Research on geo-electrical resistivity observation system specially used for earthquake monitoring in China*

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Abstract This paper deals with the design and development of the observational system of geo-electrical resistivity on the basis of the demands for exploring the temporal variations of electrical properties of Earth media in the fixed points of the networks, which would be associated with the earthquake preparation. The observation system is characterized by the high accuracy in measurement, long term stability in operation and high level of rejection to the environmental interference. It consists of three main parts, configuration system measurement system, the calibration and inspection system.

Key words: geo-electrical resistivity observation system; earthquake monitoring; configuration system; measurement system; calibration and inspection system

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1 Introduction

In China, the countermeasures of multi-approaches for dealing with the researches of earthquake predication have been adopted. Electromagnetic method is one of these approaches, in which the geo-electrical resistivity observation, called as geo-electrical resistivity method (GRM), is one of the most important means. The main objective of this observation is to study the variation of electrical properties of Earth medium with time which associates with earthquake preparation process.

After 40 years practice of earthquake predication, a lot of earthquake cases have been accumulated, especially strong earthquakes with magnitude $M_S \geq 7.0$ inside the observation networks. The outstanding features of the case studies is that the geo-electrical resistivity recorded in the monitoring stations near the epicentral area had exhibited the abnormal descending tendency

lasted for 2–3 years before strong earthquakes, with the amplitude of the trend up to several percent, even to ten more percent, while after earthquake, the trend of geo-electrical resistivity appears to be turning or ascending (Qian, 1984, 1985, 2010; Qian et al., 1985, 1993). Recently the similar phenomenon has been found in the case study of $M8.0$ Wenchun earthquake on 12 May 2008, in Sichuan province in China. A two years drastic decrease trend in geo-electrical resistivity in the Chengdu station, 35 km and Ganzi station 300 km away from the epicenter were recorded, in which the decrease amplitude of geo-electrical resistivity in Chengdu station is about 7 percent, while in Garze station is about 5 percent (Zhang et al., 2009; Qian, 2010). The decrease phenomenon near the epicentral area (or inside the earthquake preparation zones) before earthquake matched very well with the experimental result of loaded samples with cracks widely developing and re-aligned characteristics in the late stage of main rupturing period (Brace et al., 1968; Brace, 1975). Therefore, not only these case studies provided an important material for recognizing the preparation process of strong earthquake, but also would highlighting display an important role in the earthquake monitoring.

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Actually, in the history of GRM development applied in the researches of earthquake prediction, GRM originated from the DC apparent resistivity method (ARM) in geophysical prospecting and GRM has experienced the transplanting and reforming stages based on the demands for earthquake monitoring. That is to say, these two methods not only have connection, but also have difference. To say transplanting is due to the fact that the physical quantity observed for both methods is the same: apparent resistivity and even the configuration for GRM also came from ARM, for example, four-pole configuration adopted widely. To say reforming is due to the fact that they are different in the aim of the observation: ARM aims at detecting the spatial variation or spatial distribution of the electrical property of Earth media so as to find the its electrical structure, while GRM aims at the temporal changes of the Earth media in the fixed monitoring points or sites in a network, to find the temporal changes or dynamic variations of the Earth electrical structure which might be associated with earthquake preparation process. It is the main character of GRM different from ARM, which has presented requirement for observational system and information analysis system in GRM much more restrict than that in ARM. For this new goal, the Chinese scientists and technicians have made a lot of efforts in the reforming process, especially for the observational system fully satisfying the demands for earthquake monitoring by GRM. Since GRM started in China, there have been

many papers introducing the case study results, experimental and theoretical exploration achievements related to GRM. But there are rarely papers on earthquake-related geo-electrical observation technology of China. In this paper, the development and the innovation process of the design and study on earthquake-related geo-electrical observation system in China would be introduced in detail.

2 The structure and the basic technical requirements of geo-electrical resistivity observation system

2.1 The measurement principle of geo-electrical resistivity

Figure 1 is schematic diagram for the measurement principle in GRM, which coincides with the one for ARM. The capital letters A , B , M , N in Figure 1 denote the positions of four electrodes buried underground, among which, A and B are called current electrodes and connected to the device for current detection supply through wires; M and N are called potential electrodes and connected to the device for potential difference detection, detecting meter through wires. E denotes the DC power supply, and k is a switch. The measurement process is as follows.

Figure 1 The schematic diagram of the measurement principle for geo-electrical resistivity.

When the switch k is switched on, a DC current (I) is applied from the power supply to the ground through electrodes A and B . When a stable artificial electrical field was established by the current, the corresponding additional potential difference (ΔV) between M and N

as well as the current I can be measured by a special instrument where both the device for potential difference detection and the one for current detection are collected. Finally the geo-electrical resistivity, ρ_s , can be calculated by

$$\rho_s = K \frac{\Delta V}{I}, \quad (1)$$

where K is configuration coefficient or geometric factor, determined by the relative position of A , B , M , N in formula (2).

$$K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{AN} + \frac{1}{BN} - \frac{1}{BM}} \quad (2)$$

The electrodes A , B , M , and N are deployed in a symmetry mode in a line in most of observation sites and the position of each electrode must be kept fixed in the long time monitoring process in GRM in China. Based on formula (1), detecting any changes in the geo-electrical resistivity with time is always proportional to

the changes in the ratio of additional potential difference ΔV over the total current I if the configuration coefficient K would really be a fixed constant, not change with time. Namely the changes in the geo-electrical resistivity must be related to the changes in the electrical structure instead of to the changes in the configuration coefficient K which could possibly be caused by the leakage between wires or wires to ground.

