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Lin, Aiming
Ouchi, Toru
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Maruyama, Tadashi

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Morphological characteristics of the Chelungpu surface rupture zone occurred during the 1999 Chi-Chi (Taiwan) earthquake

Aiming Lin¹⁾

Toru Ouchi²⁾

Allen Chen³⁾

Tadashi Maruyama⁴⁾

Abstract: A nearly 100km-long surface rupture zone, called Chelungpu surface rupture zone, occurred mostly along the pre-existing Chelungpu fault on the northwestern side of Taiwan, accompanying the 1999 Chi-Chi Ms 7.6 earthquake. The Chelungpu surface rupture zone can be divided into four segments based on the distribution characteristics of co-seismic displacements, geometry of the surface ruptures and geological structures. These segments generally show a right-step en echelon form and strike NE-SW to N-S, and dip to the east with angles ranging from 50° to 85°. The co-seismic flexure-folding structures commonly occurred in or near the surface rupture zone from a few of m to a few hundreds of m in width, which have an orientation in fold axes parallel or oblique to the surface rupture zone. The displacements measured in the southern three segments are approximately 1.0-3.0 m horizontally and 2.0-4.0 m vertically. The largest displacements measured in the northern segment are 11.0 m horizontally and 7.5 m vertically, respectively. The co-seismic horizontal shortening amounts caused by flexure-folding and reverse faulting in the surface rupture zone is generally less than 3 m. It is evident that the co-seismic displacements of the surface rupture zone are a quantitative surface indicator of the faulting process in the earthquake source fault. The relations between the geometry of the surface rupture zone and geomorphology, dips of the co-seismic faulting planes and the striations on the main fault planes generated during the co-seismic displacement, show that the Chelungpu surface rupture zone is a reverse fault zone with a large left-lateral component.

Key words: Chi-chi earthquake, Chelungpu surface rupture zone, fault, displacement, co-seismic flexure-folding structures,

1. INTRODUCTION

On 21 September 1999, an earthquake with a magnitude of 7.6 (Ms) shook Nantou country, central Taiwan (23.85°N, 120.81°E), killing approximately 2,300 people and causing widespread damage. After the earthquake, the Central Geological Survey of Taiwan, the National Taiwan University, and the National Central University, etc., investigated the surface ruptures and published the preliminary results about the distribution of the surface fault ruptures on their Web sites. In this study, we conducted the field survey on the surface fault ruptures with the aid of the distribution maps of the surface ruptures¹⁾ and the geomorphological maps of 1:5,000.

Some prompt reports published immediately after the Chi-Chi earthquake²⁻⁴⁾ and data available from Web sites⁵⁻⁸⁾ provide the preliminary seismological background and information for further studying the mechanism of the earthquake activity. This paper tries to explain the observation of the co-seismic displacements, folding structures and shortening amounts, and the relationship between the surface ruptures and the pre-existing geological structures, which provide important field geological data to further assess the kinematics of rupturing process during the Chi-Chi earthquake.

2. TECTONIC AND GEOLOGIC SETTINGS

The study area is located in the west central Taiwan Island (Fig. 1), where the Philippine Sea plate collides the Eurasian plate from the east⁹⁻¹¹. The collision zone abuts upon the south-vergent Ryukyu subduction zone, where the Philippine Sea plate subducts beneath the Eurasian plate, and the west-vergent Manila subduction zone, where the Philippine Sea plate overrides the crust of the South China¹¹ (Fig. 1).

In this district, there are four major active faults, Tamoupu-Huangtung, Chelungpu, and Changhua faults from east to west, trending nearly north-south with dips moderately towards the east, and the Tuntzechiao fault trending northeast-southwest (Fig. 1). The former three faults are inferred as Category II active faults and the latter is a Category I active fault along which the surface ruptures occurred during the 1935 Hsinchu-Taichung earthquake (M7.1)^{1,12-15}. The Chelungpu fault is one of the major faults in the west-central Taiwan, which is a geological and topographical boundary between the Neogene sediments and Quaternary deposits and between the mountains and basins. The Changhua fault is also a geological and topographical boundary between the Pleistocene sediments and the Holocene deposits, and between the Western Coastal Plains and the Western Foothill. All these faults thrust over the Quaternary sediments or younger alluvial deposits¹³⁻¹⁶. The basement consists mainly of the Pleistocene-Pliocene shale, sandstone and mudstone, which are nearly folded and deformed.

