Analysis on Deep-Well Apparent Resistivity Measurement at Dabaishe Seismic Station

Yaling Ning¹, Haijie Lv², Tao Xie³, *, Guoling Zhang⁴

¹Shanxi Taiyuan 030021 Earthquake Administration of Shanxi Province, Continental Rift Valley Dynamics State Observatory of Taiyuan
²Henan Geology Mineral College, Zhengzhou 451464, China
³China Earthquake Networks Center, China Earthquake Administration, Beijing 100045, China
⁴Earthquake Administration of Hebei province, Shijiazhuang 050021, China

*Corresponding author: xtaolake@cea.gov.cn

Abstract. We interpret the horizontally layered homogeneous medium model of Dabaishe station according to the electric sounding data. The measurement array at the station is the fixed Schlumberger arrays. The deep-well measurement has two set of arrays. One is horizontally placed under 100 meters, and the other is vertically arranged. Under the layered model, we analyze the sensitivity coefficient variations of deep-well apparent resistivity measurement versus the different electrode depth and the spacing of current electrodes. The results show that the horizontal deep-well measurement has well ability on inhibiting disturbances from surface. However, its current electrodes spacing is relatively short, only 60 meters, thus the measurement data cannot effectively reflect the resistivity variations from deep mediums. Electrodes of the vertical deep-well measurement array locate within the layer where underground water level changes. Therefore, its measurement data suffers great affection from the water level variations and it is very difficult to distinguish the resistivity variations of deep mediums from the data. In order to better detect information associated with earthquakes, the spacing of horizontal arrays of AB/2 should be set as 250-350m, and the bury depth exceeds 150m. A Horizontal array along NS direction is also recommended.

Keywords: Apparent resistivity, Deep-well measurement, Fixed Schlumberger arrays, Sensitive coefficient, Dabaishe station.

1. Introduction

Successive observation of fixed-point georesistivity has been carried out since the 1966 Xingtai earthquake of M7.2 in China. Generally, 2-3 channels with fixed Schlumberger arrays were arranged in each seismic station. The bury depth of the ground-based electrodes was usually about 1.5~2m, of which the measurement spacing of electrodes of AB was about 500~2400m, and the underground detection varied from several hundred meters or deeper (e.g., [1, 11]). In recent 50 years of continuous monitoring, significant short to medium term resistivity anomalies had been recorded before several
great earthquakes (e.g., [3, 8, 9, 25, 27, 28]). In addition, medium-short term prediction of one-year time scale were carried out for the three elements of some earthquakes occurring in seismic network (e.g., [2, 22]), which showed that the resistivity was one of the effective methods for seismic monitoring and earthquake prediction.

With the development of regional economy, the surface electric structure had been changed by the construction of metal pipelines such as vegetable greenhouses, water pipes, steel cables, etc., as well as the infrastructure construction such as soil excavation and water storage, warehouses and roads in the surveyed area, which resulted in the serious decline in the quality of the resistivity observation data, and brought great difficulties to the analysis of seismic monitoring and earthquake prediction data (e.g., [12, 16, 18]).

In order to effectively suppress the shallow interference in the surveyed area, the geoelectric workers in China had put forward the deep-well resistivity measurement. Since the 1980s, some deep-well experimental observations had been carried out successively, and the related theoretical study on deep-well resistivity observation had been developed gradually. At present, the continuous observation was carried out in several stations (e.g., [4, 5, 6, 7, 13, 14, 15, 17, 20]). The existing researches showed that the deep-well observation could effectively restrain the annual variation caused by the variation of groundwater level, surface temperature and seasonal rainfall, and the interference caused by the change of local electric structure. While restraining the shallow interference, the deep-well observation also needed to capture the deep medium change caused by the stress effect in the seismogenic process. On the condition of the fixed bury depth of the electrode, detection range of resistivity observation largely depends on the distance of the electrode. The smaller the observation distance was, the less observation values were disturbed by the surface, but the less the deep information was reflected. Due to the heterogeneity of the underground media in the surveyed area, it showed non uniformity under the regional stress, and relevant information would be easily missed when the distance was small. Therefore, it was still necessary to adopt a larger observation distance for deep-well measurement to reflect the medium change information in a larger three-dimensional space. However, with the increase of the observation spacing, the space scope reflected by the observation values expanded, the influence of surface interference on the measurement also increased correspondingly, and the role of deep-well measurement also gradually weakened. Based on the theory of sensitive coefficient of resistivity which can quantitatively gave the influence degree of medium resistivity variation on observation values of resistivity in each region of the surveyed area (e.g., [19]), and by calculating the sensitive coefficient of the media in each region on the resistivity at different measurement spacing and different bury depths of electrodes, the ability of the deep-well observation to suppress the surface interference and the ability to respond to the change of the resistivity in the deep media could be evaluated (e.g., [20]).

