CHANGE IN THE v_p/v_s RATIO RELATED WITH OCCURRENCE OF SOME SHALLOW EARTHQUAKES IN JAPAN

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Premonitory change in the ratio of compressional to shear wave velocity, v_p/v_s was ascertained for two moderate size earthquakes which occurred at shallow depths in Japan. The anomalous periods preceding the earthquakes were about one year and three to four months for earthquakes of magnitudes 6.5 and 5.3, respectively. A similar phenomenon was also found for the Matsushiro Earthquake Swarm. Two large earthquakes located near the Japan Trench were also investigated. For those earthquakes, a post-earthquake decrease in v_p/v_s ratio was distinct, but forerunners were not confirmed. Appearance of premonitory change in v_p/v_s ratio may depend on the type of earthquake.

1. Introduction

Premonitory changes in the ratio of compressional to shear wave velocity, v_p/v_s , were found by KONDRATENKO and NERSESOV (1962) for some moderate earthquakes in the Garm-Djirgital region of the Tadzhik, USSR. Additional positive results were reported by NERSESOV *et al.* (1969) and SEMENOV (1969). AGGARWAL *et al.* (1973) and WHITCOMB *et al.* (1973) also found similar phenomena for smaller earthquakes in New York State, and for the San Fernando, California Earthquake in 1971, respectively. The authors agreed to point out distinct decreases in v_p/v_s ratio, up to 10% or more, prior to the occurrence of these earthquakes. The value of v_p/v_s seems to recover or rise above the ordinary value just before the occurrence of the earthquake. It is pointed out by many authors that the duration time of anomaly in the velocity ratio increases with increasing earthquake magnitude.

To explain such a peculiar phenomenon, NUR (1972) proposed a *dilatancy model*, developed by WHITCOMB *et al.* (1973) and SCHOLZ *et al.* (1973) based on laboratory fracture studies. According to the model, low-velocity seismic waves are brought by inelastic volumetric increase of the rock prior to the occurrence of failure. Recovery of velocity is accounted for by consequent rise of pore water pressure, which reduces the strength of the rock and results in an earthquake. This process is considered to have less effect on the velocity

of shear waves compared with that of compressional waves, and results in apparent change in the v_p/v_s ratio.

SASSA (1948), on the contrary, reported striking rise in v_p several months before the Tottori Earthquake ($M=7.4$) in 1943 and two years before the Nankai Earthquake ($M=8.1$) in 1946. On the other hand, HAYAKAWA (1950, 1951) considered the sense of premonitory velocity change to be related to the radiation pattern of an earthquake, investigating seismological data of the Japan Meteorological Agency (JMA). Unfortunately, Japanese seismologists have failed to make sufficient efforts to pursue these important studies in spite of considerable improvement in JMA data, especially in time accuracy, in the last ten years.

In the present investigation, clear premonitory changes were found in the v_p/v_s ratio for two moderate size earthquakes in the Japanese region. For other two large-scale earthquakes, however, no precursor was detected. The dilatancy model is certainly an attractive hypothesis which succeeded for the first time in giving a physical explanation of the striking change in the velocity of seismic waves. Further investigations are still necessary to confirm whether the proposed model is universally applicable to all types of earthquakes.

2. Data and Procedure of Analyses

The present study is based on the arrival time data of P and S waves which are published in the *Seismological Bulletin of Japan Meteorological Agency*. Some additional data are taken from an unpublished JMA ledger. No reexamination of the original seismograms was made.

Plotting S arrival times at each seismograph station as a function of P arrival times, we can fit a straight line for the plotted points if a sufficient number of stations are available. The slope of the fitted line will give an average value of v_p/v_s in the medium concerned. In our case, however, only two favorable stations were employed because the number of JMA stations that can be used for a certain earthquake are usually not enough for the conventional technique mentioned above.

Apparent v_p/v_s ratio is represented by τ_s/τ_p defined as

$$\tau_s/\tau_p = \{t_s(A) - t_s(B)\} / \{t_p(A) - t_p(B)\},$$

where t_p and t_s indicate arrival times of P and S at the observation points denoted by A and B in parentheses. The examined shocks were selected so that ray paths to at least one of the stations would penetrate the focal area of the earthquake in question or its vicinity. We adopt such a pair of seismograph stations so that one station records seismic waves through the focal region in question or its vicinity while the other records those from the same

source but through an unaffected region. The obtained value of τ_s/τ_p will indicate an apparent v_p/v_s ratio in the medium between the two observation points, including the focal area. It should be noted that τ_s/τ_p does not necessarily agree with v_p/v_s itself of the actual medium but is likely to be somewhat amplified as discussed in Section 7.

Although this method is not so reliable as the conventional one, our results show that it is still applicable and is useful for our present purpose when a sufficient number of stations are not available. Statistical treatment is also possible in such a case as the Matsushiro Earthquake Swarm when shocks occur frequently.