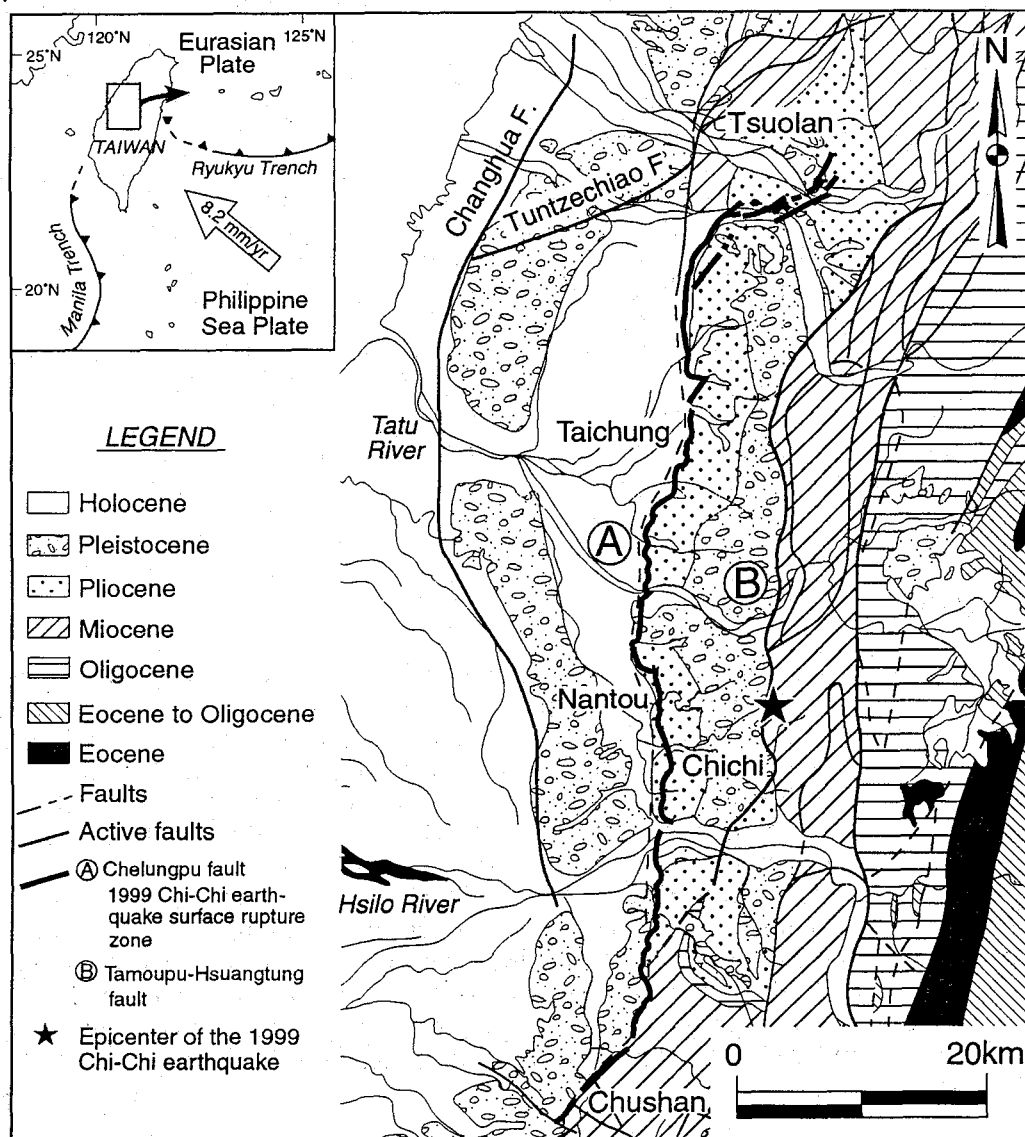


Fig. 1. Map shows the tectonic setting and geological outline of the study region (after Central Geological Survey of Taiwan, 1985¹⁰, 1999a¹ and Hu et al., 1997¹¹; Ma et al., 1999²).



Fig.2. Typical fault outcrops of the Chelungpu surface rupture zone. (a): The river channel at Loc.3 (shown in Fig.7) was displaced and uplift about 6.7 m in the hanging wall (view northeast). (b): Striations generated by the co-seismic displacement on the fault plane at the Loc.3. Arrow indicates the slip direction of the lost wall. (c): The road was sinistraly displaced about 7.0 m at Loc.4 (view northwest). Arrow indicates the co-seismic fault scarp. (d): Fault scarp occurred in terrace deposits at Loc.7. Note that the buildings on both sides near the fault scarp were only gently damaged (view southeast). (e): The co-seismic fault scarp at the location near Loc.7 occurred along the pre-existing fault scarp (indicated by arrows on the upper side) (view east). Note that the building was tilted and damaged by faulting on the fault scarp (view northeast). (f): Co-seismic fault scarp occurred in a pre-existing fault zone at Loc.8. F1 is a pre-existing fault plane, where the overlain terrace deposits are not deformed or displaced by the co-seismic faulting during the Chi-Chi earthquake (view southeast). (g): Fault scarp occurred in the bedrock at Loc.8. Striations (indicated by arrows) can be observed on the fault plane (view east). (h): Grooves and striations generated on the fault plane shown in (g).

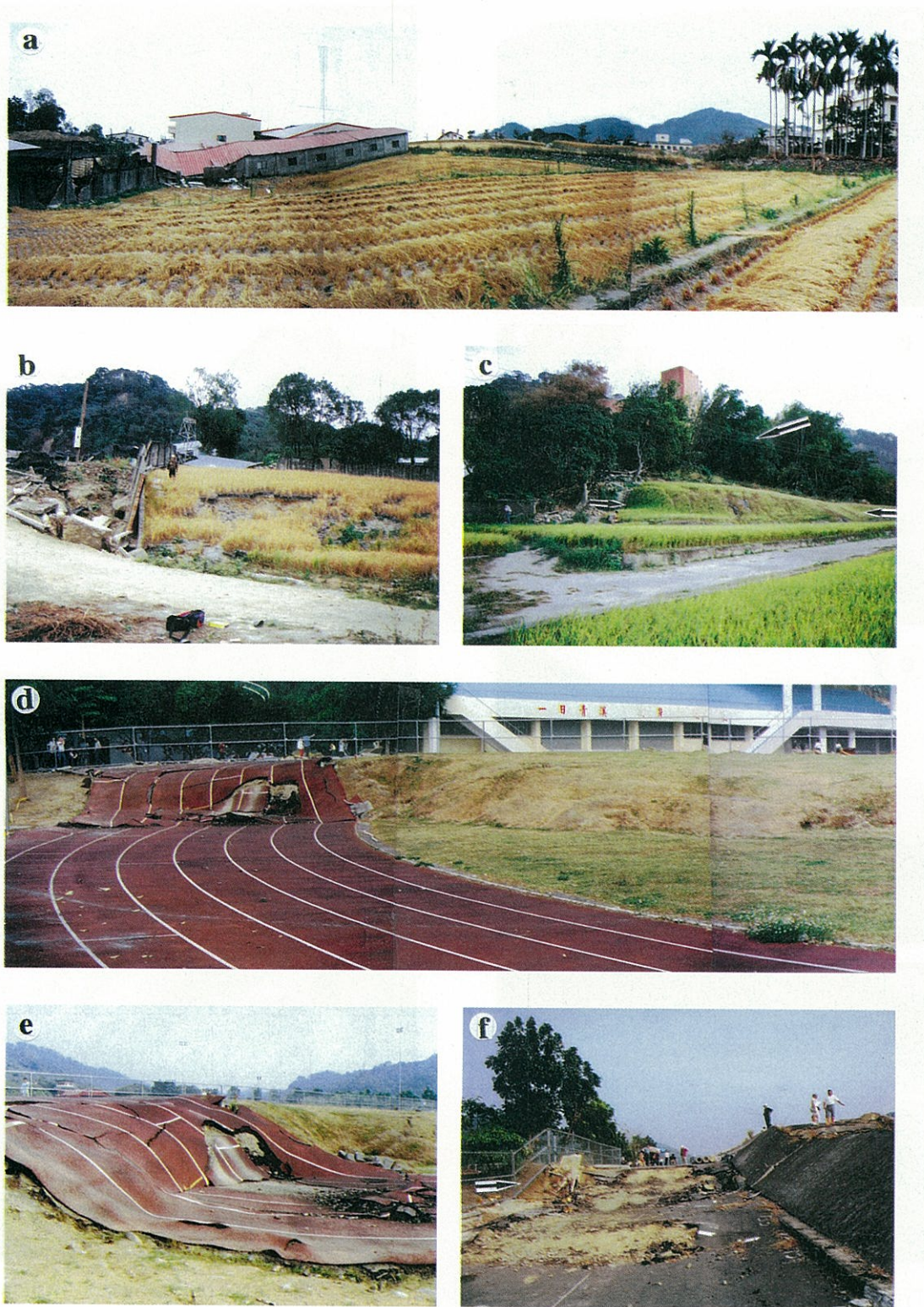


Fig.3. Typical flexure-folding structures generated by the co-seismic faulting during the Chi-Chi earthquake. (a): The paddy fields near the surface rupture zone were flexure-folded at Loc.5 (view southeast). (b): Flexure-fault scarp occurred in the paddy field at Loc.5 (view east). (c): Flexure-folding scarp (indicated by the horizontal arrows) occurred along the pre-existing fault scarp (indicated by the large arrow on the upper side) in the paddy fields at Loc.6 (view southeast). (d): The run track of the ground in the Kuangfu middle school at Loc.11 was sinistrally displaced about 30-50 cm and uplift about 2-3 m in the eastern side (view east). (e): Close-up view of (d) (view southeast). Note that the red asphalt slab was flexure-folded, but not cut and offset by the co-seismic faulting. (f): Fault scarp (indicated by arrow) occurred at the southern side of Loc.11. Note that the road was sinistrally displaced about 1.0 m and uplift about 1.8 m in the eastern side (view east).



