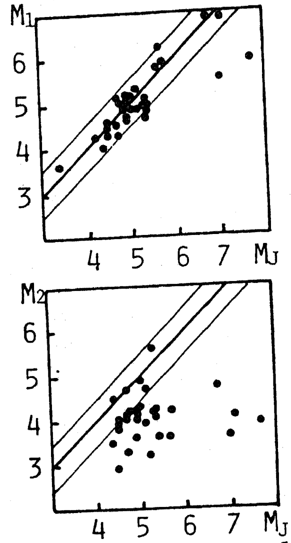


Fig. 6 Earthquake at 2h 26m on april 3, 1979



$M = 1.59(\log v_m + \log \Delta) + 1.53$

M_1 ; $\Delta = \Delta_J$

M_2 ; $\Delta = \Delta_m$

Fig. 7 Results of Magnitude Calculation