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# Reply to "Comment on 'A Vertical Exposure of the 1999 Surface Rupture of the Chelungpu Fault at Wufeng, Western Taiwan: Structural and Paleoseismic Implications for an Active Thrust Fault,' by Jian-Cheng Lee, Yue-Gau Chen, Kerry Sieh, Karl Mueller, Wen-Shan Chen, Hao-Tsu Chu, Yu-Chang Chan, Charles Rubin, and Robert Yeats," by Yuan-Hsi Lee, Shih-Ting Lu, Tung-Sheng Shih, and Wei-Yu Wu

by Jian-Cheng Lee, Charles Rubin, Karl Mueller, Yu-Chang Chan, Hao-Tsu Chu, Yue-Gau Chen, Kerry Sieh, Wen-Shan Chen, and Robert Yeats

## Introduction

We welcome Y. H. Lee *et al.*'s interest in our article (Lee *et al.*, 2001). We thank them for their comment, which provides a further opportunity for discussing the quantifi-cation of the slip amounts including horizontal and vertical components and the fault geometry for an earthquake thrust scarp in Wufeng, western Taiwan, during the 1999 **M** 7.6 earthquake.

In their comment, Y. H. Lee *et al.* used restoration of deformed concrete fence across the 1999 scarp to estimate the slip vector of the main fault. The estimated slip amount, especially the horizontal component, is different (significantly less) from our results presented in the 2001 BSSA article. They then applied an "area-balance" technique to compare their results with ours. They showed that their areabalance method favored their estimates including the slip amounts and the fault dip angle. They concluded that their estimated slip amounts are more reasonable than ours.

The fundamental questions in this issue, in our opinions, include the actual amounts of deformation (slip) and the associated deformation processes, as well as the limitation and uncertainty of the applied techniques on an earthquake-formed thrust scarp. Hereafter we attempt to answer these questions and clarify the related problems.

## Uncertainty of the Estimates

First, we shall discuss the techniques of the estimates of the horizontal shortening used for Y. H. Lee *et al.* and for our previous article. It is important to know the limitations, the uncertainties, and the possible sources of errors for any estimate or calculation of the deformation, which enables us
to evaluate the results. For our line-balancing method in the previous article, the uncertainties come mainly from the complicated deformation near the main fault zone, for instance, the overlapped structures and the ductile deformation. In particular, stretching and thinning of the sedimentary layers can be clearly observed around the core of the popup fold. The stretching effect of the depositional layers
yields an overestimation of the actual amount of shortening across the thrust scarp. On the other hand, the missing and overlapped structures yield an underestimation of shortening amounts. The clearly observed stretching layers around the core of the small pop-up fold immediately east of the main scarp suggest a slight overestimation of horizontal shortening from our line-length measurement. Thus we acknowledge that we have seemingly yielded an overestimated amount of the horizontal shortening, 3.3 m, which should be slightly less. However it is not likely to be half of this amount, as suggested by Y. H. Lee *et al.* This argument is also based on the observation of the deformation degree of the sedimentary layers involved in the estimates.

On the other hand, we are not able to evaluate the uncertainty of the techniques for the reconstruction of Y. H. Lee *et al.* Their Figure 1C illustrated the principle and the general idea of the reconstruction from the broken concrete fence. However, they did not describe in detail their measurements and calculation techniques. Without this information, it is difficult to evaluate their results. Even though the technique would be straightforward, there are always sources of error during the processes of making estimates. We cautiously anticipate that mistakes could occur due to the incompleteness of the broken fences. We speculate that their resulting horizontal shortening of 1.77 m might be too small. We will come back to this later.

