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# THE MAJOR CAUSE OF BUILDING FAILURE IN THE REGION AFFECTED BY THE TURKEY-SYRIA EARTHQUAKE

Tse-Shan Hsu
President, Institute of Mitigation for Earthquake Shear Banding Disasters
Professor, Feng-Chia University, Taiwan, R.O.C., tshsu@fcu.edu.tw

Hsin-Mao Wang, Yu-Chien Wu
Ph.D. Students, Ph.D. Program for Infrastructure Planning and Engineering,
Feng-Chia University, Taiwan, R.O.C.

Ching-Chang Lin, Da-Jie Lin
Associate Professors, Feng-Chia University, Taiwan, R.O.C.

Zong-Lin Wu
Assistant Professor, National Chin-Yi University of Technology, Taiwan, R.O.C

## Abstract

The seismic design codes for buildings in various countries have been revised repeatedly, and the fortification level against ground vibrations has continually increased. Despite this, a large number of building failures continue to be induced by tectonic earthquakes. For example, the Turkey-Syria earthquake resulted in building failures, which were attributed to inadequate vibration resistance by Taiwanese scholars and experts. In this study, the major cause of building failure due to the tectonic earthquake in Turkey were comprehensively investigated. The study reveals that similar seismic design codes are used in Turkey and other countries in earthquake zones, focusing solely on fortification against ground vibrations due to tectonic earthquakes. Secondly, buildings can maintain seismic conditions when subjected only to ground vibrations and the seismic conditions change to non-seismic conditions when the buildings are subjected to shear banding.

Thirdly, building failures occur during tectonic earthquakes because the assumptions in the design code formula for the ultimate bearing capacity of building foundations are inconsistent with facts. Fourthly, in the building foundation formula in the design code, the assumptions lead to severe overestimation of the ultimate bearing capacity, resulting in building failure due to shear banding during tectonic earthquakes. Based on the above four findings, the seismic design codes for buildings should incorporate guidelines on fortification against shear banding, and the formula for the ultimate bearing capacity of foundations should be rectified to ensure the stability of buildings during tectonic earthquakes.

Keywords: tectonic earthquake, ground vibration, shear banding, ultimate bearing capacity, foundation.

## Introduction

After the Turkey-Syria earthquake on February 6, 2023, news of the tragedy spread worldwide. Approximately 46,000 lives were lost in Turkey (CNN, 2023) due to the failure of a large number of buildings. Taiwanese scholars and experts (Zhou, *et al*., 2023) have attributed the building failures to inadequate ground vibration resistance of buildings in Turkey.

Similar to other countries located in earthquake zones, Turkey has continually revised its seismic design codes for buildings subsequent to tectonic earthquake occurrences. The Disaster and Emergency Management Authority of Turkey of the Ministry of Interior (2018) has revised the seismic design codes twice, in 2007 and 2018.

Because the expertise of scholars and experts participating in the revision of seismic design codes is mostly limited to vibration mechanics, most of them regard the inadequate ground vibration resistance of buildings as the cause of failure due to tectonic earthquakes. Therefore, subsequent revisions of the seismic design codes for buildings have emphasized fortification against ground vibration levels

Since Zhang Heng invented the seismometer in 132 A.D., buildings have been fortified against ground vibrations, but subsequent earthquakes have resulted in high death tolls in earthquake zones (Table 1). For example, Japan has recorded the largest number of deaths in four out of the eighteen most severe earthquakes despite the highest level of building fortification against ground vibrations in the world. Thus, the continual increase in fortification against ground vibrations cannot effectively reduce failures due to tectonic earthquakes. In order to enhance the effectiveness of projects aimed at reducing tectonic earthquake-induced building failures, this study focuses on the tectonic earthquake disaster in Turkey and applies the definitions of seismic conditions and non-seismic conditions proposed by Hsu (2022) to investigated whether the vibration resistance of buildings that comply with the seismic design specifications is adequate.

Table 1. The top 18 earthquakes with the highest number of deaths (Wikipedia, 2022).

| No. | Year | Country | Death |
|---|---|---|---|
| 1 | 1556 | China | 830,000 |
| 2 | 1976 | China | 655,000 |
| 3 | 2010 | Haiti | 316,000 |
| 4 | 2004 | Indonesia | 280,000 |
| 5 | 1920 | China | 273,400 |
| 6 | 1948 | Turkmenistan | 160,000 |
| 7 | 1923 | Japan | 142,800 |
| 8 | 1948 | Russia | 110,000 |
| 9 | 1922 | Philippines | 100,000 |
| 10 | 1923 | Japan | 93,000 |
| 11 | 2008 | China | 87587 |
| 12 | 2005 | Pakistan | 85,000 |
| 13 | 1908 | Italy | 82,000 |
| 14 | 1721 | Iran | 80,000 |
| 15 | 1970 | Peru | 74,194 |
| 16 | 2023 | Turkey | 46,000 |
| 17 | 1949 | Japan | 26,000 |
| 18 | 2011 | Japan | 15,500 |

## Buildings in Turkey Complying with the Seismic Design Code

The seismic design code for buildings in Turkey (Ministry of Interior, Disaster and Emergency Management Authority of Turkey, 2018), similar to that of other countries within earthquake zones, primarily focuses on fortifying against ground vibrations. With a population exceeding 84 million (Turkey iResidence, Foreigner Residence Service, 2023), Turkey witnessed approximately 46,000 deaths in the 2023 Turkey-Syria earthquake. The earthquake affected 10 out of the country's 81 provinces, four of which are adjacent to the epicenter of the main shock, namely Kahramanmaraş, Gaziantep, Kilis, and Osmamiye (Figure 1). As evident from Figures 2 and 3, which show urban and suburban buildings in these four provinces before the earthquake, the buildings conforming to the seismic design code in Turkey are not substantially different from


Figure 1. Four earthquake-affected provinces adjacent to the epicenter of the Turkey-Syria earthquake (Google Earth, 2019).

