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THE MAJOR CAUSE OF THE WANFO TEMPLE COLLAPSE IN THE 1999 JIJI EARTHQUAKE: SHEAR BANDING

Tse-Shan Hsu
Department of Civil Engineering, Feng-Chia University
Taiwan R.O.C.
tshsu@fcu.edu.tw

Sheng-Nan Li
Ph.D Program in Civil and Hydraulic Engineering, Feng-Chia University
Taiwan R.O.C.

Hao-Yi Huang
Department of Civil Engineering, Feng-Chia University
Taiwan R.O.C.

Abstract

For the past thousand years, Taiwanese have continuously built temples in mountainous areas. However, the Ministry of the Interior issued the first version of the building seismic-resistant design code in 1974. Therefore, only newly built temples meet the building seismic-resistant design code. However, the fact shows that many temples that collapsed during the 921 Jiji earthquake are new temples. Therefore, the authors of this paper use the Wanfo Temple as an example to explore the reason why new temples that meet the design criteria are easy to collapse in the earthquake. Through this paper, it is found that the only earthquakes that can cause buildings to collapse are tectonic earthquakes, and the main effect of tectonic earthquakes is shear banding, and the secondary effect is ground vibrations. However, the current building seismic- resistant design codes only include the secondary effect and not the major effect.

Therefore, although the new temples are resistant to ground vibrations, it will still collapse under shear banding. In view of this, it is recommended that the building seismic-resistant design code should include both primary and secondary effects. Only in this way can the new temples be prevented from collapsing in the future tectonic earthquakes.

Keywords: temple, collapse, tectonic earthquake, shear banding, ground vibration.

Introduction

Temples have been built in China since the Han Dynasty and most temples are built in the mountains. The choice of location of the temples comply with the rules of Feng Shui Theory (i.e., blue dragon to the left, white tiger to the right, rosefinch to the front, tortoise to the back). Moreover, the rules specify to "rather have lofty blue dragon than to have the white tiger by a foot higher" and "must have water at the rosefinch side". Therefore, the east side of the temple needs to be higher than the west side, and a river must flow from the east to the west in front of the temple. Because of this, most of the mountain temples are located in the concave hairpin bend as shown in Figure 1.

Figure 1. Temples are often selected in a concave hairpin bend located in the mountain area (Background image is from Google Earth, 2019).

Figure 1 shows the concave hairpin bend of the mountain, which is the intersection of various shear bands with different strikes. In large-magnitude tectonic earthquakes, when shear banding occurs, brittle rock fracture of the shear banding tilted slope will greatly increase, which also induces delamination and sliding failure of the side slopes.

In view of the above, an in-depth investigation of the major cause for the collapse of the Wanfo Temple in the 1999 Jiji Earthquake would be helpful in correctly revising the seismic design specifications of buildings and ensuring the safety of temples in the future.

Problem Description

The Ministry of the Interior of Taiwan (MOI) first promulgated the seismic-resistant design code for buildings in 1974 and successively revised the minimum vibration resistance required for buildings in 1982, 1989, 1997, 1999, 2005, and 2011. Since the overall structural designs meet the requirements of seismic design specifications for buildings, theoretically the temples built after 1974 should not collapse during earthquakes.

After the Jiji Earthquake in 1999, many old temples remained in Taiwan's mountain area. The designs of these old temples, which were more than a century old, were not based on the seismic-resistant design codes of buildings promulgated by the MOI. In other words, the design of these old temples, although not based on the specifications laid out by the MOI, could be stably and safely maintained even after numerous earthquakes events. In contrast, the structure of Wanfo Temple (Figure 2), which were built after 1974 in line with the seismic-resistant design code for buildings promulgated by the MOI, collapsed during the 921 Jiji earthquake within 30 years since their completion.

This shows that although the MOI has promulgated the seismic-resistant design specifications for buildings, it has not discussed whether it can ensure that the buildings that comply with the seismic requirements are stable and safe during earthquakes. Despite the continuing collapse of buildings during earthquakes, the effectiveness of the seismic-resistant design code has not been questioned yet. Therefore, after earthquakes, the researchers of the National Center for Research on Earthquake Engineering (NCREE) have always attributed the causes of collapse according to the seismic-resistant design code to underestimation of the vibration resistance required for structures. The officials even went as far as revising the

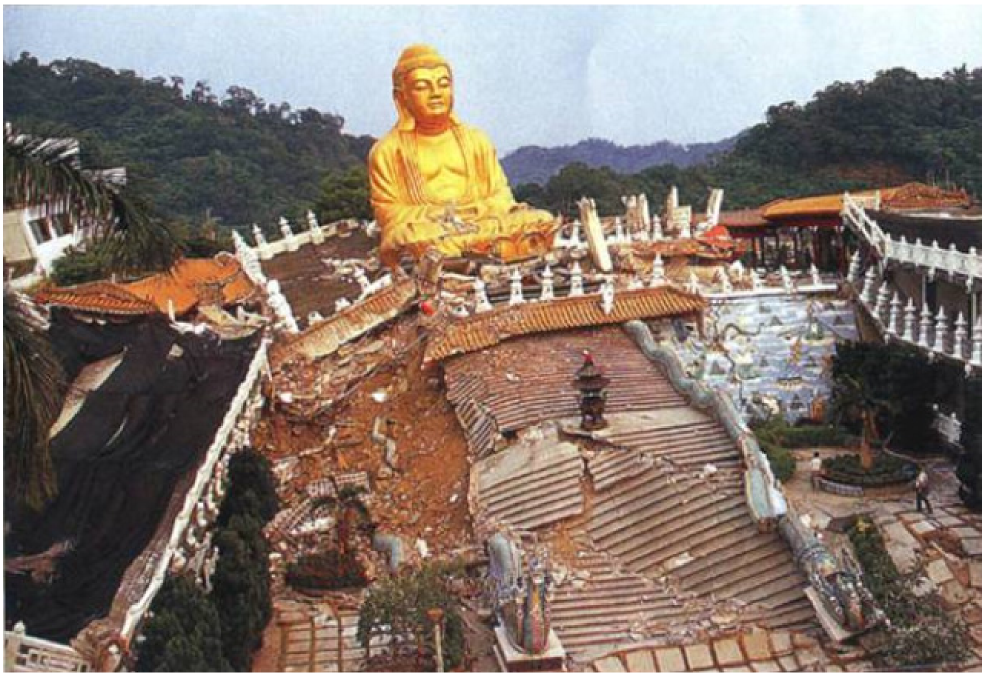


Figure 2. Collapse of the Wanfo Temple in the 921 Jiji earthquake (Wu, 1995).

seismic-resistant design specifications, only to continuously increase the vibration resistance of the superstructure elements such as columns, beams, plates, and walls.

However the main effect is shear banding, which accounts for more than 90% of the total energy of a tectonic earthquake; and the secondary effect is ground vibration, which only accounts for less than 10% of the total energy of a tectonic earthquake (Coffey, 2019). Therefore, it is almost impossible to ensure that the buildings designed to fully comply with seismic-resistant design specifications will not collapse during earthquakes.

