

## **Imaging the Subsurface Structure of the Northern Tip of the 1999 Chi-Chi Earthquake Fault in Central Taiwan Using the Electric Resistivity Method**

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### **ABSTRACT**

In order to investigate the subsurface structure of the northern tip of the Chi-Chi earthquake fault, three electric resistivity image profilings were done in the northern Shihgang area where a large surface rupture was formed during the earthquake. The survey was conducted about three weeks after the Chi-Chi earthquake which occurred on 21 September, 1999 in central Taiwan.

The pole-pole electrode configuration with electrode intervals of 6 meters was used for the profilings. Each profile consisted of 32 electrodes and 15 measured layers. The data were interpreted using the 2-D inversion method. The investigation depth was about 80-90 meters.

The results indicate that the fault zone is clearly displayed in the profiles with a steep resistivity gradient zone. They also indicate that the rupture is a reverse fault with a dip angle of about 60-80 degrees at the depth of 0-80 meters in the northern Shihgang area. The fault zone is about 30 meters wide on the ground surface and is about 10-15 meters wide at the depth of 30-80 meters. The rock sequences are similar on both sides of the fault. They are the Chinshui Shale overlain by layers of sand and gravel. It is inferred that the fault in the northern Shihgang area is a new branch of the Chelungpu fault. A low resistivity zone (6-13  $\Omega$ -m) about 40-90 meters wide appeared adjacent to the fault zone on the footwall, and a high resistivity zone (36-100  $\Omega$ -m) about 90 meters wide appeared adjacent to the fault zone on the hanging wall. Next to the high resistivity zone on the hanging wall, a low resistivity zone and a high resistivity zone each about 50-100 meters wide appeared one after the other. This low and high resistivity zoning may be correlated to the strain brought on by the seismic stress released in the earthquake, and also implies that the formations were severely and extensively disturbed on the hanging wall.

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## 1. INTRODUCTION

The Chi-Chi earthquake occurred on September 21, 1999, with its epicenter near the town of Chi-Chi in central Taiwan. Extensive surface ruptures totaling about 100 km long were formed during the earthquake (Chang et al. 1999; Lee et al. 1999). The major ruptures appeared along the Chelungpu fault running in a N-S direction between the city of Fongyuan in the north and the town of Chushan in the south, as well as in a belt about 1.5 km wide and about 20 km long trending in a NEE direction from Fongyuan to Cholan at the northern tip of the Chelungpu fault in central Taiwan (Fig. 1).

The Chelungpu fault had been known to be an active fault (Chang et al. 1998), and was regarded as the southern extension of the Sanyi fault (Lin 1957; Meng 1963). In the Chi-Chi earthquake, the major ruptures did not extend northwards from the Chelungpu fault to the Sanyi fault, but turned north-east-eastward to the town of Cholan at the northern tip where no faults had previously been found (Fig. 1). The fault in the NEE trending belt from Fongyuan to Cholan is regarded as a new branch of the Chelungpu fault formed during the 1999 Chi-Chi earthquake.

The Shihgang area is adjacent to the city of Fongyuan on the eastern side and is situated just at the turning part of the N-S trend segment to the NEE trend belt at the northern tip of the Chelungpu fault. Unlike the throw of 2-5 meters and the absence of any obvious strike-slip on the N-S trend segment of the Chelungpu fault, the ruptures in the Shihgang area show the largest vertical and horizontal displacements (both over 8 meters) from the Chi-Chi earthquake, although it is about 50 km away from the epicenter (Fig. 1).

In addition to the largest rupture displacement, a complex faulting and folding system was formed in the Shihgang area including two main faults with throws of over 4 meters (Chang et al. 1999). Of particular note, the fault has a throw of about 8 meters and a peculiar N-shaped turning between the Beefong Bridge and the Shihgang Dam in the northern Shihgang area (Fig. 1). It destroyed the Bridge and the northern spillways and gates of the Shihgang Dam with a lift of about 8 meters on the southern block relative to the northern block.

The attitude of the fault between the Beefong Bridge and the Shihgang Dam was studied from the point of view of electric resistivity structures in this study.

## 2. METHOD

The technique of electric resistivity image profiling (RIP) with the pole-pole electrode configuration was used in this study because it has a high data density for high resolution interpretation. Basically, it is a four-electrode configuration with one current electrode and one potential electrode, called the measuring electrodes, being set on the surface of the profile to be investigated, and the other two electrodes including one current electrode and one potential electrode, called the remote electrodes, being fixed at distant places. The remote electrodes are far from the profile and are far from each other with distances greater than ten times