(a) Kahramannaras

(b) Gaziantep

(c) Kilis


(d) Osmamiye

Figure 2. Urban buildings in four provinces adjacent to the epicenter of the Turkey-Syria earthquake (Google Earth, 2019).


(a) Kahramannaras

(b) Gaziantep

(c) Kilis

(d) Osmamiye

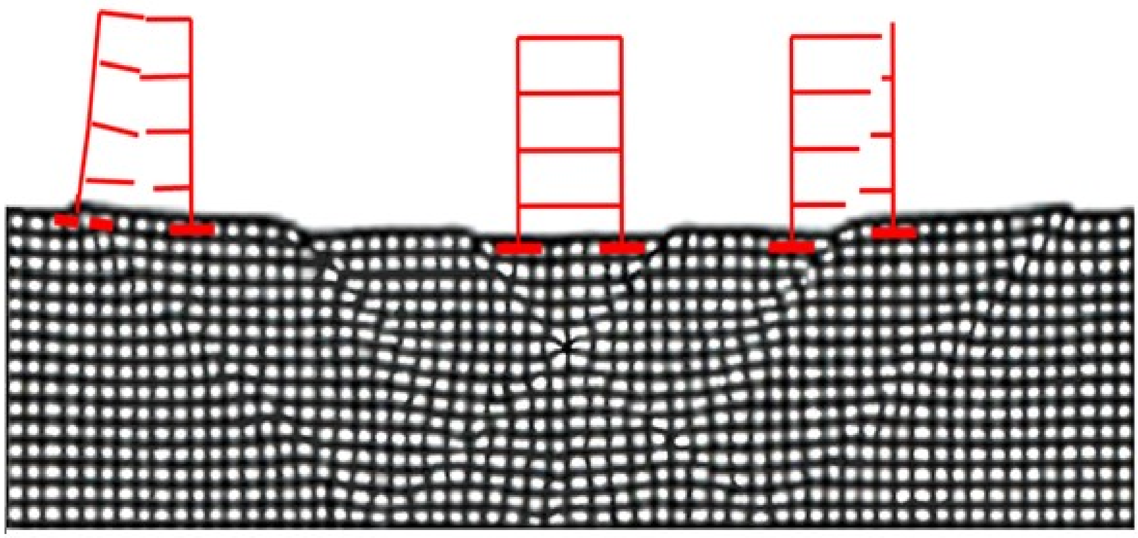
Figure 3. Suburban buildings in four provinces immediately adjacent to the epicenter of the Turkey-Syria earthquake (Google Earth, 2019).

buildings in other countries in earthquake zones.

Figure 1 clearly shows that the four provinces adjacent to the epicenter of the main shock have shear bands, which are indicated by displaced landform features. Although shear bands only occur locally and encompass less than 3% of the total area (Hsu et al., 2017), shear banding is a major cause of building failure related to tectonic earthquakes (Hsu, 2018). The region outside the shear band zone, referred to as the non-shear band zone, encompasses more than 97% of the total area. According to this area ratio, the proportion of buildings located in the shear band zone is less than 3%, and the proportion of buildings in the non-shear band zone is greater than 97%. Additionally, the shear band zone is divided into a shear banding sub-zone and a non-shear banding sub-zone during a tectonic earthquake. Consequently, only buildings located within the shear banding sub-zone undergo failure, and the proportion of buildings undergoing failure due to a tectonic earthquake is small

## Seismic Conditions and Non-seismic Conditions of Buildings

Hsu (2022) proposed that certain seismic conditions are required to maintain the stability of buildings during tectonic earthquakes. According to this proposal, the boundary conditions of all bottom ends of a building's columns should maintain the originally designed fixed-end conditions during earthquakes, ensuring that no relative displacements or rotations occur between adjacent bottom ends of columns. In other words, when shear bands induced by earthquakes do not extend to the regions where buildings are located, the buildings can maintain the seismic conditions specified in the original design of fortification against ground vibrations recommended in the seismic design code for buildings. Therefore, the buildings can maintain stability during tectonic earthquakes, as depicted in the center of Figure 4(a) and right of Figure 4(b).



(a) Schematic diagram (Hsu, 1987; Hsu, et al., 2017).