The reasons that current seismic-resistant design specifications for buildings are focused only on protecting against ground vibration are the following: (1) The expertise of scholars or experts involved in the formulation or revision of the seismic-resistant design specifications for buildings is limited to structural dynamics and soil dynamics; (2) These scholars or experts have not considered the fact that five types of earthquakes exist: tectonic earthquakes, volcanic earthquakes, subsidence earthquakes, induced earthquakes (by cyclic storage-discharge of reservoir water), and artificial earthquake (by explosion). Most of the earthquakes are tectonic earthquakes, and only tectonic earthquakes can exceed a scale of $M > 6.0$

and cause disasters; (3) These scholars or experts believed that all five types of earthquakes contained only minor ground vibration effect, and therefore ignored the main shear banding effect of tectonic earthquakes (refer to Table 1); and (4) These scholars or experts have not considered the fact that increasing protection against ground vibration does not increase the disaster prevention effect any more than 10%; therefore, although the vibration resistance of buildings has continued to increase after previous earthquakes, in the past history, tectonic earthquakes have continued to create tragedies of hundreds of thousands or tens of thousands of deaths (refer to Table 2).

Table 1. Various effects of different earthquakes (Hsu, 2019)

Earthquake Type	Main Effect	Secondary Effect
Tectonic earthquakes	Shear banding	Ground vibration
Volcanic earthquakes	---	Ground vibration
Collapse earthquakes	---	Ground vibration
Induced earthquakes	---	Ground vibration
Artificial earthquakes	---	Ground vibration

Table 2. The 18 major earthquakes with the highest number of deaths in various countries around the world (Balkhi, 2019).

No.	Time	Location	Magnitude	Death Toll
1	1556-01-23	Shaanxi, China	$M_w = 8.0$	830,000
2	2004-12-26	Sumatra–Andaman, Indonesia	$M_w = 9.3$	280,000
3	1976-07-28	Tangshan, China	$M_w = 7.6$	242,000
4	1920-12-16	Haiyuan, Ningxia, China	$M_w = 8.5$	200,000
5	185^{th}	Damgan, Iran	$M_s = 7.9$	200,000
6	1948-10-6	Ashgabat, Turkmenistan	$M_s = 7.3$	160,000
7	1290-09-27	Inner Mongolia, China	$M_w = 6.8$	100,000
8	1755-11-01	Lisbon, Portugal	$M_w = 9.0$	100,000
9	1923-09-21	Kanto, Japan	$M_L = 8.2$	93,000
10	2008-05-12	Wenchuan, Sichuan, China	$M_w = 7.9$	87,587

11	2005-10-08	Kashmir, Pakistan	$M_w = 7.6$	85,000
12	1908-12-28	Sicily & Calabria, Italy	$M_w = 7.1$	82,000
13	1667-11-25	Shamakhi, Azerbaijan	$M_s = 6.9$	80,000
14	1721-4-26	Tabriz, Iran	$M_s = 7.7$	80,000
15	1970-05-31	Ancash, Peru	$M_L = 8.0$	74,194
16	1693-01-11	Sicily, Italy	$M_w = 7.4$	60,000
17	1949-09-20	Hokkaido, Japan	$M_w = 6.6$	26,000
18	2011-03-11	Tohoku, Japan	$M_w = 9.0$	15,500

Note: By death order

In view of the above, this paper focused on the Wanfo Temple and used various images to identify the shear band or shear texture that appeared in the earthquake in order to show that the Wanfo Temple located on the shear band or the shear textures will result in collapse during shear banding.

Literature Review

1. Feng Shui Theory of Temples. In general, the ideal temple orientation is shown in Figure 3. The figure shows that when the temple has an ideal configuration, the mountains on the backside can shield the cold current from the north in the winter. The river in the front meets the cool breeze blown from the south in the summer. This configuration also provides ample sunlight through embodying yin and embracing yang.

2. History of Taiwan’s Earthquake Resistant Design Code for Buildings.

Prior to 1974, the design of temples in Taiwan did not follow the seismic design specifications. Only the seismic design specifications of Japanese buildings were being used in which the minimum horizontal vibration force required for the buildings is given by the formula V = KW (National Center for Research on Earthquake Engineering, 2019).

In 1974, the MOI promulgated the first building technical rules. After dividing Taiwan into strong, moderate, and mild earthquake regions, the design vibration coefficients of buildings were separately specified for these earthquake zones. The minimum horizontal vibration force V required for the buildings is calculated as V = ZKCW (National Center for Research on Earthquake Engineering, 2019; Ye and Li, 2005).

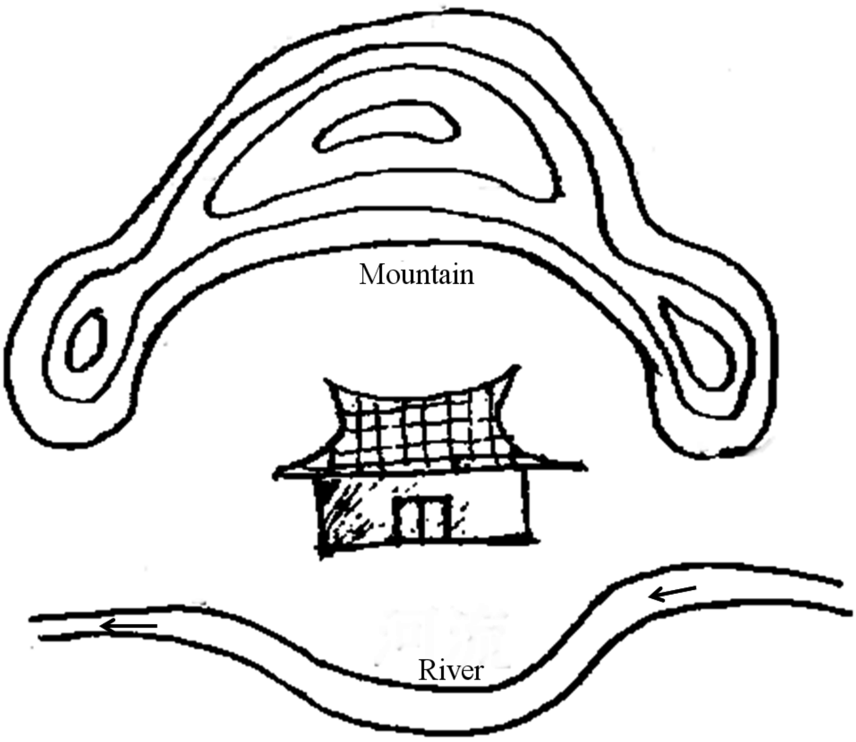


Figure 3. Ideal temple orientation (Wang, 1995).

In 1982, the vibration force coefficients of strong, moderate, and mild earthquake zones were revised to Z = 1.0, Z = 0.8, and Z = 0.6, respectively. The levels of importance for different uses of buildings were also devised accordingly (*I*). Therefore, the minimum horizontal vibration force V required for the buildings is calculated as V = ZKCIW (National Center for Research on Earthquake Engineering, 2019; Ye and Li, 2005).

In 1989, the basin effect and the vibration coefficient of the Taipei Basin *C* were updated (National Center for Research on Earthquake Engineering, 2019).

In 1997, the soil liquefaction assessment method was updated, and the site type and vertical vibration were taken into consideration. In addition, the earthquake zone was modified into the earthquake zones IA, IB, II, and III.

In 1999, the Central Geological Survey (CGS) of the Ministry of Economic Affairs (MOEA) revised the Chelungpu fault into Type 1 active fault; corrected the normalized acceleration response spectrum coefficient of the site;

adjusted the minimum vertical vibration force required for the buildings; and re-divided the earthquake zone into earthquake zones A and B.

In 2005, based on the near-fault effect of the 921 Jiji earthquake, the minimum horizontal vibration force required for near-fault buildings was added.