2.2 Structure of geo-electrical resistivity observation system

A geo-electrical resistivity observation system consists of three parts: configuration system, measurement system, and calibration and inspection system as shown in Figure 2.

Figure 2 The structure of geo-electrical resistivity observation system.

The configuration system includes (1) potential electrodes and current electrodes arranged with certain geometric configuration mode, (2) wire lines connecting electrodes to measurement system, and (3) lighting protection device and indoor wiring. The measurement system consists of detecting devices, power supply and recording (or communication) device. And the calibration and inspection system includes the appliance for voltage and resistor standard and devices for inspecting the stabilization state of the configuration system.

The measurement system is the core and key part of the geo-electrical resistivity observation system, in which the power source provides the current into ground to generate artificial signal and the device to detect the signal and produces the final results. The configuration system in good condition is the basis of measurement.

The calibration and inspection system is a kind of guarantee facility for checking whether or not the operating state of the configuration system and measurement system being normal, and ensuring them being in good condition through maintenance and repair of the meters and devices in the systems, any time if necessary, in the long term monitoring process.

2.3 Requirements for geo-electrical observation system

Compared with the measurement system in ARM, the technical requirements for that in GRM is obviously different as the following:

1) High accuracy for the measurement system in order to accurately identify and distinguish the small difference of geo-electrical resistivity in different time. Since the GRM started to popularize in China, Chinese scientists have found the least anomalous changes in geo-electrical resistivity in the monitoring stations associated with earthquakes nearby could be more than 1% (Wang et al., 2002). That is to say, in order to satisfy the demand for the study of earthquake predication, at least, the measurement system must have the ability to accurately identify the variation or difference in geo-electrical resistivity to the level of one percent (1%) in different time and different monitoring site.

2) Long term stability of the instrument functions. In order to serve for the researches of the earthquake preparatory process, the dynamic changes in the values of geo-electrical resistivity in fixed points (or say, monitoring stations) for long time period of observations would be required, in which it is necessary to demand

the measurement system with long term stability of the instrument function. According to the case studies for $M_S \geq 7.0$ earthquakes accumulated in China, the duration of geo-electrical resistivity abnormal variation can be up to several years as mentioned in the first part of the paper, and if one takes the comparison of the anomalous behalves of geo-electrical resistivity before earthquake with the variations after the quake, the long observation results would be needed. For example, Qian et al. (1993) showed 20 years observation data from 1970 to 1990 in Baodi station, Tianjin municipality, 77 km away from the epicenter of 1976 Tangshan earthquake, which covered the observations partly in the period before and partly after the quake, to discuss the correlation of the anomalous decrease from 1973 to 1976 and the preparation process of Tangshan earthquake, and to verify the reliability and objectivity of the geo-electrical resistivity trend anomaly before the quake. Therefore, it is necessary that not only the measurement systems in the network must have accuracy high enough, but also have the capability to keep the accuracy unchanged for long term observation.

3) High level of rejection to the environmental interference in order to get a higher SNR of observation. With the development of national economy, an inevitable interference from the electromagnetic environmental deterioration on the geo-electrical resistivity observation must be highly taken into consideration in the design of the measurement system, especially for the temporal observation of long term geo-electrical resistivity.

According the above analyses, the goal for the geo-electrical resistivity observation in the study of earthquake prediction is to accurately and reliably detect or discriminate the variation of geo-electrical resistivity definitely at least to the level of 1%. To this end, the following technical requirements for observation system of the geo-electrical resistivity must be satisfied:

Resolution of the system: better than $0.01 \Omega \cdot m$.

Maximum error of the system: less than $0.3\%RD + 0.02 \Omega \cdot m$

Time interval of the observation: 1 hour

3 The design of configuration system

3.1 The deployment of configuration system

As mentioned above, the configuration system consists of two parts: electrodes and wires connecting the

electrodes and measurement devices. The electrodes were deployed on the surface of the Earth medium according to a certain geometry layout. It is the basis completing apparent resistivity measurement, which is also the basic mode to be followed in the earthquake-related GRM in earthquake monitoring and ARM in geophysical prospecting.

In principle, similar to the ARM, several types of configuration systems can be chosen for DC geo-electrical resistivity measurement, such as the dipole-dipole configuration system used in many countries (Mazzella and Morrison, 1974; Sadosky et al., 1972). In China, usually the four-electrode symmetry configuration is adopted, as shown in Figure 1. One paired current electrodes and one paired potential electrodes are deployed in a straight line. The latter is symmetrically deployed at the central point of the paired current electrodes. The angle between the line and north direction is the measurement azimuth. There are two to three measurement azimuths in one site, such as SN, WE, NE or NW, deployed. And the lines can also be deployed in the modes of parallel, perpendicular or skew to the direction of tectonic strike in the sites where the geological structure is clear. The reasons for choosing such a configuration system are as follows:

1) Comparison with a dipole configuration system. A higher artificial potential difference can be gotten by using four-electrode symmetry configuration system in the same condition of electrode distance and current intensity in a site. That is to say, for the same interference, it has a higher signal to noise ratio (SNR). On the contrary, to get the same artificial potential difference or SNR, thus need to increase the current intensity, and therefore a more powerful power supply system should be needed. From the view point of the nationwide monitoring demands, it is very difficult to do this.

2) The choice of multiple azimuths of geo-electrical resistivity. It is based on the theory that most of earthquakes occur in large active fault whose electrical property structure is characterized by macro-anisotropy. Perhaps it is advantage for earthquake-related fault activities monitoring by using parallel or perpendicular multiple azimuths to the fault strike.

