

## The Detection of Active Faults on Taiwan Using Shallow Reflection Seismics

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### ABSTRACT

The purpose of this study is to detect some active faults in western Taiwan using the newly developed shallow seismic reflection method. Most of these faults are in urban areas or close to the populous regions, hence, it is important with respect to earthquake hazard mitigation. The position, fracture attitude, faulting mechanism and even activity of the fault are under investigation.

The revealed fault images from some seismic sections are so sharp that many details can be measured. It is found that every fault has its own characteristics. They all behave differently. The following conclusions are obtained:

- (1) Hsinchuang fault (Taipei basin) is obviously a normal fault with a vertical displacement of 50 m within the 150 m distance range. The fault may have slid down the basement rock in a sequence of stages. The seismic section obtained here reveals only a part of it. Many small back-thrust faults are found on the hanging wall, which has cut through the young sediment. This fault could be potentially active.
- (2) Hsintien fault (Taipei basin) is an old thrust fault with a large offset on Tertiary rocks. Obvious reflections are obtained on the hanging wall side, but not on the other. This is due to lithological variations across the fault. The apparent difference in reflection signals can be easily used to delineate the fault.
- (3) Shihtan fault (1935 earthquake) is an interesting fault. The breakage on the surface is attributed to the effect of squeezing on the vertically dipping unconsolidated sandstone layer (Shangfuchi Sandstone) by the compressional pressure which induced the earthquake. This coarse-grained sandstone 'flowed' out, protruded the overlaying alluvial deposit, and caused the surface rupture. The fault resulted in a reverse type.
- (4) Tunzuchiao fault (1935 earthquake) shows a complicated sense of movement along its fault during the earthquake. A twisted near-surface curved layer caused by the earthquake is used to explain this fault. The rupture happened at a place where the layer had large curvature. The position and the direction of rupture are random within a narrow zone surrounding the fault depending on where the layer is distorted most.

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- (5) Hsinhua fault (1946 earthquake) has developing fracture type. Two fracture zones were found, which are separated more toward the east. A large disturbance occurred within a 60 m range where the two fracture zones came together in the west. The reflection signals in this 60 m zone were totally lost due to elimination of layering by mass mixture on the fault. Outside the fault zone, however, the layer is quite flat and free of disturbance.

(Key words: Active fault, Fault detection, Shallow reflection seismics)

## 1. INTRODUCTION

Active fault detection is among one of the important problems for preparation of the earthquake risk analysis of an area (Aki, 1988). It is often beneficial to know the exact location of near-surface faults to guide more detailed studies. According to the elastic rebound theory, earthquakes tend to occur repeatedly at places where faults have been displaced before. After accumulating enough distortion stresses due to tectonic plate movement, fault breakages occur easily at these old 'wounds'. Taiwan is located along the Neotectonic belt surrounding the Pacific Ocean, and high earthquake activities have marked this island. Hundreds of faults are distributed over the mountains as well as in the plain areas (Shih, 1986). Among them, some have been identified as active faults (Bollina, 1977; Hsu, 1989). A detailed study of these active faults will provide a basis which may greatly reduce the damage when the unavoidable large earthquakes come.

The shallow reflection method has been used in finding previously unknown faults, and to provide additional details in mapping known faults (Steeple and Miller, 1990). Many successful examples have been obtained in recent years (Hunter *et al.*, 1984; Treadway *et al.*, 1988; Shedlock, *et al.*, 1990; Stephenson *et al.*, 1993; etc.). By using the specific resolution power of reflection signals, this method can provide much information about the fault that other methods may not provide (Miller *et al.*, 1990). It can map faulted bedrock under alluvium at a 200 m depth (Miller *et al.*, 1992) as well as at unconsolidated sedimentary contacts for the upper 50 m (Treadway *et al.*, 1988) or even a very shallow 5 m depth (Goforth and Hayward, 1992). The pictures of underground structures that seismic signals provide are so clear that the fault can be identified without much ambiguity. This 'direct mapping' property of the reflection method has caused it to be widely applied in the exploration for oil, and may be equally practical for shallow structure study.

In the past few years, the shallow seismic reflection method has attracted more and more attention in this nation (Wang *et al.*, 1991a). Many large construction projects such as highway systems, the high-speed railroad, nuclear power plants and dams are scheduled in the nation's development program for the coming decade. Intensive investigation of basement bedrock related to local geology is urgently required for such large scale constructions. In combination with the electric method and the refraction method, reflection seismics has proven its special ability to map underground structures, particularly around a fault. This paper will discuss five cases of active fault detection that we have conducted in the past years. Besides providing seismic images of these important faults, the cases also describe in some detail this new fault detecting technique. Some experiences are cited, that can be used as references for applying this method in similar cases. The vertical resolution power of the seismic sections in this paper is estimated to be about 2 meters by using 150 Hz dominant frequency and 1500 m/sec velocity according to one-fourth wavelength rule of Widess (1973).

## 2. DATA ACQUISITION

Three basic requirements must be fulfilled to ensure the success of the shallow seismic reflection method. The first of these is a seismograph with high dynamic range and analog filter capability. These are needed in order to suppress the low frequency, high amplitude groundroll noises by means of a low-cut filtering before A/D digitizing, and to preserve the weak reflection signals by storing the data in the high dynamic range memory (long bits). The second requirement is a high frequency receiver (50 Hz or 100 Hz) which is used to suppress unwanted low frequency noises and to record the desired signals with better resolution. Due to the small electric current output from the high frequency geophone, two or three geophones grouped together within 1 meter are recommended. It may not be very efficient for the deletion of groundroll, but is helpful in enhancing the signals.

The third requirement is an eligible source. This is perhaps the most difficult part. A capable source for shallow seismics should have properties such as sufficient power, high frequency, repeatability, portability, safety, low price, and ease to operate (Steeple and Miller, 1990). Gun instruments including .30-caliber or .50-caliber rifles and buffalo guns are typical sources in some developed countries, but are not popular in others due to security restrictions. A continuous search for better sources seems to be a fundamental problem.

In this study, a standard CDP (Common Depth Point) technique for data acquisition and processing, which has been widely used in oil exploration was employed. The CDP method has been proven efficient for improving signal-to-noise ratio under the noisy conditions which are usually met with shallow seismics (Miller and Steeples, 1990). It may take much more labor and expense by CDP survey which is however worthwhile considering so weak a signal in such a noisy background. The instruments implemented in this study were Geometrics, ES-2401x, 48 channel seismograph, 100 Hz OYO geophone, and a firecracker source developed by ourselves (Tsai *et al.*, 1990). The field work used a 1 m geophone interval (2 geophone a group), a near-trace offset of 40-60 m, a far-trace offset of 90-110 m, pre-A/D low cut filter 100 Hz, and keeping at least 12 folds. This survey geometry may not pay sufficient attention to very shallow part (above 10 m), however, overall structure above 200 m can be mapped. The produced seismic profile is suitable for a near-surface fault study with a wide enough span and a depth extension. Knapp and Steeples (1986) pointed out a main factor which affects the depth preparation of shallow seismic profiling, i.e., higher frequencies for shallower depths. Thus if the depth of interest is 5-60 m, the field parameters could be taken at a geophone interval of 0.5 m, a geophone spread between 5 m and 60 m, and a low cut of 200 Hz or 300 Hz. Different acquisition parameters need to be used for detecting different depths. It should also be noted that it had better keep one survey geometry for one seismic line to avoid inconsistent signal distortion during data processing. This is especially important for signals at shallow depths.