In 2011, the earthquake resistant design code for buildings was further revised, including structural systems and toughness capacity, site classification criteria, period upper limit coefficient, seismic micro-zoning designs of Taipei Basin, building spacing requirements, seismic isolation design, and items for determining soil liquefaction potential, such as surface horizontal acceleration.

3. Shear Band and Shear Texture. As shown in Figure 4, within the width of a shear band, some shear textures of varying strikes exist. These shear textures include the principal deformation shear D, the thrust shear P, the Riedel shear R, and the conjugate Riedel shear R', and the compression texture S.

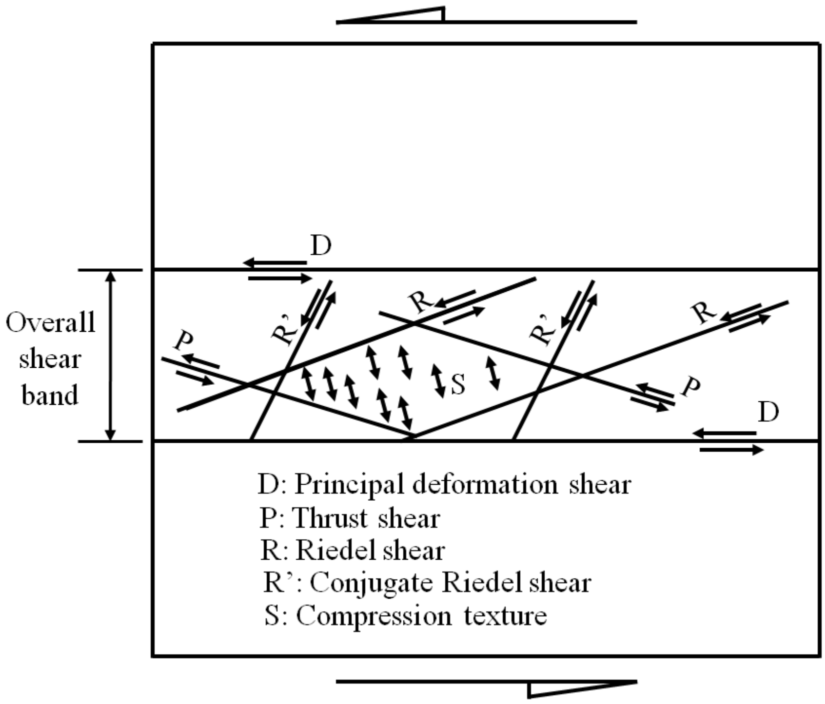
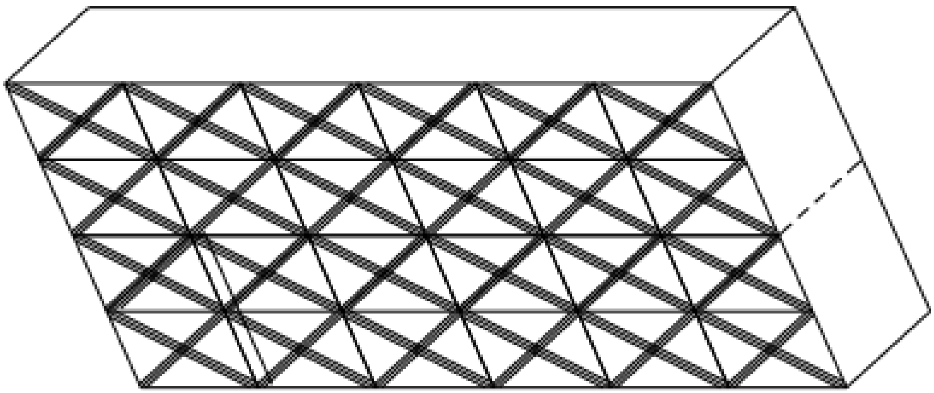
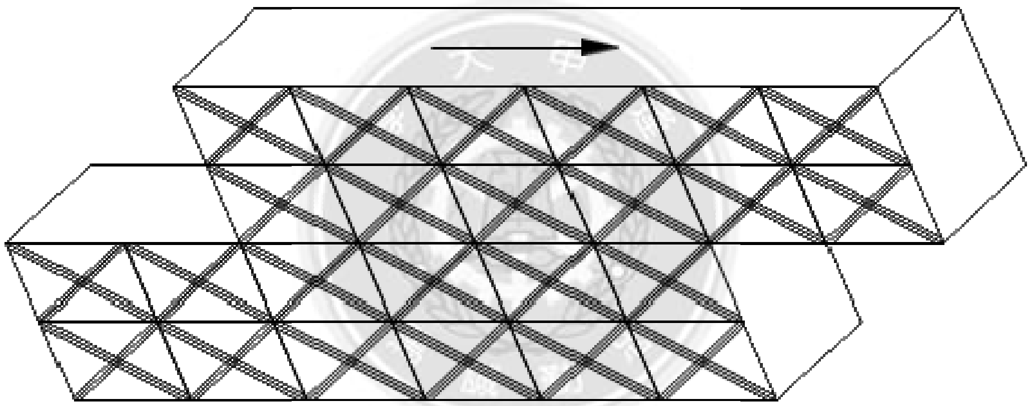


Figure 4. Various shear textures within the total width of a shear band (redrawn from Davis et. Al., 2000).

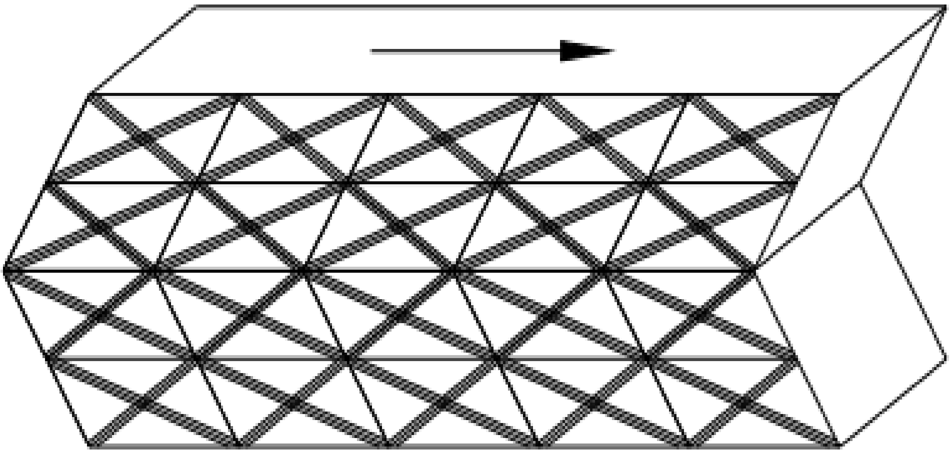
4. Types of Shear Bands. In 1983, Hertzberg (Hertzberg, 1983) proposed two different types of shear bands, namely, slip and twinning, based on the shear band block (detailed in Figure 5).