We also want to discuss the area-balance method used by Y. H. Lee *et al.* They introduced the area-balance method to check the slip amounts yielded from our line-balance method and from their restoration of concrete fence. Their

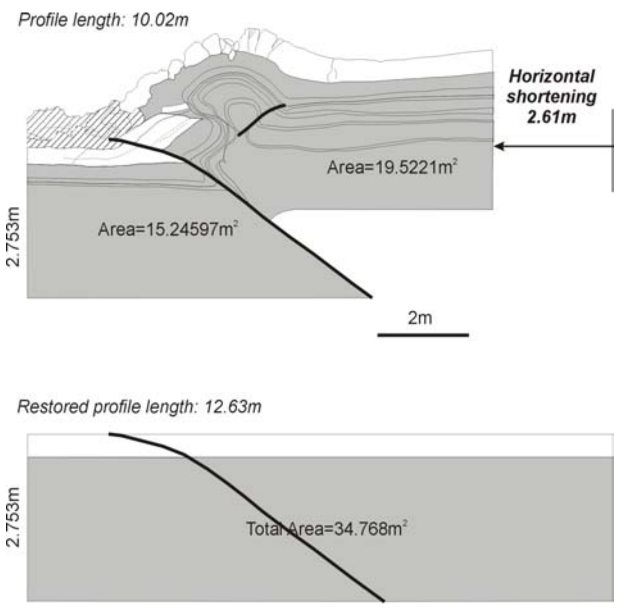


Figure 1. Restoration of the scarp and pop-up anticline based on area-balancing technique. The units of the complete assemblage (except the uppermost spoiled human soil) were used for retro-deformation. Based on the average thickness of 2.7 ±0.1 m and the area of 34.77 m2, it yields a estimate profile length of 12.6 ± 0.2 m or 2.6 _ 0.2 m of horizontal shortening.

area-balance method itself, in effect, cannot yield an estimate of the slip amounts but provides a tool to test the accuracy of the estimates of slip amounts and fault geometry. Y. H. Lee *et al.* argued that their results of 1.77 m horizontal shortening and 50_ dip angle gave the better fit for the area-balance check. However, there is a tradeoff between the dip angle and horizontal shortening in this area-balance technique. The same best fit can also be yielded by larger horizontal shortenings with lesser dip angles. Although the 3.3m of horizontal shortening in our previous *BSSA* article seems to be overestimated, their 1.77 m horizontal shortening cannot be verified solely by their area-balance check-tool. Furthermore, their resulted fault dip angle of 50_ is much larger than the observed fault dip of 34_–39_ in the excavation near the base of the trench.

## Another Area-Balancing Estimate

We thus provide another area-balance technique, which is capable of yielding the amount of the horizontal shortening. The principle of this technique and its estimate for this particular Wufeng excavation are illustrated in Figure 1. The essence of this area-balancing technique is to use the same area, which also corresponds to the original horizontally lying sedimentary layers before and after the earthquake. This technique has also been broadly used in the process of restoration for balanced cross section (Woodward *et al.*, 1989). Geometrically, on the vertical exposure in this case, the area for specific layers can be obtained by multiplying the length and the thickness. The amount of the area for the specific layers, which has deformed during the earthquake, would remain the same prior to the earthquake, assuming there was no significant density change. The amount of the area after the earthquake can be obtained by detailed mapping on the vertical exposure. We can then calculate the original length before the earthquake by dividing the amount of the area into the thickness of the specific layers. By comparing this with the present length, we obtain the horizontal shortening parallel to the exposure for these layers. Because details of this technique are presented in a separate article (Lee *et al.*, 2003), we show only the results from this area-balance method (Fig. 1). This method yielded a horizontal shortening of 2.6±0.2 m, which is between the estimates from Y. H. Lee *et al.* and from our previous line-length method.

Considering the geometry of the involved deformation structures across the thrust scarp, including the major fault, secondary faults, and fold, we can further differentiate the deformation processes into two structural levels. The lower level dealt with the slippage on the 39_ east-dipping main thrust fault with 2.1–2.3 m of horizontal shortening and 1.8 m of vertical displacement. The upper level, consisting of a high-angle wedge thrust, two opposing secondary thrusts, and an associated pop-up anticlinal fold, provides an additional deformation with 0.3–0.5 m of horizontal and vertical components of movement. Because the results of our later area-balance method are rather consistent with the geometry and the kinematics of the deformation structures observed in the excavation, we are more comfortable with these results.