After experimenting with many cases using a firecracker source (Wang *et al.*, 1994), we actually became more flexible about the selection of sources. Ground surface conditions definitely determine the quality of the data, and the source should be used in accordance with it. It is certainly of help to bury the source or even the receivers (at least 50 cm) to improve coupling or source energy release. However, if surface conditions make it too hard to dig a hole, eg. on a paved road or gravel area, impact sources like Dynasource or sledge hammers may not be a bad alternative. The hammer can strike directly on bare ground, not necessarily on a plate, if the ground is stiff enough. Furthermore, dynamite is always a good option if security problems can be overcome. 'Not big but deep' is probably a key

factor for using dynamite. Thirty gram plastic explosives buried in a hole 1 m deep, has been demonstrated to be efficient for shallow seismic purposes. Nevertheless, experience still needs to be accumulated by using appropriate sources to obtain suitable data.

The data acquired in the field need processing before a readable final section could be prepared. We used an HP-735 workstation with 4 GB hard disk and the seismic data processing software SSS developed by ourselves to treat the data. The processing procedures are essentially similar to those used in oil exploration. These procedures include: 1) pre-stack: geometry build-up, amplitude balance, trace edit, air-wave removing, frequency filtering, automatic gain control (AGC), deconvolution (if necessary), 2D filtering, 2) during-stack: velocity analysis, residual static correction, NMO stretch mute by 70%, NMO stack, 3) post-stack: frequency filtering, AGC. Due to great signal variation over a record, it is not suitable for using deconvolution. The migration after stack was not included either, owing to shallow depth and small seismic section available.

In the following sections, we will describe the seismic investigation of active faults in three different regions of western Taiwan (Figure 1). Five faults with a total of nine seismic sections are included. These examples not only provide clear insight into the faults under study but may also help in other investigation in similar geologic areas. Further studies on other active faults, especially those on the plain, the populous region in Taiwan, should be carried out as soon as possible.

### 3. HSINCHUANG FAULT AND HSINTIEN FAULT IN THE TAIPEI BASIN

The Hsinchuang fault is closely related to the origin of the Taipei basin. Geologists have considered the Taipei basin as a tectonic graben which is formed by the normal faulting of a pre-existent reverse fault along its western border. Figure 1, adapted from Wang Lee *et al.* (1978), illustrates the triangular shape of the Taipei basin and the faults around it. Among them, the Chinshan fault which is a large offset reverse fault to the north of Taipei, changes to a normal fault, renamed as the Hsinchuang fault, which cuts through the western boundary of the basin. This normal faulting happened during the expanding period of upper Pliocene and Pleistocene and is supposed to be the main mechanism for the sinking of the Taipei basin. The study of the Hsinchuang fault is of great significance for determining the geologic evolution of the Taipei basin as well as activity on this fault which is located in the highly populated Taipei neighborhood.

Figure 1 also shows the location of seismic lines HC1 and HC2 across the Hsinchuang fault, and line HT across the Hsintien fault. The geologic units on the north and the southeast border of the Taipei basin consist of Tertiary sedimentary rocks, and on the west deposits of Quaternary Linkou gravel which was supposedly uplifted after Taipei basin subsidence along the Hsinchuang fault. Two volcanos extruded in the north on both sides of the Tamshui river, the main river flowing across the basin. Four apparent faults: the Chinshan fault (also the Hsinchuang fault), the Kanchiao fault, the Taipei fault, and the Hsintien fault, all trend in the northeastern direction. These faults belong to a series of southeast-dipping imbricated thrust faults in Taiwan's western foothills probably formed during the Pliocene or Pleistocene. The small figure inserted in Figure 1 points out all known active faults on Taiwan (adapted from Hsu, 1987), on which also denotes the five seismic lines to be dealt with in this paper. Except for those taken as geologic boundaries, many faults are of purely earthquake originate. Among them, faults in the plain area especially need attention.

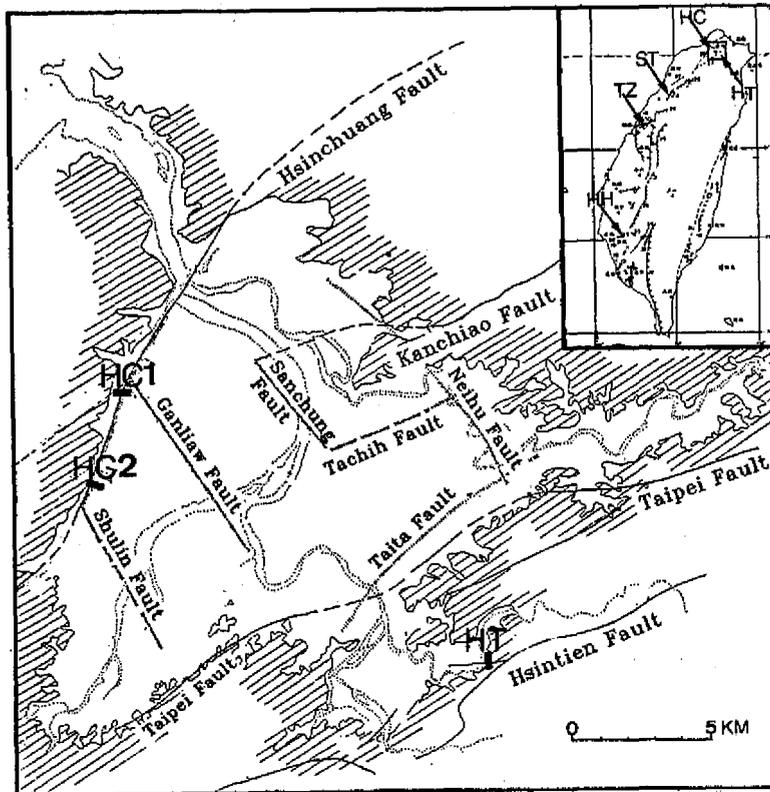


Fig. 1. Taipei basin and the faults surrounding it (adapted from Wang Lee *et al.*, 1978). The inset Figure shows the active faults distributed over Taiwan island (adapted from Hsu, 1989), of which the five faults studied in this paper are denoted. The Hsinchuang fault is along the western border of Taipei basin, which is supposed to have a close relationship with the origin of the basin. Another fault, the Hsintien fault, studied in this paper is an old Tertiary fault, which represents one of the imbricated fault systems widespread in the western foothills of Taiwan. (HC: Hsinchuang, HT: Hsintien, ST: Shihtan, TZ: Tunzuchiaio, HH: Hsinhua)

Figure 2 shows the results of seismic surveys on the Hsinchuang fault. The line HC1 obtained using a Dynasource impact source is located 4 km north of line HC2 which was obtained using the firecracker source. Except for the higher frequency content and more detail at HC2, these two seismic sections are essentially similar. The main fault appears at the location 100 m dipping toward the east, and its western side (foot wall) has apparently bent layers which could be drug by sliding down along the normal fault. The reflection layers on the eastern side (hanging wall) have been warped and dislocated by some back-thrust faults. The seismic velocities on the eastern side indicate that they come from unconsolidated layers (smaller than 1800 m/sec) which must correspond to some Quaternary formations. The back-thrust faults just cut through these young sediments. In this respect, it may imply that the Hsinchuang fault may still have action during the deposition of recent sediment. It can be ranked as a potentially active fault.