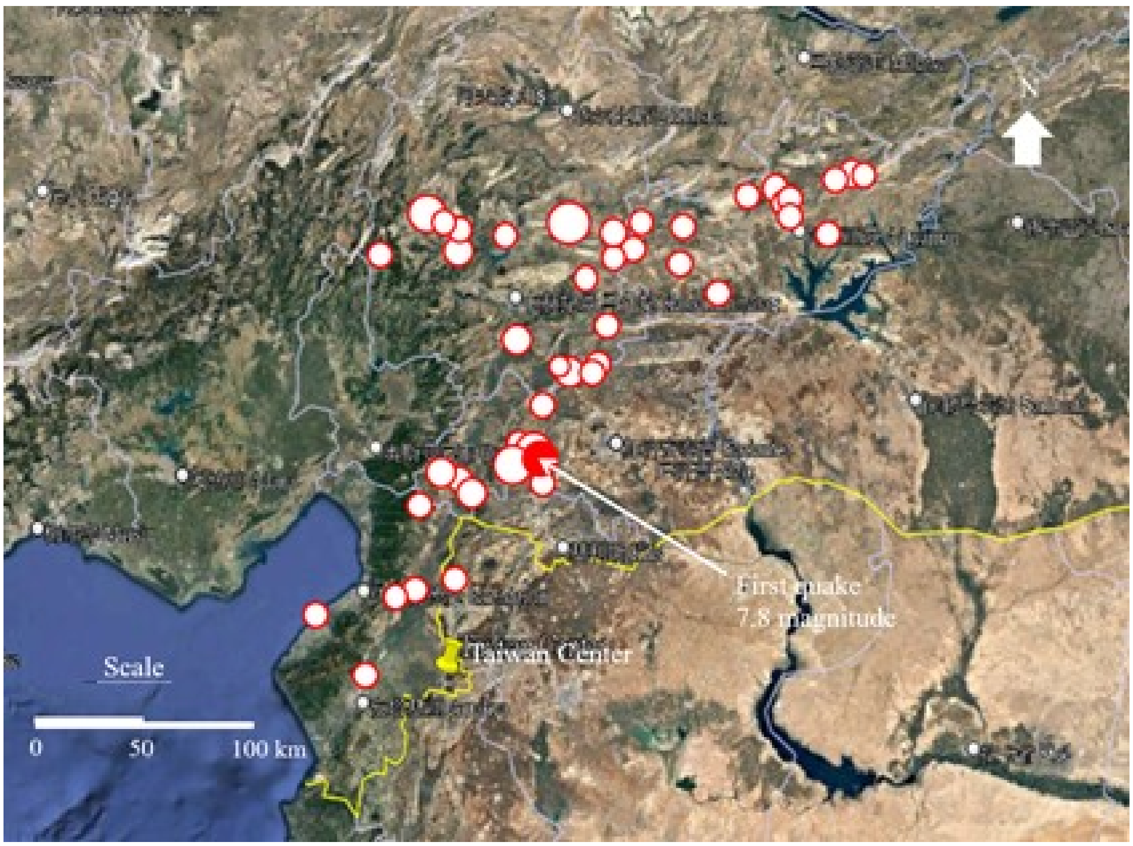
(b) Photograph of a disaster area in Turkey (CDP, 2023).

Figure 4. Comparison of building stability in a non-shear banding zone and building failure in a shear banding zone during a tectonic earthquake.

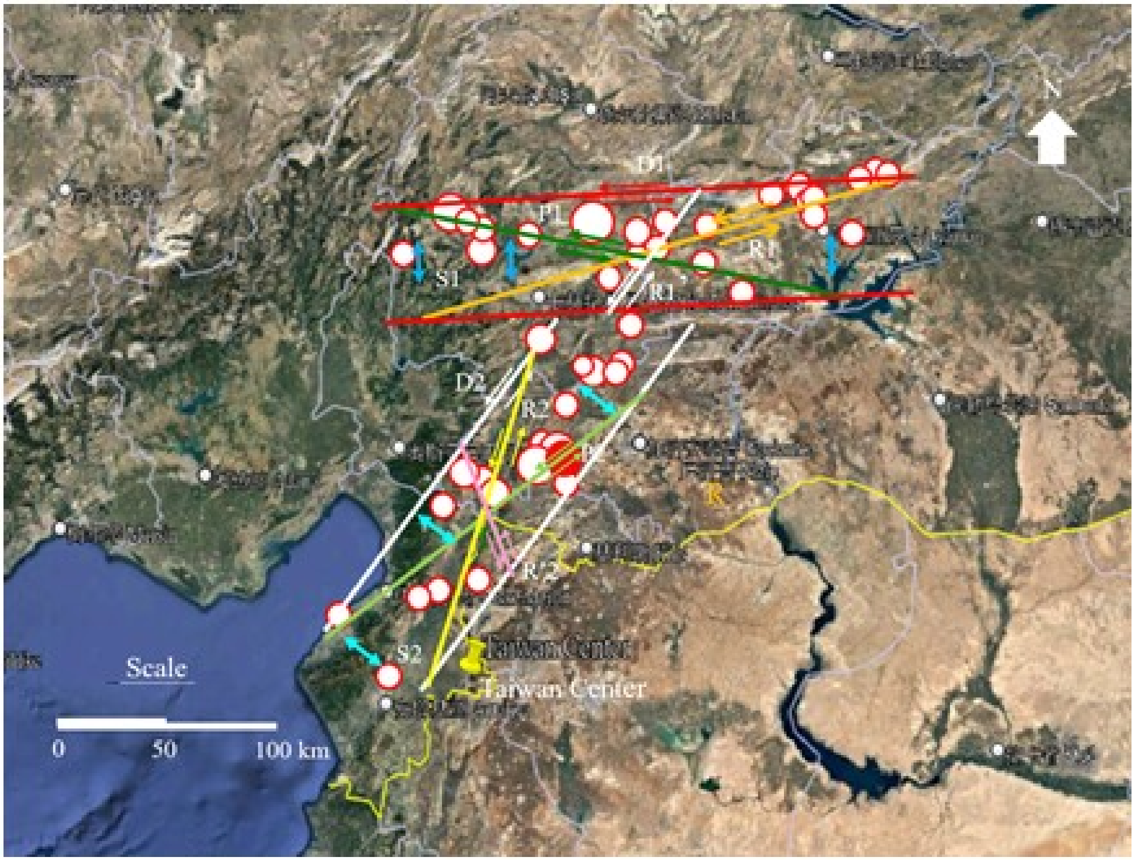
Hsu (2022) also proposed certain non-seismic conditions that contribute to building failure during tectonic earthquakes. Specifically, non-seismic conditions arise in buildings when the boundary conditions at the bottom ends of one or more columns are unable to maintain the fixed-end conditions established in the original design. Consequently, relative displacements and rotations occur between adjacent bottom ends of columns. In other words, if shear bands extend into building sites during tectonic earthquakes, the buildings are subjected to shear banding that is not accounted for in the seismic design code for buildings. Therefore, the buildings fail when seismic conditions change to non-seismic conditions (as for the failed buildings shown on the left and right sides of Figure 4(a) and in Figure 4(b)).