Fig.4. Deformational topographies generated by the co-seismic faulting. (a) and (b): The change in topography occurred at Loc.4 before (b) and after (a) the earthquake. Large arrows indicate the flexure-fault scarp. Note that the first floor of the building was in sight of the photo before the earthquake (b) but is out of sight in the photo (a). Small arrows indicate the same window of the building shown in (a) and (b). Both photos were taken from the same location and view direction by the landlord (Mr. Z.Z. Sheng) (view northwest). This indicates that the east side was uplift one-floor high during the earthquake. (c) and (d): The railway was bent by the co-seismic faulting and folding at Loc.12 near the epicenter Chi-Chi town. Arrow indicates the fault scarp in (c) where the railway was sinistrally displaced about 1.7 m (view east). (e): Extensional cracks occurred at Loc.10 in the hinge area of the flexure-folding structures (view east). The large arrows indicate the strike of the hinge line. Note that the large-scale landslide (indicated by the small arrow) occurred near the surface rupture zone. (f): Extensional cracks show a Left-step en echelon form occurred at Loc.4 (view east). (g) Extensional cracks occurred in the jog area between two distinct shear faults at Loc.2 (view southeast).

3. GENERAL CHARACTERICS OF THE SURFACE RUPTURES

The surface ruptures accompanying with the Chi-Chi earthquake occurred on the northwestern side of Taiwan extend from Tsoolan town, Taichung country in the northern end to Chushan town of the Nantou country in the southern end for approximately 100 km (Fig.1). The surface ruptures are distributed in a narrow zone of several to several tens of meters, but generally are concentrated to a strip of 5-10 m wide on the pre-existing Chelungpu fault (called Chelungpu surface rupture zone in this study). The Chelungpu surface rupture zone is composed of many distinct shear faults (Fig.2), surface flexure-folding structures (Figs.3, 4a-d) and extensional cracks (Figs.4e-g). Topographically, the Chelungpu surface rupture zone occurred almost along a boundary between the mountain ranges and basins. The distinct shear fault planes are generally observed at outcrops exposed in the valley (or river) channels where the bedrocks are exposed or covered by thin (generally <several m in thickness) alluvial deposits (Figs.2a, g). The flexure-folding structures were frequently found in the alluvial fans and terraces where the thick (generally >several m in thickness) alluvial deposits overlay the bedrocks. The extensional cracks are widespread along the surface rupture zone, but better occurred in the hinge area of the flexure-folding structures and the flexure-fault scarps, which commonly show a right-step en echelon form (Figs.4e-g).

4. DISPLACEMENTS AND SEGMENTATION OF THE SURFACE RUPTURE ZONE

After the earthquake, several research groups measured the displacement of the surface ruptures independently in field¹⁷⁻¹⁹⁾, but their results were significantly inconsistent. The different results are probably obtained by using some different measurement methods. For this study, we measured and calculated the displacement by using the method shown in Fig.5. The Chelungpu surface rupture zone occurred almost along a boundary between the mountains and basins where the Quaternary alluvial or terrace deposits generally overlay. The reverse (or thrust) fault scarps formed during co-seismic displacement were usually disturbed, and collapsed in some cases. The fault planes were exposed only at several locations along some river channels where the bedrocks were already exposed before the earthquake. It is difficult, therefore, to measure the displacements directly on the fault scarps where the unconsolidated alluvial deposits covered. In this study, the vertical displacement is calculated by measuring the topographical profiles across the fault-flexure scarps (Figs.5a, b), and measured directly on the fault scarps where the bedrocks were exposed on (Fig.5c). It is well-known that the horizontal shortening associated with thrust or reverse faulting could result in apparent strike-slip movements (apparent horizontal displacements)²⁰⁾. In order to understand the strike-slip movement sense and horizontal displacement component, we carefully measured the vertical and horizontal displacements along the surface rupture zone by using some distinguishable surface deformation markers such as road, footpath, wall and fence which are generally perpendicular to the surface ruptures (Fig.5). The measured results are shown in Fig.6. The displacements vary from 1-11 m horizontally and 1-7.5 m vertically, but are generally 1-3 m horizontally and 2-5 m vertically, except in the northern end segment. The maximum displacements measured in the northern segment are 11.1 m horizontally and 7.5 m vertically, respectively, which are the largest amounts observed in the surface fault ruptures formed by co-seismic reverse (or thrust) faulting reported so far for inland earthquake as shown in Yeats et al. (1996)²¹⁾.

The Chelungpu surface rupture zone can be divided into four segments: A, B, C and D (Fig.6), based on the distribution characteristics of co-seismic displacements, geometry of the surface rupture zone, and geological structures. These four segments generally form a right-step en echelon form. The jog areas between two segments are generally connected with some surface ruptures and extensional cracks striking E-W to NW-SE. The segments B-D are generally composed of a <10 m narrow surface rupture zone striking NNE-SSW to N-S, which are distributed along the boundary between the mountain ranges and basins and almost along the pre-existing Chelungpu fault. Segment A is a 11-km-long rupture zone striking NE-SW to ENE-WSW, which is composed of a series of 10-100-m-wide rupture zones, including many extensional cracks striking E-W to WNW-ENE. The general trend of segment A is oblique to that of the other three segments and is distributed along the unmapped pre-existing faults. The