(a) Block before shear force is applied



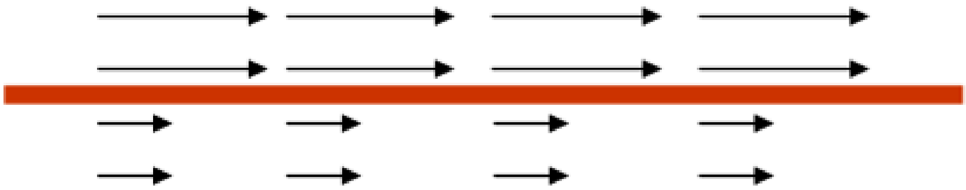
(b) Slip-type shear band block



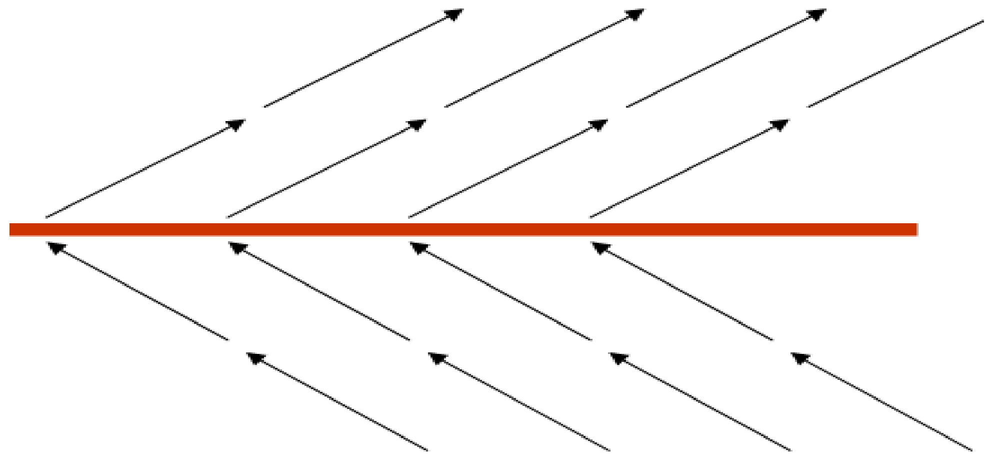
(c) Twinning-type shear band block

Figure 5. Two different types of shear bands proposed by Hertzberg (1983).

The two different types of shear bands shown in Figure 5 can also be represented by the velocity vector map (detailed in Figure 6). The twinning-type shear band is composed of the velocity vectors of equal magnitude and different directions, whereas the slip-type shear band consists of velocity vectors of equal directions and different magnitudes.



(a) Slip-type shear band



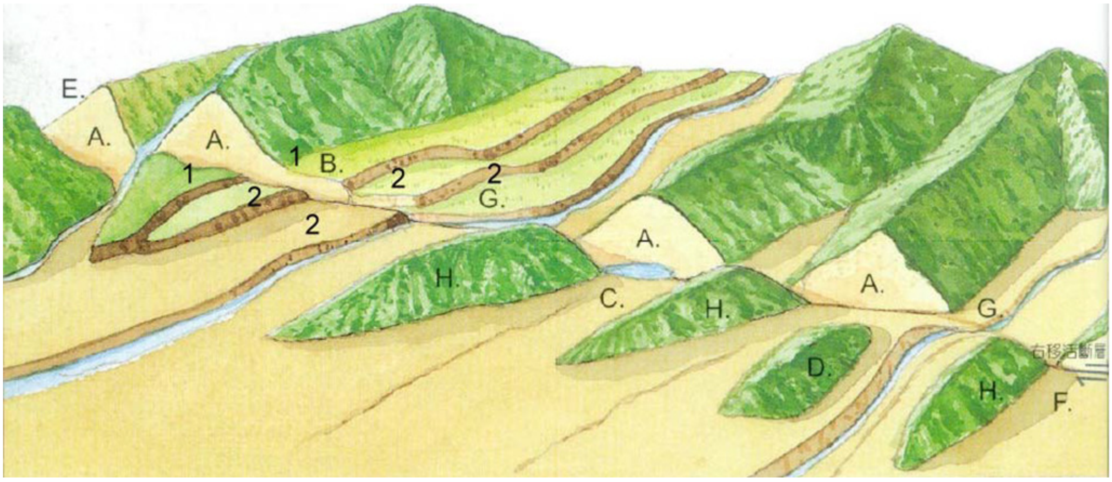
(b) Twinning-type shear band

Figure 6. Shear band types defined by a velocity vector map (Hsu, 1987).

5. Shear Banding Landform Features. The tectonic plates will retain some features due to shear banding. Vertical banding will produce a high and low differential terrain, and horizontal shear banding will produce a horizontal displacement terrain. The above-mentioned shear banding landform features are also called displaced landform features(Earle, 2004; Hsu, 2018; Taichung Literature Landscape, 2019).

The shear banding landform is obvious in the initial phase of the dislocation, and later on due to erosion or alluvial effect, it tends to be not so obvious.

Figure 7 shows various shear banding landform features. These features include: (1) tectonic depression including fault valley, fault sag, graben, fault trench, fault saddle, and fault angle basin, etc.; (2) tectonic scarp including fault scarp, flexure scarp, fault scarplet, reverse scarplet, and triangular facet, etc.; (3) fault scarp, a part of which has lineament and the other part becomes river erosion scarp due to the erosion by river; (4) tectonic bulge including horst, fault slice ridge, pressure ridge, mound, and fault-block mountain, etc.; (5) laterally offset including offset stream, offset of river terrace, and shutter ridge, etc.



Legend: (A) triangular facet, (B) low fault scarp, (C) fault sag, (D) bulge, (E) fault saddle, (F) horst, (G) beheaded stream, (H) shutterridge, (1-1') offset of piedmont line, (2-2') offset of terrace

Figure 7. Features of the displaced landform (Cai and Yang, 2004).

Geology and Geological Structure

Figure 8 shows that the geology in the vicinity of the Wanfo Temple is mainly composed of alluvium from the Quaternary, Huoyenshan member, Toukoshan formation from the Pleistocene, and Chinshui shale and Cholan formation from the Pliocene.

1. factions induced in tectonic earthquakes.