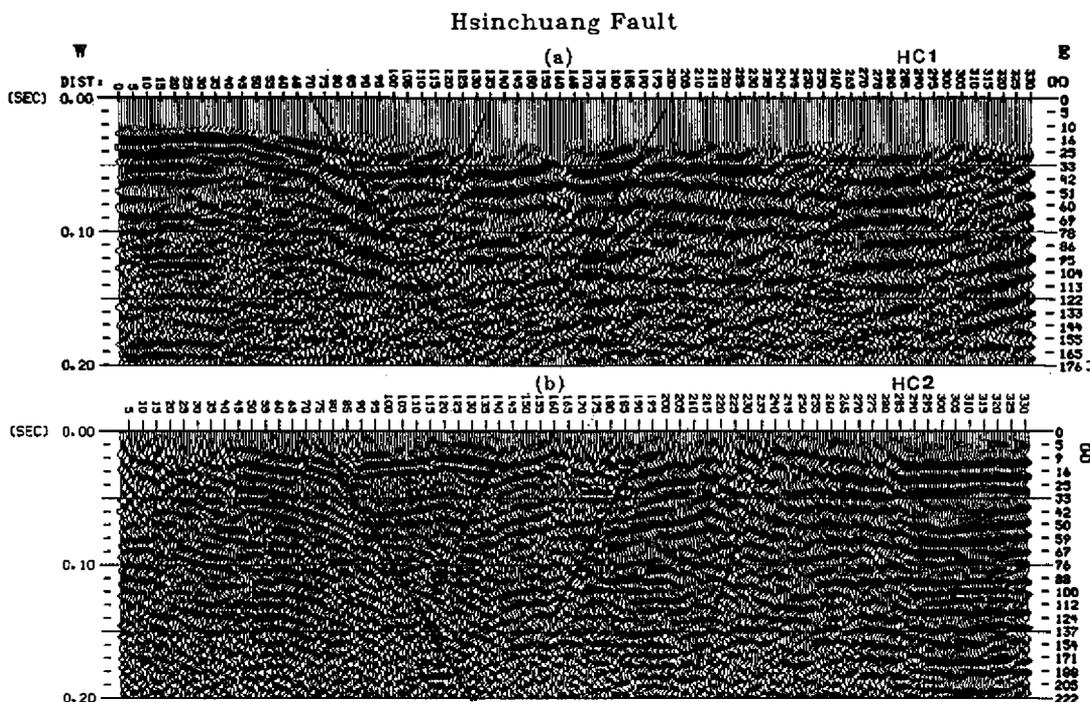
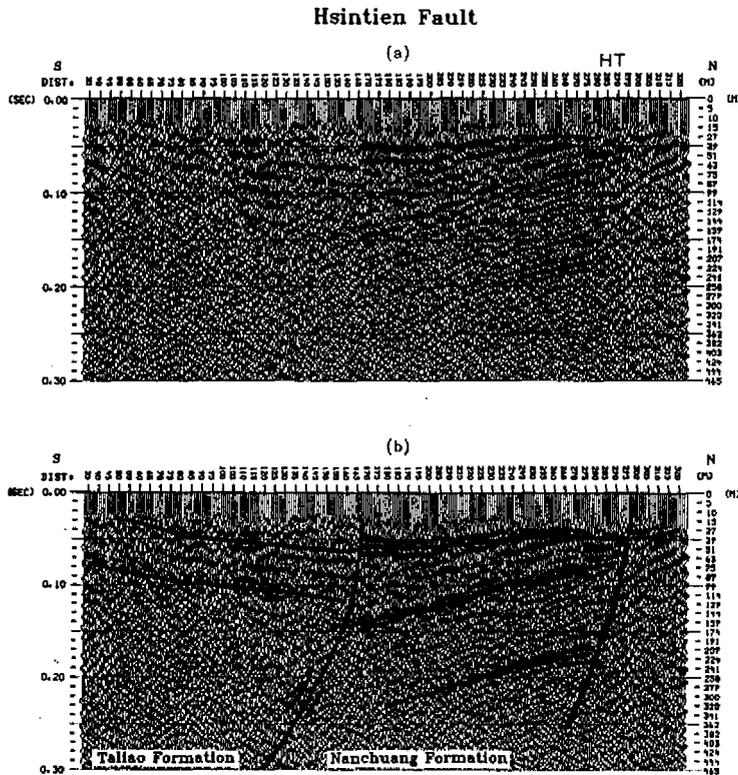


Fig. 2. Reflection seismic sections of the Hsinchuang fault. Two sections (a) HC1 and (b) HC2 are separated by 4 km, but their faulting types are quite similar. HC1 was obtained using the Dynasource impact source, and HC2 used the firecracker source. The main fault at the 100 m location appears as a normal fault with a slippage of 50 meters. It is interesting to find some back-thrusts (antithetics?) which cut through the unconsolidated sediment on hanging wall side. This fault can be explained to form by consecutive sliding in successive steps and is still active even very recent. The disturbed zone spans approximately 200 meters.

These back-thrust faults can also be explained as antithetics accompanied with the normal faulting. Due to the reverse type of antithetics, the corresponding main normal fault could concave upward in the deeper place (Wu, 1965), which may push the mass above it to rotate and cause a series of breakages on the hanging wall block. The disturbed zone spans about 150 meters wide. The vertical displacement of the main fault found in Figure 2 is not more than 50 meters. It is known that the Tertiary basement of the Taipei basin is at a depth more than 400 meters (Wang *et al.*, 1994). Thus, the Hsinchuang fault may have slid down the basement layers in a sequence of stages. The seismic sections obtained here may just represent a part of it. This fault could be much more complicated than originally thought.

