International Research Journal of Geology and Mining (IRJGM) (ISSN: 2276-6618) Vol. 2 (2) pp. 32-40, March 2012
Available online http://www.interesjournals.org/IRJGM

Review

Applicability of several seismic wave parameters in earthquake prediction

Wenlong Liu[1] and Yucheng Liu[2]*

[1]Shanghai Earthquake Administration, Shanghai, China, 200062.
[2]Department of Mechanical Engineering, University of Louisiana, Lafayette, LA 70504, USA.

Accepted 06 February, 2012

This paper introduces several important seismic parameters that is carried by seismic wave and discusses the applicability of those parameters in earthquake prediction. Methods are presented and examples are demonstrated to show how to correctly apply the seismic wave method to achieve accurate earthquake prediction data. Current limitations that prevent those parameters from being further applied for earthquake prediction are also discussed.

Keywords: Seismic wave method, earthquake prediction, wave velocity ratio v_p/v_s, coda wave, S wave.

INTRODUCTION

Seismic wave method is an emerging earthquake prediction method, which predicts the future earthquakes based on information carried by the seismic waves. The information extracted from the seismic waves such as the medium characteristics and source stress has explicit physical meaning and is easy for quantification, which has received a lot of recognition from many seismologists. In the past time, the seismic wave method developed slowly because of the low precision of analog records, the short of digitized records, and the heavy workload in digitization and in conducting general study of seismic examples. Thus, only a few seismic wave parameters have been applied for earthquake prediction, including v_p/v_s ratio of small earthquakes before medium and strong main shock, consistency of P axis, direction of first motion, and amplitude ratio, etc. The three important factors that affect the reliability of the seismic wave method are v_p/v_s ratio, splitting and polarization of coda wave and S wave, and among which the velocity ratio is most influential. Other important source kinetic parameters include the stress drop ($\Delta\sigma$), ambient shear stress (τ_0), hypocentral radius (a), quality factor of medium (Q), temporal and spatial linearity of seismic waveform (Feng et al., 1994), and rupture characteristic of small earthquakes (L_0/L) (Wang et al., 2002; Liu et al., 2006). This paper summarizes the recent development and problems in advancing seismic wave method in predicting future earthquakes based on the use of wave velocity ratio v_p/v_s, coda wave, and S wave. The mechanism of S wave polarization and splitting are also discussed.

Wave Velocity Ratio v_p/v_s

Survey of Application of Wave Velocity Ratio

In 1960s, scholars from Former Soviet Union found anomalies in variation of velocity ratio (v_p/v_s) of M3.5~5.5 earthquakes occurred in Garm district. It was observed that before the main shock, the velocity ratio of small earthquakes first decreased from its normal value and then increased. Shortly after that ratio returned or slightly exceeded its normal value, the main shock would occur. Duration and coverage of such anomalies were related to the main shock's magnitude. Similar anomalies were also observed before the earthquakes occurred in Kamchatka Peninsula and Kirghizia.

Aggarwal et al. (Aggarwal et al., 1975) observed several abnormal wave velocity ratios (t_s/t_p) before small earthquakes of M1~3 at Blue Mountain Lake with more dense observatories and higher precision. Based on those findings they successfully forecasted the M2.6 earthquake occurred on August 3, 1973 at Blue Mountain Lake. In addition to the seismic activity a number of

*Corresponding author E-mail: yucheng.liu@louisiana.edu; yxl5763@louisiana.edu

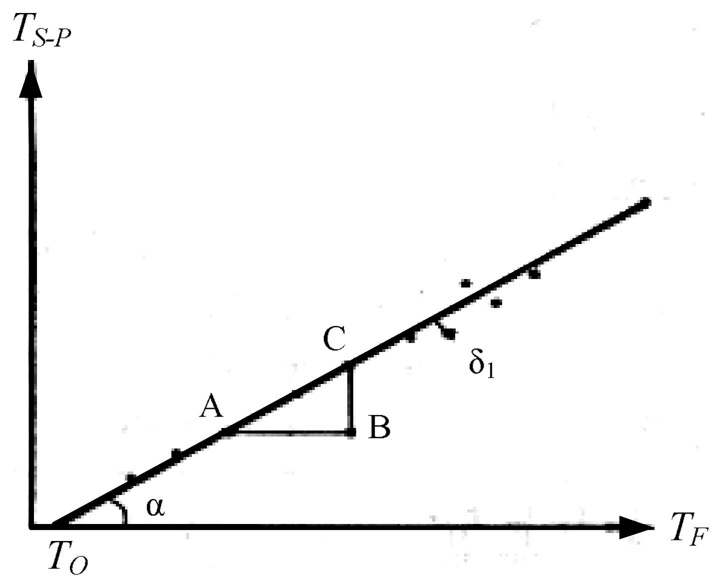

Figure 1. Wadachi line

explosions were recorded from a variety of azimuths to verify the velocity anomalies monitored before the M2.6 earthquake.

In order to explain the velocity ratio (v_p/v_s) anomalies, Scholz (Scholz and Sykes, 1973) presented a famous model, the DD (dilatancy diffusion) model, and Mjachkin (Mjachkin et al., 1975) also developed the IPE model. Both models were supported by results of rock experiments and well explained the v_p/v_s anomalies as well as other precursory anomalies during the seismogenic process. Unlike the IPE model, the DD model did require the participation of ground water. Therefore, DD model is also called as the damp model, and IPE model is known as the dry model.