## Shear Bands and Shear Textures in the Earthquake-Stricken Area of Turkey

The fault plane, where a tectonic earthquake originates, represents the hypocenter, and the epicenter refers to the point where the line connecting the center of the Earth and the hypocenter extends to the Earth's surface. The radius of the Earth is 6,371 km, and the focal depth of the earthquake in Turkey was only 17.9 km. Therefore, the method proposed by Hsu and Kang (2010) can be applied in conjunction with the epicentral distribution map of the mainshock and aftershocks of the Turkey-Syria earthquake (Figure 5(a)) to identify the shear textures within the entire width of the shear band in Turkey (depicted in Figure 5(b)) that occurred during the Turkey-Syria earthquake. These shear textures encompass the principal displacement shears D1 and D2 of strikes $N87^\circ E$ and $N37^\circ E$, the thrust shears P1 and P2 of strikes $N79^\circ W$ and $N53^\circ E$, the Riedel shears R1 and R2 of strikes $N74^\circ E$ and $N18^\circ E$, the conjugate Riedel shears R1' and R2' of strikes $N37^\circ E$ and $N24^\circ W$, and compression textures S1 and S2 of strikes $N3^\circ W$ and $N53^\circ W$.




(a) Before the overlaying of the shear band and shear structures



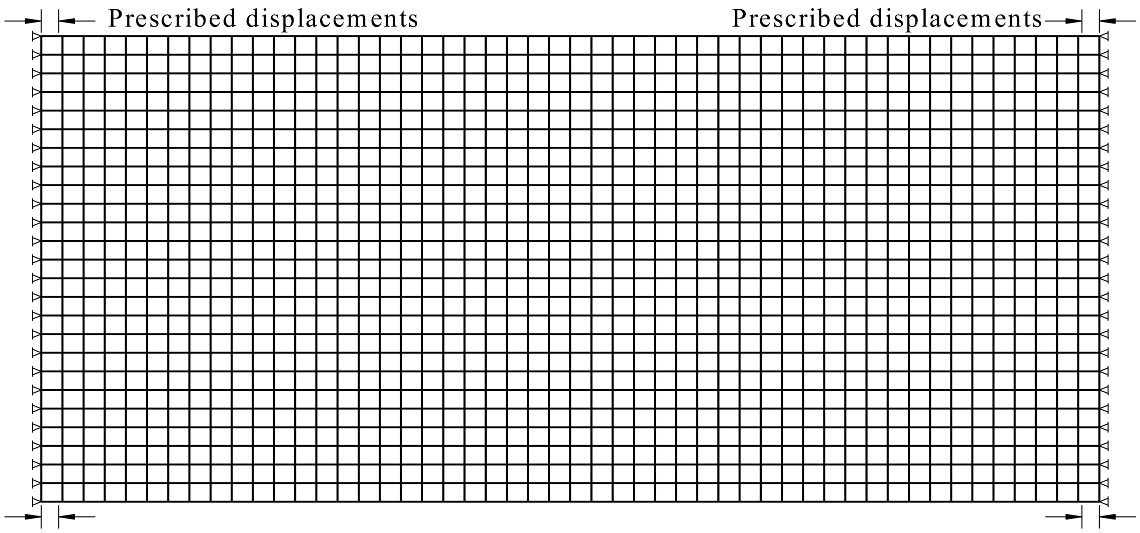

Note: The yellow needle indicates the Taiwan Center

(b) After the overlaying of the shear band and shear structures

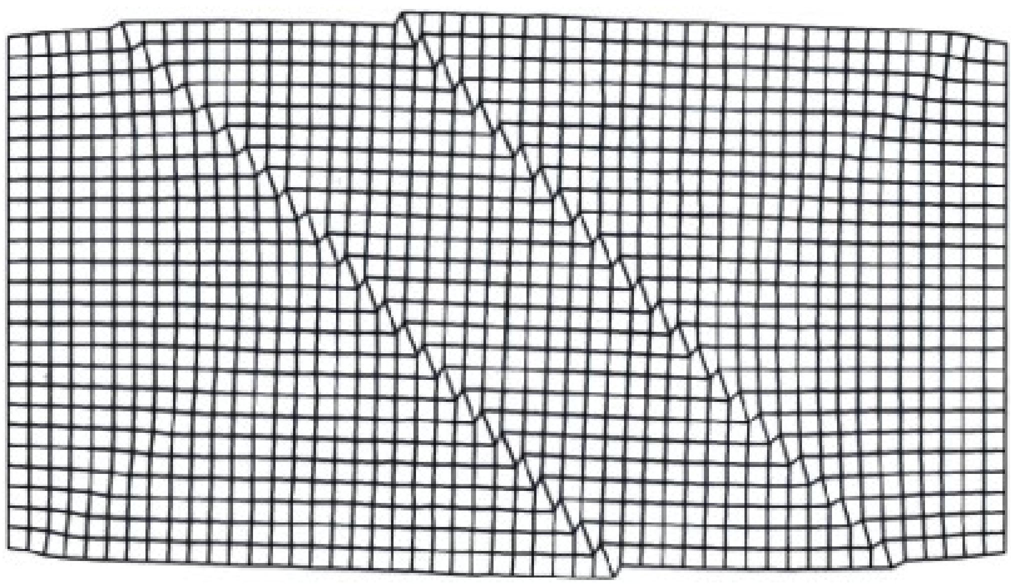
Figure 5. Identification of the shear band and shear textures using the epicentral distribution map of the mainshock and aftershock of the Turkey-Syria earthquake (background image from Google Earth, 2022; epicentral data from USGS, 2023).