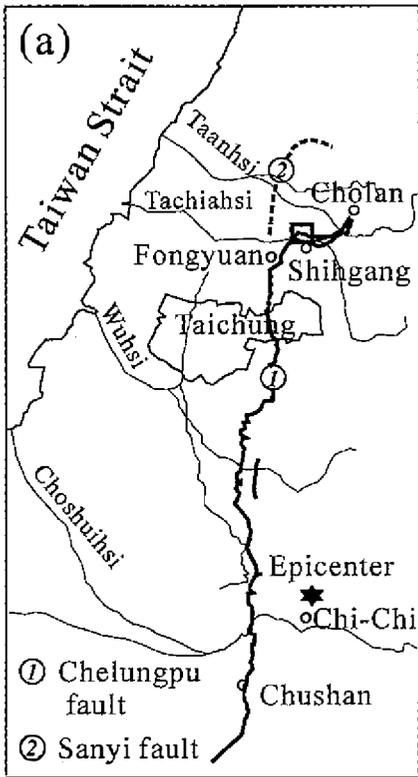
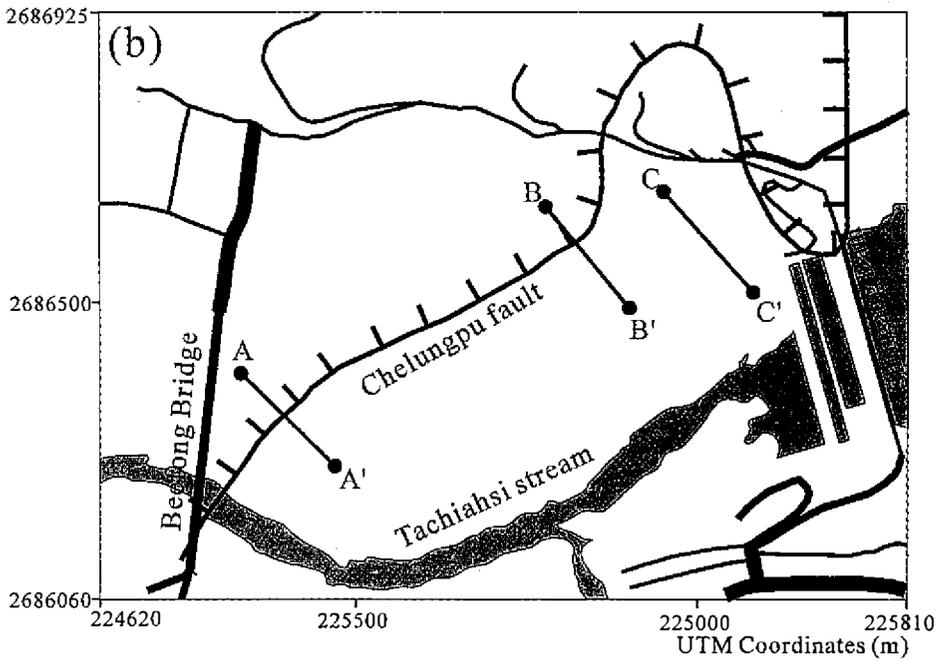


Fig. 1. (a) Surface ruptures along the Chelungpu fault formed during the Chi-Chi earthquake; (b) locations of geoelectric Profiles A-A', B-B', and C-C' in the northern Shihang area.



the largest measuring electrode-spacing (Fig. 2a).

In the field practice, many electrodes were arranged on the surface of the profile at equal intervals to enable the automatic changing of the measuring electrodes (Fig. 2b). To start, the first electrode was used as the measuring current electrode, and the second electrode, the third electrode, ..., and eventually the  $(N+1)$ th electrode were used in turn as the measuring potential electrodes. Then the first sequence of  $N$  data was obtained, where  $N$  was the number of measured layers. The largest measuring electrode-spacing was  $Nl$  for an electrode interval  $l$ . Afterwards, the second electrode was used as the measuring current electrode, and the third electrode, the fourth electrode, ..., and eventually the  $(N+2)$ th electrode were used in turn as the measuring potential electrodes for  $N$  measured layers. In this way, the second sequence of  $N$  data was obtained. Similarly, the third electrode, the fourth electrode, ..., and the  $(M-1)$ th electrode were used in turn as the measuring current electrodes, and their successive  $N$  electrodes (if adequate) were used in turn as the measuring potential electrodes. Accordingly, a set of RIP data with  $N$  measured layers and  $M$  measuring electrodes was obtained.

A set of RIP data is usually displayed in the form of apparent resistivity pseudosection, by which each apparent resistivity is plotted at the mid-point of the measuring electrodes, which serve as the abscissa, and the measuring electrode-spacing, which serve as the ordinate (pseudo depth). Theoretically, the depth of the investigation is proportional to electrode-spacing. Hence, the apparent resistivities for the shorter electrode-spacings are the responses of shallow strata, those of the larger electrode-spacings are the responses of deeper strata. An apparent resistivity pseudosection looks like an image of the total resistivity distribution of the formations. The apparent resistivity is not the true resistivity at that place, but rather an equivalent resistivity of the formations in that electrode geometry. The true resistivities of the strata can be obtained with the proper interpretation.

The RIP data were interpreted following the 2-D inversion method because a fault can be regarded as a 2-D structure. The forward part of the 2-D inversion program used in this study is based on the finite element method and the inverse part is based on the least-squares optimization technique (deGroot-Hedlin and Constable 1990; Loke and Barker 1996; Tong and Yang 1990).

### 3. RESULTS

Three RIP data sets were obtained in the northern Shihgang area about three weeks after the 1999 Chi-Chi earthquake. The profiles were located between the Shihgang Dam in the east and the Beefong Bridge in the west on the northern side of the Tachiahsi stream. They are labeled A-A', B-B', and C-C' in Fig. 1.

The measured apparent resistivities of the RIP are shown in Fig. 3. They were obtained using 32 electrodes at electrode intervals of 6 meters in the pole-pole array.

The interpreted results of the RIP are shown in Figs. 4-6. There are three sections in each figure. The top is the measured apparent resistivity pseudosection, the middle is the calculated apparent resistivity pseudosection, while the bottom is the model resistivity section as interpreted from the measured RIP data. The number of iterations and the root mean square errors are also shown in each figure.