As to illustrate the geologically defined old fault, we also take a seismic section HT along the Hsintien fault (Figure 1). Figure 3 displays such a profile, in which 3(b) is an interpretation of 3(a). The Hsintien fault separates the Taliao formation to the south from the younger Nanchuang formation to the north. Both formations are of Tertiary age. It is apparent that the dip angles of layers on the two sides of the fault are different. The Nanchuang



*Fig. 3.* A seismic section across the Hsintien fault. This fault is obviously a boundary between the Taliao formation (in the south, left-hand side) and the younger Nanchuang formation (in the north, right-hand side). The subsurface structures are totally different on either side of the fault.

formation has good layering dipping to the south and the Taliao formation, probably due to the interruption of tuff, lack of reflection events. The near surface deposits at the top of these two units are also different. This may be a result of the erosion on different lithology. Due to structural distinction, it may not be too difficult to delineate this old fault. This obviously differs from other active fault detection. Many 'young' active faults generally do not have enough lithologic variation to distinguish them. This point is worth consideration when studying these two different kinds of faults.

#### 4. SHIHTAN FAULT OF 1935 EARTHQUAKE

The 1935 Hsinchu-Taichung Earthquake ( $M=7.1$ ) was the most damaging earthquake (3279 casualties) in Taiwan's history. The earthquake was shallow (5-10 km) with its epicenter located near to the present Liyutan dam site, Maoli. Due to the intensive investigation after the earthquake by the Japanese who occupied Taiwan at that time, many earthquake fault details were reported (Otuka, 1936). Figure 4 describes the location of the earthquake, the surface rupture, and land slides. This earthquake induced two faults: (1) Shihtan fault at

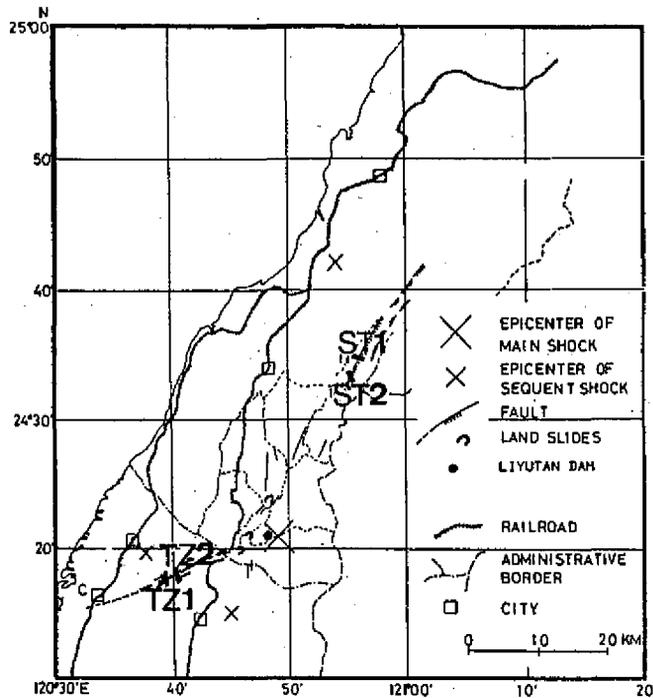
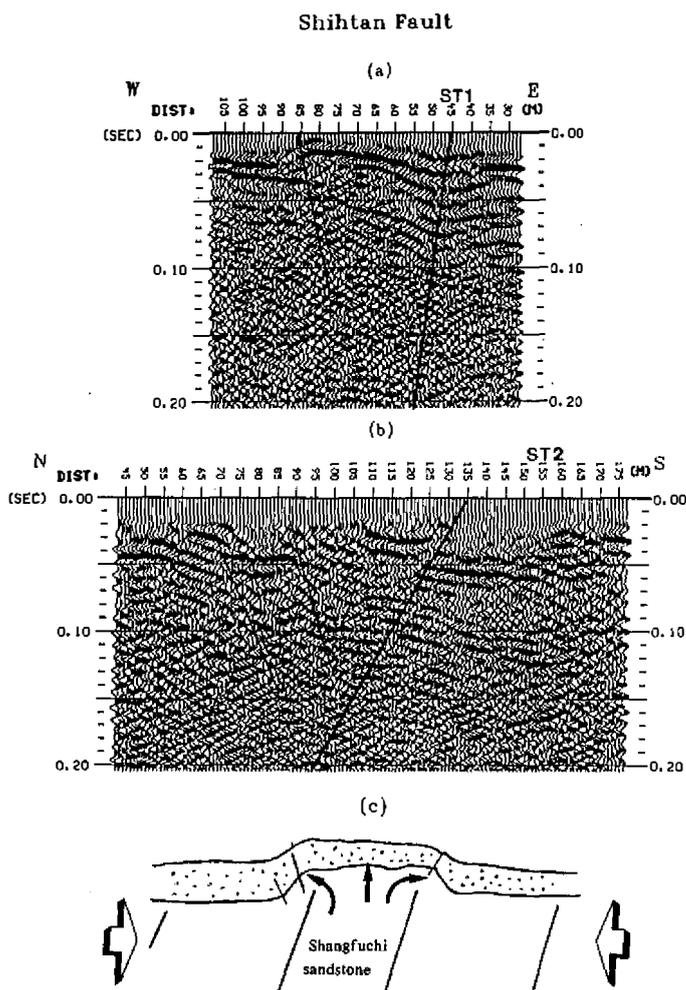


Fig. 4. The map shows ground breakage of the 1935 Hsinchu-Taichung earthquake ( $M=7.1$ ) (modified from Miyamura, 1985). This earthquake killed more than 3000 people and is the most hazardous earthquake in Taiwan's history. Two surface ruptures: Shihtan fault in the north trending in a N30E direction and the Tunzuchiao fault in the southwest trending in S30W direction. The survey lines ST1, ST2, TZ1, and TZ2 are also indicated.

the north, a dip-slip reverse fault, trending N30E dipping 70-80 degrees to the west with a maximum of 3 m uplift on the western side without appreciable horizontal displacement, and (2) Tunzuchiao fault at the southwest, a right lateral strike-slip fault, trending N60E dipping vertically with a maximum horizontal displacement of more than 1 m and vertical displacement of less than 60 cm. There is a gap between these two faults, where only randomly distributed land slides were reported. The epicenter was located in this gap, which has a focal mechanism (dip=83, slip=190, strike=225), i.e., an almost purely right-lateral strike-slip fault oriented in the same direction as the Tunzuchiao fault (Figure 4). The Shihtan and Tunzuchiao faults both have a length of 20 km, but behave quite differently. At Shihtan fault, there were groups of parallel and steep ground fractures accompanying the main fault. On the other hand, Tunzuchiao fault had several segments disappear along its length, and which was the uplift side of the fault is uncertain. The Shihtan fault is of the compression type, and the Tunzuchiao fault is of the shear type. Much larger damage was found around the Tunzuchiao fault as a consequence of shear type shaking. It would be interesting to compare these two faults by their underground breakage features.