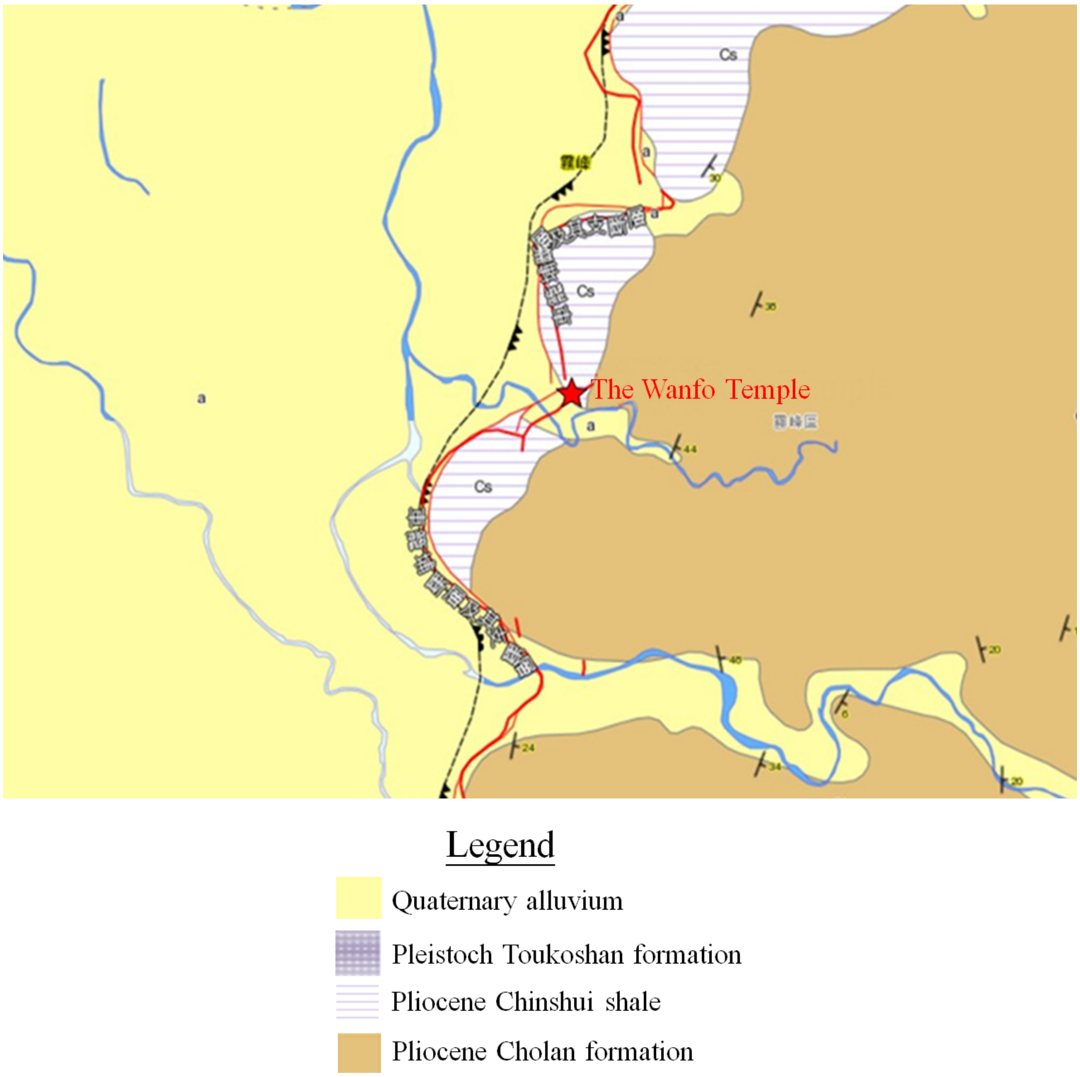


Figure 8 Geological map of the vicinity of the Wanfo Temple (Central Geological Survey of the Ministry of Economic Affairs, 2019)

Earthquakes

Figure 9 shows all the earthquake data from the Seismological Center (SC) of the Central Weather Bureau (CWB) of Taiwan from 1999 to May 2019 (Central Weather Bureau of the Ministry of Transportation and Communications, 2019). Figure 9 shows that the earthquakes were recorded in the years 2018 (1007 times), 2012 (769 times), 2009 (752 times), 2013 (690 times), and 2016 (678 times).

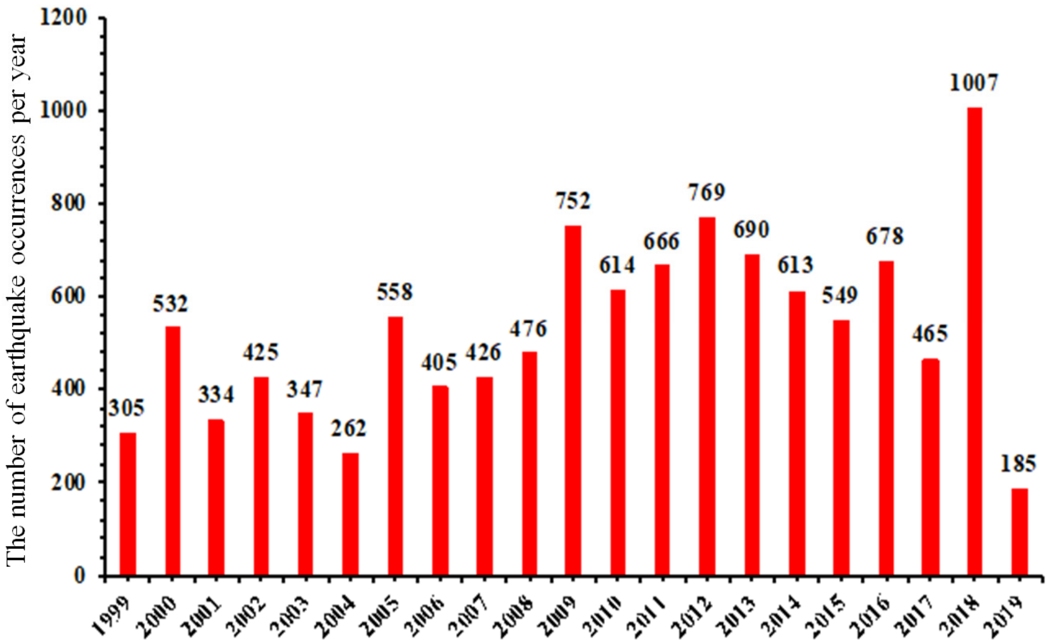


Figure 9. The number of earthquake occurrences per year in Taiwan from 1999 to May 2018.

The Major Cause For The Collapse Of Temples

For tectonic earthquakes with a magnitude of less than 6.0, although the maximum amount of shear banding can be measured only in millimeters, the magnitude of ground vibration still can be large enough in these tectonic earthquakes. However, in the case of a small amount of shear banding, collapse of temples will almost never happen.

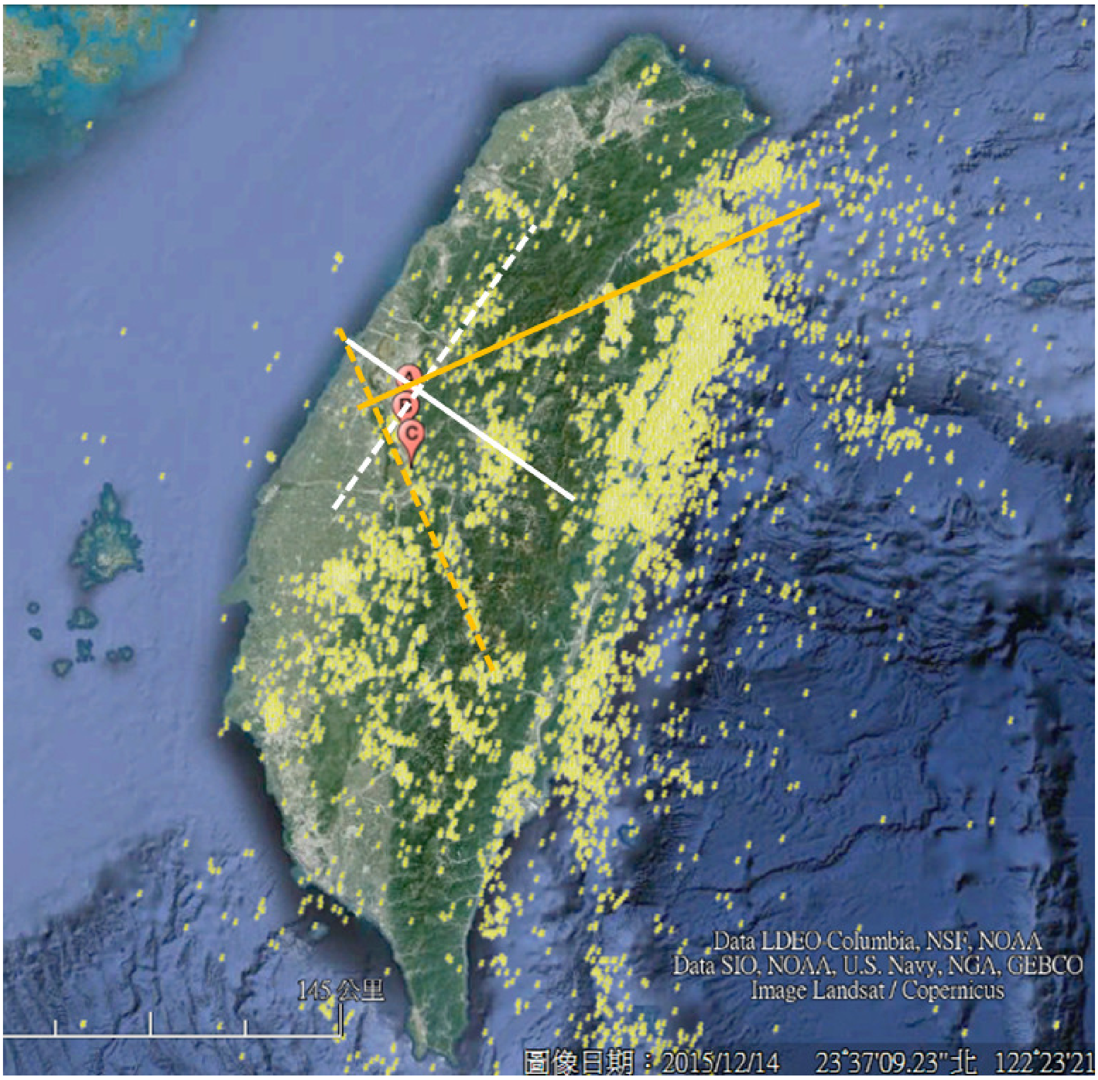
For tectonic earthquakes with a magnitude greater than 6.0, the maximum amount of shear banding is measured in centimeters or meters. In these tectonic earthquakes, if the temple is located in the non-shear banding zone, it will almost never result in collapse because the temple has been designed to be protected against ground vibrations. However, if the temple is located in the shear banding zone, in the case that the temple is only designed against ground vibration, collapse will almost always occur during shear banding.