The choice of electrode distance is one of most important aspects in four-electrode symmetry configuration system design. To have the total observational system with enough SNR and enough exploration depth are important factors in the design of selection for separations of AB and MN . For the current electrode separation, the longer current electrode separation are, the

deeper exploration depth, and the less interference from the Earth surface. But the configuration with too long separation of the current electrodes would decrease the artificial potential difference (i.e. decrease SNR) in MN under the condition of fixed current intensity, and also increase difficulties in wires' maintenance as well as increase the possibility of the leakage between wires and wires to the ground equivalent to the changes of the configuration coefficient which would lead to the wrong results. Based on the experimental result and considering the demands for system maintenance of long term monitoring, a compromised measures for the selection of separation between A and B in most stations in the GRM network in China, being approximately 1 km, have been adopted, which is much longer than that in Japan where the maximum separation of AB was 2.4 m of configuration of geo-electrical resistivity measurement in the roof and floor of a mountain cave near the sea (Yamazaki, 1965) .

The potential electrode separation MN is, in general, selected to be $1/3$ to $1/5$ of separation of AB . The configuration with too long potential electrode distance would decrease the exploration depth and lead to the measurement affected by the nonuniformity of electrical field between M and N , according to the principle of measurement in ARM although the artificial potential difference and SNR would increase, while for the configuration with too short separation of MN , SNR of the artificial potential difference would decrease and the observation might be affected from locally non-uniform structure of the top layer of the Earth media. Only in those sites with higher apparent resistivity, MN distance could be selected shorter.

3.2 The technical requirements for configuration system

In earthquake monitoring, the configuration system must be stable enough, which is one of important parts of the total requirements of stabilization of geo-electrical resistivity observation in long term monitoring. In other words, the configuration coefficient K for each site must be kept unchanged with time, or the change of K is so small, that actually no effect on the geo-electrical resistivity observation could be detected, even if the change is existing inevitably due to some kind of leakage in the configuration system.

In configuration system, the position of the electrodes generally would not change with time. The state of insulation between outdoor wire lines or between wires and ground, however, might change with time due to wires being exposed in the air or buried in the under-

ground soil in the long term observation, which would result in the some kind of leakage. In the case of existence of leakage, the current would flow into and out the Earth incompletely which changes the actual current, or the received signal is not complete from MN which changes the artificial potential difference. That is to say, the appearance of leakage actually reveals a certain change of configuration system, the wrong or incorrect observation results of geo-electrical resistivity should be attributed or equivalent to the change of configuration coefficient K .

According to the monitoring practice in China, the concrete technical requirements for the configuration system are as follows: to check the influence of the configuration system on the observation results regularly, to discriminate or eliminate all the possible factors which could lead the configuration system being unstable in time, so that the maximum permissible error due to the instability of the configuration system must be less than 0.3%, in order to satisfy the total requirement of the observational system mentioned above in section 2.3.

To realize this index for the configuration system in the long term observation, it is necessary to take some approaches in the electrodes and wires management which will deal with in next sections.

3.3 Electrode and its technical requirements

The deployment and layout of electrodes is an important technical aspect in the configuration system. The electrodes consist of current electrodes and potential electrodes. The function of current electrodes is to supply the current to ground, while the potential electrodes is to transmit the potential difference to the measurement system.

1) The requirements for current electrodes are that the grounding resistivity R_e and electrode resistivity R_i should be as smaller as possible. Usually the material used for current electrode is metal. So the R_i can be ignored. The reason for a smaller R_e is the small R_e would require small electrical power P , and also small voltage, in the case of fixed current by the DC stabilized current supply, so that the interference of common mode voltage on the measurement of geo-electrical resistivity and the leakage effect of the configuration system would decrease.

Because the load required by the stabilized current supply in most stations in China, is 80–100 Ω , so the requirement for the grounding resistance of each current electrode is 30 Ω , when the total resistance of current wire line is supposed to be less than 20 Ω .

Usually, the electrode was made of lead (Pb) whose chemistry property is stable. The size is about 800 mm×800 mm×4 mm ($l \times w \times t$). The electrode made of other materials, such as iron and copper, will be corroded quickly and with a very short lifespan because of the active chemistry property.

In case of the grounding resistance insatiable for the requirement some countermeasures for decreasing the grounding resistance, such as increasing the electrode's size, decreasing the resistivity of medium where the electrode is buried, adopting mode of electrodes combination, would be needed (Qian and Lin, 1995).

2) The requirements for the potential electrodes as follows. Firstly, the polarization potential of each electrode should be stable after being buried into ground; secondly, the grounding resistance R_e of each electrode should also be as small as possible. The potential electrodes with stable polarization would decrease the noise level and measuring error in the measurement of the artificial (additional) potential difference produced by the current from power supply. Usually, the potential electrode would be also made of lead with the size of about 600 mm×600 mm×4 mm ($l \times w \times t$). It is noted that it would be very important in keeping the stability of the function of buried electrodes to take the following the approaches for the treatment of potential electrodes, such as carefully cleaning electrode's surface, and processing the soil for burring the electrode, and making the good joining between electrode and metal wires (Qian and Lin, 1995). The decrease of grounding resistance would also decrease the effect of leakage of the configuration system.

As for the effect of the grounding resistance on the configuration system stability will be discussed in the next section.