Figure 5 shows the final sections of seismic lines, ST1 and ST2, for the Shihtan fault. These two sections have been described in Wang *et al.* (1991b) and are reproduced here for

comparison with the Tunzuchiaio fault. The geologic units in the Shihtan area are composed of later Miocene rocks, including shelf facies deposited Nanchuang formation and shallow marine deposited Kueichulin formation. The structural layers have high dip angles and there is a Shihtan syncline to the west and a Pakuali anticline to the east. The Shihtan fault has a close relationship with the white sandstone member, called Shangfuchi sandstone, which belongs to the upper Nanchuang formation. In most places, the fault follows this sandstone layer. The Shangfuchi sandstone layer is composed of coarse-grained white sandstone containing rounded quartz grains loosely cemented by clay and sand. It can be easily scratched off by the fingers and is used as an indexed layer for the Nanchuang formation in this area. From the viewpoint of rock, Sungfuchi sandstone is thought to be very 'soft' and easy to reshape under pressure.



*Fig. 5.* Two seismic sections (a) ST1 and (b) ST2 across the Shihtan fault. (c) gives an explanation of the constitution of this fault. The earthquake compressional force has squeezed the soft Shangfuchi sandstone, causing it to flow out and distort the overlying alluvial layers. A rupture zone of about 60 meters is visible.

The seismic sections ST1 and ST2 as shown in Figures 5(a) and 5(b) have obviously distorted and broken upper layers. A main fault can be defined together with many back-thrust faults, which form a type of bulge rising up by slippage along fault cracks. ST1 and ST2 can be explained by the mechanism illustrated in Figure 5(c). Under enormous earthquake compressional pressure, the soft Shangfuchi sandstone was squeezed and 'flowed' out to protrude the overlying alluvial fill, and split the ground surface. The main distortion zone is about 50 m wide, surrounded by many small fractures. The Shihtan fault can be thought of as a result of breakdown of a soft structural layer under the great compressional pressures which induced the earthquake.

At the same locations of ST1 and ST2 we also conducted a seismic refraction survey. The results are shown in Figure 6. The refraction method is supposed to be sensitive to the investigation of fracture zones either by travel time curve anomalies or refractor velocity variations. This method, however, is only effective in detecting the bedrock surface. Figure 6 indicates exactly the same fault positions as the reflection method does in Figure 5. A shape of bulge is also visible. The lateral velocity changes in the bedrock imply that the material next to the fault is greatly disturbed, but outside the bulge fault zone it may return to normal. The results of both methods are in good match. The refraction method is much easier to carry out than the reflection method and can be used as a supplement for fault detection as this example shows.

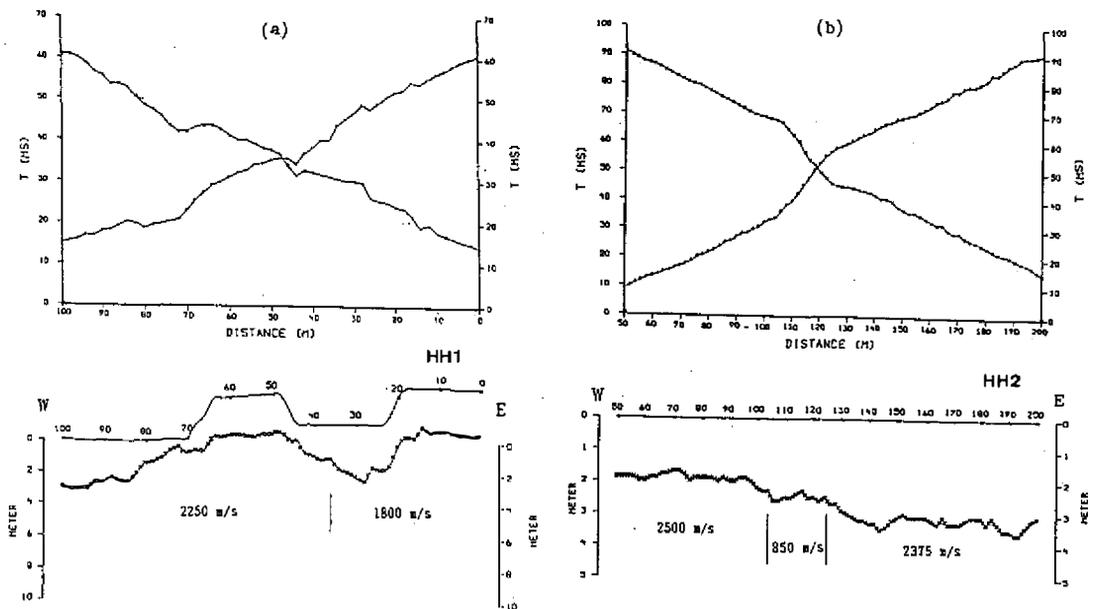


Fig. 6. Seismic refraction sections on the lines ST1 (a) and ST2 (b). These sections express obvious distortions of the bedrock surface. A squeeze type of faulting is visible on (a) with disturbance zone spreading over a range of 50 meters. The reflection (Figure 5) and the refraction (this Figure) results are consistent.

## 5. TUNZUCHIAO FAULT OF 1935 EARTHQUAKE

Besides the Shihtan fault, the 1935 earthquake also created another east-west trending, right-lateral strike-slip fault, i.e., Tunzuchiaofault. The Tunzuchiaofault is thought to be the major fault associated with this earthquake. According to Neotectonics of Taiwan (Seno, 1977; Biq, 1981), the Philippine island arc collides with the Eurasian continental margin in a northwest direction at a speed of 7 cm/year. Represented by the eastern Coastal Mountain Range which is thought of as a part of the Philippine-sea plate, the arc-continental collision started about 6 million years ago (Teng, 1990) and still persists now. Plate collision in such a direction could induce the left-lateral strike-slip fault trending in north-south such as the Coastal Mountain Range fault in Longitudinal Valley, and the east-west right-lateral strike-slip fault such as the Meishan fault in the Chianan plain. The Tunzuchiaofault studied here is a typical example belonging to the latter.

The Tunzuchiaofault, as opposed to the Shihtan fault, is quite tender in its seismic appearance (Figure 7). Figure 4 denotes the location of seismic lines TZ1 and TZ2. The fault is situated on the Houli terrace which is composed of Pleistocene lateritic deposits with flat unconsolidated gravel beds intercalated by sandy or silty lenses. The seismic sections in Figure 7 reflect much of the character of such a gravel layer. The seismic signals are difficult