As a result, whether a temple is located in the shear banding zone becomes the major cause the temple collapses during a tectonic earthquake. In view of this, this paper will use a historical epicenter map, a GPS velocity vector map, and satellite imagery to identify shear bands or shear textures for the Wanfo

Temple and the Baihou Temple sites, thereby illustrating the major cause for the collapse of these two temples in the tectonic earthquake.

1. Identification of the Shear Band using Historical Epicenter Map. Tectonic earthquakes originate from shear banding. For different focuses located on the same shear band, the epicenters corresponding to these focuses will have a linear distribution. Therefore, if the locations for the historical epicenters announced by the CWB are compiled before observing the linear distributions, the shear bands passing through the Wanfo Temple can be identified.

According to Figure 10, four groups of shear bands passing through the Wanfo Temple can be identified via the historical epicenter map. The four groups of shear bands are represented by the white solid line (N54^{o}W), white dashed line (N36^{o}E), orange solid line (N66^{o}E), and orange dashed line (N24^{o}W).

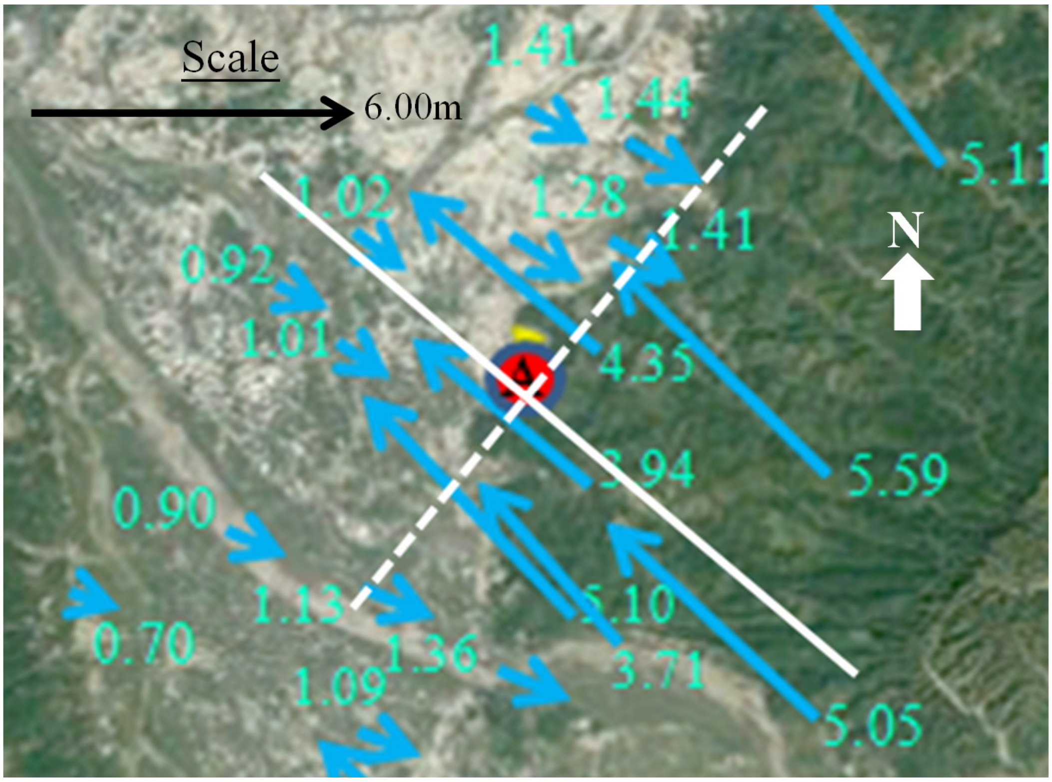


Note: The center point of Circle A is where the Wanfo Temple was located

Figure 10. Using the historical epicenter map to identify the shear bands that pass through the Wanfo Temple (background image is taken from Google Earth, 2019).

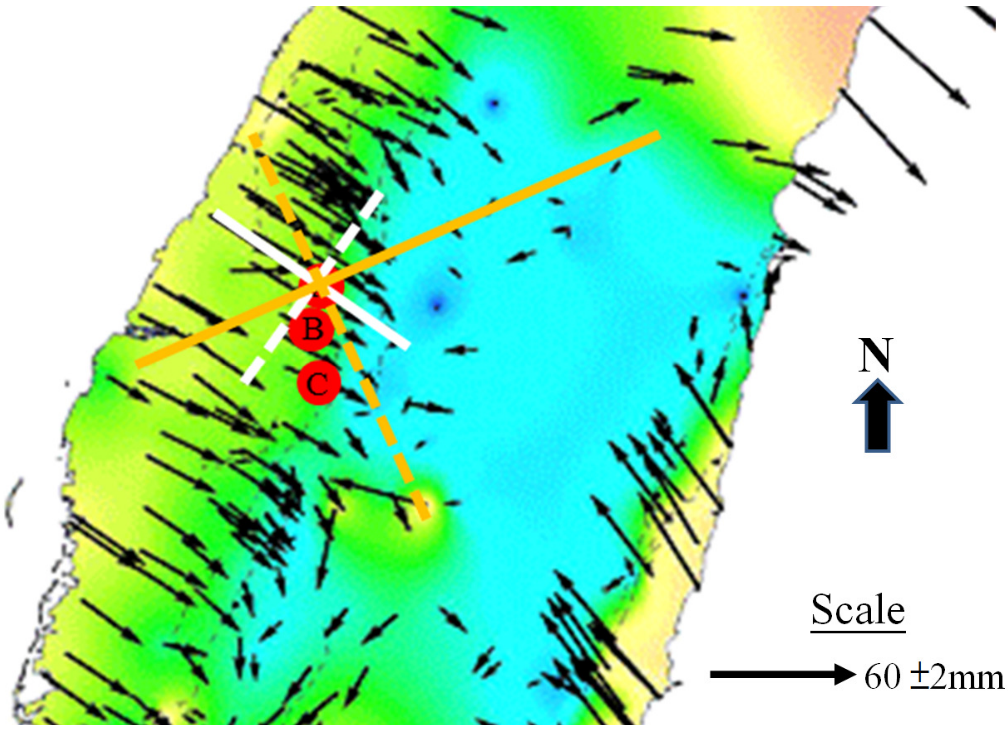
Identification Of The Shear Band By GPS Velocity Vector Map