3.4 The requirements for outdoor lines

As mentioned in section 2, there are two types of outdoor wires in the configuration system: the one is so called current line, for transferring the current from power supply to the ground through current electrodes; the another is so called measurement lines, for transferring the potential difference, either self potential difference or artificial additional one due to the current, between two potential electrodes, to measurement devices. The main requirement for outdoor lines is to avoid the leakage effect on the measurement so that every result from the measurement devices would be authentic.

The leakage effect of outdoor lines can be described in terms of the two indexes ε_1 and ε_2 . The index ε_1 shows the influence of leakage current, which is denoted

by the ratio of leakage current (I_L) to the total current (I) through current lines, supplied from the power source to the ground.

$$\varepsilon_1 = \frac{I_L}{I} \quad (3)$$

The other index ε_2 , shows the influence of leakage potential difference, which is denoted in terms of the ratio of leak voltage (V_L) to artificial or additional potential difference (ΔV) in the process of measuring the geo-electrical resistivity.

$$\varepsilon_2 = \frac{V_L}{\Delta V} \quad (4)$$

Based on the technical requirements for measurement system of the geo-electrical resistivity of maximum error of the system less than 0.3%RD+0.02 $\Omega \cdot m$ as mentioned in the section 2.3, ε_1 should be smaller than 0.1% and ε_2 smaller than 0.3%.

3.4.1 The leakage effect by index ε_1

In general, it is easy to satisfy the requirement for ε_1 less than 0.1% in the monitoring stations, because of the fact that the resistances between wire lines or between wires and ground in general would be much higher than the grounding resistance of the electrodes which is small enough, e.g., less than 30 Ω .

3.4.2 The leakage effect by index ε_2

It would be complicated to deal with the leakage effect by index ε_2 . In this paper, we prefer to give more attention to the second index ε_2 , the influence of leakage potential difference and adequate approaches for reducing the influences in the following paragraphs.

The requirement for ε_2 being less than 0.3%, could be satisfied when some adequate approaches being adopted based on the experience and theoretical analyses of the leakage affect the measurement, which have revealed that the leakage effect could be attributed to the following two kinds: (1) the leakage between lines which means that the leakage occurs between the line connecting the electrode of A or B and the line connecting the potential electrode of M or N ; (2) the leakage of lines to ground which means that the leakage of the line either connecting the current electrodes or connecting the potential electrode B to ground.

Figure 3 shows the equivalent circuit models of these two kinds of leakage effects. Figure 3a shows the equivalent circuit model for the leakage occurring between the current line connecting electrode A (or B) and the potential line connecting electrode M (or N) as an example of analysis for the case of leakage between lines. Figure 3b shows the equivalent circuit model for

the leakage of the current line connecting electrode A (or B) to ground as an example of analysis for the case of leakage of lines to ground.

The circuit analysis gives the following formula to express the relationship between the ε_2 and parameters shown in Figure 3 for the two cases. In the case of Figure 3a,

$$\varepsilon_{IJ} = \frac{K}{\rho_s} \frac{1}{R_P} R_{EI} R_{EJ} \quad (I = A, B; J = M, N) \quad (5)$$

and in the case in Figure 3b,

$$\varepsilon_I = \frac{K}{2\pi} \frac{R_{EI}}{R_P} \left(\frac{1}{PM} - \frac{1}{PN} \right) \quad (I = A, B), \quad (6)$$

$$\varepsilon_J = \frac{K}{2\pi} \left(\frac{1}{AP} - \frac{1}{BP} - \frac{1}{AM} + \frac{1}{BM} \right) \frac{R_{EJ}}{R_P} \quad (J = M, N), \quad (7)$$

In the formula (5–7), ε_{IJ} , ε_I and ε_J are the indications of the index ε_2 in different cases, and K is the configu-

ration coefficient, ρ_s is geo-electrical resistivity, P is the position of leakage, R_P is leakage resistance, R_{EI} ($I=A, B$) and R_{EJ} ($J=M, N$) is the grounding resistance of A, B, M and N respectively; ε_U denotes the effect of leakage between current line I and potential line J , and R_{EI} and R_{EJ} denote the ground resistances of the current electrode A and B respectively in Figure 3a; and PA, PB, PM, PN are the distances between leakage point P and the electrodes A, B, M and N respectively; $\varepsilon_I, \varepsilon_J$ denote the leakage effect of the current electrode (A or B) to ground and the potential electrode (M or N) to ground respectively in Figure 3b.

Figures 4a and b show the results of mathematic modeling of index ε_2 for the effects of A, B line leakage to ground and M, N line leakage to ground respectively, in case of A, B, M and N electrodes being arranged in a straight line and the point of leakage locating in the line with $AB=900$ m, $MN=300$ m and $R_P=5$ M Ω .

Figure 3 Equivalent circuit models for mathematical modeling of ε_2 in two cases. (a) The leakage from the current line connecting electrode A (or B) to the potential line connecting electrode M (or N). The letters E denotes DC power source, R_A, R_B, R_M and R_N denote the grounding resistance of electrode A, B, M and N respectively, R_P denotes the leakage resistance. (b) The leakage from the current line connecting electrode A (or B) to the ground. The letters I_A denotes inflow current to electrode A , point P denotes the position of leakage appearing, I_P denotes the leakage current through point P inflowing to ground.

It could be seen from formula (5) to formula (7) as follows.

1) The index ε_2 in the existence of the leakage either between lines or the leakage between lines and ground should be related to the grounding resistance of electrode with which corresponding line are connected, so one of the countermeasures for reducing the leakage effect would be to keep the grounding resistance of electrodes as small as possible.

2) The index ε_2 in the case of existence of leakage between lines to the ground is related to the position of leakage point, and could be small enough if one could let the possible leakage point apart from the potential

electrodes (or current electrodes) to a certain distance.