The bury depth of the horizontal deep-well measurement array in Dabaish was 100m and the electrodes spacing was only 60m, which could well restrain the interference caused by factors such as surface irrigation and seasonal rainfall (e.g., [24]). However, it needs further analysis whether the information of deep media could be better captured. In this paper, based on the theory of influence coefficient of resistivity, the reasons of restraining the surface interference and the ability of capturing the change information of deep mediums were analyzed for the observation data of deep-well resistivity, which provided certain references for the selections of the depth and observation distance of electrodes in the construction of deep-well resistivity in the future.

2. Brief of the Dabaish seismic station
Dabaish seismic station is located about 5km south of Longyao County, Hebei Province. It is at the intersection of Longyao fault, which is located at the junction of Nienjeng upwarping and Julu depression, and Xinde fault (Figure 1). Faults are comparatively developed around the station, and most of them are still active recently. The station, located in the old earthquake region of Xingtai, is sensitive for the seismic precursor monitoring. The Dabaish resistivity observation system was built and put into operation in 1967. It is the earliest seismic analysis and prediction platform in China, and
the observation data has good performance in earthquake reflecting ability. The surveyed area of the resistivity is mainly in agricultural land use, with flat terrain, no obvious difference in terrain elevation, and underground water about 50m deep. The ZD8B digital terrameter was currently used in the surface resistivity observation, which used the fixed Schlumberger arrays (Figure 2a), with two measurement arrays of EW and NS. The electrodes spacing of \( AB \) was 1500m, the measurement spacing of electrodes of \( MN \) 500m, and the bury depth of electrodes was 2.5-3m. Thus, the quality of the surface observation data is high. Due to the increase of rainfall and temperature in summer and the decrease of apparent resistivity in surface layer, the observed value was at peak, while it was low in winter, presenting the annual variation form of "high in summer and low in winter". Deep-well measurement was added in Dabaishi station on January 1, 2010. Initially ATS-SR with deep-well electrodes was adopted, but was replaced with ZD8B in June, 2013. The deep-well measurement was arranged with a horizontal measurement array in EW direction and a vertical measurement array, and electrodes were distributed along a straight line in each measurement array (Figure 2b). The electrodes spacing of \( AB \) was 60m, and the measurement spacing of electrodes of \( MN \) was 20m. The bury depth of all electrodes of the horizontal measurement array was 100m, and the bury depth of the four electrodes of the vertical measurement array was 40m, 60m, 80m and 100m respectively. Among them, the vertical current electrode B2 and the horizontal current electrodes A1 shared one electrode.

3. Analysis of observation data

Observation data of the horizontal measurement array showed no significant change in annual variation forms(Figure 3a),while the data of the vertical measurement had the annual variation form of of "low in summer and high in winter" , with the annual variation amplitude of 0.6 Ω, m(Figure 3b).The station was located in Hebei Plain area,where water consumption of agriculture was large, groundwater exploitation was serious, and depth of groundwater table was relatively big (Figure 3c). The investigation of the groundwater level in Longyao area showed that the groundwater level was affected by agricultural exploitation and rainfall, with the annual variation characteristics of “high in winter and low in summer” (e.g.,[23]). From March to June every year, a large amount of groundwater was exploited for irrigation in the growth stage of winter-wheat. The groundwater couldn’t be replenished in time, and thus the groundwater level dropped. During this period, the observed value of vertical resistivity also dropped. Since the rainy season began in July, the amount of underground water exploitation decreased correspondingly. At the same time, due to the replenishment of the lateral runoff in the piedmont zone of Taihang mountain, the groundwater level began to rise, and the vertical resistivity showed an upward change. In mid-November, due to the impact of winter irrigation and pumping, the groundwater level rose slowly or slightly decreased, during which the vertical resistivity decreased. From January to February of the next year, thanks to the cessation of groundwater exploitation for agricultural irrigation, the groundwater reached the highest level of the year at the end of February.,during which the vertical resistivity showed an upward change again. There was a good corresponding relation between the seasonal annual variation of the vertical resistivity and the variation of groundwater level. In summer, the depth of groundwater table was small and the observed value of the resistivity was high,while in winter, the depth of groundwater table was big ,and the observed value of the resistivity was low. The groundwater level changed rapidly and greatly from March to June and November each year, when the vertical resistivity also changed rapidly accordingly. The data of the groundwater level near the Dabaishi seismic station showed that it belonged to the type of deep groundwater level. Due to the influence of seasonal rainfall and pumping, the depth of the groundwater level in recent years was around 50m and decreased year by year. The bury depths of the electrodes of the vertical measurement array A2 and M2 were 40m and 60m respectively, between which the depth of the groundwater table fluctuated. Therefore, the fluctuation of the groundwater level had a great impact on the measurement data of the vertical resistivity.
4. Theory of sensitive coefficient