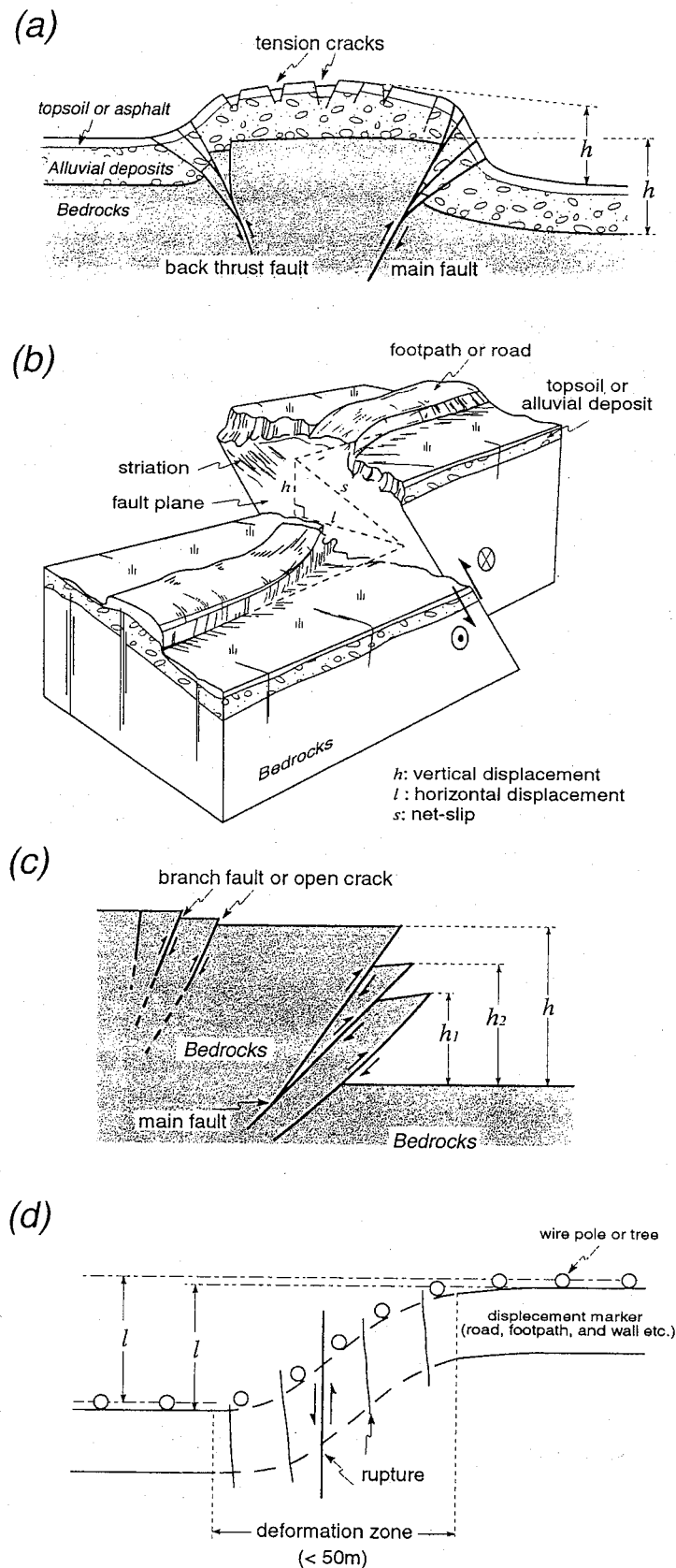


Fig.5. Schematic diagram showing the methods used to measure the displacements. (a): Vertical displacement (h) is measured on the flexure-fault scarp by using the topographical deformation markers such as terrace and alluvial fan surfaces in the region where the bedrocks are covered by thick deposit layers. (b): 3-D schematic diagram shows that the displacements are measured by using the surface deformation markers such as footpath and road in the region where the bedrocks are overlain by thin deposit layers. (c): Vertical displacement (h) is measured directly on the fault outcrop where the fault planes are exposed in bedrocks. h_1 and h_2 : Vertical displacements in the branch faults. Horizontal displacement is measured by using the surface deformation marker such as road, footpath and wall, etc., which are almost perpendicular to the surface rupture.

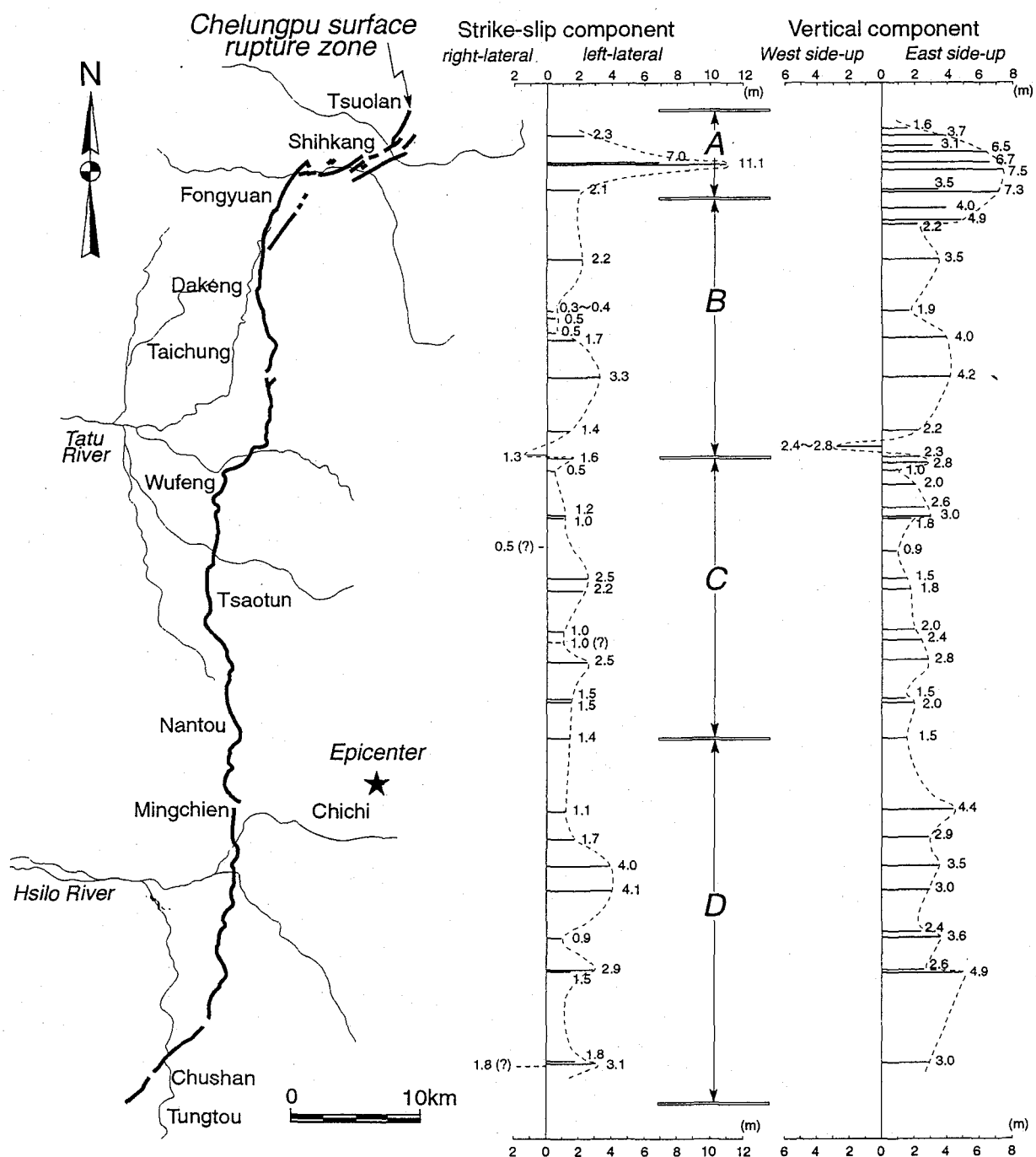


Fig.6. Map shows the distribution of horizontal and vertical displacements along the Chelungpu surface rupture zone. Details see text.