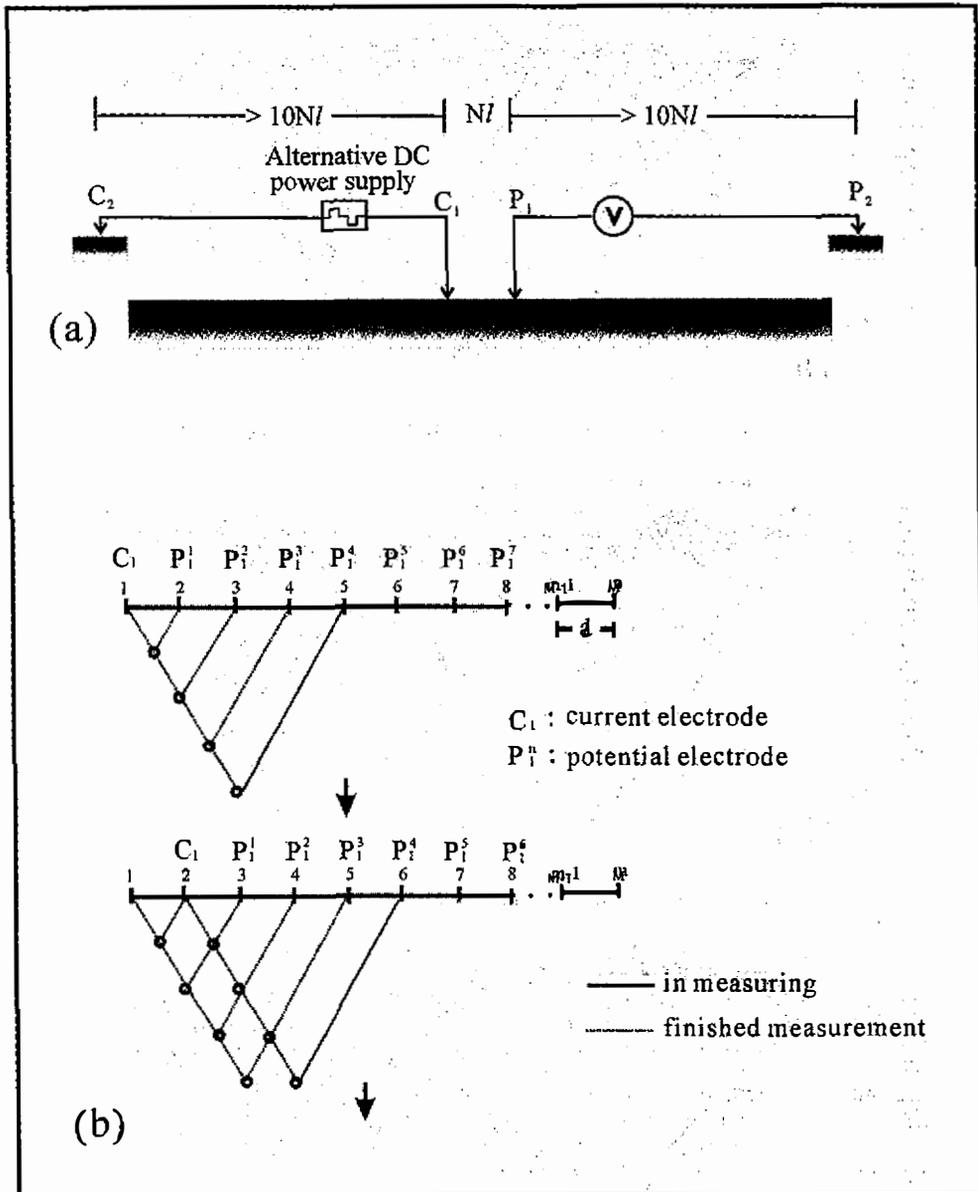


Fig. 2. Electrode configuration of the pole-pole array used in RIP. (a) The measuring electrodes  $C_1$  and  $P_1$  were arranged on the surface of the profile to be investigated. They have a electrode-spacing varying from  $l$  to  $Nl$ . The remote electrodes  $C_2$  and  $P_2$  are fixed at distant places greater than ten times of the largest measuring electrode-spacing. (b) A number of electrodes were arranged on the surface of the profile to enable the automatic changing of the measuring electrodes.