## Ground Vibration Induced by Shear Banding

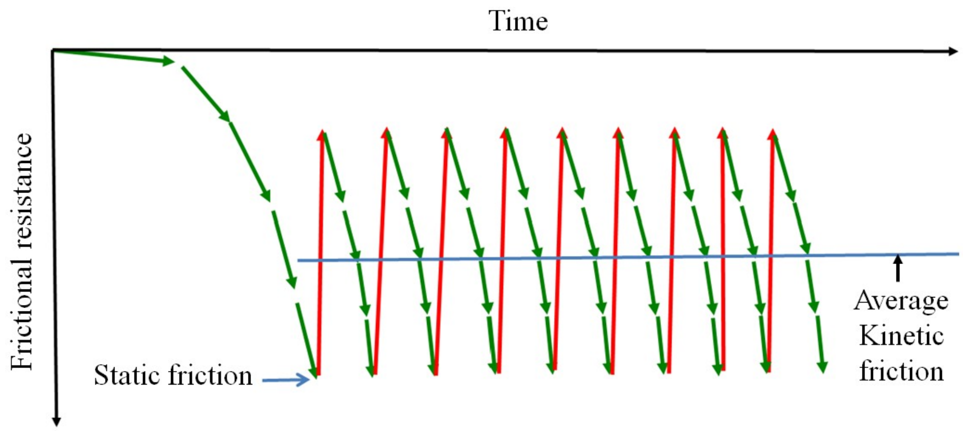
As illustrated in Figure 6(a), when a plate is continuously subjected to lateral compression, localized deformation occurs due to strain softening after the strain reaches the plastic range, resulting in shear bands (Figure 6(b)). During shear banding, a slip–stick phenomenon occurs repeatedly because of frictional resistance (Figure 6(c)). During the slip process, the ground surface accelerates, and during the stick process, the ground surface decelerates. Therefore, with the repeated occurrence of the slip–stick phenomenon, the ground exhibits a vibration acceleration time curve, as depicted in Figure 6(d). This ground vibration arises from shear banding, and Coffee's (2000) research confirms that shear banding accounts for more than 90% of the total energy of tectonic earthquakes, whereas ground vibration contributes less than 10% of the total energy.



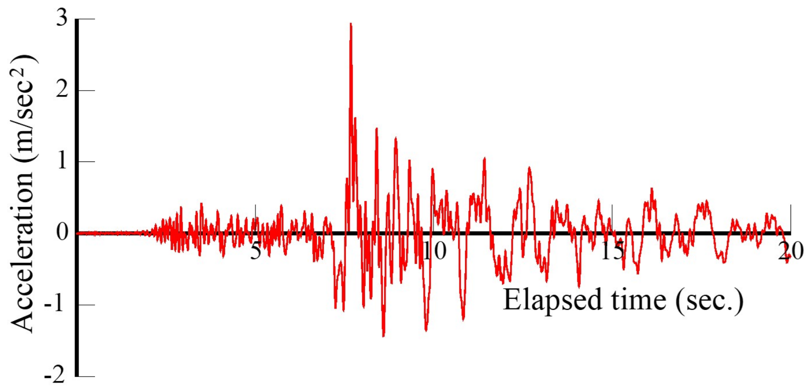

(a) Initial finite element mesh for a plate under lateral compression (Hsu, 1987)



(b) Deformed finite element mesh when the shear band appears (Hsu, 1987)




(c) Stick-slip phenomenon in shear banding (modified from Lambe and Whitman, 1969).




(d) Seismometer record of the ground acceleration time-history curve (Hsu, 1987)

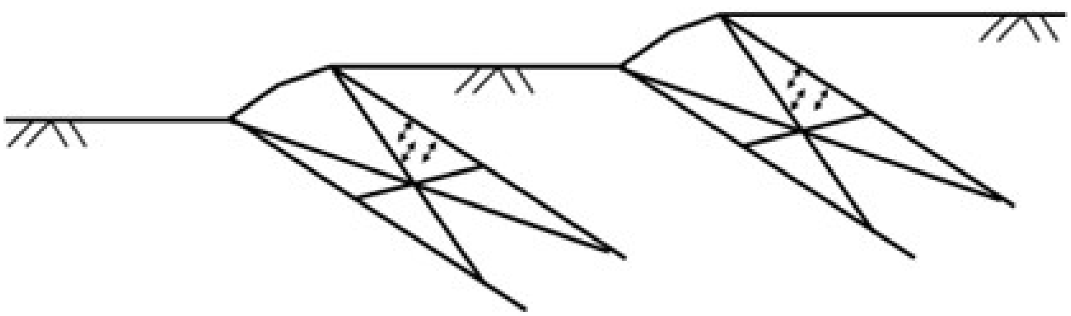
Figure 6. Shear banding and ground vibration induced in a plate under lateral compression.

## Failure Mechanisms of Buildings

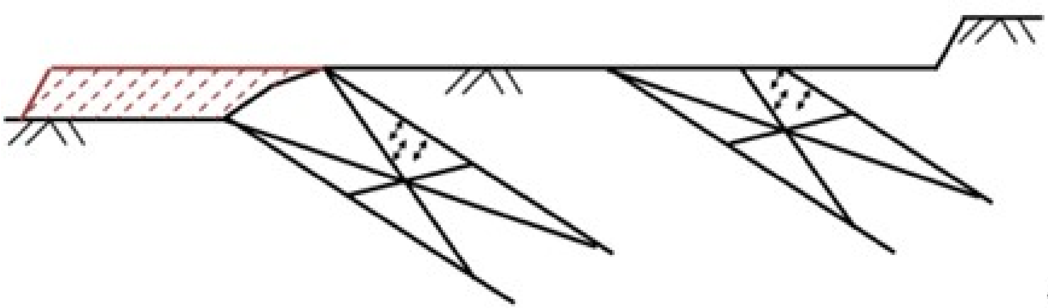
### *Building Collapse Mechanism*

Figure 7 shows the Guangfu Junior High School in Taichung, Taiwan that collapsed in the 921 Jiji earthquake in 1999. Figure 8(a) illustrates two stages of shear banding, involving tilting and uplift slopes before construction. As illustrated in Figure 8(b), the site was leveled by cutting and filling during the construction process, but two shear bands persisted below the site after leveling. As shown in Figure 8(c), the school building was constructed on the leveled surface. The school building collapsed because of shear banding during the 921 Jiji earthquake, as shown in Figures 7 and 8(d).