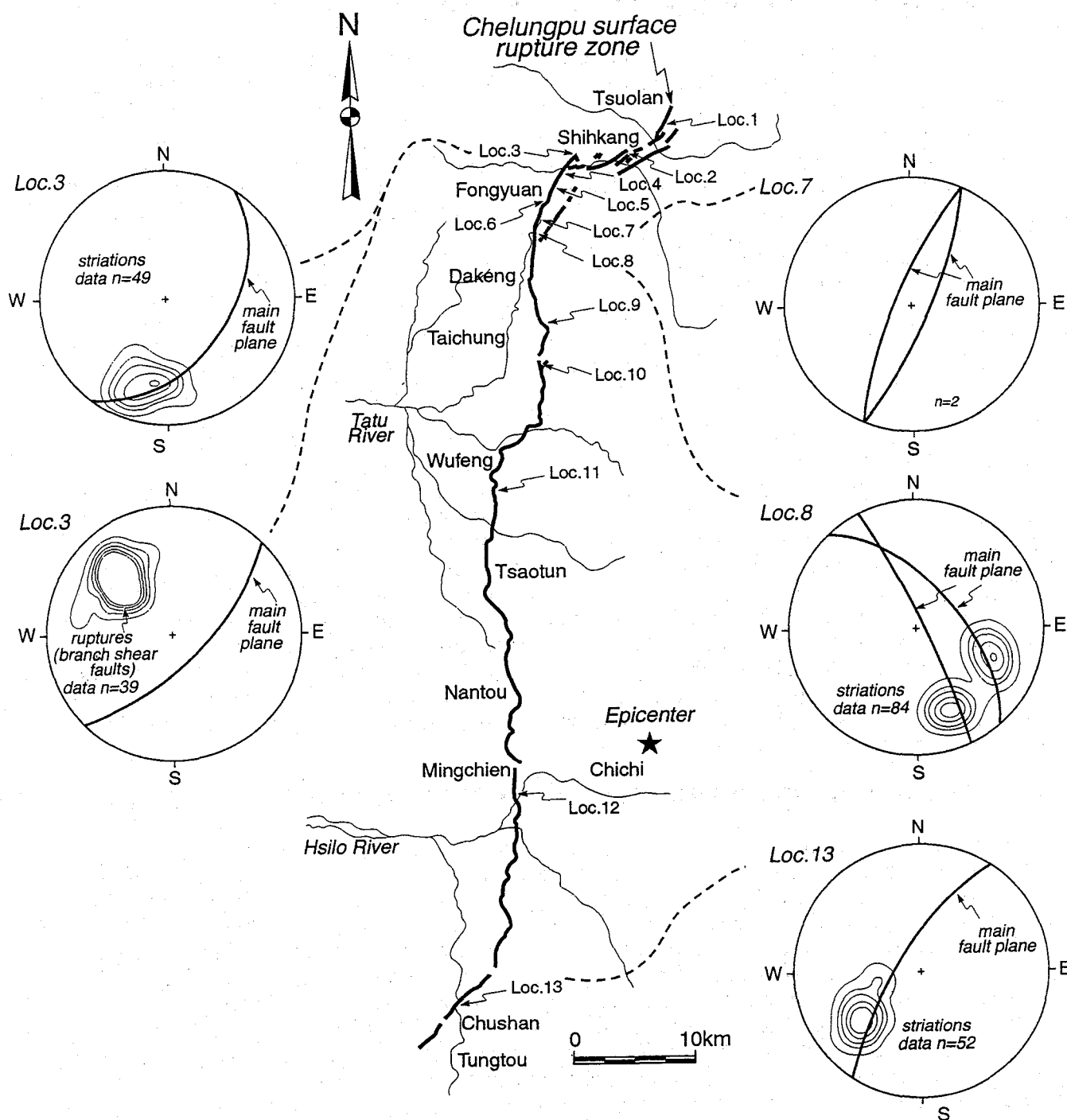


Fig. 7. Equal area projections of striations and co-seismic faulting planes (Lower hemisphere). Counters (per 1% area): 1%, 5%, 10%, 20%, 30% and >30%.

largest displacements and the maximum horizontal and vertical displacements generally occurred along segment A, and the less horizontal and vertical displacements along segment C. Segments B and D have a similar amount both in vertical and horizontal displacements (Fig.6). The details are discussed below.

5. CO-SEISMIC FAULTING PLANES AND STRIATIONS

The reverse (or thrust) flexure-fault scarps formed by the co-seismic faulting are well-observed along the Chelungpu surface rupture zone (Figs.3b-f). The co-seismic faulting planes, however, can only be observed in several outcrops exposed in the valley (or river) channels where the bedrocks were exposed before the earthquake (Figs.2a-b, g-h) because the fault planes occurred in the unconsolidated alluvial deposits are generally disturbed due to collapse of reverse (or thrust) fault scarps. The co-seismic faulting planes found in five outcrops vary their trends from WNW-ESE to NE-SW, but generally strike NE-SW and dip east with 50° - 85° high-angles (Fig.7). Some fault gouge thin layers of a few mm to a few cm thick are common on the co-seismic faulting planes (Figs.2b, g). This shows that the co-seismic displacement occurred along the pre-existing fault planes.

A number of striations generated on the fault planes by the co-seismic displacement can be observed at several locations. The slickenside striations were measured at three locations (Fig.7) where the slip direction was well determined with the reference of displaced surface markers along the surface ruptures. It is usually difficult to determine which striations were generated during or before this earthquake. It is easy, however, to recognize the striations generated during the co-seismic faulting in these three locations, because they were generated on the thin fault gouge layers, a few mm to a few cm in width and are light-gray, gray to light-brown in color (Figs.2b, h). The striations are marked by parallel lineations in the fine-grained materials with some grooves several mm to 2-3 cm wide. At Loc.8, the main fault plane is bounded with terrace deposits, where the scratches and furrows were produced by the rotation of pebbles (Fig.2g). The plunges of striations were measured at these three locations and plotted on Schmidt net shown in Fig.7. It is clear that the striations have a concentrated tendency plunging 25° - 35° southeast to southwest at these three locations where the fault planes have high-angle dips of 50° - 85° . This indicates a left-lateral displacement sense with a large thrust component. The sense of fault movement indicated by the striations at Loc.3 shows that the horizontal displacement component is larger than the vertical displacement component. This is in accordance with that measured on the surface at Locs.3 and 4 where the maximum displacement are 11.1 m in horizontal and 6.7 m in vertical, respectively.

6. FLEXURE-FOLDING STRUCTURES AND SHORTENING AMOUNTS

The near-surface deformation in contractile regions is expressed by flexural-slip folding, in which a sequence of relatively stiff bedrocks, alternating with thin, more flexible, less-stiff bedrocks, is accommodated by slip on mechanically weak bedding surfaces²¹⁻²²⁾ (Fig.5a). This type of near-surface deformation structures formed by co-seismic faulting is common^{21,23-28)}.

The near-surface flexure-folding structures generated by the co-seismic faulting during the Chi-Chi earthquake are also common along the Chelungpu surface rupture zone (Figs.3, 5a). Typical flexure-folding structures were observed on the hanging wall in or near the surface rupture zone from a few tens of meters to a few hundreds of meters in width (Figs.3, 8, 9). The original level topographical surfaces such as paddy fields, terraces and flat roads were folded like curves and waves in shape, and the flexure-folding axes struck NE-SW parallel or oblique to that of the surface rupture zone. The flexure-folding structures are also present on the back-thrust fault zone which are a few to several hundreds of m far from the main rupture zone (Figs.8a, 9a). Some extension cracks are common on the hinge area of the flexure-folding structures, showing a right-step en echelon form (Figs.4f, g).

