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MAJOR CAUSE OF FALL FAILURE OF MARKET BUILDINGS DURING TECTONIC EARTHQUAKES

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Abstract

Since the seismic design code of buildings was promulgated for the first time in Taiwan in 1974, the ground vibration fortification level has been continuously improved after each severe earthquake. However, the failure of market buildings has not been prevented. In view of this, the authors of this paper explore the fall failure of the Dazhi Market building in Tainan, Taiwan, as a case study. It is revealed that ground vibration accounts for less than 10% of the total seismic energy dissipation associated with an earthquake, so that structural seismic reinforcement of market buildings against ground vibration accounts for less than 10% of the effectiveness of protection. On the other hand, the major cause of fall failure of market buildings situated on alluvial sandy silt layers above shear banding zones is identified as plastic strain softening, which causes the earthquake induced subsidence of the building foundation to occur suddenly. All columns connected to the foundation collapse because of the influence of excessive impact forces. Based on these findings, the authors suggest that market buildings should be strategically situated to avoid shear banding zones. Furthermore, the initial version of the seismic design code for fortification of buildings specifically against ground vibration, is inadequate. Only through consideration of the effect of shear bands can the fall failure of market buildings and the unnecessary expenditure on ground vibration fortification in non-shear banding zones be prevented.

Keywords: market building, tectonic earthquake, shear banding, ground vibration, strain softening, fall failure.

Introduction

In 1999, the 921 Jiji earthquake with a magnitude of 7.3 occurred in Taiwan. Subsequently, the National Center for Research on Earthquake Engineering (NCREE) revised the seismic design code for buildings at first, notably increasing the requirements for fortification against ground vibrations. The NCREE was then entrusted by the Ministry of Education to develop seismic reinforcement methods for school building structures. After completion of the seismic reinforcement of school buildings, similar methods were applied to reinforce market buildings.

Hsu (2022b) noted that the seismic design codes of buildings used worldwide only focus on ground vibrations, regarding them as the major cause for the fall failure of buildings without adequate proof. Subsequently, fortification levels against the effects of ground vibrations during tectonic earthquakes were increased. However, despite fulfilling the requirements in the new design code, buildings collapsed in the 6.4-magnitude Meinong earthquake in 2016. The new code for the seismic design of buildings (Construction and Planning Agency, Ministry of the Interior, 2011) is also used as the basis for identifying the causes of the collapse of buildings, so the lack of vibration resistance in upper structural elements, such as columns, beams, slabs, and walls, is an inevitable result of this identification.

The China Earthquake Disaster Prevention Center (2017) classifies earthquakes into five categories: tectonic earthquakes, volcanic earthquakes, subsidence earthquakes, reservoir-induced earthquakes, and explosion-induced earthquakes. The primary effect of tectonic earthquakes is shear banding, which accounts for more than 90% of the total energy of tectonic earthquakes. The secondary effect of tectonic earthquakes is ground vibration, which accounts for less than 10% of the total energy (Coffey, 2019). Therefore, seismic design codes for buildings worldwide present the unrealistic problem of emphasizing only the low-energy effect while disregarding the high-energy effect.

Hsu (2022a) proposed the instability condition for buildings during tectonic earthquakes based on observed phenomena. This condition can be used to verify whether the theory and in-situ conditions of pushover analysis and testing for the seismic building structure reinforcement proposed by the NCREE align with actual requirements.

Because the bottom ends of all columns are fixed before pushover analysis and testing, they cannot exhibit relative displacements during the analysis and testing; in other words, the horizontal ground surface, continuous ground, and rigid ground remain unchanged throughout the analysis and testing. However, the conditions leading to building instability during tectonic earthquakes include changes in the state of the horizontal ground surface, continuous ground, and rigid ground. Therefore, the results of pushover analysis and testing do not align with the actual conditions of building instability during tectonic earthquakes.

Hsu (2018) suggested that the major cause for the collapse of a school building located on a slope during the 1999 Jiji earthquake was the tilting-uplift effect induced by shear banding. This study extends this inference to determine the major cause for the fall failure of a market located on an alluvial plain during the 2016 Meinong earthquake.