3) The index ε_2 has nothing to do with the position of leakage point in the case of the leakage existing between the lines. Therefore, the ε_2 could be reduced greatly if some approaches could be taken for the leakage between lines being transformed to the case of leakage between wire lines to ground and keeping leakage point apart from the electrodes in an appropriate distance. For example as shown in Figure 4b, ε_2 would be less than 0.000 2 for the configuration with $AB=900$ m and $MN=300$ m in the case of leakage resistance of $R_P>5$ M Ω as long as the distance of leakage point to the electrode being larger than 25 m.

Figure 4 The mathematic modeling for ε_2 in the effect of the leakage of wire lines AB (a) and potential line MN (b) to ground. The abscissa denotes the relative location of the leakage point and the ordinate denotes the value of ε_2 .

The above-mentioned mathematical modeling results have been verified in the practical operations in Chinese geo-electrical resistivity monitoring network and have become the guide in the construction of the wire line lying (either in the overhead mode or in the underground burring mode) for reducing the leakage effect to the minimum extent and ensuring to satisfy the technical requirement of index ε_2 for long term monitoring (Zhao et al., 1982). Actually in the monitoring stations in China, the leakage effects could be controlled to the satisfactory condition when the following countermeasures have been widely adopted: in the mode of burring to the ground of lines lying, the electrodes connecting the potential lines being buried in the position 25 m farther apart from the cable duct of the current line (or, the electrodes connecting the current lines being buried in the position 25 m farther apart from the cable duct of the potential line); and the insulated potential lines and insulated current lines being able to bury in a com-

mon trench cable duct as long as the distance between them being more than 30 cm.

4 The design of geo-electrical resistivity measurement system

4.1 The development of measurement system

Geo-electrical resistivity measurement system consists of measurement instrument and current supply device. The current supply device provides DC current to the ground through current electrodes A and B , and establishes a stable artificial potential difference in the measurement field. The measurement instrument is used for measuring the artificial potential difference (ΔV) coming from potential electrodes M and N and the current (I) flows through A and B . So the demanded information of ΔV and I of equation (1) can be gotten and output the calculated result of geo-electrical re-

sistivity ρ_s . The geo-electrical resistivity variation map can be constructed by comparing the difference of geo-electrical resistivity in different time.

The measurement system has experienced a long term development since 1967 when GRM was used in earthquake monitoring.

At the earlier stage of geo-electrical resistivity observation in China, the observation system with the manual operated analogy measurement instrument and the battery or storage battery as the current power supply was simulated to that of the moving observation of ARM in geophysical prospecting. Up to now, the current power supply has experienced the transients from storage battery, rectification power supply, DC stabilized voltage power supply, DC stabilized current power supply to switching DC stabilized current power supply. The latter is used in most of geo-electrical resistivity monitoring stations in China.

For the measurement instrument, it has experienced the stages of transients from automatization, digitalization, intelligentization to networking. The goal of

the relevant work is to improve the observation accuracy and anti-interference ability. At the earlier stage, some digital voltage meter, such as PZ5, PZ8, PZ26, DS13 and self-made PZ40 digital geo-electrical meter, has been used for the experimental measurement in some earthquake stations. Then with the development of electronic technique in China, the digital geo-electrical observation system with intelligence design was developed, and many kinds of digital instruments have been developed and promoted, such as ZD8 geo-electrical meter series, ATS automatic geo-electrical system, CATS geo-electrical meter and WDA geo-electrical meter, among which the ZD8B geo-electrical meter series is the most popular one, and now the geo-electrical measurement system has entered the networking stage. This enables remote management of the system and quasi-real time data transmission on-line. Figure 5 is the picture of ZD8I geo-electrical measurement system, the most popular one applied in Chinese geo-electrical resistivity monitoring network at present.

Figure 5 ZD8BI geo-electrical resistivity measurement system, which consists of ZD8B geo-electrical meter (right), DC stabilized current supply (bottom-left) and the ZD8T meter (upper-left) for configuration stabilization checking.

4.2 The requirement for the measurement system design

The measurement system is the core part of the whole observation system, so whether the requirement for the observation system can be achieved would mainly rely on that for the measurement system. As described above, the measurement system consists of two parts: the measurement instrument and the DC stabilized current power supply. In order to achieve the requirements for the observation system of GRM as men-

tioned in the section 2, the design for each part of the measurement system must be able to satisfy the special requirements described in the next paragraphs respectively.

4.2.1 The requirements for the design of the measurement instrument

1) Resolution of voltage measurement

Natural potential difference (V_{sp}): 0.1 mv

Artificial potential difference (ΔV): 0.01 mv

Current: 0.1 mA

2) Maximum permissible error for voltage measurement

$$\pm(0.02\%R+0.003\%FS) \quad (20\pm2)^\circ\text{C}$$

$$\pm(0.2\%R+0.05\%FS) \quad 0\text{--}40^\circ\text{C}$$

3) Maximum permissible error for geo-electrical resistivity measurement

$$\pm(0.1\%R+0.02\ \Omega\cdot\text{m}) \quad 0\text{--}40^\circ\text{C}$$

(at artificial potential difference $>10\text{ mV}$)

4.2.2 The requirements for the design of DC stabilized current power supply

Output current: 0.3–2.5 A

Load resistance: 30–80 Ω

Output current stabilization: $<1\%$

Ripple factor of output current: $<1\%$

Setup time of output current: $<3\text{ s}$

Insulation between output terminal and power line: $\geq 1\ 000\text{ M}\Omega$ (1 000 V)

4.3 Key issues and main technical approaches associated with improving the observation accuracy in the design of measurement instrument

In order to achieve the requirements for the measurement system, especially to make the geo-electrical resistivity measurement error less than 0.1% , two key points should be carefully considered, the first is to reduce the system error, the second is to reduce the random error.