According to incomplete statistics, foreign seismologists had obtained about 50 earthquake samples with abnormal v_p/v_s from 1969 to 1976. During that time, Chinese seismologists also had obtained dozens of earthquake samples with abnormal v_p/v_s. Those earthquakes occurred in Haicheng, Tanshan, Liyang, and northwestern area (Feng, 1975; Feng et al., 1976; Feng et al., 1980; Feng, 1976).

Based on the achievements made during that time, an optimistic air on accurately predicting earthquakes spread over the scientific community. US Geological Survey (USGS) planned to publish official earthquake forecasting within five years based on detecting the precursory anomalies in decreasing velocity ratios of two waves that penetrated rocks (Press and Brace, 1966). A similar project was also presented by three Japanese scientists who affirmed that the earthquakes can be safely predicted after ten years. However, when the scientists believed that the physical basis of earthquakes had been found and the earthquakes could be successfully predicted (Scholz, 1973), several later findings overturned such opinion. From 1960 to 1976, a number of earthquakes that occurred in China, United States, and Japan were recorded from which no v_p/v_s anomalies were found (Mcevilly and Johnson, 1973; Bolt, 1977; Lizuka, 1976). Anyhow, velocity ratio v_p/v_s has been the most matured tool in the seismic wave method and is being broadly used in daily earthquake monitoring and prediction.

Methods of Application of v_p/v_s

Calculation of v_p/v_s

(1) Multi-station method. Such method requires that the epicentral area of future strong earthquakes is surrounded by a number of earthquake stations. The selected small earthquakes should be monitored by these stations with a minimum number n ≥ 3. These earthquakes should be primarily selected before being used for calculating v_p/v_s, and those data that obviously deviate from the Wadachi line (Figure 1) should be neglected. Eqn. (1) explains how to use multi-station method to calculate the wave velocity ratio, where K is the slope of Wadachi line, T_0 is its intercept (occurring times of earthquakes), γ represents the wave velocity ratio, σ_γ is the standard deviation of γ, T_{Pi} means the arrival time of the P wave of the ith earthquake, and $T_{(S\text{-}P)i}$ is the arrival time difference of the P wave and S wave of the ith earthquake. The multi-station method has high stability and precision but it does require a number of well-distributed earthquake observatories and a high time service precision.

$$\left.\begin{aligned}
K &= \frac{\sum_{i=1}^{n} T_{(\bar{s}-\bar{P})i} \cdot T_{\bar{P}i} - \frac{1}{n}\sum_{i=1}^{n} T_{(\bar{s}-\bar{P})i} \cdot \sum_{i=1}^{n} T_{\bar{P}i}}{\sum_{I=1}^{n} T_{\bar{P}i}^{2} - \frac{1}{n}\left(\sum_{i=1}^{n} T_{\bar{P}_I}\right)^{2}} \\
\gamma &= 1 + K \\
T_0 &= \frac{1}{n}\left[\sum_{i=1}^{n} T_{\bar{P}I} - \frac{1}{K}\sum_{i=1}^{n} T_{(\bar{s}-\bar{P})i}\right] \\
\sigma_\gamma &= \sqrt{\frac{n}{n-2} \cdot \frac{\sum\left[T_{(\bar{S}-\bar{P})i} - K \cdot (T_{\bar{P}} - T_0)_i\right]^2}{n \cdot \sum_{i=1}^{n} T_{\bar{P}i}^{2} - (\sum_{i=1}^{n} T_{\bar{P}i})^2}}
\end{aligned}\right\} \quad (1)$$

(2) Single-station four seismic phases method. When the distribution of observatories does not satisfy the requirements of multi-station method, the wave velocity ratio γ can be calculated based on seismic data observed from a single station. In this method, we select earthquakes with epicentral distances range from 80 to 120km, whose seismic phases of direct waves and reflected waves can be clearly recorded. Assuming the Earth's crust is a monolayer structure and we have:

$$\left.\begin{aligned}
\gamma &= \frac{T_{S11} - T_{\bar{S}}}{T_{P11} - T_{\bar{P}}} \\
\sigma_\gamma &= \gamma \cdot \frac{\Delta T_{S11} + \Delta T_{\bar{S}}}{T_{S11} - T_{\bar{S}}} + \gamma \cdot \frac{\Delta T_{P11} + \Delta T_{\bar{P}}}{T_{P11} - T_{\bar{P}}}
\end{aligned}\right\} \quad (2)$$

where ΔT_P, ΔT_S, ΔT_{P11}, ΔT_{S11} are measurement errors of direct and reflected P- and S- waves, respectively.

(3) Two-station direct wave method. γ can also be calculated based on direct waves recorded by two stations and the formula is:

$$\left.\begin{aligned}
\gamma &= 1 + \frac{T_{(\bar{S}-\bar{P})2} - T_{(\bar{S}-\bar{P})1}}{T_{\bar{P}2} - T_{\bar{P}1}} \\
\sigma'_\gamma &= \frac{\Delta T_{(\bar{S}-\bar{P})2} + \Delta T_{(\bar{S}-\bar{P})1}}{T_{\bar{P}2} - T_{\bar{P}1}} + (\gamma - 1)\frac{\Delta T_{\bar{P}2} + \Delta T_{\bar{P}1} + \Delta T}{T_{\bar{P}2} - T_{\bar{P}1}}
\end{aligned}\right\} \quad (3)$$

where ΔT is the time service precision and other ΔT's are measurement errors of related seismic phases.