## Comparison with the Neighbor Site

Y. H. Lee *et al.* also made an estimate of surface slip motion by reconstruction in a neighboring parking lot, some 250 m south of the excavation site. They obtained a horizontal slip of 2.5–2.67 m and a vertical displacement of 1.3–1.5 m, which yields an averaged fault dip angle of 28°. At the same location, we obtained similar (though slightly larger) amounts of horizontal slip (2.82 _ 0.40 m) and vertical offset (1.62 _ 0.06 m) (Angelier *et al.*, 2003), which yielded a fault dip angle of 30_. The amounts of the horizontal shortening from both reconstructions in the parking lot are close to our latest estimate from the area-balance technique for the excavation site (see comparison in Table 1).

Although it is not necessary that the surface fault motions be identical on the two neighboring sites (for instance, there was stronger localized anticlinal folding near the major scarp at the excavation site), the results of reconstruction of the slip amounts in the parking lot site suggest that our latest area-balance estimate provides the

Table 1
Estimates of Slip Amounts and Dip Angle of the Primary Thrust Fault During the 1999 Chi-Chi Earthquake in the Excavation Site and the Parking Lot Site, Wufeng City, Western Taiwan*

| | Excavation site | | | Parking lot site | |
|---|---|---|---|---|---|
| | Lee *et al.*, 2001 | Y. H. Lee *et al.* | Our revised model | Y. H. Lee *et al.* | Angelier *et al.*, 2002 |
| Horizontal shortening (m) | 3.3 ± 0.3 | 1.77 | 2.6 ± 0.2 | 2.5-2.67 | 2.82 ± 0.40 |
| Vertical offset (m) | 2.2 ± 0.1 | 2.1 | 2.2 ± 0.1 | 1.3-1.5 | 1.62 ± 0.06 |
| Total slip (m) | 4.0 ± 0.2 | 2.75 | 3.4 ± 0.2 | 2.8-3.06 | 3.25 ± 0.38 |
| Thrust dip-angle (°) | 34 ± 3 | 50 | 39 ± 2 | 28 | 30 |

*Three estimates are presented for the excavation site, including from our previous article, Y. H. Lee *et al.*'s comment, and our revised model of area-balance technique. Two estimates are presented for the parking lot site, 250 m south of the excavation site along the strike of fault.

best agreement in terms of the geometry of the basal thrust and the slip amounts. This provides another favorable factor that we prefer to the estimates determined by our area-balance method.

## Further Discussion

Assuming Y. H. Lee *et al.*'s calculation from the broken fence on top of the surface scarp was correct, there are still other possibilities for explaining the discrepancy between
the different techniques of estimates. One likely possibility is that the discrepancy was due to strain transfer, from the semiductile deformation in the soil and sand materials of the alluvium deposits to the brittle ruptures of the concrete fence on top of the surface. In this case, the deposits of the soil and sand layers have absorbed more deformation than the concrete fence. This brings up the issue of decoupling along the boundary of different deformed materials and their response to deformation with various rheology during earthquake faulting. These phenomena have also been described at several places along the 1999 surface ruptures (Kelson *et al.*, 2001). It would be interesting to discuss the difference between the deformation on the surface level and that on the subsurface level; however, it is beyond the scope of the present study.

Finally, there is a possibility that Y. H. Lee *et al.* have made some mistakes on the restoration of the broken fence. This speculation also came from the fact that we found a segment of missing fence buried completely within the soil deposits in the core of the deformation zone beneath the scarp. If they indeed missed this _0.7-m-long segment of fence during the measurement, their result of the horizontal slip would be 2.47 m, rather close to our latest estimate. However, this speculation cannot be confirmed without details of their measurements.

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Institute of Earth Sciences
Academia Sinica
P.O. Box 1-55
Nankang, Taipei, R.O.C., Taiwan
(J.-C.L., Y.-C.C.)

Department of Geology
Central Washington University
Ellensberg, Washington
(C.R.)

Department of Geology
University of Colorado
Boulder, Colorado
(K.M.)

Central Geological Survey
P.O. Box 968
Taipei, R.O.C., Taiwan
(H.-T.C.)

Division of Geological and Planetary Sciences
100-23
Caltech
Pasadena, California
(K.S.)

Department of Geology
National Taiwan University
Taipei, R.O.C., Taiwan
(Y.-G.C., W.-S.C.)

Department of Geosciences
Orgon State University
Corvallis, Oregon
(R.Y.)

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