To this end, many key approaches have been adopted. The design of ZD8B series geo-electrical meter was a good example in this aspect as described as follows.

4.3.1 Reduction of the system error

In the measurement of geo-electrical resistivity, the artificial current (I) was detected by measuring the voltage V_{R_I} on the sample resistor R_I set in the circuit of ZD8 and calculated by the following equation:

$$I = \frac{V_{R_I}}{R_I}. \quad (8)$$

Substitute equation (8) into equation (1), we can get

$$\rho_s = K \cdot R_I \cdot \frac{\Delta V}{V_{R_I}}. \quad (9)$$

Equation (9) shows that the system error of geo-electrical resistivity (ρ_s) determined by the errors in the configuration coefficient K , sample resistor R_I , and the ratio $\Delta V/V_{R_I}$. The effect from the configuration coefficient has been discussed in the section 3, so that only the effects from R and $\Delta V/V_{R_I}$, and the approaches to improve their accuracy need to be analyzed.

1) Choose sample resistors R_I with high enough accuracy. The variation of R_I depends on the temperature.

In order to minimum the temperature effect, besides using the material with very small temperature coefficient, it also needs very fine process measures. Therefore a standard resistor that is designed and manufactured according to the national professional standard was used in the geo-electrical resistivity equipment. The grade of the resistor is 0.01, the error of the resistance is less than $\pm 0.01\%$ in one year. On the condition of temperature variation, the relative error (E_{R_I}) of R_I is

$$E_{R_I} = \alpha(t - 20) + \beta(t - 20)^2, \quad (10)$$

where α and β are the temperature coefficients of standard resistor provided by the manufacturer.

2) Improve the detecting accuracy of ΔV and V_{R_I} . During measurement of geo-electrical resistivity, ΔV and V_{R_I} are digitalized by A/D converter firstly, and then $\Delta V/V_{R_I}$ is calculated. In terms of A/D convert, the relationship between output D and input voltage V is $D=aV+D_0$, as shown in Figure 6.

In Figure 6, α is the slope of line L , the intercept D_0 is the zero shift or nonlinearity of zero-zone of the A/D converter. The changes in α and D_0 with time and environment conditions, such as temperature and humidity, would be the main reasons for A/D convert error. Decreasing the changes in D_0 and α would decrease the system error of $\Delta V/V_{R_I}$. So the following countermeasures are taken in order to improve the detecting accuracy of ΔV and V_{R_I} .

Figure 6 The relationship between output D and input voltage V in A/D convert.

(1) Application of floating method for reducing the effects of D_0 . The floating method used in V_R ZD8B meter means that the voltage ΔV is measured in the alternative way in terms of bi-directional switch as shown in Figure 7, with the principal as follows.

Assuming that the positive and negative reading D_+ and D_- are available respectively when the switch are operated in different directions:

Figure 7 Principle diagram of floating method.

$$D_+ = aV + D_0 \quad (11)$$

$$D_- = -aV + D_0 \quad (12)$$

set $D = (D_+ - D_-)/2$, then

$$D = aV, \quad (13)$$

thus the effect of D_0 can be removed.

(2) The identical A/D converter used for measuring ΔV and V_{R_I} to reduce and even ignore the effect of α on the measurements. To this end, it is necessary to select the A/D converter with nonlinear error as small as possible, which could come into true because usually the nonlinear error of an A/D converter with very small temperature coefficient could be 1–2 orders of magnitude smaller than the error in the accuracy of the instrument.

(3) Adoption of wide dynamic range and high resolution A/D converter to decrease quantization error. A/D quantization error is one of sources of the system error, which is usually of $\pm 1/2$ LSB (lowest significant bit) and depends on the value of measurement, which means that the higher the resolution and the larger the reading, the less the quantization error effect would be. Therefore a suitable R_I could be selected so as to make the V_{R_I} reading large enough. As for the measurement of ΔV , a little more complicated consideration should be taken into account, because the reading of ΔV depends on ρ_s , current I and K , and ΔV could be up to more than 10 mV in most geo-electrical observation stations in China, so that the quantization error would decrease to the level of less than 0.1% as long as the resolution of A/D can reach 10 μ V, it is necessary to select A/D converters with a wide dynamic range and good linearity, for example, the 24-bit Σ - Δ type A/D converters which have widely been adopted in the measurement instruments.

The system error would be less than 0.1% after these approaches mentioned above being taken in the system design, e.g. in the ZD8 series meters design, which could ensure the convergence of observed data

when a meter is necessary to be replaced by another one, which would be of great significance to the long term continuous observation of geo-electrical resistivity.

4.3.2 Reduction of the random error

In the measurement of geo-electrical resistivity, the additional potential difference ΔV associated with the current I is always mixed with the variations from the natural field background so called natural potential (V_{SP}). The variation in natural potential are usually caused by the telluric, the industrial stray currents in the ground from various power facilities and EM-F (electromagnetic force) induced from the wires connecting electrodes M and N swaying in the wind, which would be the sources of interferences in measuring the additional potential difference ΔV . These interferences would contain different components: high frequency, industrial frequency and DC, in the frequency domain, and be divided into two kinds: common mode and serial mode ones according to the interference morphology. It should be, in particular, pointed out here that, a kind of strong common mode interferences, could come from the geo-electrical resistivity measurement process itself and had not been noted by many designers of the geo-electrical resistivity instrument, which are the strong DC common mode one inevitably occurring in measuring the current and the industrial frequency common mode one in the case of using industrial power as the power supply of the measurement system respectively. The errors in the measurement of geo-electrical resistivity resulted from all these interferences are attributed to the category of random errors. Actually, to restrain the random errors has been one of very important tasks in the design of measurement instrument of geo-electrical resistivity. To this end, the following special technical approaches have been used in the instrument design.