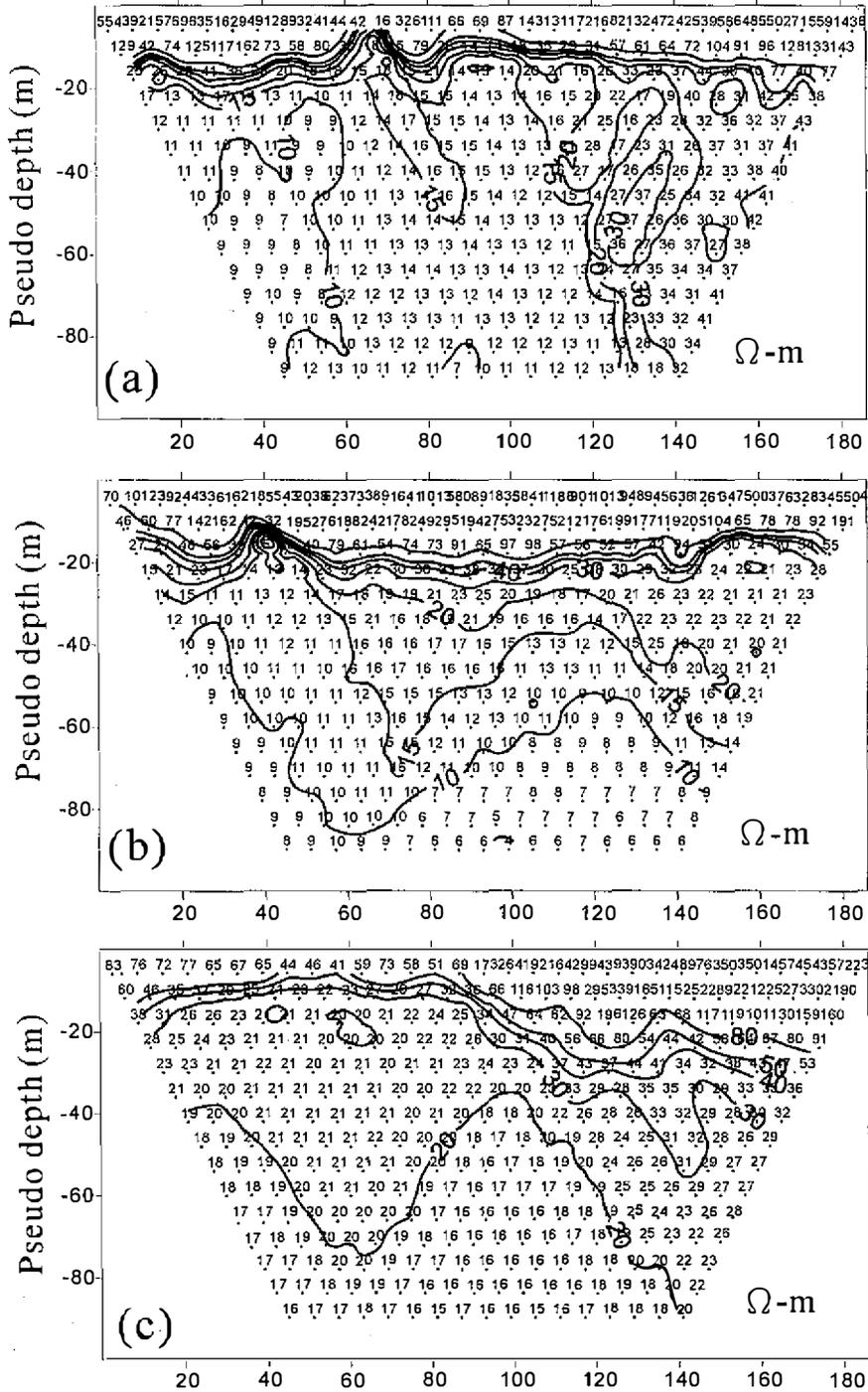


Fig. 3. Measured apparent resistivities of the RIP Profiles AA', BB' and CC' are displayed in the form of pseudosections.