Identification of the Cause of Fall Failure of Market Buildings

1) By the traditional scholars

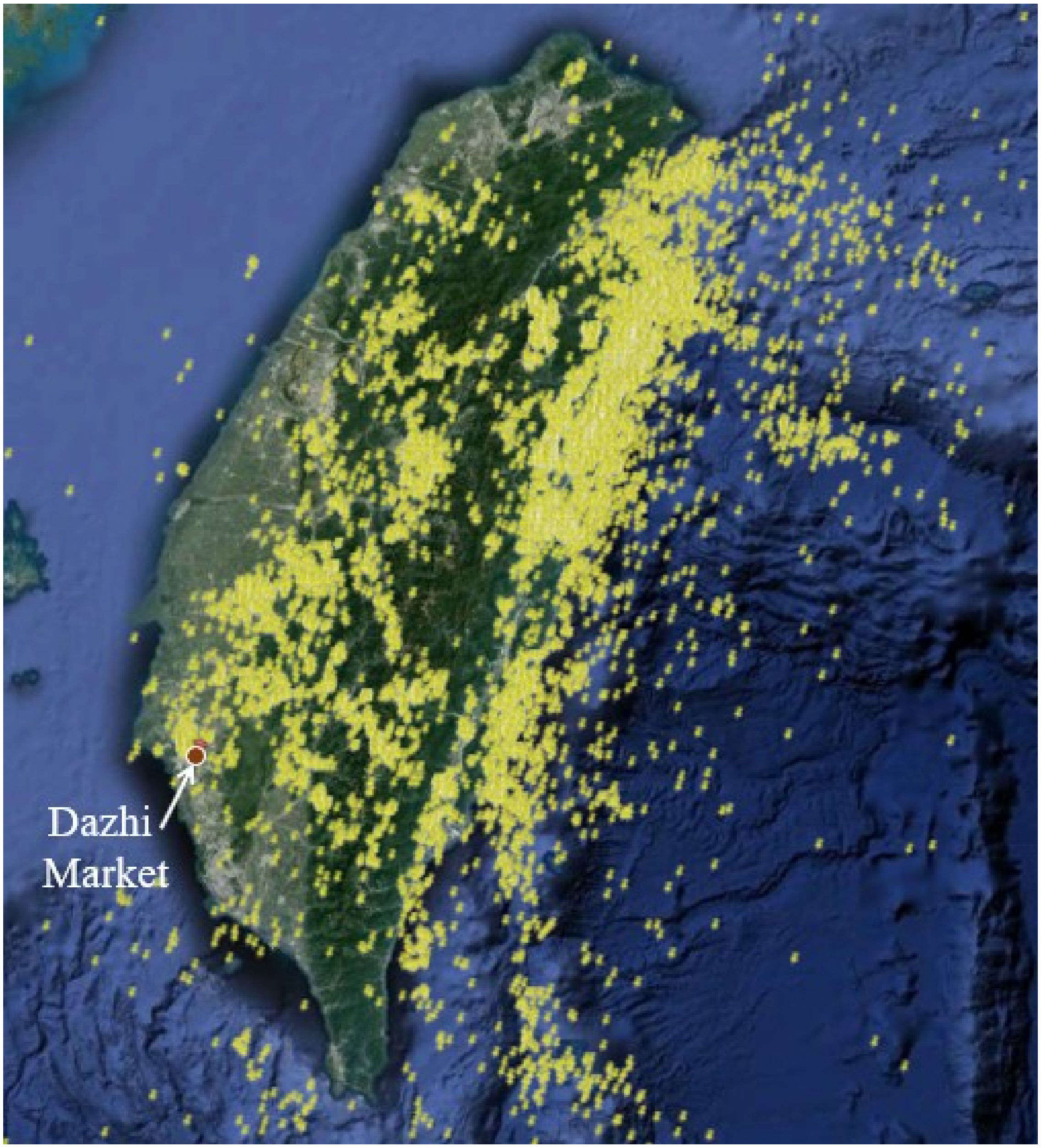
After the fall failure of market buildings, when scholars were tasked with identifying the cause, most of their analyses were based on the code for seismic design of buildings and the code for construction of structures promulgated by the Construction Administration of the Ministry of the Interior.