1) Passive filtering and decoupling. A passive serial connected filter was used for filtering high frequency serial-mode interference; a parallel connected decoupling device was used for decreasing the high frequency and DC impulse common mode interference.

2) Multiple isolations between signal and power supply. In the geo-electrical resistivity measurement, the measured signals are connected to the ground in a certain way. In order to decrease this kind of interference, the AC circuit power supply of control unit and the power supply of measurement unit are isolated by transformer, while the analog signal, digital signal and transmit signal are isolated by optoelectronic coupled devices. Practical result shows that this method can significantly reduce the common mode interference.

3) Rejection of power frequency interference in terms of special techniques. In terms of the program control that makes the integral time of the signal in the double-T type AD converter fixed to be integer times of the circle of power supply, the integrity of industrial interference in the measured signal would be zero.

In terms of the function of digital filtering in Σ - Δ type A/D converter, setting notch frequency at industrial frequency, the power frequency interference is easily to be rejected.

To expand the dynamic range of measurement instrument as large as possible would avoid the occur-

rences of errors due to clipping in the case of overhigh industrial frequency interferences.

4) Utilization of the forward and reverse power transmission mode. The time sequence of the current I in the forward and reverse power transmission mode is shown in Figure 8. It is clear that this technique has made the SNR (signal-noise ratio) of ΔV to the variations of V_{sp} being twice of that in single side power transmission mode, and would eliminate the effects of the long tendency variation in V_{sp} in the way of one direction drift if the drift exists.

Figure 8 The time sequence of current with forward and reverse power transmission mode where A denotes the time when the V_{sp} are measured, B denotes the time of current I measured; C denote each time when the artificial potential difference ΔV are measured in the cases of power supply transmission in the forward direction while C' denote each time when ΔV are measured in cases of power in reverse direction, t is current time, and I means current.

The measuring process shown in Figure 8 could be repeated for N times (N is the number and controlled by programmer according to the special condition of each station) and each time could obtained a measured value averaged from the values of multiple samplings at points C and C' . The average of N measured values and the corresponding standard deviation are calculated automatically by the program set in the instrument and would be taken as an observational result (or say, the hourly observation data, when the time interval of observation is set as one hour) for certain measuring azimuth (channel). Utilization of this technique would significantly reduce the effects on the measurement of geo-electrical resistivity from the random errors.

5) Utilization of the forward and reverse transmission mode with pseudo-random periods. Actually, the procedures shown in Figure 8 is the forward and reverse transmission mode with equal periods (cycles), which has theoretically some limitation with little or no interference rejection capability to the AC interference whose cycle is close to the current cycle. This would cause the

error in the measurement of geo-electrical resistivity. In order to solve this problem, the equal cycle should be changed into non-equal cycle. If the cycle of current I is provided randomly, the spectrum of signals produced in the measurement should be of white noise without any components equal to a certain interference frequency, so the effects from interferences at certain frequency would be reduced greatly or even eliminated. In actual design, the cycle is set to be in the pseudo random mode as shown in Figure 9b.

4.3.3 Elimination of gross error

Gross error, also known as negligent error, caused by some accidental factors, mainly caused by misoperations, sometimes due to the sudden changes in measurement condition or equipment, would significantly distort the normal measuring results which should be removed. According to the Larit criterion, among repetitive measurement, if the i th measured value ΔV_i is satisfied with $|\Delta V_i - \overline{\Delta V}| > 2\sigma_n$, the measuring value ΔV_i can be removed so as to decrease the effects from gross error.

Figure 9 The current waveforms of equal cycle (a) and of pseudo random sequence (b).

4.4 Specifications of the measurement instrument

On the bases of the approaches about the design of measurement instrument of geo-electrical resistivity mentioned above, the instrument installed in the geo-electrical resistivity monitoring stations in China, has been of features as described in the following specifications.

1) Resolution of voltage measurement

Natural potential difference (V_{sp}): 0.1 mV

Artificial potential difference (ΔV): 0.01 mV

Current: 0.1 mA

2) Maximum permissible error for voltage measurement

$\pm(0.02\%R+0.003\%FS)$ $20\pm2\text{ }^{\circ}\text{C}$

$\pm(0.2\%R+0.05\%FS)$ $0\text{--}40\text{ }^{\circ}\text{C}$

3) Maximum permissible error for geo-electrical resistivity measurement

$\pm(0.1\%R+0.02\text{ }\Omega\cdot\text{m})$ $0^{\circ}\text{C}\text{--}40^{\circ}\text{C}$

(at artificial potential difference $>10\text{ mV}$)

4) Linearity of voltage measurement

$\pm(0.02\%R+0.005\%FS)$ $0\text{--}40^{\circ}\text{C}$

5) Dynamic range: $\geq 100\text{ dB}$

6) Input impedance: $\geq 100\text{ M}\Omega$

7) Industrial frequency SMRR: $\geq 80\text{ dB}$ (Industrial frequency noise peak to peak value is within the measurement range)

8) Industrial frequency CMRR: $\geq 160\text{ dB}$ (Industrial frequency noise peak to peak value less than 200 V)

9) DC CMRR: $\geq 140\text{ dB}$ (DC common mode voltage is less than 100 V)

10) Measurement mode: manual, automatic (the measurement time interval can be set to 1, 2, 3, 4, 6, 8 or 12 hours)

11) Current/voltage convert precision: 0.05% (in one year)

12) Power supply: AC $220\text{V}\pm 10\%$ or DC 12 V

13) Insulation of input terminal to chassis: $\geq 500\text{ M}\Omega$ (500 V)

14) Measurement channel: 3 channels

15) Interface: parallel port; RJ-45 network interface; display, mouse and keyboard interface

16) Communication protocol: Compatible with the earthquake precursor observation network communication protocol issued by China Earthquake Administration, and with WEB, FTP services.