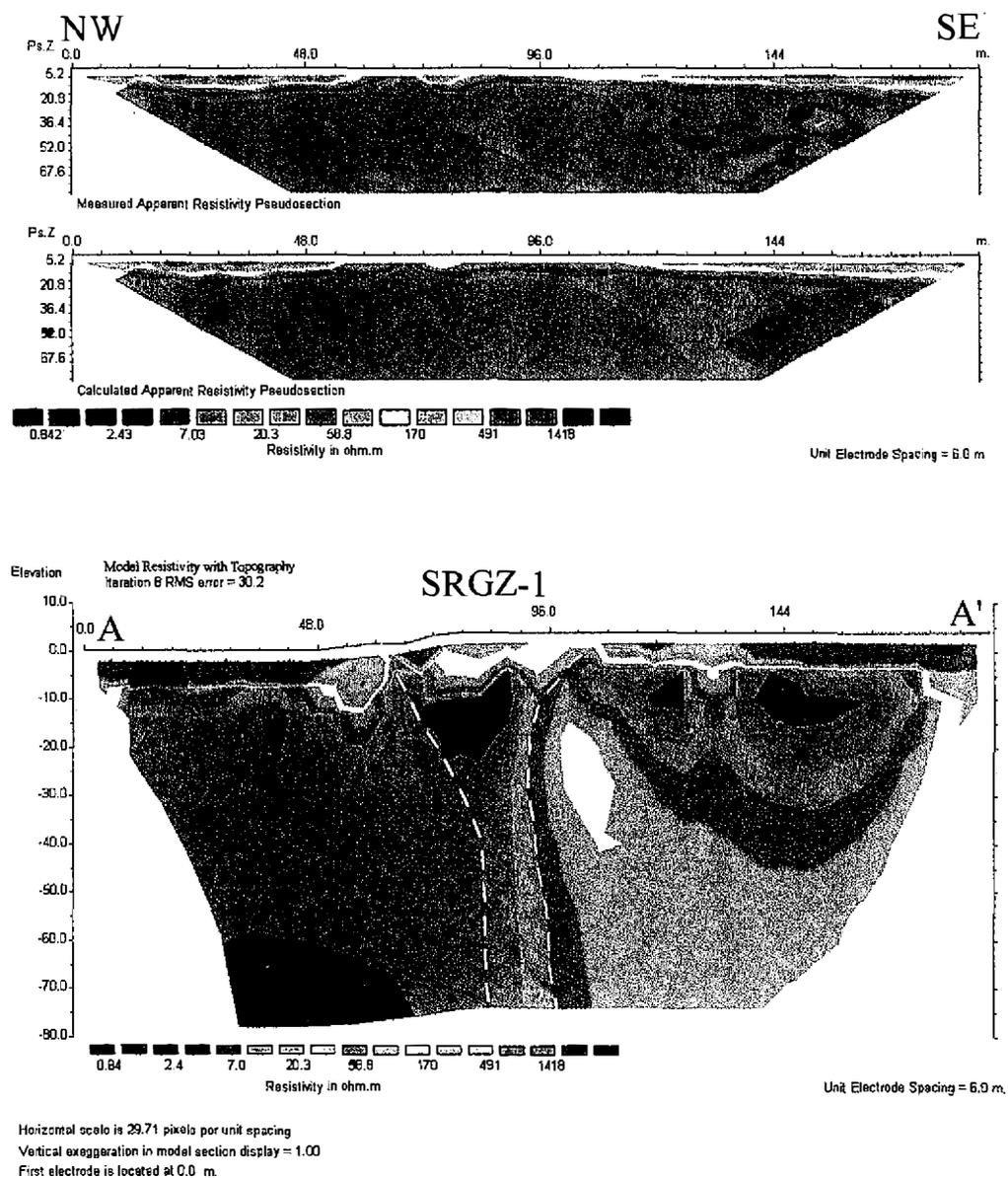
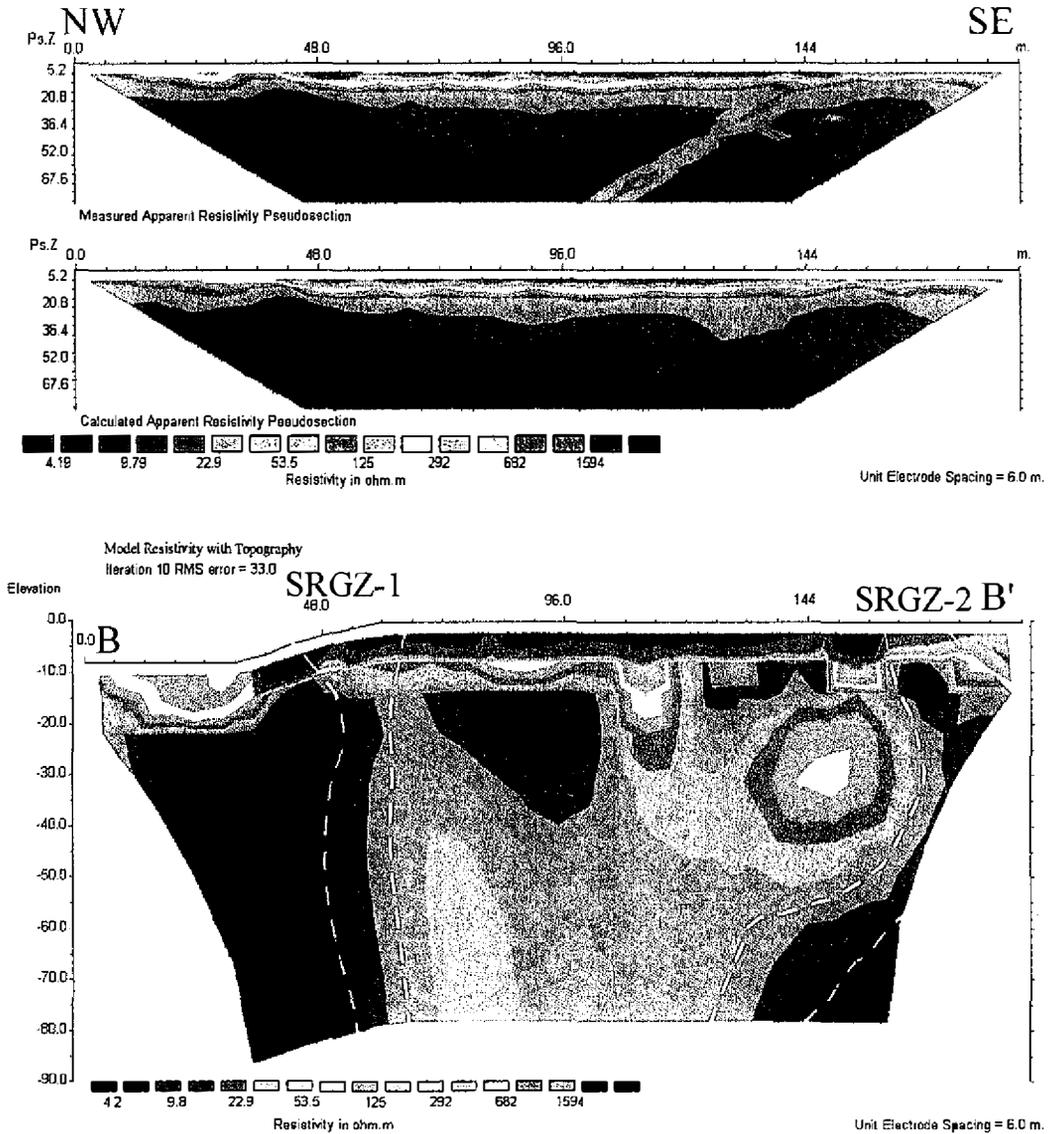
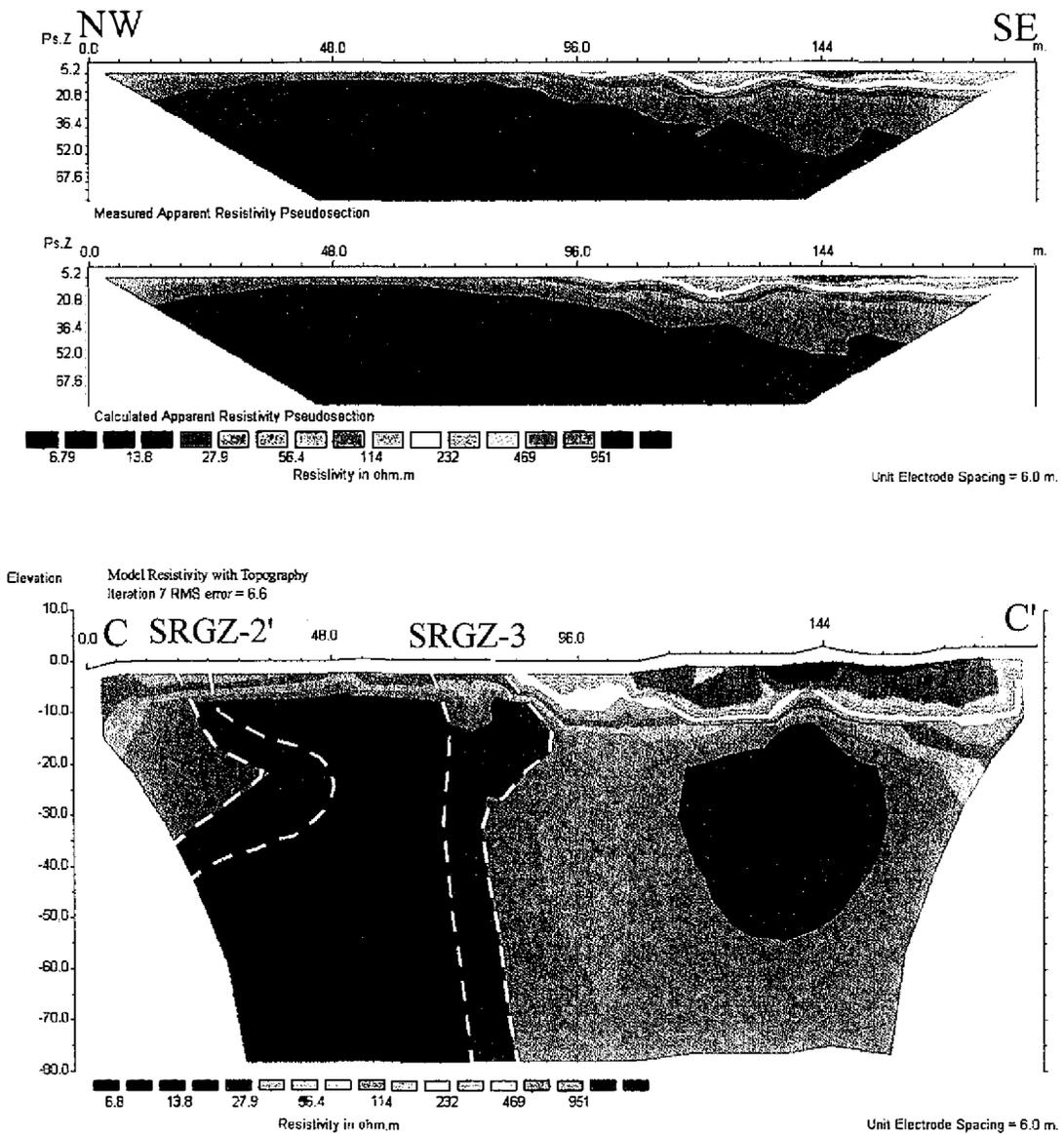