The identification results obtained using the above identification basis indicated issues such as insufficient reinforcement bars, excessive stirrup spacing, eccentric beam-column joints, underestimated ground vibration force, insufficient beam and column cross-sections, insufficient reinforcement, illegal construction practices, cost-cutting measures, and unrealistic manufacturing supervision.

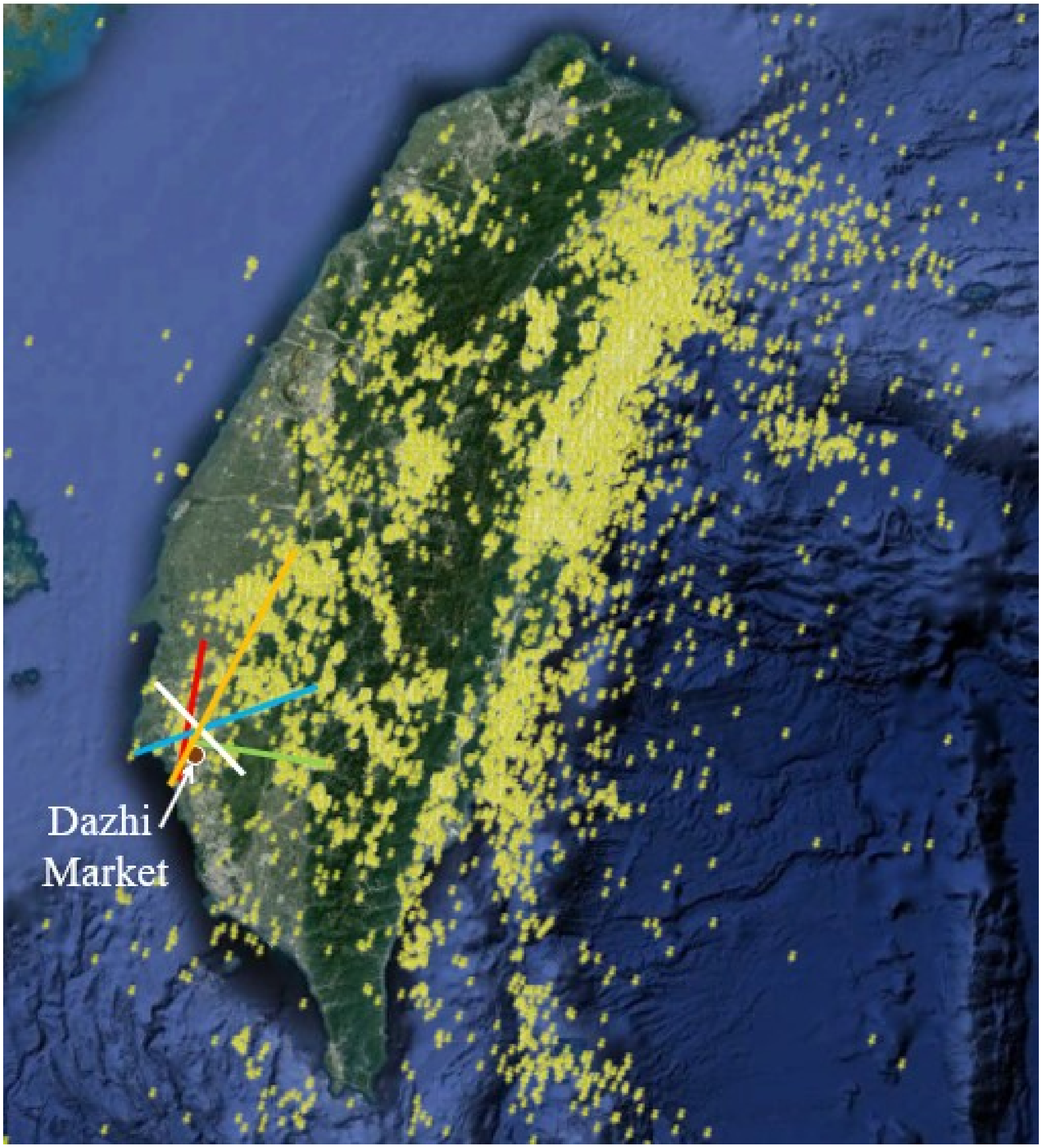
2) By the authors of this paper

A professional cause of disaster consistent with actual conditions must simultaneously satisfy the three elements of uniqueness, integrity, and comprehensiveness (Hsu et al., 2009).