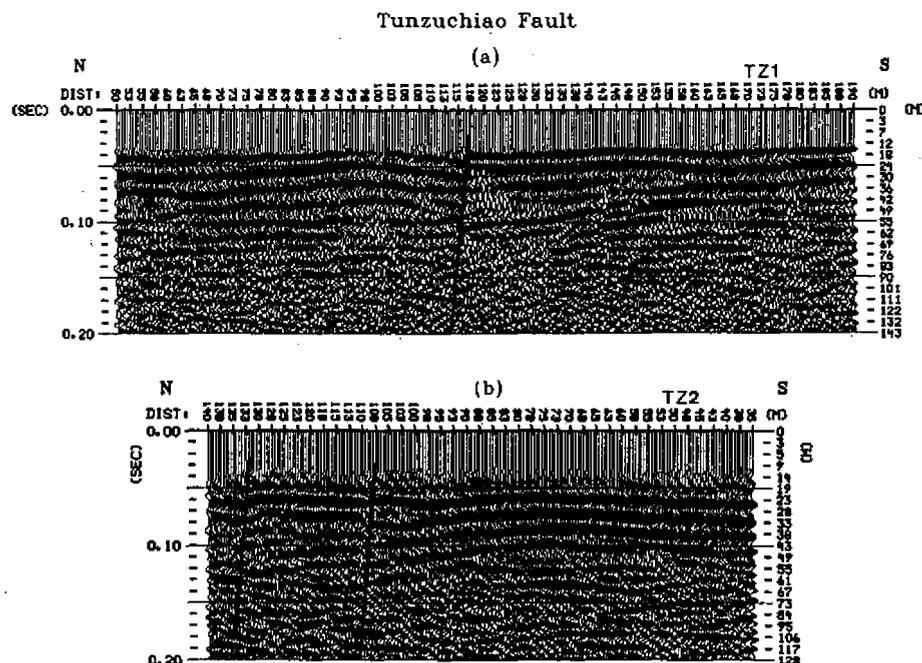


Fig. 7. The seismic section of the Tunzuchiaofault. The Tunzuchiaofault has little vertical displacement (80 cm), there appears on the sections a small breakage offset together with a long wavelength swing on the upper gravel layer surface. The deposit sequences on the two sides of fault seem different, which may form a weak zone where the earthquake rupture occurred.

to propagate through gravels (Hunter *et al.*, 1984). In order to detect this tiny vertical offset (60 cm) fault under such unfavorable conditions, we chose a dynamite source (40 gm plastic explosive), 1 m interval, 24 folds, and 200 Hz low-cut. As presented in Figure 7, TZ1 and TZ2 have similar data quality. The seismic signals may not penetrate deeply but the layers near the surface are still clear enough to describe the associated fault.

Since the Tunzuchiao fault is mainly a strike-slip fault with a very small vertical offset, the fracture may not be easy to see in a seismic section. However, Figure 7(a) still gives an apparent rupture at the middle, and more interestingly, the gravel layer (first reflection layer) shows a slightly up-and-down wavy shape with a wavelength of about 70 m. One explanation for this observation is that the shear force of earthquake may have twisted this area to make its 'skin layer' (gravel layer) 'crinkle'. The ruptures may have happened at the places of largest curvature with a certain degree of randomness. Figure 7(b), seismic line TZ2, shows two ruptures with the upthrust side to either the south or the north. This makes the surface ruptures look like being composed of several segments distributed along a zone centering on the main fault line. Which side uplifted depends on where the rupture sits on the up- or down-wave side of wavy bedrock surface. The Tunzuchiao fault provides an example of shear distortion due to an earthquake. The ruptures discovered by seismic images may not be large, however, the twist effect of shear faulting should be taken into account to recognize their seismic meaning.

## 6. HSINHUA FAULT OF 1946 EARTHQUAKE

The Hsinhua fault was caused by the 1946 Tainan earthquake ( $M=6.3$ ). Its epicenter was near the town of Hsinhua, Tainan county, with a rupture length of 6 km trending in the direction of N80E. The inset figure of Figure 8 sketches the surface disturbances after the earthquake (Hsu, 1985). The ground breakage appears segment by segment, but can be lined up. Many places where muddy water was ejected were found distributed within 500 m around the fault. The fault has a maximum right-lateral slippage of 2 m and a vertical displacement of 76 cm with the northern side upthrown. Many people have explained east-west trending earthquake faults in western Taiwan as oblique faults. Big (1991) proposed a different mechanism of 'stop-and-turn' when rupture is approaching the edge of a fault. Several fault branches, either old or new, can be induced and slide to balance the dislocated mass. The Hsinhua fault is probably of this kind. •

Figure 8 also depicts the locations of two seismic lines, HH1 and HH2, conducted for this study. There is some earthquake damage still visible today. The bending of the irrigation waterway and the Taisugar railroad (indicated by small arrows on Figure 8) are still apparent. These old earthquake damage relics may provide us with some check points for the seismic results. The breakage positions as indicated by the small arrows in Figure 8 are not parallel to each other. The fracture zone seems to expand toward the east. A charity house in this direction had been reported being destroyed almost completely during this earthquake.

Due to unfavorable surface conditions (dry and coarse-grained), the signals in the seismic section do not penetrate too deep (Figure 9). Near-surface top reflection layers, however, still show obvious earthquake traces. HH1 (Figure 9(a)), the eastern line, has the northern side thrown up within two disturbance zones, denoted as zones L and R. Zone L corresponds to the main fault and zone R is a branch extending toward the east. The layers in each zone are twisted along two fractures both obviously with the north side up. The reflection layers are generally continuous, which are distorted but do not slip away. The regions outside the