If the underground three-dimensional space of the surveyed area was divided into \( N \) three-dimensional subregions by any size, each subregion was regarded as homogeneous medium, and the resistivity was set as \( \rho_i, \quad i=1,2,…,N \), given the determined observation device, the measuring space and the current electrodes spacing, the observations of the resistivity were the function of the media resistivity of each subregion (e.g.,[10,11,28,29]):

\[
\frac{\text{d}(\ln \rho_a)}{\text{d}(\ln \rho_i)} = \sum_{i=1}^{N} \frac{\partial}{\partial \ln \rho_i} \text{d}(\ln \rho_i)
\]  

(1)

At normal state, the media resistivity of each subregion changed slowly, of which the relative variation was very small over a certain period of time, namely \( \Delta \rho_i / \rho_i \ll 1 \). Therefore, if we performed equation (1) by the Taylor series expansion, and neglected second-order terms and higher-order terms, the relative variation of resistivity observations could be represented by the weighted sums of the relative variation of the media resistivity in each subregion:

\[
\frac{\Delta \rho_a}{\rho_a} = \sum_{i=1}^{N} B_i \frac{\Delta \rho_i}{\rho_i}
\]  

(2)

In the equation (2), \( B_i \) was referred as the sensitive coefficient of the resistivity:

\[
B_i = \frac{\partial}{\partial \ln \rho_i} \frac{\rho_a}{\rho_i} \frac{\partial \rho_a}{\partial \rho_i}
\]  

(3)

Meanwhile, the sensitive coefficient of all subregions met the following equation (e.g.,[30]):

\[
\sum_{i=1}^{N} B_i = 1
\]  

(4)

From the equation (2), it could be concluded that in the area with large absolute values of the sensitive coefficient, the media resistivity variation had prominent effect on the measurement data of the resistivity; otherwise, it would have a small impact.

5. Analysis on resistivity measurement

In the surveyed area of Dabaishe station, there was thick overburden, with the bedrock depth up to 700m, and the underground medium had excellent conductivity. According to the electrical sounding curves, the stratum could be regarded as QH type electrical structure ((Figure 4a), and the electrical structure was inverted by using the horizontal layered medium model. As is shown in Figure 4a, the first medium layer was loess with the thickness of about 5m and the resistivity of about 70 \( \Omega \cdot m \). The second layer was sand and gravel, the thickness of about 100m and the resistivity of 25 \( \Omega \cdot m \). The thickness of the third medium layer was about 580m, which was the interbedded layer of sandy loam and mild clay, and the resistivity was low, about 10-12 \( \Omega \cdot m \). Below it was the bedrock with high resistivity.