The co-seismic flexure-folding should produce deformation and shortening of near-surface strata. The shortening amounts in a wide region have been detected by GPS⁸⁾. It is, however, difficult to measure directly in field the shortening amounts produced by the co-seismic faulting in or near the surface rupture zone because most of the fault scarps were disturbed or collapsed. The horizontal shortening amounts produced by the co-seismic faulting and folding, in a zone of a

Flexural folding structures

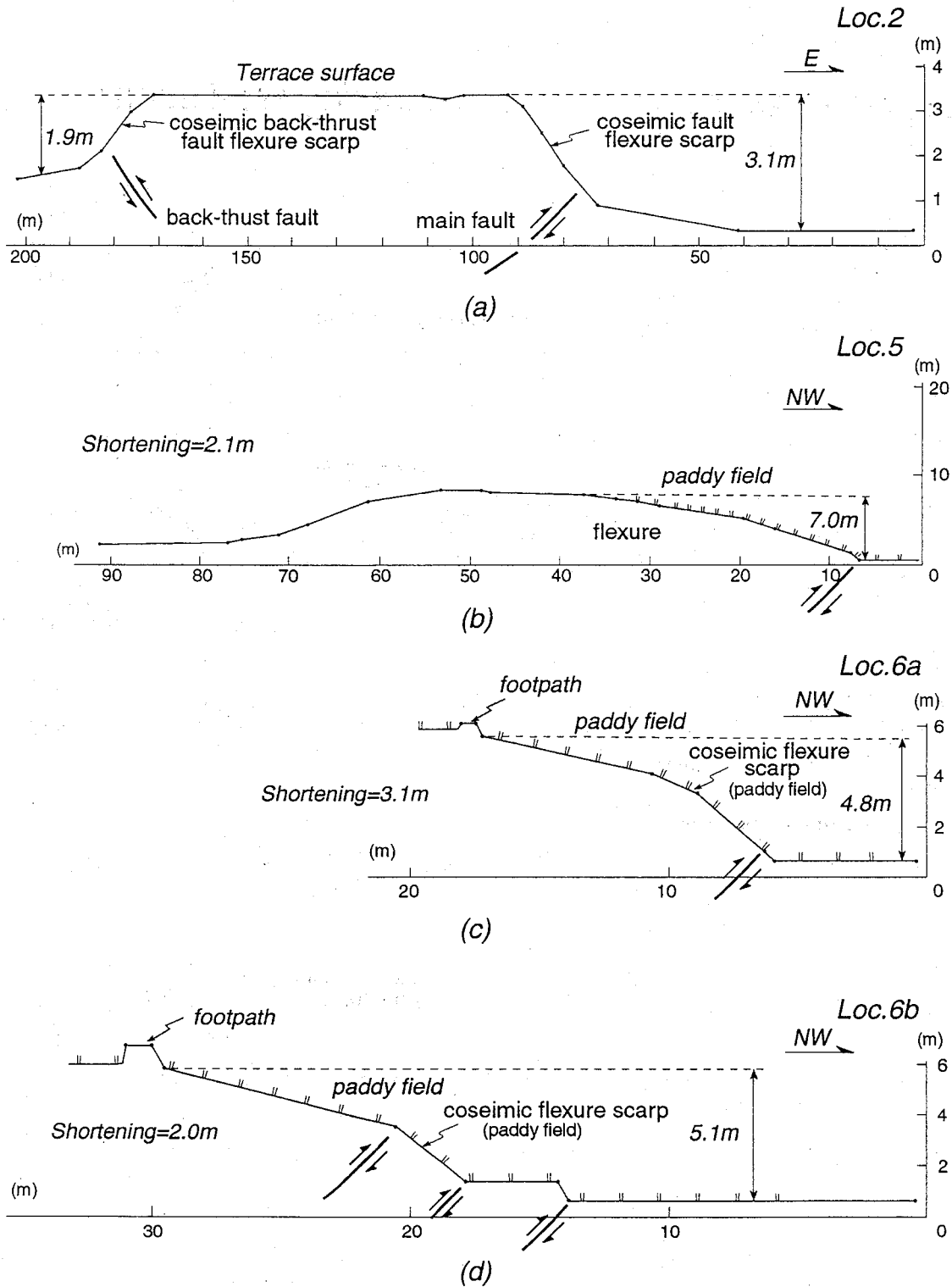


Fig.8. Topographical profiles of the flexure-folding structures occurred at Locs.2, 5 and 6. The flexure-folding structures were generated in paddy fields and terraces. The shortening amounts measured and calculated by using the method shown in Fig. 10 are 2.1 m at Loc.5 and 2.0-3.1 m at Loc.6.