Application of Abnormal Wave Velocity Ratios in Earthquake Prediction

(1) Time prediction. The normal value of wave velocity ratio is around 1.72 and if a low-value anomaly is detected which exceeds the range of error, the anomalous area can be primarily determined from the diagram. If the measured wave velocity ratios are constantly lower than the normal value in certain areas, it indicates the medium-term anomaly of mid-strong earthquakes. When the wave velocity ratio values obviously return to vicinity of the normal value, the short-term anomaly can be decided.

(2) Location prediction. The future mid-strong earthquake always occurs at marginal zones of the anomalous area, and the comeback of the anomaly more often than not starts from the periphery and then gradually shrinks to the hypocenter of future mid-strong earthquake. Based on that criterion, we can roughly estimate the future hypocenter.

(3) Magnitude prediction. The earthquake magnitude (Ms) is related to the range of anomalous area as well as the duration of the anomaly, while irrelevant to the extent of the anomaly. Their relationships differ from place to place and some frequently-used empirical equations are listed below for reference.

Ms = 0.6 + 3.4lgb ± 0.5 (b is minor axis of the anomalous area, in km)

Ms = – 0.4 + 3.4lga ± 0.7 (a is major axis of the anomalous area, in km)

Ms = a – 0.7 + 1.7lgS ± 0.7 (S is area of the anomalous area, in km^2)

Ms = 1.45lgT + 2.11 (T is duration of the anomaly, in day，applicable in western China)

Ms = 1.10lgΔT + 4.3 ± 0.5 (ΔT is the time interval between the comeback of the anomaly and the occurrence of the earthquake, in day, applicable in western China)

Limitations

As mentioned before, the abnormal wave velocity ratio cannot be observed from every earthquake. It was found that in IPE model, it was the openings and closings of the oriented micro fractures caused by avalanches that lead to abnormal wave velocity ratios. The anomalies are most distinct in the seismic waves that transmit perpendicular to orientations of the micro fractures while in those waves that transmit along the orientations of the micro fractures, such anomalies can hardly be detected. In addition, the anomaly in wave velocity ration is also related to the type of hypocenter. For reverse fault, such anomalies can be observed in every direction, especially along the direction perpendicular to the fault. For normal fault, the anomalies can only be observed along the direction parallel to the fault. However, for strike-slip fault, the anomalies cannot be detected in any direction (Gupta, 1973).

Coda Wave

Formation Mechanism of Coda Wave

Coda waves from small local earthquakes (hypocentral distance < 100km) are interpreted as backscattering waves from numerous heterogeneities distributed uniformly in the Earth's crust. A system of coda wave theories was presented by Aki and Chouet (Aki and Chouet, 1975) and has been well recognized. In their works, they revealed several important features of the coda wave. (1) Early records in seismogram are dependent on epicentral distance and route, however, such difference caused by the distance and route vanishes in the code wave. (2) The duration of local earthquakes (from the beginning of P wave till the end of coda wave) is almost irrelevant to the epicentral distance and azimuth angle. (3) Power spectra of the coda waves of different local earthquakes follow the same time attenuation function and do not differ from different epicentral distance and propagation path. (4) At least for the local earthquakes with Ms < 6, above time attenuation function is irrelevant to magnitude. (5) The excitation of the code waves is associated with the local geological environment around seismic stations, compare to granite, sedimentary rocks causes a high code waves excitation factor. However, the duration of the code waves is independent of the geological environment. (6) As monitored and studied from seismic stations, the code waves do not come from the regular surface waves from the earthquake sources. Possible sources of the coda waves may include (1) surface waves from sedimentary rocks and/or surface of water; (2) seismic waves caused by aftershocks occurred around the earthquake sources; (3) scattering waves from heterogeneities of the earthquake sources. It was found that only the source (3) can satisfactorily explain all aforementioned features. Thus, the generation of the code waves can be described as this: the seismic waves radiated from the earthquake sources are scattered by the heterogeneities during the transmission process, such scattering waves are then superposed together when they arrive the seismic station to generate the code waves. Aki and Chouet proposed two extreme models of the wave medium that account for the observations on the coda: the single backscattering model and the diffusion model. The coda wave A was obtained as:

$$\left.\begin{aligned} A(\omega,t) &= Ct - k\exp\left(-\frac{\omega t}{2Q}\right) \\ \frac{1}{Q} &= \frac{1}{Q_i} + \frac{1}{Q_S} \end{aligned}\right\} \tag{4}$$

where C is a constant, Q is medium's quality factor, Q_i relates to the absorbed waves, Q_s relates to the scattered waves, k can be 1 (for bulk waves), 0.5 (for surface waves), and 0.75 (for diffusion).

It was further found that Q correlates to the dominating frequency component f in coda waves as $Q = Q_0 f^{\eta}$, where η generally varies from 0.5 to 0.8. It was calculated that $\eta = 0.6$, Q_0 varies from 120 to 290 in Beijing area and $\eta = 1$, $Q_0 = 100$ in southern Yunnan Province.