On the basis of the horizontal layered electrical structure shown in Figure 4a, given the current electrodes spacing of AB 60m, the measurement spacing of electrodes of MN 20m, when calculated with the horizontal deep-well measurement array, the sensitive coefficient in each medium layer varied with depth, as shown in Figure 4b. As the observation value of deep-well apparent resistivity
was represent by $\rho_{aw}$, given the bury depth of electrodes 100m, the relative change value $\rho_{aw}$ could be expressed as follows:

$$\frac{\Delta \rho_{aw}}{\rho_{aw}} = 0.0001 \frac{\Delta \rho_1}{\rho_1} + 0.4952 \frac{\Delta \rho_2}{\rho_2} + 5054 \frac{\Delta \rho_3}{\rho_3} - 0.0007 \frac{\Delta \rho_4}{\rho_4}$$  \hspace{1cm} (5)

Because of the big bury depth and short measurement spacing of electrodes, the horizontal deep-well measurement mainly reflected the information of the medium resistivity in the second and third layers. Set the sensitive coefficient in the first layer as 0.0001, the influence of the shallow medium near the free surface on the resistivity observation could be ignored, so no significant annual change was observed in the horizontal measurement. The sensitive coefficient in the fourth layer was also very small, so the response ability of the horizontal measurement to the deep bedrock resistivity variation was very little too. As is shown in Figure 4c, the sensitive coefficient of surface observation varied with the measurement spacing of electrodes. Given the electrodes spacing of AB 1500m, the sensitive coefficient in surface layer was negative. The increase and decrease in surface layer on resistivity would lead to the decrease and increase on the observed apparent resistivity value. Therefore, the anomalous annual variation pattern of "high in summer and low in winter" appeared. If the bury depth of electrodes of H was fixed at 100m, the variation of the sensitive coefficient with the measurement spacing of electrodes was shown in Figure 4d. It can be seen that with the increase of the measurement spacing, the sensitive coefficient in each layer gradually tended to be consistent with that of the surface observation, indicating that for the fixed bury depth of electrodes, the effect of deep-well observation would be lost if the measurement spacing exceeded a certain range.

According to the electrical structure shown in Figure 4a, during the horizontal deep-well measurement, the distribution of the sensitive coefficient in each layer along with the measurement spacing of electrodes and the bury depth of devices was shown in Figure 5. It can be seen from the figure that the observation with small measurement spacing mainly reflected the medium information in the region where devices were located, and if the device was buried at a relatively shallow depth, it mainly reflected the medium information in the shallow layer. Due to the large thickness of the medium and low resistivity in the third layer, the observed apparent resistivity value mainly reflected the information of the medium in this layer. Only when the measurement spacing of electrodes was large and the bury depth of the device was also large, the deep-well measurement could reflect the information in bottom layer. The resistivity of shallow medium was easily affected by the change of groundwater level, seasonal increase and decrease of water saturation and temperature change, so the deep-well measurement should reflect the disturbance information as little as possible. It is generally believed that the deep medium could transfer the stress more effectively than the shallow loose sedimentary layer, and the earthquake preparation or the tectonic stress mainly caused the change of resistivity of the deep medium, so the third layer and the bottom layer should be the main objects observed in the deep-well measurement at Dabaishhe station. As can be seen from Figure 5, it could meet the requirements when the current electrodes spacing of AB/2 in the horizontal deep-well measurement was adopted as 250-350m, and the bury depth of the device of H was over 150m. Taken into account that the groundwater level varied around 50m, the bury depth of the top electrode in the vertical measurement should be a certain distance below the underground water level, so as to reduce the influence of the change of underground water level on the resistivity observation.

6. Discussion and Conclusions

Deep-well measurement is to suppress the shallow surface interference through the formation shielding effect and by increasing the spacing between the observation devices and the surface interference sources. Therefore, as long as observation devices are buried deep enough, the interference generated by the resistivity change of the shallow surface medium, which is caused by non-tectonic factors, could always be effectively suppressed. On the other hand, the deep-well
measurement also reduces the distance between the observation device and the underlying layer, which is helpful to obtain the change information of deep medium. Because of the cost of current deep-well measurement and the requirements on the stability of the measurement system, the bury depth of the observation devices could reach to about 250m. For most stations, the change of bedrock resistivity could be observed effectively with appropriate electrodes spacing at this depth. Although the existing horizontal deep-well measurement at Dabaish station could effectively suppress the interference information from the surface, it is not enough to reflect the deep information due to the small measurement spacing. The annual variation of the vertical deep-well measurement is obvious. The bury depth of the first electrode is 40m, and is located in the dynamic variation layer, which is greatly affected by the fluctuation of underground water level, so the information in deep formations is buried. As the current electrodes at the top of the vertical deep-well measurement are close to the surface, the interference couldn’t be well suppressed, so it is suggested to cancel the vertical deep-well measurement. In order to record as much information as possible that was related to earthquakes, the measurement spacing of electrodes and the bury depth of devices at Dabaish station should be appropriately increased. To meet the requirements, the spacing of horizontal arrays of $AB/2$ should be set as 250-350m, and the bury depth exceeds 150m. If conditions permitted, the bury depth could be further increased to better obtain the information in deep layers. Considering that the change of apparent resistivity was related to the direction of principal stress, a horizontal array along NS direction is also recommended.