By using the linear trends in the distribution of historical epicenters (Hsu and Kang, 2010) in Taiwan, as shown in Figure 1(a), five groups of shear bands shown in Figure 1(b) were identified, with strikes of N11^{o}E (red), N28^{o}E (orange), N70^{o}E (blue), N45^{o}W (white), and N80^{o}W (green).



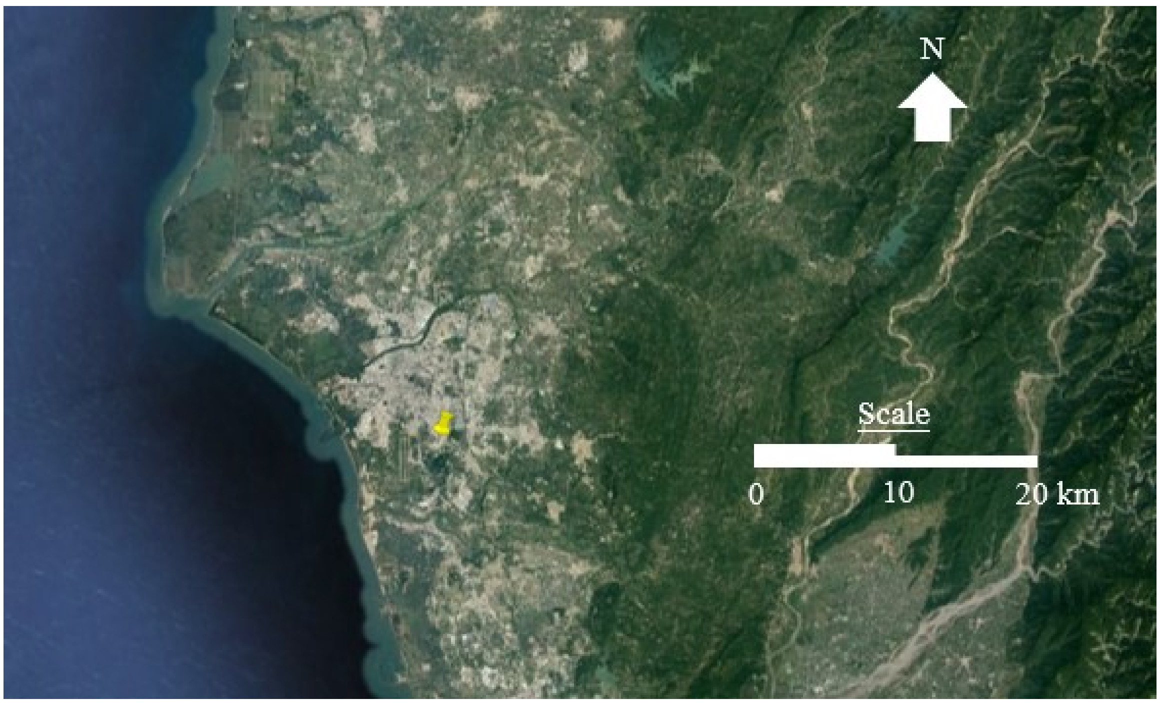
(a) Before identification.



(b) After identification.

Figure 1. Shear bands identified by the distribution of earthquake epicenters (Google Earth, 2020; GPS LAB, 2007).

Using the satellite image (Hsu and Kang, 2010) of the adjacent area of the Dazhi Market building shown in Figure 2(a), shear-band landform features, and the definitions of shear textures, five groups of shear textures were identified in the overall shear band width, as shown in Figure 2(b), with strikes of N11^{o}E (compression texture in red), N28^{o}E (conjugate Riedel shear in orange), N70^{o}E (Riedel shear in blue), N45^{o}W (thrust shear in white), and N80^{o}W (principal deformation shear in green).