Fig. 4. Measured apparent resistivity pseudosection and the interpreted results of Profile A-A'. Top: the measured apparent resistivity pseudosection; middle: the calculated apparent resistivity pseudosection; and bottom: the interpretative model derived from the measured data. The step resistivity gradient zone (SRGZ-1) is the fault zone separating a low resistivity block on the footwall and a high resistivity block on the hanging wall. This represents the fault formed during the Chi-Chi earthquake (bottom).



Horizontal scale is 29.71 pixels per unit spacing  
 Vertical exaggeration in model section display = 1.00  
 First electrode is located at 0.0 m.  
 Last electrode is located at 188.0 m.

Fig. 5. Measured apparent resistivity pseudosection and the interpreted results of Profile B-B'. Top: the measured apparent resistivity pseudosection; middle: the calculated apparent resistivity pseudosection; and bottom: the interpretative model derived from the measured data. Resistivity zoning appeared in the profile. The steep resistivity gradient zone (SRGZ-1) is the fault zone formed during the Chi-Chi earthquake (bottom).



Horizontal scale is 29.71 pixels per unit spacing  
 Vertical exaggeration in model section display = 1.00  
 First electrode is located at 0.0 m

Fig. 6. Measured apparent resistivity pseudosection and the interpreted results of Profile C-C'. Top: the measured apparent resistivity pseudosection; middle: the calculated apparent resistivity pseudosection; and bottom: the interpretative model derived from the measured data. The steep resistivity gradient zones, SRGZ-2' and SRGZ-3, separate the formations into alternating high and low resistivity zones on the hanging wall.

### 3.1 Profile A-A'

Profile A-A' is located on the eastern side of the Beefong Bridge. It is 186 meters long on the ground surface and is spread in the N140° E direction. The profile crosses an irregular sloping fault zone transversely at 48-78 meters from the northwestern end of the profile (point A, Fig. 1). The sloping fault zone was formed during the 1999 Chi-Chi earthquake with a trend in the N50° E direction. The southeastern block was lifted about 5 meters relative to the northwestern block. A large rupture dipping steeply southeastwardly appears at 60 meters from point A and is accompanied by several small ruptures in the sloping fault zone and on the northwestern margin of the southeastern block. The outcrops on the hanging wall show that the strata consist of layers of sand, gravel, and shale in descending order. The sand and gravel beds are about 4 meters thick.

The measured data and the interpreted results of Profile A-A' are shown in Figs. 3a and 4. The interpretative results indicate that, in terms of resistivity, the strata at the depth of 30-80 meters are divided into two parts by a steep resistivity gradient zone, or SRGZ-1 (Fig. 4) existing in the middle part of the profile. The SRGZ-1 dips southeastwardly at an angle of about 80 degrees at the depth of 30-80 meters. The strata at the depth of 30-80 meters have a resistivity of 6-13  $\Omega$ -m on the northwestern side but greater than 58  $\Omega$ -m on the southeastern side of the SRGZ-1. The top layer has a uniform thickness of about 5 meters and a resistivity range of about 300-1400  $\Omega$ -m on both sides of a disturbed zone present in the middle part. The disturbed zone is located at 60-108 meters from point A, where the thickness is irregular and the resistivity is mostly reduced to 100-170  $\Omega$ -m (Fig. 4). The resistivity pattern indicates that the disturbed zone is the upper part of the SRGZ-1 which separates two distinct resistivity blocks. The lower (northwestern) boundary of the SRGZ-1 dips southeastwardly at an angle of about 60 degrees at the depth of 0-30 meters and at about 80 degrees at the depth of 40-80 meters.