Afterward, other Chinese scholars like Gao et al. proposed more complicated twice backscattering model, thrice backscattering model, and diffuse reflection model (Gao et al., 1983).

Since the coda wave reflects the average Q values of the medium of areas close to earthquake observatories, it does not have directionality and is hardly affected by small-scale inhomogeneity of terranes. Because of its stability, the coda wave can be used for following purposes. It can be used to decide the magnitude of local earthquakes, including the strong local earthquakes, whose dispersion is less than the magnitude measured using amplitude of the S wave. As shown in Eqn. (5):

$$M = A(\lg \Delta T) + B \tag{5}$$

where A and B are constants, ΔT is duration of all seismic waves, and M denotes the magnitude. The coda wave can also be used to measure regional Q values and for mid- and short term earthquake predictions. People pressurized fractures in Los Alamos geothermal field and found that the Q value of coda waves decreased with the increasing pressure. It was also observed that this Q value decreased by 20% with confidence level 0.95 in the year before three M > 8 earthquakes occurred in Kurile Islands and Kamchatka area. However, in general the coda wave has not been used much in earthquake predictions. Following sections provide several prediction methods using the coda wave to predict and analyze earthquakes occurred in China.

Predicting Earthquake Using Coda Waves

Shape of Envelope Curve of Attenuation of Coda Waves, α Value

From Eqn. (5) the shape of envelope curve of attenuation of coda waves A(t) can be represented as:

$$\lg A(t) = C - 0.5\lg t - \alpha t \tag{6}$$

where

$$\left.\begin{aligned} C &= \frac{1}{2}\lg\left[\frac{\Delta\omega}{\pi}\cdot 1.23(n_0\sigma_r)^2\cdot S(\omega_0)\right] + 0.33 n_0\sigma_r \lg e \\ \alpha &= \omega_0 \lg e / 2Q_C \end{aligned}\right\} \tag{7}$$

In above equations, n_0 is scatter density, σ_x is average scattering cross-sectional area, $S(\omega_0)$ is source factor of coda waves, Q_c is quality factor of coda waves. It can be seen that α has the same physical meaning as Q_c but is inversely proportional to Q_c. As shown from Eqn. (7), C and α are constants at a small bandwidth Δω close to the frequency ω_0. For the two regular short-period micro seismometers DD-1 and 573, the coda wave records at time t can be assumed as monochromatic waves when $t/Q_c \geq 0.2$. When $t/Q_c < 1$ (for DD-1) or $1 < t/Q_c < 0.1$ (for 573), the earthquake dominant frequency fp has very little change along with the varying t/Q_c. Thus, for small and medium earthquakes, C and α can be considered as constants when $0.2 \leq t/Q_c < 0.1$.

The author studied the Haicheng M7.4 earthquake occurred on February 4th of 1975 and its later-period

Table 1. Abnormal α values before and after three medium and strong earthquakes in Haicheng

Earthquakes	Seismic stations	Local areas	Anomalies	Confidence level	Anomaly amplitude
Haicheng, M_L7.4, 2/14/1975	Yingkou	Haicheng	Y	0.02	56.6%
	Yingkou	Haicheng, Shenwo, Gaixian	Y	0.05	34.4%
	Jinzhou	Haicheng	Y	0.2	23.8%
	Dandong	Haicheng	N/A		
	Shenyang	Shenwo	N		
	Fushun	Shenwo	N		
Haicheng, M_L6.3, 6/18/1978	Yingkou	Haicheng	Y	0.1	38.2%
	Yingkou	Haicheng, Shenwo, Gaixian	Y	0.05	36.9%
	Jinzhou	Haicheng	Y	0.4	12.3%
	Dandong	Haicheng	N		
	Shenyang	Shenwo	N		
	Fushun	Shenwo	N/A		
Haicheng, M_L5.1, 6/12/1981	Yingkou	Haicheng	Y	0.2	35.6%
	Yingkou	Haicheng, Shenwo, Gaixian	N/A		
	Jinzhou	Haicheng	N		
	Dandong	Haicheng	N/A		
	Shenyang	Shenwo	N		
	Fushun	Shenwo	N		

Table 2. Abnormal α values before and after M5.0 Guzhen earthquake on March 2nd, 1979

Seismic stations	Local areas	Anomalies	Confidence level	Anomaly amplitude
Bengbu	Guzhen	Y	0.4	14.7%
Lingbi	Guzhen	Y	0.4	20.2%
Mengchen	Guzhen	Y	0.4	19.5%
Jiashan	Guzhen	Y	0.2	36.7%
Huaibei	Guzhen	N		

strong aftershocks (including coda waves of all recorded 299 small earthquakes with magnitude ranges from M2 to M4), as well as the M5.0 earthquake occurred on March 2nd of 1979 in Guzhen, Anhui Province (including coda waves of 99 small earthquakes with magnitude ranges from M2 to M4). In those studies, the coda waves were extracted from the time it was 1.5 times Ts-p after the arrival of the S wave until it attenuated to three times as the noise level. For a strong earthquake, the coda waves were sampled for 150 seconds since that earthquake occurred. The peak-to-peak amplitude was then measured and α could be obtained from the curve fitting. Afterwards, average α values were estimated at several time periods and the significance level among those values were tested using T-test method. The sampling process was performed on a stereocomparator, whose reading precision is 0.005mm and it was analyzed that the measurement error was within 20%. Our results showed that the α value was found to decrease by most seismic stations within months before the Haicheng earthquake. That value restored after the earthquake and the confidence level was 0.05. However, only Jiashan station detected the change of α before the Guzhen earthquake with a confidence level of 0.2 (Tables 1 and 2).