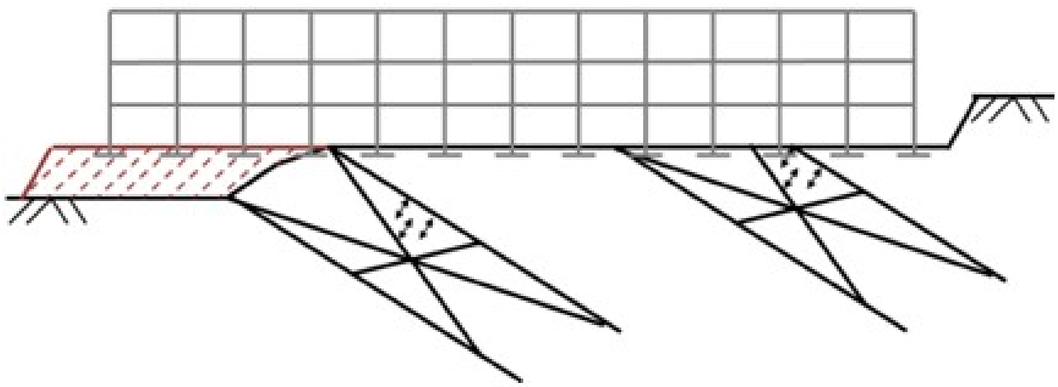
Figure 7. Collapse of Guangfu Junior High School in Taichung, Taiwan during the 921 Jiji earthquake in 1999 (Hsu, 2022).



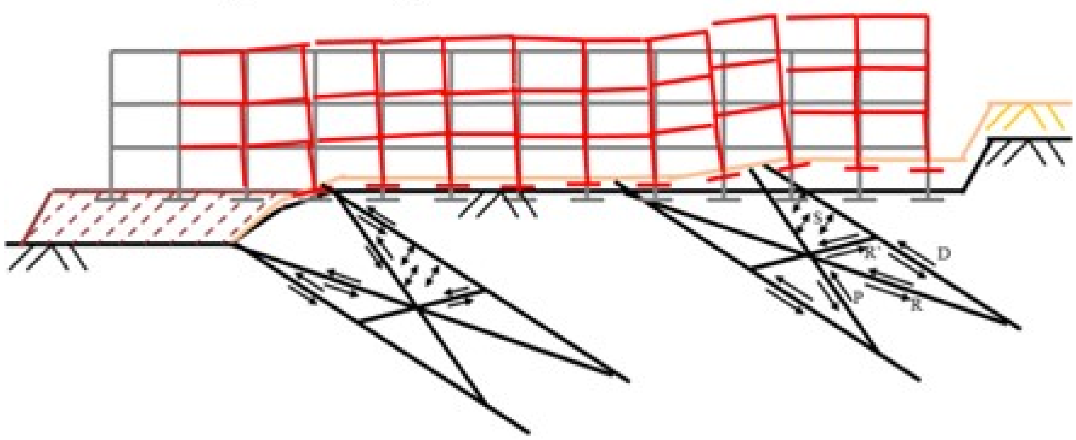
(a) Multiple-step tilted shear banding and uplift slopes



(b) Ground leveling



(c) Building constructed on shear bands




(d) Building collapsed due to shear banding

Figure 8. Schematic diagrams of the building construction process and collapse mechanism (Hsu, 2018).

*Fall Failure Mechanism of Buildings*

According to Hsu et al. (2018), the major cause for the fall failure of buildings is that the safety factor of the earthquake bearing capacity of the foundation is less than 1.0, leading to seismic settlement in the building's foundation (Richards et al., 1993). When the seismic settlement of the foundation ceases, the columns of the building endure the impact force transmitted from the foundation. This impact force is equivalent to twice the sum of all dead loads and live loads. Consequently, the piles of the building are severely fractured and damaged because of excessive loading, resulting in fall failure, as shown in Figure 9.

(a) Jiji earthquake in 1999 (Nantou, Taiwan; Hsu et al., 2018)

(b) Kashmir Earthquake in 2005 (Carayannis, 2012)

Figure 9. Cases of fall failures in previous earthquakes.

The design code for building foundations (Construction and Planning Agency, Ministry of the Interior, 2011) stipulates that the safety factor of the static bearing capacity of the foundation must be greater than or equal to 3.0, and the safety factor of the seismic bearing capacity of the foundation must be greater than or equal to 1.2. If the perfectly plastic model, which satisfies Drucker's stability conditions (Drucker, 1950) and employs symmetrical shear failure planes to derive the ultimate bearing capacity formula of the foundation (Terzaghi, 1943), is consistent with actual conditions, then the occurrence of building fall failure depicted in Figure 9 can be prevented when the calculated safety factor of the static bearing capacity of the foundation is equal to or exceeds 3.0. However, under static ultimate loads, the foundation’s shear failure plane only emerges in conditions of unstable plastic strain softening (Hsu, 2018), and the actual shear failure plane is asymmetric. Therefore, the soil model and symmetry conditions adopted to derive the ultimate bearing capacity of the foundation are inconsistent with the facts. Using the formula for the ultimate bearing capacity of the foundation provided in the design code for building foundations may lead to severe overestimation of the ultimate bearing capacity and the fall failure of buildings, as shown in Figure 9.