![Geological structure map of Dabaish](image)

**Figure 1.** Geological structure map of Dabaish
Figure 2. Schematic diagram of electrodes arrangement of the surface resistivity and deep-well resistivity at Dabaish station.

Figure 3. Observation data of deep-well resistivity and data of groundwater level.
Figure 4. Electrical structure and sensitive coefficient at Dabaishe station. (a) electrical sounding curves and inversion results of horizontal-layer electrical structure. (b) variation of sensitive coefficient in each layer with bury depth of electrodes. (c) variation of sensitive coefficient of surface observation with electrodes spacing. (d) variation of sensitive coefficient of deep-well measurement with the bury depth of electrodes at 100m.

Figure 5. Variation of sensitive coefficient in each layer with measurement spacing and bury depth of electrodes at Dabaishe seismic station. (a) sensitive coefficient of medium in first layer. (b) sensitive coefficient of medium in second layer. (c) sensitive coefficient of medium in third layer. (d) sensitive coefficient of medium in fourth layer.
References

[1] X. Du, Q. Ye, Z. Ma, “The detection depth of symmetric four-electrode resistivity observation in/near the epicentral region of strong earthquakes”, Chinese Journal of Geophysics, vol. 51, no. 06, pp. 1943-1949, 2008. (in Chinese with English abstract)

[2] Du X B. Two types of changes in apparent resistivity in earthquake prediction. Sci China Earth Sci, 2010, doi: 10.1007/s11430-010-4031-y

[3] X. Gui, H. Guan, J. Dai, “The short-term and immediate anomalous pattern recurrences of the apparent resistivity before the Tangshan and Songpan earthquakes of 1976”, China Earthquake Engineering Journal, vol. 11, no. 4, pp. 71~75, 1989. (in Chinese with English abstract)

[4] C. Liu, X. Gui, J. Chai, “The observation test in deeo-hole electrodes(whole space)resistivity at the Heyuan geoelectrical observatory”, South China Journal of Seismology, vol. 13, no. 3, pp. 40~45, 1994. (in Chinese with English abstract)

[5] Y. Liu, G. Wu, F. Wang, “Experimental results of observations at buried electrodes resistivity”, Fujian Science and Technology Publishing House, Fujian, pp. 206~216, 1985. (in Chinese)

[6] Y. Nie, L. Yao, “Study on Electrical Potential by Buried Source Electrode Within Horizontally Layered Half-space Model”, Earthquake Research in China, vol. 25, no. 3, pp.246~225, 2009. (in Chinese with English abstract)

[7] Y. Nie, Z. Ba, Y. Nie, “Study on buried electrode resistivity monitoring system”, Acta Seismologica Sinica, vol. 32, no. 1, pp. 33~40, 2010. (in Chinese with English abstract)

[8] F. Qian, Y. Zhao, J. Liu, “Power spectrum anomaly of earthresistivity immediately before Tangshan earthquake M 7.8”, Earthquake, no. 3, pp.33~395, 1990. (in Chinese with English abstract)

[9] F. Qian, Y. Zhao, M. Yu, “Anomaly of earthresistivity before earthquake “, Scientia Sinica(Chimica), no. 9, pp.831~839, 1982. (in Chinese)

[10] J. Qian, Y. Chen, A. Jin, “Application of resistivity in earthquake prediction “, Seismological Press, Beijing, pp.83~103, 1985. (in Chinese)

[11] J. Qian, A. Cao, “Research on comprehensive mechanism of precursors in apparent resistivity and water table associated with 1976 Tangshan earthquake(M=7.8)”, Earthquake, no. S1, pp.3~5, 1998. (in Chinese with English abstract)

[12] F. Shi, G. Zhang, W. Fang, “Anual variation characterristics of geo resistivity at Zhouzhi geoelectric station, Shaanxi Province”, Acta Seismologica Sinica, vol. 36, no.6, pp. 1113~1123, 2014. (in Chinese with English abstract)