Characteristic Indices of Coda Waves

Gu et al. (Gu et al., 1994) presented time-entropy of the coda wave (ST) from the point of view of systematic science as:

$$\left.\begin{aligned} ST &= -\sum_{i=1}^{n} P_i \lg P_i / \lg(n-1) \\ P_i &= \Delta t_i / T \ldots . i = 1,2,\ldots,n \end{aligned}\right\} \quad (8)$$

where T is the length of observation time window, Δt_i is the interval of two neighboring measuring points. Each measuring point must satisfy two conditions: the peak-to-peak amplitude of coda waves corresponding to each measuring point must satisfy $A_1 \geq A_2 \geq A_2 \geq \ldots$, and $A_{j-1, i} \geq A_{j, i}$, j = 1, 2, 3, …, m, where $A_{j, i}$ is the jth peak-to-peak amplitude of coda waves during the ith measuring interval.

On analyzing seismic materials recorded by Changshu,

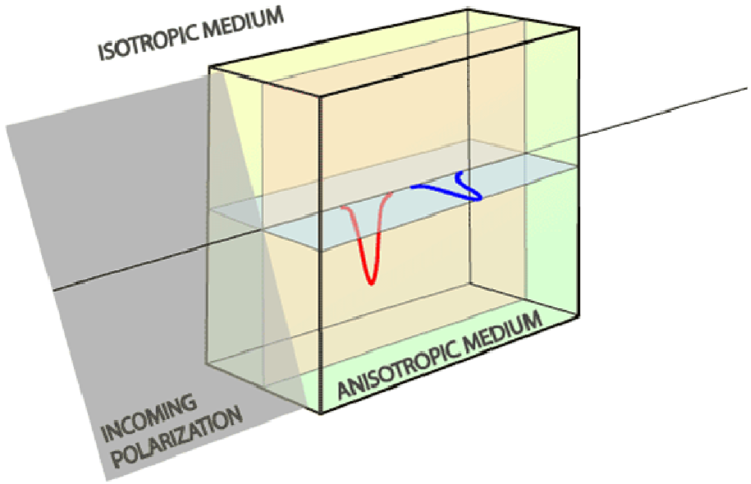

Figure 2. S wave splitting on passing through an anisotropic medium

Liyang, Dafeng, Guanyun, and Lianyungang earthquake observatories (all these observatories are located in Jiangsu Province) during 1989 ~ 1992, it was found that during that time, 4 $M_L \geq 5.0$ earthquakes occurred in Jiangsu and its coastal area: M_L5.5 earthquake occurred at Changshu on 02/10/1990, M_L5.1 earthquake occurred at Sheyang on 11/15/1991, M_L5.6 earthquake occurred in Yellow Sea on 10/23/1992, and M_L5.0 earthquake occurred at Sheyang on 11/23/1992. Normally, ST varies between 0.95 and 1, whose value is fairly stable and its variation is less than 0.02. However, before those $M_L \geq 5.0$ earthquakes, obvious entropy anomalies were observed, which reflected the process of increasing energy of seismogenic systems. The variation scope of ST also increased to 0.04 ~ 0.08 accordingly.

Amplitude ratio of coda waves (r_{co}) is another important characteristic index, which is defined as the ratio between the amplitude of the coda wave in the selected window C_A and the maximum amplitude of the S wave S_A (Eqn. 11). The coda wave window starts at 1.5 to 2 times as the travel time of the S wave with a fixed length 5 second.

$$r_{co} = C_A/S_A \quad (9)$$

When the medium is in a dilatation process, micro fractures increase and scattering on the seismic waves also intensifies, which cause the weakening of the direct waves and the strengthening of the coda waves, the amplitude ratio r_{co} therefore rises up. On the contrary, when the micro fractures close, r_{co} will decrease.

Based on the same earthquake samples, it was also found that the variations of r_{co} differed from near regions to far regions. In the near regions (within 120km from the hypocenter) the r_{co} value was stable during regular time and evidently decreased during months before the earthquakes. However, the r_{co} value in the far regions (120 ~ 200km from the hypocenter) significantly fluctuated and peak values appeared imminently before the earthquakes.

Wave Polarization and Splitting

Physical Mechanism of S Wave Splitting

S wave splitting, also called seismic birefringence is the phenomenon that occurs when a polarized S wave enters an anisotropic media. The incident S wave splits into two polarized S waves. S wave splitting is typically used as a tool for testing the anisotropy of an area of interest. These measurements reflect the degree of anisotropy and leads to a better understanding of the area’s crack density and orientation or crystal alignment.

An incident S wave may enter an anisotropic medium from an isotropic media by encountering a change in the preferred orientation or character of the medium. When a polarized S wave enters a new, anisotropic medium, it splits into two S waves, fast S wave and slow S wave (Figure 2). One of these S waves will be faster than the other and oriented parallel to the cracks or crystals in the medium. The second wave will be slower than the first and sometimes orthogonal to both the first S wave and the cracks or crystals in the media. The time delays observed between the slow and fast S waves give information about the density of cracks in the medium. The orientation of the fast S wave records the direction of the cracks in the medium. When plotted using polarization diagrams, the arrival of split S waves can be identified by the abrupt changes in direction of the particle motion.