3. Northern Miyagi Earthquake

A destructive earthquake took place in the northern part of Miyagi Prefecture, northeastern Japan on April 30, 1962. Its focal depth was estimated to be 0 km and its magnitude, 6.5 by JMA. Variation of v_p/v_s was examined for a period of eight years in the area surrounding the Northern Miyagi

Fig. 1. Large double circle shows the location of the Northern Miyagi Earthquake in 1962. The smaller earthquakes which were used for arrival time analyses are indicated by small open (ordinary stage) or solid (anomalous stage) circles. Cross marks indicate the employed seismograph stations: MIZ, Mizusawa; ISN, Ishinomaki; SEN, Sendai. The shadowed portion is the seismic area of the Northern Miyagi Earthquake where the aftershocks took place.

Fig. 2. Change in τ_s/τ_p value in and near the Northern Miyagi Region. Distinct decrease in τ_s/τ_p began about one year before the occurrence of the Northern Miyagi Earthquake with magnitude 6.5. after OHTAKE (1973)

Earthquake by analysing the arrival times of the shocks plotted in Fig. 1 with depths less than 40 km. Stations used were Mizusawa (MIZ) and Ishinomaki (ISN); the latter was occasionally replaced by Sendai (SEN) when the MIZ-SEN pair gives better ray path.

Figure 2 expresses the variation of τ_s/τ_p with respect to time. Ordinary values range between 1.7 and 2.0. About one year before the occurrence of the Northern Miyagi Earthquake, the values suddenly decreased as shown in the figure, and an anomalously low τ_s/τ_p lasted for about one year. For lack of data, it is not clear whether ordinary values were recovered just before the destructive earthquake or not. The contrast between τ_s/τ_p values in ordinary and in anomalous periods is very distinct in spite of considerable scattering of the plotted points.

Obtained values of τ_s/τ_p may depend on the locations of the shocks, arrival times of which were analysed because the v_p/v_s ratio probably varies in different localities. It is necessary to ascertain that the analysed shocks in the anomalous period are not partially distributed. In our case, the observed anomaly cannot be attributed to a biased epicentral distribution because there is no definite difference between the geographical distributions of the shocks used for the analysis in the ordinary period (open circles in Fig. 1) and the anomalous one (solid circles). Some of the open and solid circles share almost the same places.

When deeper shocks are employed to check τ_s/τ_p , its change becomes quite obscure. The zone where v_p/v_s became anomalous before this earthquake, therefore, seems to be limited in the upper lithosphere which is shallower than about 50 km.

4. Northern Nagano Earthquake

Figure 3 presents the location of the Northern Nagano Earthquake

($M=5.3$) of September 21, 1968 and its large aftershocks. This earthquake was as shallow as 10 km in depth and was accompanied with felt foreshocks. Open circles in the figure indicate the shocks used for the examination, most of which belong to the Matsushiro Earthquakes. The seismograph stations used were Takada (TKD) and Nagano (NGN). A decrease of τ_s/τ_p began three

Fig. 3. Locations of the Northern Nagano Earthquake in 1968 (large double circle), its aftershocks (solid circles) and the shocks which were used for arrival time analyses (open circles). Seismograph stations of JMA are indicated with crosses: TKD, Takada; NGN, Nagano; MAT, Matsushiro; MTM, Matsumoto. TKD and NGN are used for the study of the Northern Nagano Earthquake. *after OHTAKE (1973)*

Fig. 4. Change in τ_s/τ_p value in Nagano-Niigata Border Region. Decrease in τ_s/τ_p began three to four months before the occurrence of the Northern Nagano Earthquake with magnitude 5.3. The anomalous τ_s/τ_p recovered ordinary value at least half a month prior to the coming earthquake. *after OHTAKE (1973)*

to four months prior to the occurrence of the earthquake as shown in Fig. 4. Contrast of τ_s/τ_p values between the ordinary and anomalous periods is again distinct. Furthermore, a recovery of τ_s/τ_p value just before the earthquake was clearly detected in this case.

5. Matsushiro Earthquake Swarm

In August of 1965, the Matsushiro Earthquake Swarm started at a shallow depth beneath Mt. Minakami, a tertiary volcano. The number of the shocks increased daily, and a maximum frequency of 661 felt shocks per day was recorded at Matsushiro Town on April 17 in the following year. After three notable peaks of the swarm activity, it turned to decay in the autumn of 1966 (Fig. 5). The depths of the shocks were less than 20 km. The magnitude of the largest shocks during the swarm was 5.4, and the total seismic energy released is estimated to be equivalent to that of a single earthquake of magnitude 6.3 (HAGIWARA and IWATA, 1968).