## Buildings on Multi-Step Tilted and Uplifted Slopes with Shear Banding in the Earthquake-Stricken Area of Turkey

Figure 10 shows the epicenter of the Turkey-Syria earthquake and its four neighboring provinces, namely Kahramanmaras, Gaziantep, Kilis, and Osmamiye, where notable building failures occurred. Figures 11(a)–11(d) show the elevation profiles of the four provinces, indicating multi-step shear banded, tilted, and uplifted slopes in these areas. Moreover, buildings similar to those shown in Figure 12 are situated on such slopes in these four provinces.

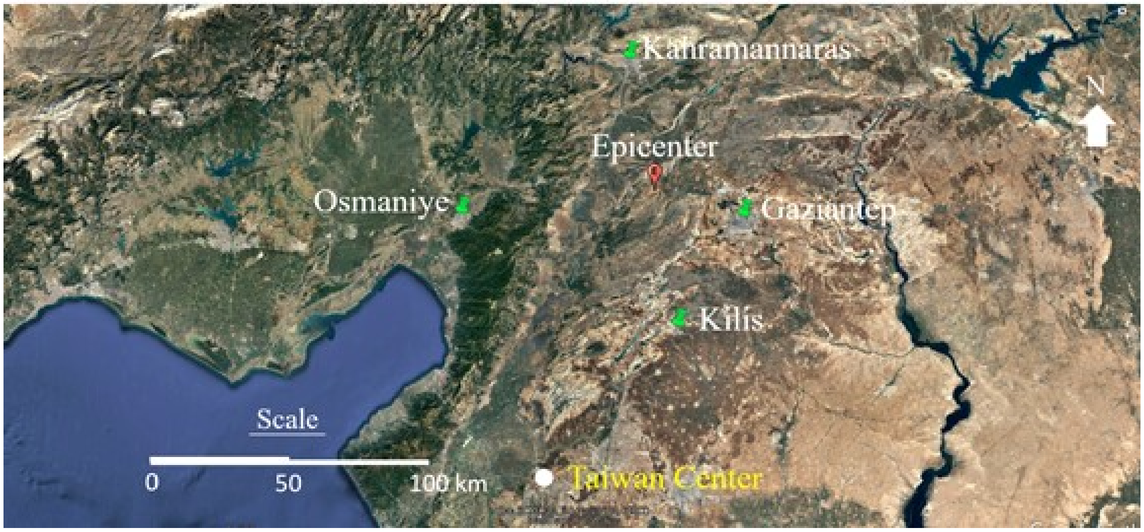
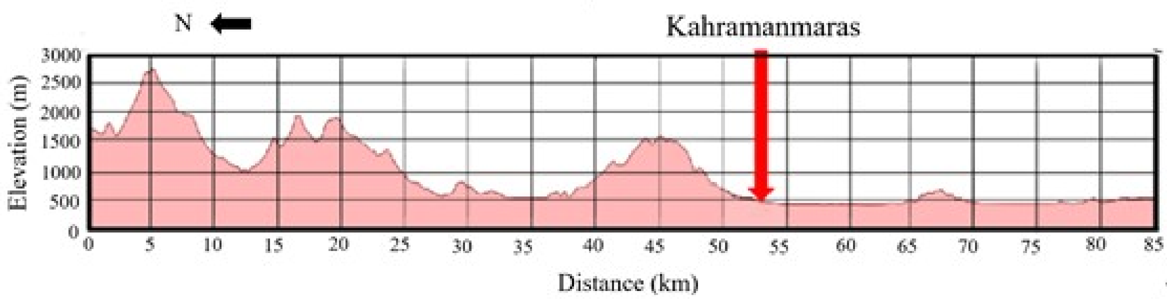
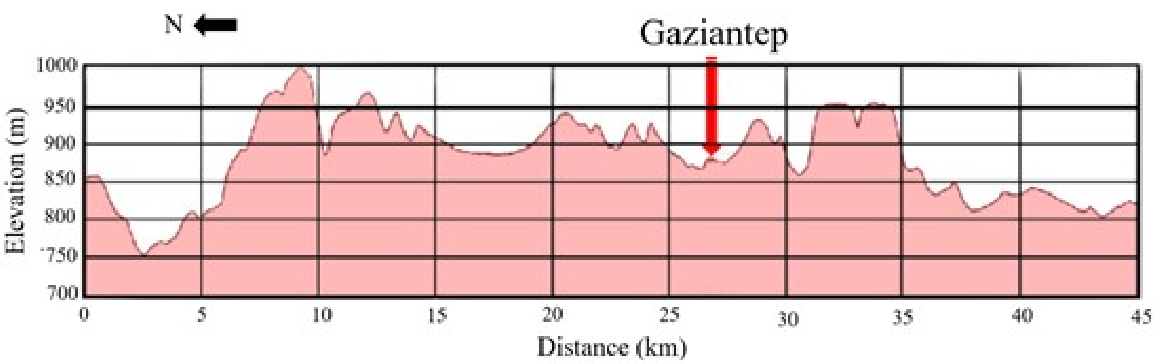