In a homogeneous material that is weakly anisotropic, the incident shear wave will split into two quasi S waves with approximately orthogonal polarizations that reach the receiver at approximately the same time. In the deeper crust and upper mantle, the high frequency S waves split completely into two separate S waves with different polarizations and a time delay between them that may be up to a few seconds.

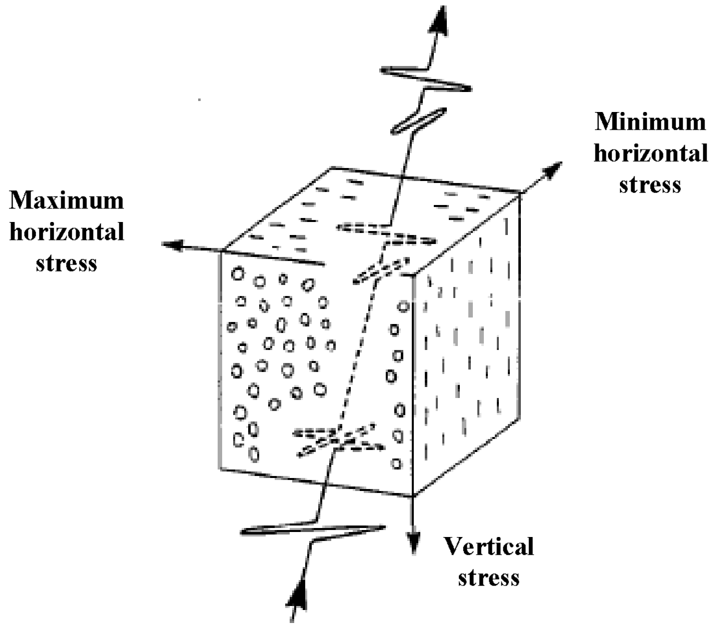

Figure 3. Schematic illustration of S wave splitting in the crust

The difference in the travel velocities of the two S waves can be explained by comparing their polarizations with the dominant direction of anisotropy in the area. The interactions between the tiny particles that make up solids and liquids can be used as an analogue for the way a wave travels through a medium. Solids have very tightly bound particles that transmit energy very quickly and efficiently. In a liquid, the particles are much less tightly bound and it generally takes a longer time for the energy to be transmitted. This is because the particles have further to travel to transfer the energy from one to another. If an S wave is polarized parallel to the cracks in this anisotropic medium, then this wave is acting on the particles like energy being transferred through a solid. It will have a high velocity because of the proximity of the grains to each other. If there is an S wave that is polarized perpendicular to the liquid-filled cracks or elongated olivine crystals present in the medium, then it would act upon these particles like those that make up a liquid or gas. The energy would be transferred more slowly through the medium and the velocity would be slower than the first S wave. The time delay between the S wave arrivals depends on several factors including the degree of anisotropy and the distance the waves travel to the recording station. Media with wider, larger cracks will have a longer time delay than a media with small or even closed cracks. S wave splitting will continue to occur until the S wave velocity anisotropy reaches about 5.5% (Crampin and Peacock, 2008).

The splitting and elliptical polarization of S wave make it superior to P wave in studying the anisotropy of crustal media.

Research Achievements in S Wave Splitting

An early and famous program on investigating the S wave splitting is the Turkish Dilatancy Project which was conducted by Crampin, a British scientist (Crampin and Lovell, 1991). In that project, a series of closely spaced three-component instruments designed to search for S wave splitting in stress-induced dilatancy were deployed over a swarm of small earthquakes near the North Anatolian Fault in Turkey. Researchers and scientists found that in most cases, the splitting appeared to be caused by the stress-aligned fluid-filled cracks, microcracks, and preferentially oriented pore space pervading most rocks in the uppermost 10 to 20 km of the crust. These distributions of aligned inclusions are known as extensive-dilatancy anisotropy, or EDA (Figure 3). Similar phenomena of S wave splitting were also found by Crampin in former Soviet Union and southern California, USA, and the same results compared very well with what were obtained from the TDP project.

Through years' research, following conclusions were drawn about EDA as well as the S wave splitting. (1) EDA cracks generally exist in both stable platforms and active geosynclines, which explains the existence of high pore pressure in fault motions, flexibility of the crustal media, precursory mechanisms, as well as the attenuation of P wave and S wave, etc. (2) P-S and S-P converted waves can be used to determine the scale and degree of the fracture zones. (3) The polarizations of the faster split S wave are parallel to the EDA cracks, which align parallel to the maximum compressive direction. (4) The time delay between the arrivals of the fast and the slow S