Complete data of arrival times for more than four hundred earthquakes are available at Nagano (NGN) and Matsumoto (MTM). A statistical estimation of apparent v_p/v_s ratio, therefore, is possible fitting a straight line through τ_p - τ_s plots for the shocks which occurred during successive time intervals appropriately chosen during the swarm activity. Some examples are shown in Fig. 6. The slope of the fitted line, $d\tau_s/d\tau_p$ can also serve as an indicator of v_p/v_s , and it is statistically much more reliable than τ_s/τ_p . Figure 5

Fig. 5. Monthly number of the Matsushiro Earthquakes felt at Matsushiro (top) and $d\tau_s/d\tau_p$ value obtained from the arrival time data at Nagano and Matsumoto (bottom). Vertical and horizontal segments of each cross indicate 90% confidence limits of computed $d\tau_s/d\tau_p$ and the period in which data are utilized, respectively.

Fig. 6. Some examples of $\tau_p - \tau_s$ plotting for pre-seismic, seismic and post-seismic stages of the Matsushiro Earthquake Swarm. Abscissa and ordinate indicate time differences in P arrivals between NGN and MTM and those in S arrivals, respectively. The values of $d\tau_s/d\tau_p$ are computed by least squares method fitting straight lines to the plotted points.

illustrates the variation of $d\tau_s/d\tau_p$ with respect to time. Each vertical and horizontal segments indicate 90% confidence limits of computed $d\tau_s/d\tau_p$ and the period in which data are utilized, respectively.

A clear correlation is found between the two time series, namely, those of $d\tau_s/d\tau_p$ and the monthly number of felt shocks at Matsushiro. $d\tau_s/d\tau_p$ keeps extremely low values during the period when seismic activity is high, and it almost recovered its ordinary values in 1971, showing a transient stage of about four years. In detail, monthly fluctuations of the two time series are not exactly correlated with each other. It is interesting to point out that the lowest values of $d\tau_s/d\tau_p$ seem to appear in the previous month before the beginning of second and third peaks of seismic activity although the statistical reliability is not very high (Fig. 5).

Unfortunately, for lack of suitable data, it is not clear as to the most important question of when the premonitory change started prior to the beginning of the swarm. Nevertheless we can say that the change in v_p/v_s ratio, if any, had not begun more than a few years before the swarm.

An elaborate explosion seismic study conducted in the Matsushiro area toward the end of 1967 revealed anomalously delayed arrivals of the compressional waves which penetrated the most active portion of the Matsushiro swarm area. OKADA *et al.* (1970) concluded that the observed travel time anomaly requires a decrease in P wave velocity by about 5% compared with the surrounding regions. This fact supports the author's finding shown in

Fig. 5. The number of 5% decreases in the P velocity in 1967 and the value of $d\tau_s/d\tau_p$ at that time are quantitatively compatible. Comparing P wave spectra before and after the Matsushiro Earthquake Swarm, SUYEHIO (1968) concluded that the swarm area had been highly fractured by the successive occurrence of small earthquakes. His conclusion gives a physical explanation of the observed decrease in the velocity of the seismic waves which penetrate the swarm area.

6. Sanriku Earthquake (1960) and Tokachi-oki Earthquake (1968)

On May 16, 1968 the Tokachi-oki Earthquake ($M=7.9$) took place near the junction of the Japan Trench and the Kuril-Kamchatka Trench. The focal depth is reported to be 0 km. Figure 7 shows the epicenters of the aftershocks and location of the two stations used, Urakawa (URA) and Miyako (MIY). The same method as employed for the Matsushiro Earthquake Swarm was applied for about 300 shallow shocks which occurred in the region bounded by 39°N and 42°N in latitude, and 142°E and 145°E in longitude. Most of the aftershocks following the main shock were distributed in this region. The Sanriku Earthquake on March 21, 1960 was also located in this region, about one degree to the south of the Tokachi-oki Earthquake in 1968.

Variation of $d\tau_s/d\tau_p$ for 17 years is illustrated in Fig. 8. Premonitory change in v_p/v_s is not detected by the present method for these two large

Fig. 7. Locations of the Tokachi-oki Earthquake in 1968 (solid circle) and its aftershocks (other circles) after Japan Meteorological Agency (1969). Employed seismograph stations, Urakawa (URA) and Miyako (MIY) are also plotted with cross marks. The Sanriku Earthquake in 1960 was located about one degree to the south of the Tokachi-oki Earthquake in 1968.

Fig. 8. Variation of $d\tau_s/d\tau_p$ with respect to time for the period of seventeen years including the Sanriku Earthquake in 1960 and the Tokachi-oki Earthquake in 1968. after OHTAKE (1973)

earthquakes. Those earthquakes, however, are followed by a temporary decrease of apparent v_p/v_s ratio, which may be related with a large scale fracturing caused by the main shocks.