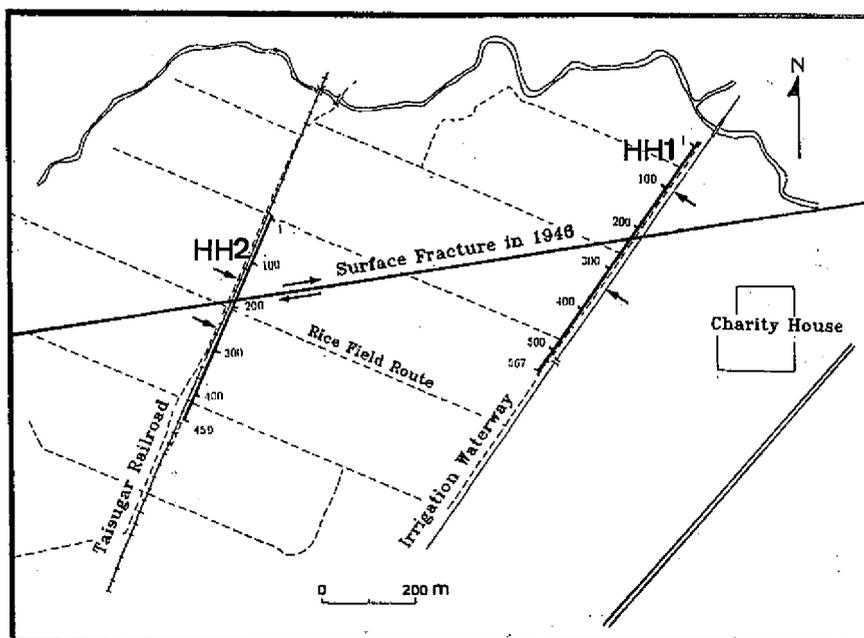


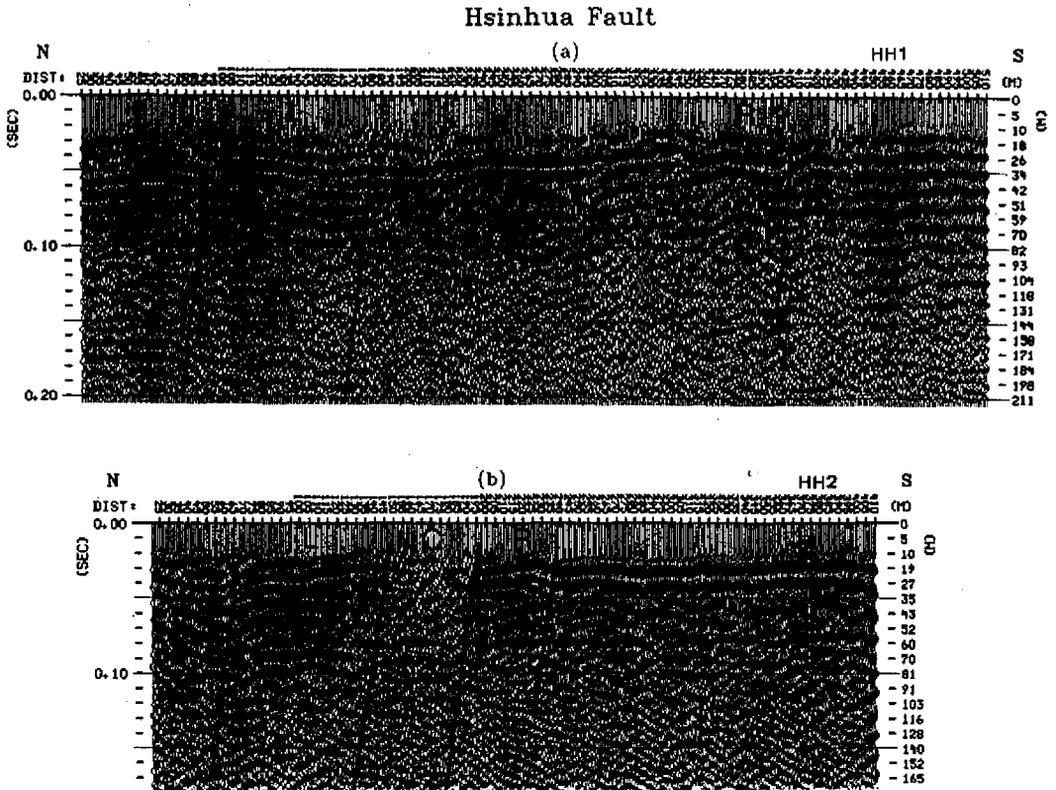
Fig. 8. The map shows the Hsinhua fault and two seismic survey lines, HH1 and HH2. The arrows indicate the old earthquake caused damages still visible today.

fracture zones seem quite flat and free of disturbance. This may be a typical result of strike-slip dominant fault. The locations of underground breakages grossly agree with the shape change of the surface irrigation waterway alongside the seismic line mentioned before.

HH2 (Figure 9(b)), to the west, gives another description of this earthquake fault. It shows up as a 'no-signal' zone, i.e., the seismic signals at the place where the earthquake fault passes seem to have been 'lost' (C zone in Figure 9(b)). This is not due to the data processing artifacts. We have checked several consecutive shot records acquired near the proposed fault position and found that some records were totally devoid of signals. It clearly demonstrates that the seismic signals are 'absorbed' into the masses induced by earthquake turmoil. The tremendous earthquake force may have crushed the layers close to the fault and mixed them up to become non-layering material. By comparing Figures 9(a) and 9(b), it may not be too unreasonable to assume that zones L and R come close together to make this special 'lost-signal' zone at seismic line HH2. The Hsinhua fault could have several branches. This is probably due to the mechanism of 'stop-and-turn' as it comes close to the Chukou fault, one of the big boundary faults in the western foothills of Taiwan (Figure 1).

## 7. DISCUSSION AND CONCLUSIONS

The shallow seismic reflection method can be useful for detecting near-surface active faults as discussed in this paper. The revealed fault pictures in some cases are so sharp that many details can be measured. The signal-detectable depth is between 10 and 200 meters,



*Fig. 9.* Seismic sections HH1(a) and HH2(b) across the Hsinhua fault. Two rupture zones, denoted as L and R, stand out. Along HH1, there is an apparent twisted uplift of north side, each zone with two fractures. The top layer was distorted without much breakage. On HH2, L and R zones come closer and form a region, denoted as C zone, on which there is no seismic signal received. The structural distortions are more serious on HH2.

however, an earthquake fault might span a much larger distance than this. Nevertheless, faults near the surface mostly agree with the focal mechanism of the earthquake. A detail study using shallow reflection seismics would be able to discover the main characteristics of the earthquake and its rupture.

The refraction method is traditionally used in fracture zone investigation for engineering purposes. In the Shihtan case we have compared different contribution of reflection and refraction methods. By using the first arrival time, we can map very shallow refractors (as bedrock) in the refraction approach. Due to refracted ray geometry, the method is more accurate for velocity measurement. Although the refraction method worked well for engineering purpose, the bedrock surface more or less represented a barrier which hinders the discovery of deeper refraction layers. The reflection method, the other approach, collects reflected signals directly from the inner structure. It seems to take a photograph of underground. The rays penetrate into the bedrock and bring back plentiful structural information, though with weak signals. The enhancement of such weak signals has made the method sophisticated

and expensive to use. Considering this, we feel that both the reflection and the refraction methods have their own advantages and disadvantages. A combined use of both methods could be more fruitful, especially in fault detection.

Although the sites studied in this paper are confined to places with evident fault either from earthquake history or geologic certification, seismic reflections still reveal many details about the faulting. The horizontal length of fault affected area in most cases is less than 100 meters in which the most seriously distorted zone is about 50 meters. This size may depend on local geology, although in western Taiwan it must actually be around this. The seismic images indicate not only the breakage of layers but variations of reflection strength, character, and disturbance pattern. All these can be used to settle down the fault and its possible derivations. Two close parallel seismic lines are designated in this study. This seems necessary as to provide related data to confirm the fault images as well as to measure the extent of the rupture. In poor data areas or for important projects, parallel line surveys might be of some help. They could be used to establish a basis for the drawing of reliable conclusions after the examination and comparison of both data sets.

The seismic sections of the Tunzuchiaio fault and the Hsinhua fault in this study come out quite clean. Massive disturbances do not appear to suggest the possibility of repeated earthquakes. It is probably difficult to conclude that these young earthquake faults have occurred once and for all, however, considering their geographic locations we cannot exclude this implication. The earthquake faults on the plain area of Taiwan have their own complicated 'simplicity'. This topic is interesting to study further.