Figure 11a shows the two groups of shear bands passing through the Wanfo Temple as obtained from the GPS velocity vector map of the 921 Jiji earthquake. The two groups of shear bands are represented by the white solid line (N54°W) and white dashed line (N36°E). Figure 11b shows that the four sets of shear bands passing through the Wanfo Temple can be identified by the 2007 GPS velocity vector map. The four groups of shear bands are represented by the white solid line (N54°W), white dashed line (N36°E), orange solid line (N66°E), orange dashed line (N24°W).



Note: The center point of Circle A is where the Wanfo Temple was located

(a) 1999 Jiji Earthquake GPS velocity vector map (Google Earth, 2019; GPS LAB, 2019).



Note: The center point of Circle A is where the Wanfo Temple was located

(b) 2007 GPS velocity vector map

Figure 12. Using GPS velocity vector map to identify the shear bands that pass through the Wanfo Temple (GPS LAB, 2019).

Identification Of Shear Bands Passing Through The Wanfo Temple Using Satellite Imagery

Figure 13 shows that the five groups of shear textures within the total width of a shear band can be identified by the features of displaced landform in satellite imagery of the vicinity of the Wanfo Temple. The five groups of shear textures and their strikes are the principal deformation shear D (orange solid line) N66°E, the thrust shear P (white dashed line) N36°E, the Riedel shear R (red solid line N85°W), the conjugate Riedel shear R' (white solid line) N54°W, and the compression texture S (double arrow orange line) N24°W.

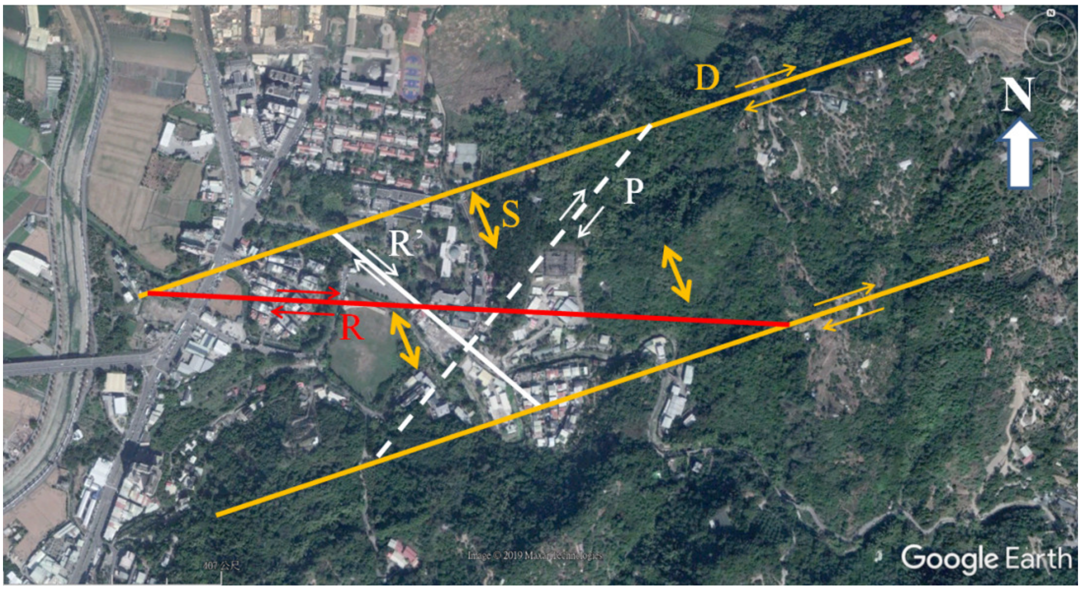


Figure 13. Shear textures obtained by satellite imagery identification in the vicinity of the Wanfo Temple (Background image is from Google Earth, 2019).

Identification Of Shear Bands Passing Through The Wanfo Temple Using Local Imagery

Figure 14 shows that the five groups of shear textures within the total width of a shear band can be identified by the features of displaced landform in local imagery of the vicinity of the Wanfo Temple. The five groups of shear textures and their strikes are the principal deformation shear D (orange solid line) N66°E, the thrust shear P (white dashed line) N36°E, the Riedel shear R (red solid line N85°W), the conjugate Riedel shear R' (white solid line) N54°W, and the compression texture S (double arrow orange line) N24°W.

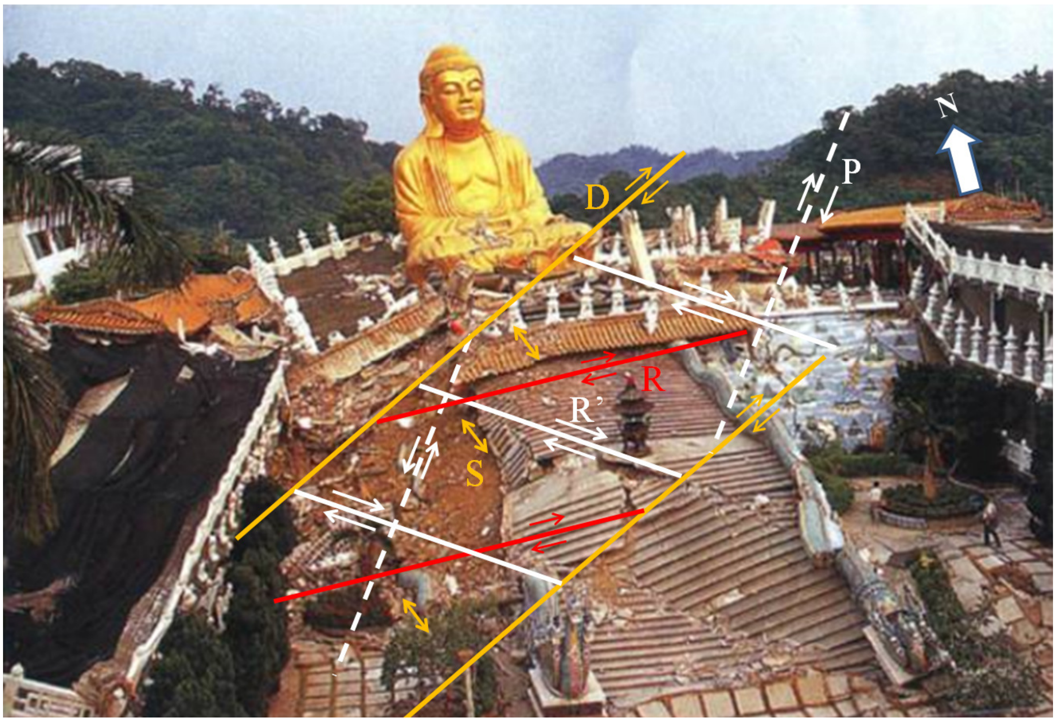


Figure 14. Shear textures obtained by local imagery identification in the vicinity of the Wanfo Temple (Background image is from Wu, 1995).