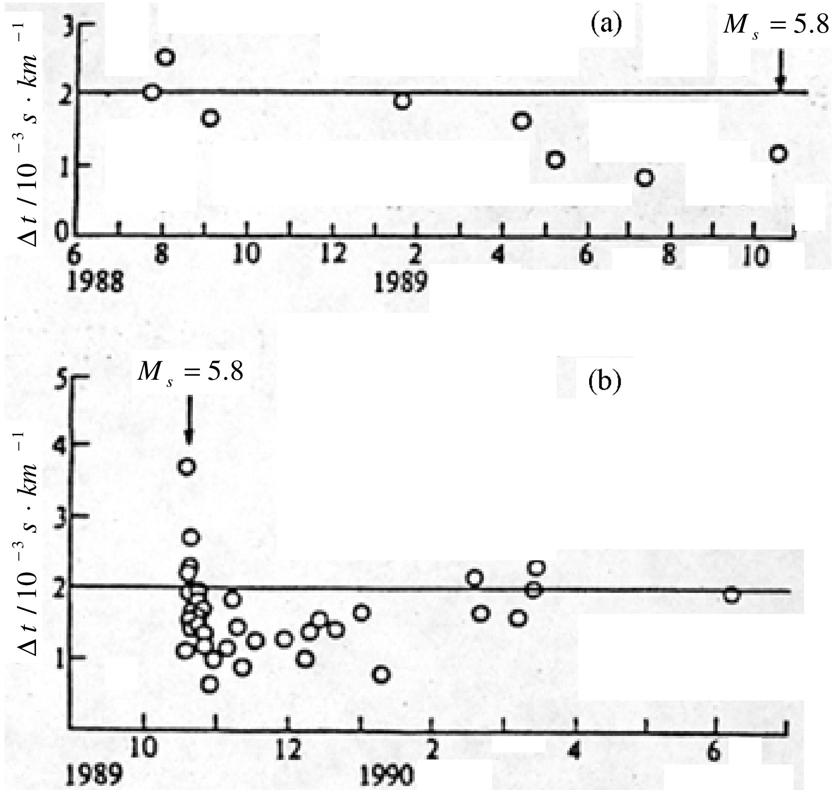

Figure 4. Change in Δt of the split S waves before and after the M5.8 earthquake

waves is proportional to the EDA crack density, which can be used for monitoring during the seismic precursory dilatancy phase.

S wave can be applied in many areas. (1) In seismology, it can be used to monitor the dilatancy process, invert internal structures, and detect the variation in the stress field. (2) In geology, it can be applied to study the flexibility of media and the profound meanings of fault structure. (3) In industry, the S wave can be employed to predict the direction of hydraulic fracture in oil field or in measuring stress. It can also be utilized in exploring natural gas, discovering the internal structure of geothermal reservoir, processing nuclear waste, and monitoring accidents such as mine subsidence and sliding.

Hitherto S wave splitting has been seldom used in earthquake prediction. This is because the time delay between the arrivals of the fast and the slow S waves is as small as several milliseconds per kilometer. Meanwhile, it is difficult to correctly identify the arrivals of the fast and slow S waves. In order to do that, we need to use three-component digital S wave records (array preferred, which is good for tracing and identifying slow S wave) to synthesize the seismograms in anisotropic media, and tuning multiple parameters based on related theories and observed polarized diagrams. Thus, optimal seismic station networking and high-precision time server are demanded in order to use S wave splitting to predict future earthquake and the required workload is extremely heavy. Owing to above reasons, the application of the S wave splitting in earthquake prediction is limited. Figure 4 plots the change in the time delay between the fast and the slow S waves before and after the M5.8 Datong-Yanggao Earthquake.

CONCLUSION

Based on the practices of earthquake prediction, it was found that if a method can be used for earthquake prediction, several conditions have to be satisfied. (1) The measured seismic parameters and their abnormal changes are reliable and supported by certain number of earthquake samples. (2) Such changes can be well explained by existing theories such as seismogenic model, which have been validated by laboratory data and/or numerical simulation results and should be able to explain various anomalies appear during the seismic preparation process. (3) Such methods do not have high requirements on layout of networks of seismic stations and quality of recorded data. Data processing should be simple for those methods.

Comparing the aforementioned seismic parameters, the wave velocity ratio method best satisfies above conditions. The measured wave velocity ratio is around 1.72, which differs from area to area. The theoretical value of the wave velocity ratio is

$$v_p / v_s = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{1-\sigma}{1-2\sigma}} \quad (10)$$

where λ and μ are Lame constants, ρ is density of media, σ is Poisson's ratio. If σ is 0.252, according to Eqn. (10), v_p/v_s is calculated as 1.73, which agrees well to the measured value. The measurement error of wave velocity ratio from analog record is 0.02 ~ 0.03, which can be above 0.05 when anomalies happen. Therefore the analog data is reliable. The wave velocity ratio and other precursory anomalies can be well interpreted by DD model or IPE model and are easy to process, and hence have high practicality. Nevertheless, as explained before, the abnormal wave velocity ratio would not be observed from every earthquake sample. In the future, we need to further study its mechanism and investigate more earthquake samples to correctly decide area of the abnormal wave velocity.

In the past, the seismic coda wave was seldom used for earthquake prediction, which is because of the difficulty in processing analog data. With the application of digital data acquisition, the coda wave method has a broad prospect in seismic analysis and research.

Physical mechanisms of S wave polarization and splitting and EDA cracks have been thoroughly investigated. However, two difficulties have to be overcome in order to apply the S wave polarization and splitting and EDA cracks in earthquake prediction. First, a network of closely spaced seismic observatories is required. This is because that the anomalies of the S wave polarization and splitting are as small as about thousandth of seconds per kilometer and are only detectable when seismic rays penetrate vertically through the EDA cracks. If an observatory is a little bit far from the hypocenter or is located at an unsuited observed angle, the anomalies may not be observed. The second problem is that with current data processing technology, it is even hard to accurately identify the arrival of the first P wave, still less to correctly indicate three components of seismic phases of fast and slow S waves after the P wave groups. These problems badly restrict application of the S wave polarization and splitting in earthquake prediction.