The consistency between the locations of the resistivity-disturbed zone and the sloping fault zone on the ground surface implies that the SRGZ-1 is the fault zone formed during the Chi-Chi earthquake. The southeast dipping of the SRGZ-1 is consistent with the outcrop which appeared in the fault zone. This implies that the lifted block is the hanging wall and the rupture is a reverse fault, and that the masses in the forepart of the sloping zone (54-60 meters from point A) are the materials which collapsed from the advanced hanging wall.

### 3.2 Profile B-B'

Profile B-B' is located at about 400 meters west of the northern end of the Shihgang Dam. It is 186 meters long on the ground surface and is spread in the N135° E direction. The profile crosses an irregular sloping fault zone transversely at 30-60 meters from the northwestern end of the profile (point B, Fig. 1). The sloping fault zone was formed during the Chi-Chi earthquake with a trend in the N45° E direction. The southeastern block was lifted about 8 meters relative to the northwestern block. The southeastern block is covered with gravel and sand, whereas the northwestern block is covered with sand. There are several ruptures in the sloping zone and on the northwestern margin of the southeastern block. On the outcrops, a large rup-

ture dips southeastwardly suggesting that the fault is a reverse fault.

The measured data and the interpreted results are shown in Figs. 3b and 5. The interpretative results indicate that the formations are divided into three parts by two steep resistivity gradient zones. One of the steep resistivity gradient zones (SRGZ-1, Fig. 5) exists beneath 42-60 meters from point B. It dips southeastwardly at an angle of about 80 degrees at the depth of 20-80 meters. The resistivity is 6-10  $\Omega$ -m for the formations at the 20- to 80- meter depth on the northwestern side of the SRGZ-1 but is higher than 36  $\Omega$ -m for the formations in a zone of about 70-100 meters wide on the southeastern side of the SRGZ-1. The other steep resistivity gradient zone exists beneath about 160-172 meters from point B (SRGZ-2, Fig. 5). The SRGZ-2 separates a high resistivity (greater than 36  $\Omega$ -m) block on the northwestern side and a low resistivity (less than 10  $\Omega$ -m) block on the southeastern side. It dips southeastwardly at an angle of about 45-80 degrees at the 5- to 20- meter depth, and dips northwestwardly at an angle of about 45-80 degrees at the depth of 30-80 meters.

In agreement with the findings for Profile A-A', the consistency between the locations of the SRGZ-1 and the sloping fault zone for Profile B-B' indicates that the SRGZ-1 is the fault zone which was formed in the Chi-Chi earthquake. It is a reverse fault with a 10- to 30- meter wide zone located at 42-60 meters from point B (Fig. 5). The fault dips southeastwardly at an angle of about 60 degrees at the depth of 0-25 meters and at an angle of about 80 degrees at the depth of 30-80 meters. The masses in the forepart of the sloping zone (30-42 meters from point B) are the materials which collapsed from the advanced hanging wall.

### 3.3 Profile C-C'

Profile C-C' is located at about 200 meters west of the northern end of the Shihgang Dam. It is 186 meters long on the ground surface and spreads in the N135° E direction (Fig. 1). There is no rupture on the surface, but a peculiar N-shaped turning of the fault zone is evident around the profile. The northwestern end of the profile (point C, Fig. 1) is about 84 meters east of the fault zone.

The measured data and the interpreted results are shown in Figures 3c and 6. The interpretative results indicate that there are two steep resistivity gradient zones, SRGZ-3 and SRGZ-2', beneath the profile (Fig. 6). The SRGZ-3 is located at 66-78 meters from point C. The resistivity is 6-20  $\Omega$ -m for the strata below the 30-meter depth on the northwestern block and is 28-56  $\Omega$ -m for that on the southeastern block. The SRGZ-3 is about 10 meters wide and dips southeastwardly at an angle of about 80 degrees at the depth of 30-80 meters. The other steep resistivity gradient zone, SRGZ-2', is located at 16-24 meters from point C (Fig. 6) and is about 100-110 meters from the fault zone. It separates a high resistivity block on the northwestern side and a low resistivity block on the southeastern side. The SRGZ-2' dips southeastwardly at an angle of about 30-60 degrees at the depth of 5-20 meters and dips northwestwardly at an angle of about 30-60 degrees at the depth of 25-40 meters.

## 4. DISCUSSION

The root mean square errors are 30.2%, 33% and 6.6% for the interpretative results of

Profiles A-A', B-B' and C-C', respectively. The root mean square error is low for the interpretative results of Profile C-C', implying that the fitting is good and the results are acceptable. The root mean square errors are high for the interpretative results of Profiles A-A' and B-B', largely due to noise in the data caused by the irregular topography of the sloping fault zone and perhaps partly by the geologic heterogeneity disturbed by the earthquake. Although the interpretative results are not fitted well with the measured data, they are acceptable because the characteristic patterns which appeared on the measured apparent resistivity pseudosections do not deviate from the calculated pseudosections derived from the interpretative results.