In this study, we find that every fault has its own characteristics. They all behave differently. The properties of these faults can be summarized as following:

- (1) Hsinchuang fault (Taipei basin) is obviously a normal fault with a vertical displacement of at least 50 m. Many small back-thrust faults (or antithetics) are found on the hanging wall, which cut through the young sediment. This fault could be potentially active.
- (2) Hsintien fault (Taipei basin) is an old thrust type with a large offset. The seismic signals on both sides of the fault come out quite different. Obvious reflections are obtained on the hanging wall side, but not on the other. This is due to lithological changes across the fault. The difference in the signal's appearance can be easily used to define the position of the fault.
- (3) Shihtan fault (1935 earthquake) is an interesting fault. The breakage on the surface is attributed to the squeezing effect on the vertically dipping unconsolidated sandstone layer (Shangfuchi Sandstone) by the earthquake compression force. The coarse-grained sandstone 'flowed' out and pushed the overlaying alluvial deposit causing the surface rupture.
- (4) Tunzuchiaio fault (1935 earthquake) showed a complicated movement along the fault during the earthquake. A near-surface twisted layer is used to explain this fault. The rupture happens at the place where the layer was mostly distorted. The break position and the direction of movement are random in a narrow zone surrounding the fault.
- (5) Hsinhua fault (1946 earthquake) has the developing type of fractures. Two fracture zones were found, which are separated more toward the east. Large disturbances occurred within a 60 m range where these two fracture zones came together in the west. This 60 m zone has reflection signals that are totally lost due to elimination of the layering by mass mixtures on the fault. But outside the fault zone, the layer is quite flat and free of disturbance.

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## REFERENCES

- Aki, K., 1988: Local site effects on strong ground motion. in *Earthquake Engineering and Soil Dynamics II*, Geotechnical Special Publication No. 20, Am. Soc. Civil Eng., New York, 103-155.
- Biq, C. C., 1981: Collision: Taiwan-style. *Mem. Geol. Soc. China*, 4, 91-102.
- Biq, C. C., 1991: The shear properties of Meishan earthquake fault. *Ti-Chih*, 11, 111-119 (in Chinese).
- Bollina, M. G., 1977: Summary of Quaternary faulting and elevation changes in Taiwan. *Mem. of Geol. Soc. of China*, 2, 43-55.
- Goforth, T., and C. Hayward, 1992: Seismic reflection investigation of a bedrock surface buried under alluvium. *Geophysics*, 57, 1217-1227.
- Hunter, J. A., S. E. Pullan, R. A. Burns, R. M. Gagne, and R. L. Good, 1984: Shallow seismic reflection mapping of the overburden-bedrock interface with engineering seismograph—some simple techniques. *Geophysics*, 49, 1381-1385.
- Hsu, M. T., 1985: *Earthquake Engineering*. 2nd ed., Ker-Chi Book Company, Taipei (in Chinese).
- Hsu, T. L., 1989: *Geology and Engineering*. 8th ed., Ker-Chi Book Company, Taipei (in Chinese).
- Knapp, R. W., and D. W. Steeples, 1986: High-resolution common depth point seismic reflection profiling: Field acquisition parameter design. *Geophysics*, 51, 283-291.
- Miyamura, S., 1985: The Hsinchu-Taichung, Taiwan, Earthquake of April 20, 1935. in: Special Issue for the Fifty-year Memorial Ceremony of 1935 Hsinchu-Taichung Earthquake, Central Weather Bureau, Taipei.
- Miller, R. D., and D. W. Steeples, 1990: A shallow reflection survey in basalts of the Snake River Plain, Idaho. *Geophysics*, 55, 761-768.
- Miller, R. D., D. W. Steeples, and P. B. Myers, 1990: Shallow seismic reflection survey across the Meers fault, Oklahoma. *Geol. Soc. Am. Bull.*, 102, 18-25.
- Miller, R. D., V. Saenz, and R. J. Huggins, 1992: Feasibility of CDP seismic reflection to image structures in a 220-m deep, 3-m thick coal zone near Palau, Coahuila, Mexico. *Geophysics*, 57, 1373-1380.
- Otuka, Y., 1936: The earthquake of Central Taiwan (Formosa), April 21, 1935. in: Papers and Reports on the Formosa Earthquake of 1935, Bull. of the Earthq. Res. Inst., Tokyo, Japan.

- Seno, T., 1977: The instantaneous rotation vector of the Philippine Sea plate relative to the Eurasian plate. *Tectonophysics*, **42**, 209-226.
- Shedlock, K. M., T. M. Brocher, and S. T. Harding, 1990: Shallow structure and deformation along the San Andreas fault in Cholame Valley, California, based on high-resolution reflection profiling. *J. Geophys. Res.*, **95**, 5003-5030.
- Shih, T. T., 1986: A geomorphological study of active fault in Taiwan. *Geograph. Res.*, **12**, 1-35 (in Chinese).
- Steeple, D. W., and R. D. Miller, 1990: Seismic reflection methods applied to engineering, environmental, and groundwater problems. in S. H. Ward (Ed.), *Geotechnical and Environmental Geophysics, Vol. I: Review and Tutorial*, SEG publications, Tulsa, USA.
- Stephenson, W. J., R. B. Smith, and J. R. Pelton, 1993: A high-resolution seismic reflection and gravity survey of Quaternary deformation across the Wasatch fault, Utah. *J. Geophys. Res.*, **98**, 8211-8223.
- Teng, L. S., 1990: Geotectonic evolution of late Cenozoic arc-continent collision in Taiwan. *Tectonophysics*, **183**, 57-76.
- Treadway, J. A., D. W. Steeples, and R. D. Miller, 1988: Shallow seismic study of a fault scarp near Borah Peak, Idaho. *J. Geophys. Res.*, **93**, 6325-6337.
- Tsai, D. T., C. Y. Wang, and R. K. Yang, 1990: Shallow reflection seismics using firecrackers as the source, I: firecracker source. *TAO*, **1**, 307-320.
- Wang, C. Y., C. H. Hsieh, D. T. Tsai, and L. W. Hsu, 1991a: Experiences with the shallow reflection seismics as applied to the shallow structure studies. *Proc. Geol. Soc. China*, **55**, 394-401.
- Wang, C. Y., R. K. Yang, and D. T. Tsai, 1991b: Shallow reflection seismics using firecrackers as the source, II: field experiments. *TAO*, **2**, 163-185.
- Wang, C. Y., W. C. Hsiao, and C. T. Sun, 1994: Reflection seismic stratigraphy in the Taipei basin (I) - northwestern Taipei basin. *J. Geol. Soc. China*, **37**, 69-95.
- Wang Lee, C. M., Y. M. Cheng, and Y. Wang, 1978: Geology of Taipei basin. *Taiwan Mining*, **30**, 350-380 (in Chinese).
- Widess, M. B., 1973: How thin is a thin bed?. *Geophysics*, **38**, 1176-1180.
- Wu, F. T., 1965: Subsurface geology of Hsinchuang structure in the Taipei basin. *Petrol. Geol. Taiwan*, **4**, 271-282.