REFERENCE

Aggarwal YP, Sykes LR, Simpson DW, Richards PG (1975). "Spatial and Temporal Variations in t_s/t_p and in P Wave Residuals at Blue Mountain Lake, New York: Application to Earthquake Prediction", *J. Geophysical Res. Solid Earth*, 80(5):718-732.

Aki K, Chouet B (1975). "Origin of Coda Waves: Source, Attenuation, and Scattering Effects", *Journal of Geophysical Research*, 80(B23): 3322-3342.

Bolt BA (1977). "Constancy of P Travel Times from Nevada Explosions to Oroville Dam Station 1970-1976", *Bulletin of the Seismol. Society of Am.* 67(1): 27-32.

Crampin S, Lovell JH (1991). "A Decade of Shear-Wave Splitting in the Earth's Crust, What Does It Mean? What Use Can We Make of It? And What Should We Do Next?", *Geophysical J. Int.* 107, , 387-407.

Crampin S, Peacock S (2008). "A Review of the Current Understanding of Seismic Shear-Wave Splitting in the Earth's Crust and Common Fallacies in Interpretation", *Wave Motion*, 45(6):675-722.

Feng DY (1975). "Abnormal Variation of Velocity Ratios Before M7.1 Yongshan-Daguan Earthquake Occurred on May 1974 in Yunnan Province", *Chinese J. Geophysics*, 18(4).

Feng DY, Wang ZY, Gu JP, Sheng GY, Li KL (1980). "Abnormal Variation of Velocity Ratios Before Songpan-Pingwu Earthquake Occurred in Sichuan Province at 1976", *ACTA Seismologica Sinica*, 2(4).

Feng DY, Wu GY, Chen HR, Guo RZ, Yu XJ, Ding WG (1994). "Application of Indicators of Variation of Seismic Wave's Kinetic Characteristics in Short Term Earthquake Prediction", *Earthquake*, 14(1): 12-21.

Feng DY, Zhen SH, Sheng GY, Fu ZX, Gao SL, Luo RM, Li BC (1976). "Preliminary Study on Wave Velocity Anomalies Before and After Several Medium and Strong Earthquakes Occurred in Western China I – Anomalies in Velocity Ratio", *Chinese J. Geophysics*, 19(3).

Feng R (1976). "Variation of Velocity Ratio Before and After Haicheng Earthquake", *Chinese J. Geophysics*, 19(4),

Gao LS, Biswas NN, Lee LC, Aki K (1983). "Effects of Multiple Scattering on Coda Waves in Three-Dimensional Medium", *Pure and Applied Geophysics*, 121(1), , 3-15.

Gu JP, Yang CX, Huang Y, Huang CZ (1994). "Variations of Characteristic Indices of Coda Waves and Precursory Analysis", *ACTA Seismologica Sinica*, 16: 73-81.

Gupta IN (1973). "Dilatancy and Promonitory Variations of P, S Travel Times", *Bulletin of the Seismol. Society of Am.*63 (3): 1157-1161.

Liu WL (1989). "Occurrence of Medium and Strong Earthquakes and Variations of Characteristics of Attenuation of Seismic Coda Waves", *Collected Works of the 7th Five-Year Program for Earthquake Predictions*, *Collection of Seismology*, Academic Books and Periodicals Publisher, Beijing, China,

Liu WL, Xu YL, Zhang C, Zhang H, Shen WD, Zhong WX (2006). "Study on the Distinguish Elements of the Seismic Wave of The Gap, Belt and Foreshock", *Seismol. Res. of Northeast China*, 22(2).

Lizuka S (1976). "Changes in v_p/v_s Before the Tokachi-Oki Earthquake of May 16, 1968 off NE Japan", *Nature*, 260(5550): 415-417.

Mcevilly TV, Johnson LR (1973). "Earthquakes of Strike-Slip Type in Central California: Evidence on the Question of Dilatancy", *Sci.*, 182(4112): 581-584.

Mjachkin VI, Brace WF, Sobolev GA, Dieterich JH (1975). "Two Models for Earthquake Forerunners", *Pure and Appl. Geophysics*, 113(1): 169-181.

Press F, Brace WF (1966). "Earthquake Prediction: Recent Developments Reopen the Question of the Predicability of Earthquakes", *Science*, 152(3729): 1575-1584.

Scholz CH (1973). "Earthquake Prediction: A Physical Basis: Rock Dilatancy and Water Diffusion May Explain A Large Class of Phenomena Precursory to Earthquakes", *Science*, 181(4102): 803-809.

Scholz CH, Sykes LR (1973). Aggarwal YP "Earthquake Prediction: A Physical Basis", *Science*, 181(4102): 803-810.

Wang JZ, Liu WL, Chen YW, Ling XS, He XW, Liu DW (2002). "Study on Three Earthquake Cases for Fracture Feature of Moderate and Small Shocks Near Seismic Belts and Gaps", *Northwestern Seismol. J.* 24(2).