Some outcrops on the hanging wall indicate that the rock sequences are shales overlain by thin layers of gravel and sand. On the basis of the textures of the rocks on the hanging wall, the shales can be recognized to be Miocene Chinshui Shale and the gravel and sand layers to be Holocene deposits. Normally, undisturbed and water-saturated Chinshui Shale has a resistivity of 9-15  $\Omega$ -m (You et al. 1999) and is the formation of lowest resistivity beyond the coastal area. The rocks at the depth of 5-80 meters of the footwall are interpreted as being Chinshui Shale, for they have a resistivity of 6-13  $\Omega$ -m. It is inferred that the fault was newly formed since the rock sequences are similar and the overlying Holocene deposits have equivalent ranges of thickness and resistivity on both sides of the fault. The dip angle is about 60-80 degrees for the new branch, which is greater than the previously-investigated value of 25-60 degrees on the N-S segment of the Chelungpu fault (Lin 1957; Meng 1963; Pan 1967; Chang 1971; Chang et al. 1998; You et al. 1999).

The SRGZ-2 on Profile B-B' is located about 100-110 meters southeast of the fault zone. It dips southeastwardly at an angle of about 45-80 degrees at the depth of 5-20 meters and dips northwestwardly at an angle of about 45-80 degrees at the depth of 30-80 meters. The SRGZ-2' on Profile C-C' is located about 100-110 meters southeast of the fault zone and dips southeastwardly at an angle of about 30-60 degrees at the depth of 5-20 meters and dips northwestwardly at an angle of about 30-60 degrees at the depth of 25-40 meters. The consistency of the locations and the similarity in the dipping trends between the SRGZ-2 and SRGZ-2' imply that the SRGZ-2 and the SRGZ-2' are correlated to the same structure. Combining Profile C-C' with Profiles A-A' and B-B', three vertical resistivity zones are found on the hanging wall (Fig. 7). They appear in a wave-like form of high and low in alternation and each has a width of about 50-100 meters. The high resistivity is about three times or more greater than that of the undisturbed state. Archie's law, written as  $\rho = a\phi^{-m}\rho_w$  for water-saturated stratum, indicates that the bulk resistivity  $\rho$  increases (or decreases) with decreasing (or increasing) porosity  $\phi$ , if the parameters  $a$  and  $m$  (being positive) and the pore water resistivity  $\rho_w$  are unchanged. From the evidence, it is reasoned that the high and low resistivity zoning which appears around the fault zone is a result of an increase and decrease in porosity caused by seismic stress. The displacement of the blocks which occurred during the earthquake observed by the GPS method on the ground surface indicates that the direction of the displacement is to the northwest (Lee et al. 1999; Chang et al. 1999), which is consistent with the direction of the zoning sequence in this area. This supports the inference that the resistivity zoning was caused by the seismic stress released with the Chi-Chi earthquake.

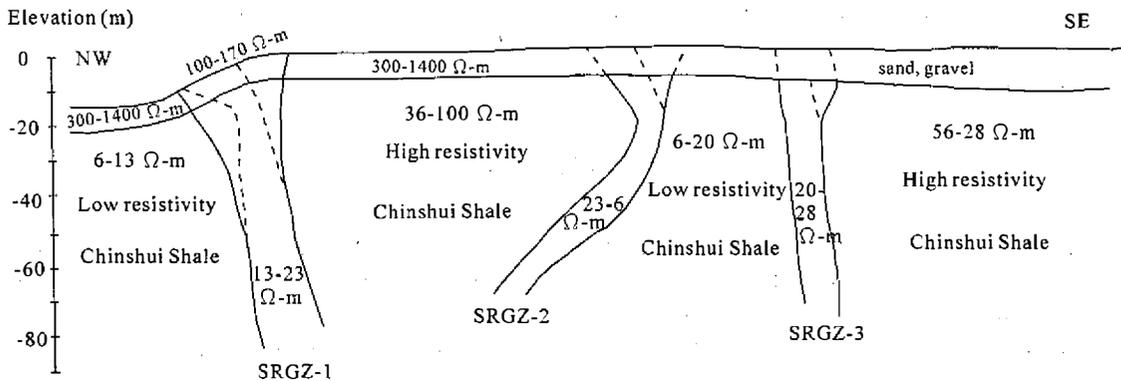


Fig. 7. Cross-section of the structure across the major fault zone in the northern Shihgang area. The steep resistivity gradient zone-1 (SRGZ-1) is the major fault zone formed during the Chi-Chi earthquake. The wave-like resistivity zoning which appears on the hanging wall demonstrates that the rocks were severely disturbed.

## 5. CONCLUSIONS

The electric resistivity structures indicate that the major fault between the Shihgang Dam and the Beefong Bridge in the northern Shihgang area is a reverse fault. It runs in a northeast direction and dips southeastwardly at an angle of about 60-80 degrees at the depth of 0-80 meters.

The rock sequences are similar on both of the footwall and the hanging wall. They are Chinshui Shale overlain unconformably with gravel and sand layers. The gravel and sand layers are Holocene deposits and are about 5 meters thick on both sides of the fault zone. It is inferred that the fault was newly formed at the time of the 1999 Chi-Chi earthquake.

The fault zone is about 10-30 meters wide and has a steep gradient in resistivity from 13 to 23  $\Omega$ -m or more. The resistivity of the strata at the depth of 20-80 meters on the footwall is 6-13  $\Omega$ -m and is slightly lower than that in the undisturbed state indicative of a slight increase in porosity and a slight dilation of the rocks. On the other hand, the resistivity of the strata at the depth of 20-80 meters in a zone of about 70-100 meters wide adjacent to the fault zone on the hanging wall is mainly in a range of 36-80  $\Omega$ -m. It is three times or more greater than that in the undisturbed state implying that the porosity was reduced and the rocks were compressed. Next to the high resistivity zone, a low resistivity zone and another high resistivity zone each about 50-70 meters wide appear successively on the hanging wall. This high and low resistivity wave-like zoning in alternation indicates that the rocks on the hanging wall were compressed and dilated in alternation. The formations on the hanging wall were severely and extensively disturbed by the seismic stress released during the earthquake.

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