Coseismic fault scarp and pre-existing fault scarp

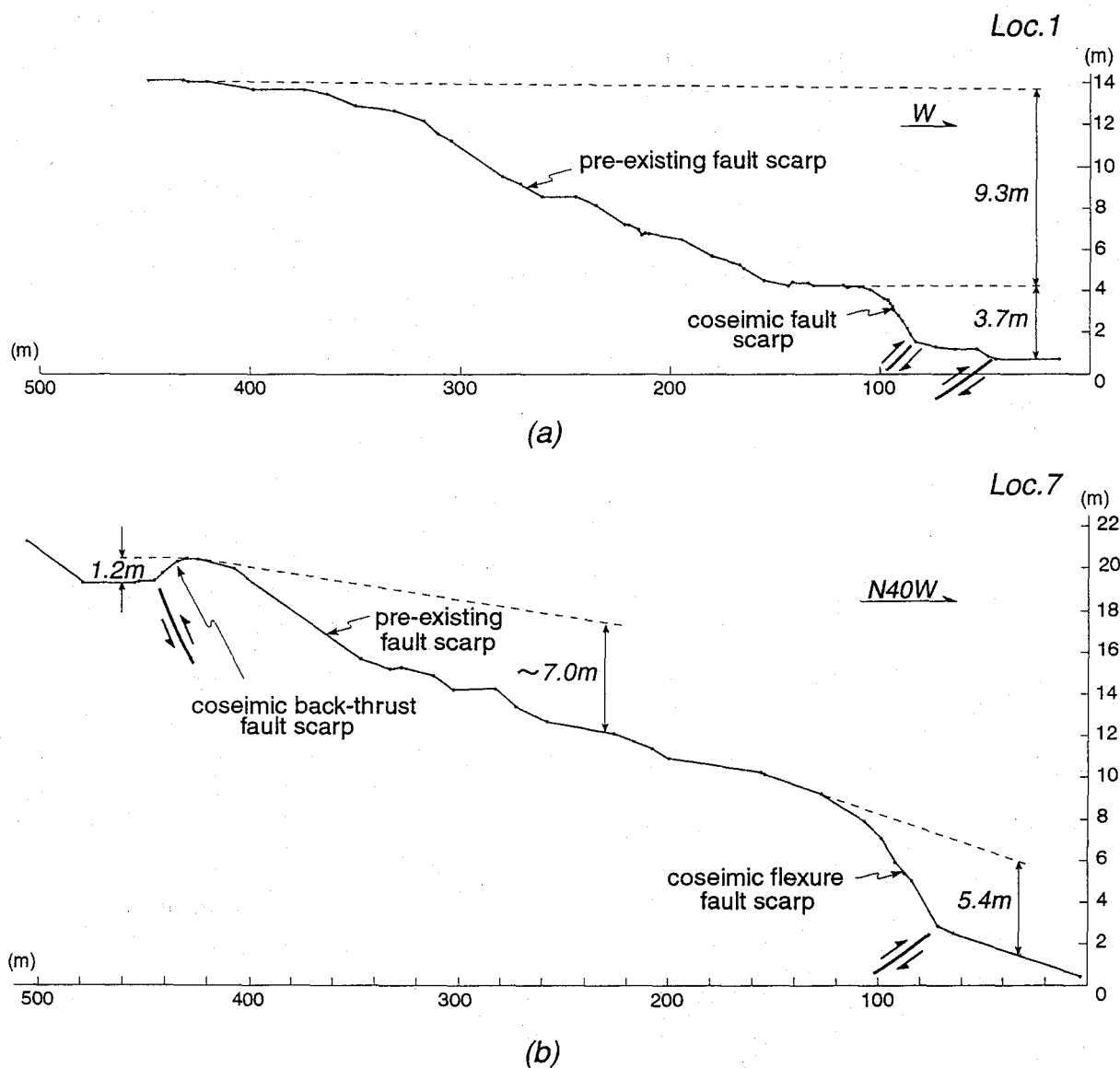


Fig.9. Topographical profiles of the flexure-fault scarps occurred in terraces at Locs.1 and 7. Note that the coseismic flexure-fault scarps occurred in a new location about 200 m far from the pre-existing fault scarps of 7-10 m high. This shows that the accumulative deformation occurred in the same location.

few tens of m to a few hundreds of m from the main rupture zone were measured and calculated in the following two cases shown in Fig.10. One, the horizontal shortening was mainly formed by thrusting in the river channels where the bedrocks are exposed and the co-seismic faulting planes can be observed well (Fig. 10a). Secondly, the shortening was caused by flexure-folding in the region where the bedrocks are covered by the thick alluvial deposits and topsoil layers which were folded but not displaced on the surface (Fig. 10b). The shortening amount in the former case can be measured and calculated easily by using the dip of fault plane and vertical displacement (Fig. 10a), and the amounts in the later case are calculated by using the curved surface length and the horizontal length as shown in Fig. 10b. The shortening amounts measured at 4 locations are 2.4 m in the fault outcrop (Loc.4) where vertical displacement is 6.7 m (Figs.6.7), and 2.0-3.1 m in the flexure-folding zone of 10-100 m wide at Locs.5 and 6 (Fig.8), respectively. The results show that the shortening amounts formed by the co-seismic faulting and flexure-folding in a <200 m wide zone in or near the main surface rupture zone are approximately 2-3 m in order. This amount is much less than that measured by GPS in a wide region. The relationship between these two horizontal shortening amounts measured by GPS and this study is discussed below.

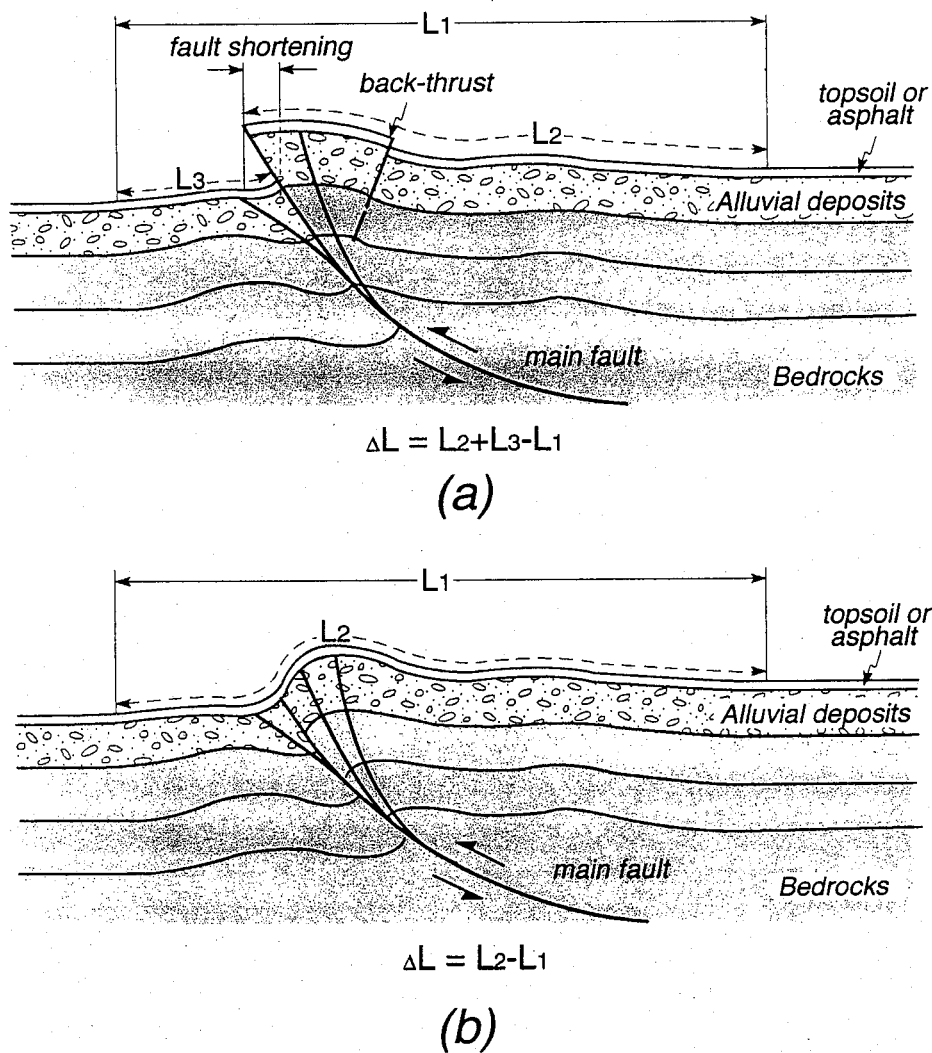


Fig.10. Schematic diagram showing the methods used to measure the shortening amounts on fault scarp (a) and flexure-fault scarp (b). Not to scale.

7. DISCUSSION AND CONCLUSIONS

(1) Tectonic Significance of the Co-seismic Displacements

The fault displacement that caused the Ms7.6 Chi-Chi earthquake ruptured the mapped Chelungpu fault in the main rupture zone and unmapped pre-existing fault in the northern segment. We are documenting the displacements along the surface rupture zone because the slip amounts of the surface ruptures at the surface may quantitatively reflect the faulting process along the earthquake source fault in the subsurface. The combination of the pattern of surface ruptures, displacements and the geometry of surface ruptures provide an unusual opportunity to document the nature of surface ruptures.