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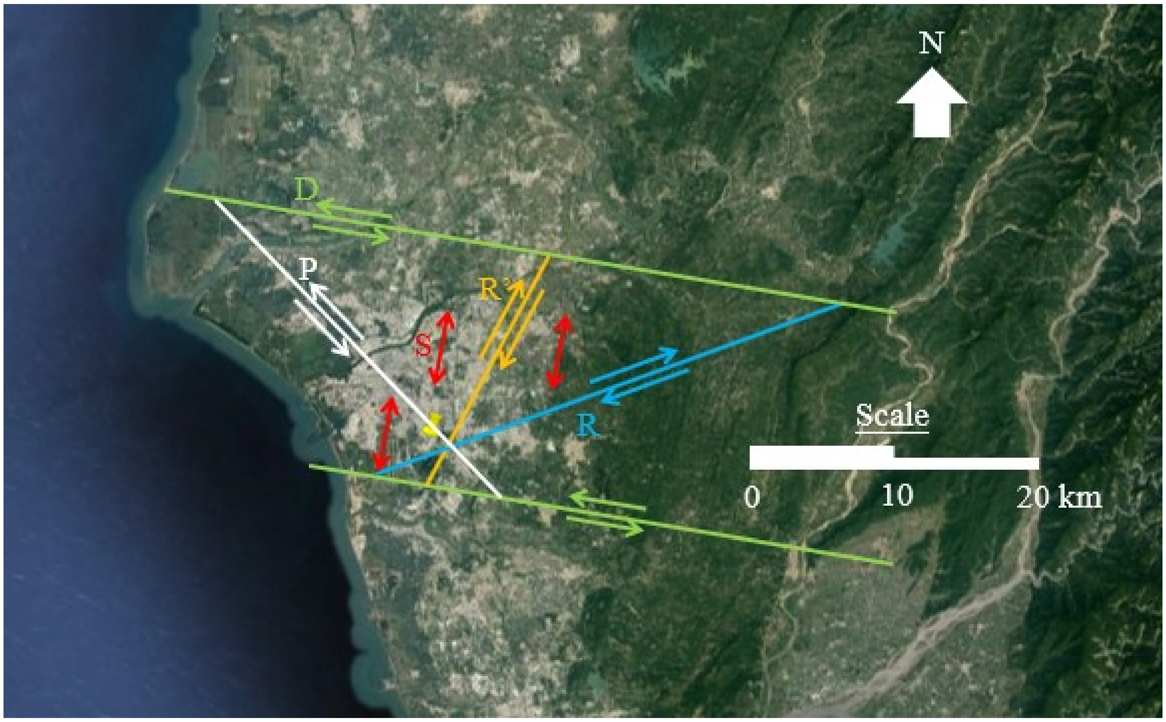
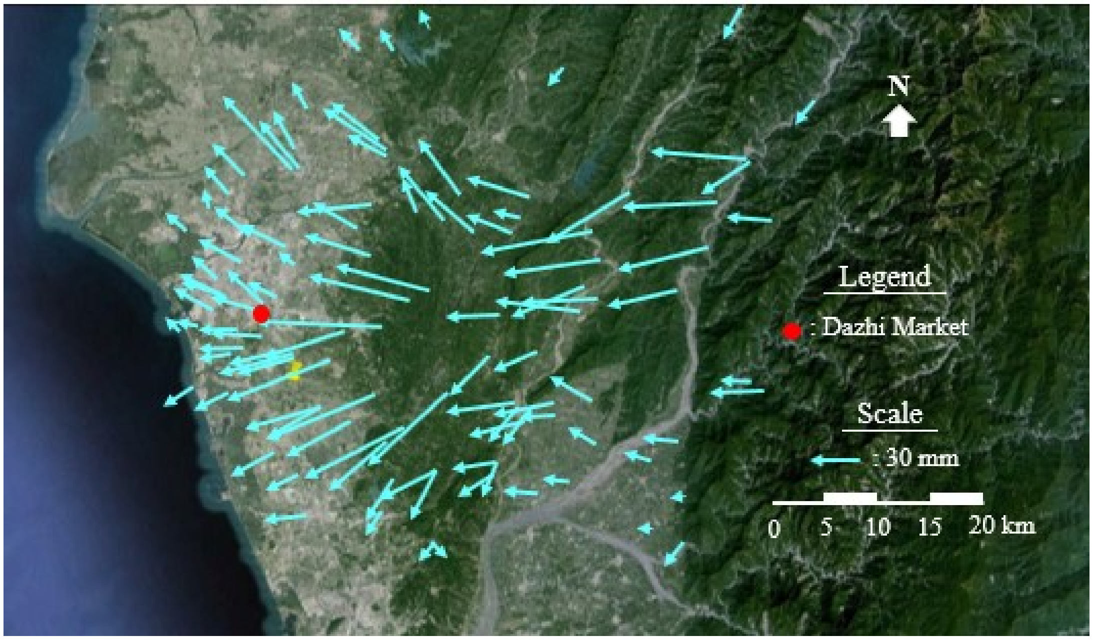


(b) After identification.