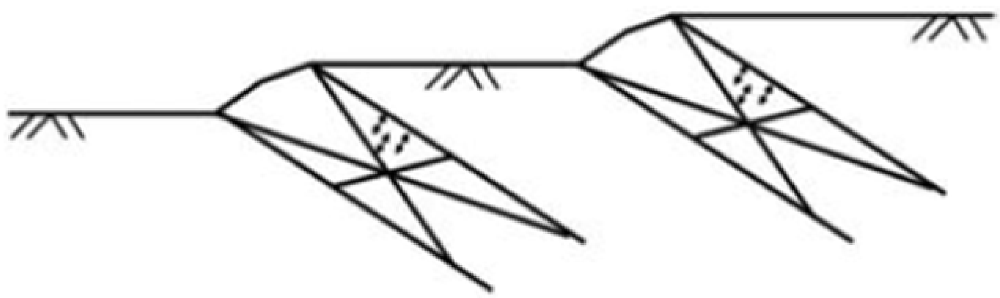
Comparisons And Discussions

1. The Major Cause of the Collapse of Temples during the 921 Jiji erthquake. The Wanfo Temple is located within the total width of a shear band. During the 921 Jiji erthquake, the faulting of the Chelungpu fault induced the principal deformation shear D, the thrust shear P, the Riedel shear R, the conjugate Riedel shear R', and the compression texture S, which caused severe collapse of the Wanfo Temple (detailed in Figures 2 and 14).

According to Figures 12, 13 and 14, after the completion of the Wanfo Temple, the foundation spaned the shear banding zone. During the 921 Jiji earthquake, various shear textures with different strikes existing in the total width of a shear band caused uneven uplifts of the ground, which in turn caused the foundation to break. Then, the columns were broken during being uplifted, and the beams and the adjacent floor were ruptured after the beam-column joints were broken. As a result, the temple collapsed randomly.

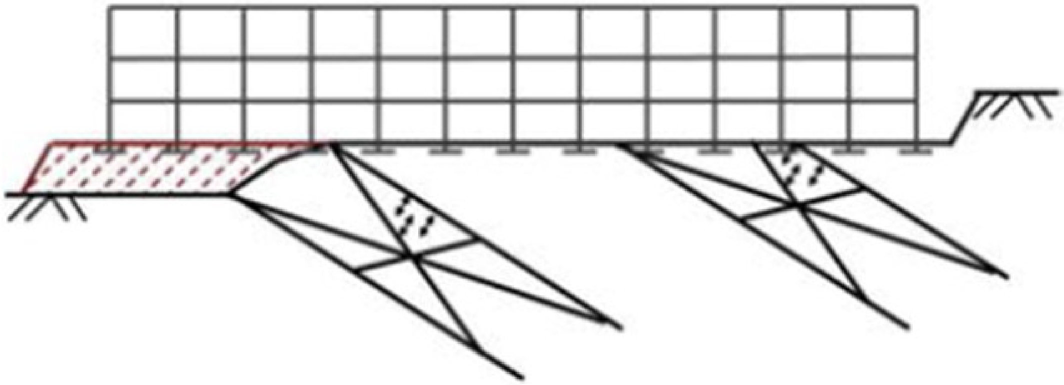
2. Model of Damaged Temple Induced by Shear Banding. Figure 16 shows that when the temple is built on a

shear banding tilted slope (Figure 16a), the whole site of the templeg foundation needs to be leveled by balancing excavation and backfill (Figure 16b). Because of this, the shear banding tilted slope still partially remains below the foundation of the temple after completion (Figure 16c). Consequently, during subsequent sensible tectonic earthquakes, the growing dislocation of the shear band will worsen damage caused to the temple (Figure 16d).

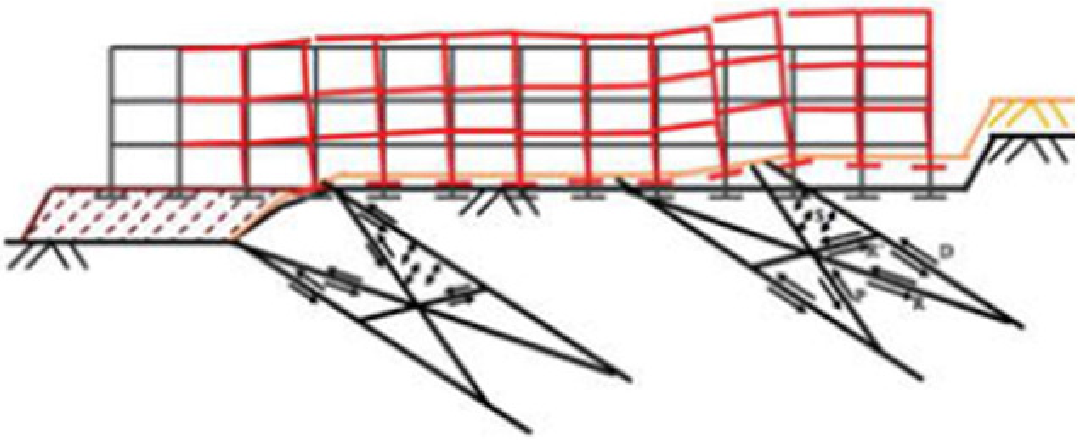


(a) Shear banding tilted slope

(b) Leveling the whole site of the temple foundation by excavation and backfilling



(c) Completing temple construction at the site after leveling



(d) After the completion of the temple, it is destroyed by shear banding

Figure 16. Mechanism of temple failure induced by shear banding (Hsu, 2018).

Conclusions And Recommendations

Most of the temples in Taiwan are built in the mountains. As they are built complying with Feng Shui Theory, most of these temples are located in the concave hairpin bends of intersecting shear bands. To ensure the long-term stability and safety of the temples, this paper investigates the major cause for the collapse of the Wanfo Temple in the 921 Jiji earthquake. From the results, the following two conclusions are inferred:

1. For the Wanfo Temple that conform to the seismic design code, the occurrence of collapse during a tectonic earthquake depends entirely on whether the foundation is spanning shear bands or shear textures.

2. This study adopted various methods to identify the strikes of shear bands or shearing textures that affect the stability and safety of the Wanfo Temple: N54°W, N36°E, N66°E, N24°W, and N87°W.

Based on the above two conclusions, the authors proposed the following two recommendations to ensure the long-term stability and safety of mountain temples:

1. Although seismic design code for buildings were unavailable in the past, mountain temples could still be maintained for more than 100 years; yet some of the mountain temples built in the last 30 years, despite being built according to seismic design specifications and the growing standards thereof, collapsed and were destroyed in the 921 Jiji erthquake. In view of this, the authors strongly recommend that before the planning of mountain temples, the shear bands and shear textures that exist at the site must be monitored first and the foundations must be planned in a non-shear banding area.

2. At present, although the temples meet the requirements of seismic design specifications, the seismic design specifications for buildings are only protected against ground vibrations. Because ground vibration is a secondary effect of tectonic earthquakes, and the effect of such protection is no more than 10%, it is recommended that design engineers require the MOI and NCREE to add preventive measures against the dislocation of shear bands and shear textures in the seismic design specifications for buildings.

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