[13] L. Su, B. Wang, L. Xia, “Elimination of surface disturbances in earth resistivity measurment by lowering the electrodes in shallow wells”, Acta Seismologica Sinica, vol. 4, no.3, pp. 274~276, 1982. (in Chinese with English abstract)

[14] S. Tian, Y. Liu, Y. Nie, “Improved method of earth resistivity observation:Transplant application and numerical model analysis”, Acta Seismologica Sinica, vol. 31, no.3, pp. 272~281, 2009. (in Chinese with English abstract)

[15] B. Wang, Y. Liu, Y. Li, “The electric resistivity in the boreholes and the earthquake prediction”, Journal of Seismological Research, vol. 41, no.1, pp. 378~403, 1981. (in Chinese with English abstract)

[16] D. Wei, C Li, “Analysis about influence of green house on apparent resistivity observation at Guyuan seismic station”, Seismological and Geomagnetic Observation and Research, vol. 30, no.2, pp. 77~82, 2009. (in Chinese with English abstract)

[17] T. Xie, X. Du, J. Chen, “Calculation for the influence from the surface disturbance current in the deep-well geoelectrical resistivity observation”, Progress in Geophysics, vol. 27, no.1, pp. 112~121, 2012. (in Chinese with English abstract)

[18] T. Xie, J. Lu, M. Li, “Quantitative analysis of disturbance cause by burned wirerope in Baochang geoelectric resistivity station”, Progress in Geophysics, vol. 28, no.2, pp. 727~734, 2013. (in Chinese with English abstract)
[19] T. Xie, J. Lu, “Three-dimensional sensitivity coefficients of apparent resistivity and preliminary application”, Seismology and Geology, vol. 37, no. 4, pp. 1125~1135, 2015. (in Chinese with English abstract)

[20] T. Xie, X. Du, J. Lu, “Sensitivity coefficients analysis of deep-well apparent resistivity measurement”, Earthquake Research in China, vol. 32, no. 1, pp. 40~53, 2016. (in Chinese with English abstract)

[21] W. Yao, “Introduction to the calculation and interpretation of electrical sounding”, Seismological Press, Beijing, pp. 85~87, 1989. (in Chinese)

[22] Q. Ye, X. Du, J. Chen, “One-Year Prediction for the Dayao and Minle-Shandan Earthquakes in 2003”, Journal of Seismological Research, vol. 28, no. 3, pp. 226~230, 2005. (in Chinese with English abstract)

[23] G. Zhang, Z. Qiao, L. Jia, “The study of relationship between earth resistivity and ground water level at Longyao seismic station”, Seismological and Geomagnetic Observation and Research, vol. 34, no. 5/6, pp. 141~143, 2013. (in Chinese with English abstract)

[24] L. Zhang, Z. Qiao, N. Luo, “Contrastive analysis of georesistivity in deep-well and on ground at Dabaishe station”, North China Earthquake Sciences, vol. 32, no. 4, pp. 49~53, 2015. (in Chinese with English abstract)

[25] X. Zhang, M. Li, H. Guan, “Anomaly Analysis of Earth Resistivity Observations before the Wenchuan Earthquake”, Earthquake, vol. 29, no. 1, pp. 108~115, 2009. (in Chinese with English abstract)

[26] Y. Zhao, J. Lu, H. Zhang, “The application of electrical measurement to earthquake prediction in China”, Seismology and Geology, vol. 23, no. 2, pp. 277~285, 2001. (in Chinese with English abstract)

[27] Lu J, Qian F Y, Zhao Y L, 1999, Sensitivity analysis of the Schlumberger monitoring array: Application to changes of resistivity prior to the 1976 rathquake in Tangshan, China. Tectonophysics, 307(3): 397~405.

[28] Lu J, Xue S Z, Qian F Y, et al, 2004, Unexpected changes in resistivity monitoring for earthquakes of the Longmenshan in Sichuan, China, with a fixed Schlumberger sounding array. Pepi., 145(1-4): 87~97.

[29] Park S K, Van G P, 1991, Inversion of pole-pole data for 3-D resistivity structure beneath arrays of electrodes. Geophysics, 56(7): 951~960.

[30] Seigel H O, 1959, Mathematical formulation and type curves for induced polarization. Geophysics, 24(3): 547~565.