5 Functions and technical requirement of the calibration and inspection system

The functions of the calibration and inspection system is to check whether or not the technical features of the measuring system and configuration system of the total observational system of geo-electrical resistivity could keep consistency during long term observation and satisfy the requirements of the original design. This is the basis for the requirement of the design of the calibration and inspection system.

5.1 The inspection and calibration of measurement system

5.1.1 Inspection on the accuracy of voltage measurement

It should be noticed that in the geo-electrical resistivity measurement, the physical quantity for the detections of artificial potential difference ΔV , natural potential difference (i.e. V_{sp}) and current I is the voltage (the current is measured in terms of the voltage on a sample resistor), and the long term stability of the measurement instrument is important as mentioned in section 2. Thus the inspection device must satisfy the following two requirements.

1) A voltage standard with higher level (with the voltage reference in the grade 0.01) is used to test and

calibrate the geo-electrical resistivity measurement system, as shown in Figure 10.

Figure 10 The diagram of calibrating of geo-electrical resistivity system.

In Figure 10, the voltage reference consists of unsaturated standard battery of grade 0.005 and a high potential potentiometer of grade 0.01.

2) Time interval of the inspection is a month, that is to say, the measurement system must be tested every month. The standard battery and potential potentiometer must be tested and calibrated by national legal metrological and inspection agency every year.

5.1.2 Calibration of the system error

As shown in Figure 11, the measurement instrument, current power supply and recording device are connected as a whole system to simulate a testing geo-electrical resistivity measurement system with a resistor substituting the load of current circuit in the operating mode. In the test, the artificial potential difference (ΔV) is obtained from the standard resistor (R_V).

Figure 11 The structure of the testing geo-electrical resistivity measurement system.

So the standard resistivity (ρ_s) can be given through the calculation as follows:

$$\Delta V = I \cdot R_V \quad (14)$$

$$\rho_s = K \frac{\Delta V}{I} = K \frac{I \cdot R_V}{I} = K \cdot R_V \quad (15)$$

Generally, in order to get a very high precision of standard resistivity value, a high precision standard resistor R_V must be used for the testing process. So with different K values, different standard resistivity values could be given. The measurement error can be got from

comparisons between the measured resistivity values in the tested instrument and these standard values.

5.2 Inspection of the long term stability of configuration system

The long term stability test of configuration system is mainly to inspect the effects of the leakage of current lines on the measurements, that is to say, check whether indexes $\varepsilon_1 < 0.1\%$ and $\varepsilon_2 < 0.5\%$ are satisfied as described in section 3.4.

The method of inspection is shown in Figure 12. The procedure of inspection is the following: firstly, the

Figure 12 The scheme for the inspection of the configuration system.

tested wire lines must be disconnected from the line end-point connecting the corresponding current electrodes, therefore it is necessary to have an equivalent resistors combination $R_{LA}+R_{LB}$, simulating the resistances of the current lines and the ground resistances of current electrodes in the working mode, as a load to connect to the output terminals of the DC stabilized current power supply due to the operating principle of the supply, and also the resistors combination $R_{LA}+R_{LB}$ has to connect to the ground as shown in the left part of Figure 12; then let the power supply and measurement instrument be operating, and the leakage current I_L and the corresponding leakage potential difference ΔV_L would be detected by the measuring instrument if the wires leakages exist; finally to compare I_L and ΔV_L in the inspection mode with I and ΔV in the working mode respectively, and to describe the state of configuration leakage by the results of effects of leakage current (ε_1) and of leakage voltage (ε_2), according to formulas (3) and (4). This inspection should be done in a regular time interval for instance, a half-month, in the monitoring process in order to give the estimation for the long term stability of the configuration in each station. Actually, whenever people have found any effects of leakages exceeding the criteria mentioned in the section 3.4, the corresponding countermeasures to eliminate the effects should be done immediately in each monitoring station.

6 Summary

The observation system of earthquake-related geoelectrical resistivity in China has been well developed as a rather perfect one after more than 40 years of reformation and exploration in the practice of earthquake monitoring on the basis of transplanting techniques from ARM in the geo-electrical prospecting. With the accommodation of exploring the temporal variations of electrical properties of Earth media associated with the earthquake preparation, we have made all aspects of transformations necessary for the construction of a new observational system with clear specific technical requirements, and the technical countermeasures on the basis of theoretical analysis and the methodology of their corresponding detections that are connected to the metrological standard. At present, the statistics of investigations shows that except a few stations in the environment with strong interferences, the relative variance (3σ) of daily average of the geo-electrical resistivity observation data in most monitoring stations, where the observation system with the techniques in this paper has been installed, could be less 0.3%, sizably among them, even less than 0.1%. All of them well

satisfy the demands for earthquake monitoring and the researches of earthquake prediction.

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