A peculiarly low value appeared in 1961, which happened to coincide with the anomalous period prior to the Northern Miyagi Earthquake in 1962 (See Fig. 4). The earthquakes and stations used here did not have any relation to the earthquake in 1962 which was considerably to the southwest of the region discussed here. In the investigated region, there was no distinct earthquake which could have caused the above-mentioned anomaly.

7. Discussions and Conclusions

The v_p/v_s ratio in actual material cannot be smaller than $\sqrt{2}$ so far as Lamé's constants are positive. Nevertheless, much smaller values have been found in Figs. 2, 4 and 5. Some of them may be due to inaccurate reading of seismograms, especially for S waves. It is, however, very difficult to assume that such inaccurate readings were concentrated in a specific period prior to large earthquakes. Furthermore, there exist unquestionable examples as

Fig. 9. Schematic representation of the relation between actual v_p/v_s value in the medium and τ_s/τ_p or $d\tau_s/d\tau_p$ value (see the text).

shown in Fig. 6. The contradiction between observation, namely unreasonably low τ_s/τ_p or $d\tau_s/d\tau_p$, and theory must be solved.

In Fig. 9, let us suppose that seismic waves radiated at the hypocenter O get to the station A through *ordinary* crust and to the other station B through *anomalous* crust (Fig. 9(a)). If A is nearer the hypocenter than B , apparent v_p/v_s ratio defined by τ_s/τ_p will be less than actual v_p/v_s ratio (Case I in (b)). On the other hand, τ_s/τ_p will be greater if A is farther than B (Case II in (b)). When $\overline{OA}$ is almost equal to $\overline{OB}$, τ_s/τ_p will be very unstable because it is largely affected by unavoidable small uncertainties in the reading of arrival times. It is, therefore, possible that τ_s/τ_p or $d\tau_s/d\tau_p$ changes over a wide range of $-\infty \sim +\infty$ in such an extreme case as represented in Fig. 9(a), where $\overline{OA}$ is entirely in the normal region and $\overline{OB}$ is entirely in the anomalous region. For nearly all the earthquakes employed, the ray paths which penetrate the supposed anomalous area are longer than the other paths (Case I in Fig. 9(b)) in our cases, and τ_s/τ_p in anomalous stage is inclined to give smaller values than values actual v_p/v_s ratio. Figure 9(c) accounts for the observed low $d\tau_s/d\tau_p$ less than $\sqrt{2}$ in the case of the Matsushiro Earthquakes.

Changes in the apparent v_p/v_s ratio and parameters of the investigated earthquakes are summarized in Table 1. Premonitory change in the v_p/v_s ratio is confirmed for two moderate size earthquakes. As shown in Fig. 10, these new data fit fairly well with the linear relation between the magnitude of earthquakes and logarithm of anomalous period by SCHOLZ *et al.* (1973). Small deviations from the curve may indicate possible differences in geological and geophysical conditions of the crust in different regions. The Northern Miyagi and the Northern Nagano Earthquakes accompanied by the premonitory change in the v_p/v_s share some common features such as land epicenter,

Table 1. Results of v_p/v_s study and the parameters of the investigated earthquakes.

Earthquake	Date	Depth (km)	Magnitude	Fault type	Premonitory change in v_p/v_s (anomalous period)
Sanriku	Mar. 21, 1960	40	7.5	strike-slip*	not detected
Northern Miyagi	Apr. 30, 1962	0	6.5	thrust*	detected (one year)
Matsushiro	Aug. 3, 1965~	0~20	≤ 5.4	strike-slip*	unknown
Tokachi-oki	May 16, 1968	0	7.9	thrust with considerable strike-slip component**	not detected
Northern Nagano	Sep. 21, 1968	10	5.3	thrust*	detected (3~4 months)

* After ICHIKAWA (1971)

** After KANAMORI (1971)

after OHTAKE (1973)

Fig. 10. Relation between the magnitude of the earthquake and the period from the beginning of the anomalous v_p/v_s ratio to the occurrence of the earthquake in question. The curve fitted by SCHOLZ *et al.* (1973) is also illustrated. after OHTAKE (1973)

very shallow depth, source mechanism of thrust type and magnitude of moderate size.

On the other hand, premonitory changes are not found for the large-scale earthquakes on the sea bottom near trenches. It is, however, not certain yet whether such earthquakes were not actually preceded by the premonitory change or the simplified method employed in this study overlooked it. Our study requires further accumulation of examples from a viewpoint of ascertaining the existence of a premonitory change and, if it is not universal, in what types of earthquakes the forerunner in question appears and in what types it does not.

Decrease in the v_p/v_s ratio was also found to accompany the occurrence of earthquakes for the Matsushiro Earthquake Swarm and others. Although the physical mechanism of such post-earthquake change might be quite different from that of the premonitory change, this phenomenon gives a powerful support to the possibility of remarkable changes in the v_p/v_s ratio with respect to time.

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