The term of "co-seismic displacement" is employed commonly in the prompt publications related to the Chi-Chi earthquake^{8,17-19}. There are two different meanings of the term used in these publications: one is used for the fault displacements both in vertical and horizontal measured along the narrow surface rupture zone of a few of m to a few tens of m as that shown in this study; another is used for the near-surface horizontal shortening and the uplift amount as that measured by GPS in a wide region of a few of m to several tens of km away from the surface rupture zone. The co-seismic displacements measured by GPS on both sides of the Chelungpu fault suggest that the eastern side (hanging wall) of the fault was moved northwestward 3-8 m horizontally and upward 2-4 m, while the western side (foot wall) was moved east- to northeastward <1 m horizontally and upward < 0.5 m⁸. The GPS data also show that the co-seismic deformation of the near-surface shallow crust occurred in a wide region up to several km on both sides of the surface rupture zone. The shortening amounts caused by thrusting in a narrow zone of <200 m near the surface rupture zone, as stated above, are in the order of 2-3 m, which are 3-5 m less than that measured by GPS. The displacements measured by GPS include the shortening amount caused by the co-seismic thrusting in the rupture zone and the co-seismic flexure-folding in a several-km-wide zone. Therefore, the displacements detected by GPS are not the co-seismic slip-amounts generated in the surface rupture zone, which probably reflect the deformation of the shallow crust in a wide region up to several to several hundred of km. The maximum displacements measured by GPS data are distributed in the northern segment A, which are also consistent with that measured in this study along the surface rupture zone. The vertical displacements measured in this study along the surface rupture zone are 6-11 m in the northern segment A, and 2-5 m in the other three segments B-D which are generally larger than the uplift amounts measured by GPS. The changes of level elevation on the sections across the Chelungpu fault along the segments B-D measured before and after the earthquake⁴ show that the co-seismic vertical displacements (uplift amounts on the eastern side) of the Chelungpu fault are about 2-5 m, which are consistent with that measured in this study. The focal mechanisms show that the maximum slip occurred in the northern segment (segment A) and the minimum slip occurred in the hypocenter-neighboring segment (segment C)²⁹. This result is consistent with that measured in this study and shows that the co-seismic displacements observed along the surface rupture zone are a quantitative surface indicator of the fault slipping on the earthquake source fault in the subsurface.

(2) Relations between the Surface Rupture Zone and the Pre-existing Geological Structures

The geometry of co-seismic surface ruptures not only reflects the surface morphology, but also shows the structural characteristics of depth tectonic environment^{28,30}. The Chelungpu surface rupture zone appeared along the geomorphological boundary between the mountain ranges and basins, which is also the geological boundary between the Neogene sediments and the late Quaternary alluvial deposits (Fig.1). The pre-existing Chelungpu fault trending along the geomorphological boundary displaced the alluvial deposits and formed fault scarp (Figs.2e, f, 3c). It is, therefore, clear that segments B-C of the surface rupture zone occurred roughly along the pre-existing Chelungpu fault, and segment A occurred along the unmapped pre-existing fault. The fault gouge layers observed on the fault plane show that the co-seismic faulting planes are the pre-existing fault planes of the fault zone. The co-seismic fault scarps occurred near or along the pre-existing fault scarps in the alluvial deposits show that the co-seismic displacement ruptured the pre-existing active fault (Figs. 2e,f, 3c). The flexure-folding structures generated during the co-seismic faulting occurred on both sides of the surface rupture zone where the bedrocks and

alluvial deposits have also been folded before the earthquake⁵⁾. These observations are summarized by Fig.11. The geological and geomorphological evidence documented in this study indicates clearly that the geometry of the Chelungpu surface rupture zone is controlled by the pre-existing geological structures.

The focal mechanisms determined by Harvard, SWBSN (Taiwan Central Weather Bureau Seismological Center) and ERI (Earthquake Research Institute of Tokyo University) show that the earthquake source fault is a 20°-30° low-angle thrust fault. The low-angle pre-existing fault planes are also observed in a few outcrops⁷⁾ along the Chelungpu fault, but where the surface ruptures are not found. The co-seismic faulting planes observed on the surface show that the Chelungpu surface rupture zone is generally a reverse fault zone dipping east with 50°-85° high-angle (Fig.7). In the geometry of fault, if the fault plane is 0° in dip, the fault trace on the surface would be followed the topographical contour which is curved or wriggled parallel to the boundary between the mountains and valleys or basins; and if the fault plane is 90° in dip, the fault trace on the surface is independent of topography and would be straight linear. That trace of the Chelungpu surface rupture zone across the hill and valley area is generally linear or slightly curved shows clearly that the main co-seismic near-surface faulting plane is a high-angle fault plane. We interpret, therefore, that the main co-seismic shear fault of the surface rupture zone is controlled by a main high-angle near-surface branch fault of the Chelungpu fault zone. The relationship between the geometry of the surface rupture zone and geomorphology, dips of the fault plane and striations on the main fault plane generated during the co-seismic displacement, show that the Chelungpu surface rupture zone is a reverse fault zone with a large left-lateral component.

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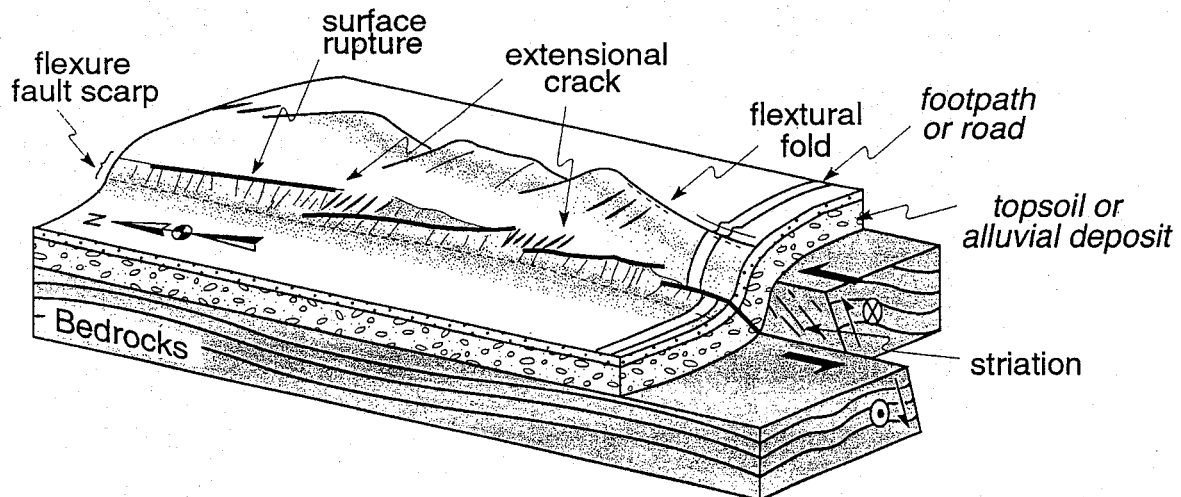


Fig.11. Schematic diagram showing the surficial features associated with Chelungpu surface rupture zone. Not to scale.

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Authors: 1) Department of Earth & Planetary Sciences, Faculty of Science, Kobe University, Kobe 657-8501, Japan. Present address: Institute of Geosciences, Faculty of Science, Shizuoka University, 836 Ohya, Shizuoka 422-8529, Japan

2) Research Center for Urban Safety and Security, Kobe University, Kobe 657-8501, Japan

3) Institute of Applied Geophysics, National Taiwan Ocean University, Keelung, Taiwan

4) Graduate School of Sciences and Technology, Kobe University, Kobe 657-8501, Japan