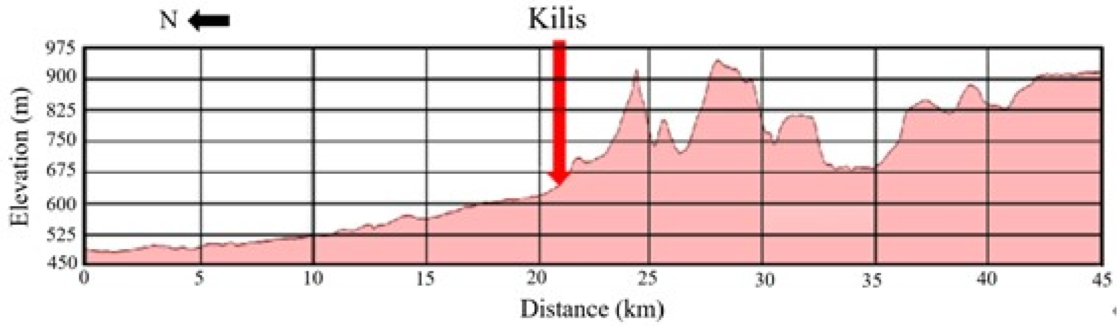

Figure 10. Epicenter of the Turkey-Syria earthquake and notable building failures in four neighboring provinces (Google Earth, 2019).



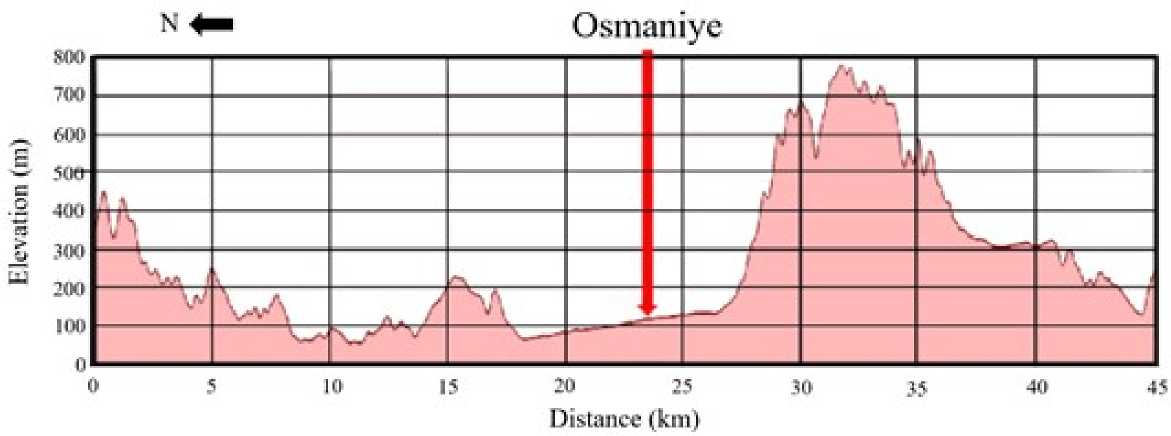

(a) Kahramanmaras




(b) Gaziantep




(c) Kilis




(d) Osmamiye

Figure 11. Elevation profiles of the four provinces of the Turkey-Syria earthquake-stricken area (Google Earth, 2019).

Figure 12. Buildings located on the shear banded, tilted, and uplifted slopes in Turkey (Google Earth, 2019).

## Major Reason for the Stability of the Taiwan Center in Turkey

After the Turkey-Syria earthquake, the media continued to report a large number of building fall failures in the disaster-stricken region of Turkey. However, one notable exception was the Taiwan Center in Turkey, which remained stable during the earthquake (see Figure 5). Scholars and experts from Taiwan attributed the stability of the Taiwan Center to the incorporation of adequate ground vibration resistance during the design phase, achieved through a high level of fortification against ground vibrations and excellent construction quality.

However, as illustrated in Figure 5, the Taiwan Center is situated outside the shear banding zone formed during the Turkey-Syria earthquake. In other words, similar to other buildings in Turkey located in non-shear banding zones, the Taiwan Center is stable against ground vibrations because the design provides protection against ground vibrations.

## Conclusions and Suggestions

The invention of the seismometer dates back nearly 1900 years, but despite the increasing fortification level of buildings against ground vibrations in countries in earthquake zones, the death toll after tectonic earthquakes has been high. Previous studies by scholars and experts have attributed tectonic earthquake-induced building damage to the lack of ground vibration resistance in buildings. In light of this, this study investigated the major cause of building failure during the Turkey-Syria earthquake under seismic and non-seismic conditions. The main conclusions of this study are as follows:

1) The main effect of tectonic earthquakes is shear banding, and the secondary effect is ground vibration. At present, the seismic design codes for buildings in Turkey and other earthquake-prone countries primarily focus on fortifying buildings against ground vibrations.

2) A building remains intact despite ground vibrations of a tectonic earthquake when the boundary conditions at all column ends of the building maintain seismic conditions, while a building fails because of shear banding due to a tectonic earthquake when the boundary conditions at some or all column ends change from seismic conditions to non-seismic conditions.

3) During tectonic earthquakes, buildings fail under shear banding. The reason is that when deriving the formula for the ultimate bearing capacity of foundations provided in the design code, two assumptions that are inconsistent with the facts were adopted. The two assumptions were that the plastic strain softening foundation soil was perfectly plastic and that the asymmetric shear failure plane of the foundation under the ultimate load was symmetrical.

4) Using the formula for the ultimate bearing capacity of foundations provided in the current design code results in severe overestimations of the ultimate bearing capacity of the foundations. Therefore, building failures may occur under shear banding during tectonic earthquakes if the foundation design is inappropriate.

Based on these conclusions, the authors propose that seismic design codes for buildings should include fortification against shear banding, and the formula for the ultimate bearing capacity of foundations in the design code should be revised by adopting a plastic strain softening soil model and considering an asymmetric sliding surface of the foundation soil under ultimate load. These amendments are necessary to ensure the stability of buildings during tectonic earthquakes.

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