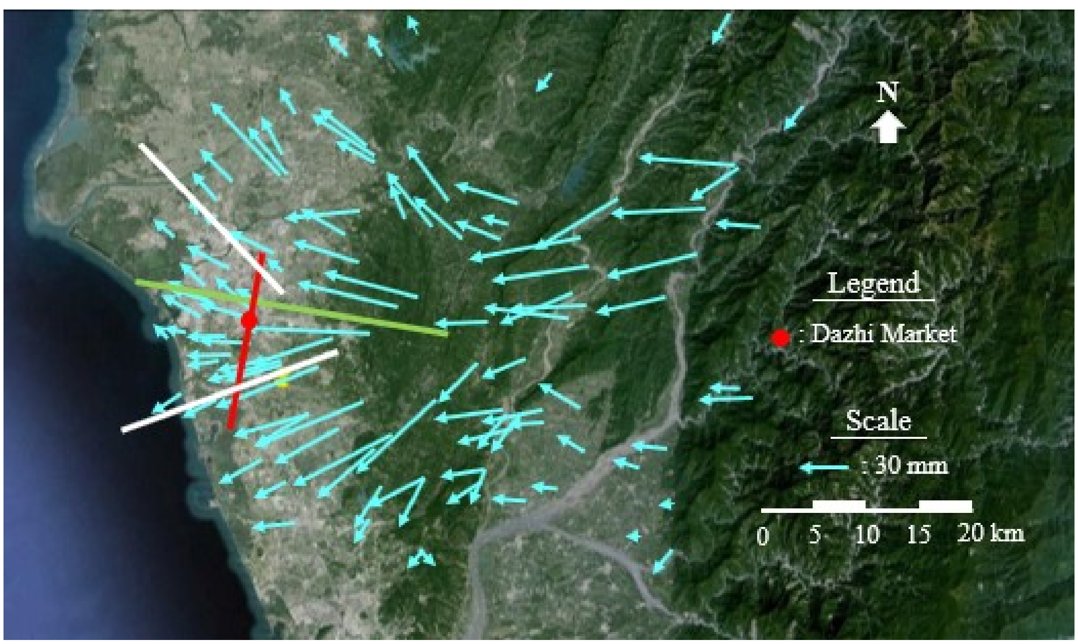
Note: The yellow needle point indicates the Dazhi Market building.

Figure 2. Shear band and shear textures identified by satellite imagery (Google Earth, 2020).

Using the GPS velocity vector distribution map shown Figure 3(a) in conjunction with the definition of shear bands in the vicinity of the site, four groups of shear bands shown in Figure 3(b) were identified in the vicinity of the site; the corresponding strikes are N11°E (red), N70°E (blue), N45°W (white), and N80°W (green).



(a) Before identification.



(b) After identification.

Figure 3. Shear bands identified by GPS velocity vectors
(Google Earth, 2020; Central Geological Survey, MOEA, 2016).

The shear banding effect is confined to shear band zones, and the main processes include the tilt-uplift effect and the strain softening effect. In the case of the fall failure of the Dazhi Market building in Tainan, the shear banding effect includes the strain softening of the dense alluvial sandy silt layer. For this layer, the internal friction angle φ is 34^{o} in non-shear band zones and 30^{o} in shear band zones.

According to the investigation of Rao (2017), the peak ground acceleration (PGA) of the Dazhi Market building during the 2016 Meinong earthquake was 0.255 g, and the peak ground velocity (PGV) was 0.49 m/s.

Furthermore, according to the relationship between PGA and the seismic horizontal acceleration coefficient k_h proposed by the Ministry of Economic Affairs (2008), the horizontal and vertical seismic acceleration coefficients k_h and k_v corresponding to PGA = 0.255 g are equal to 0.1294 and 0.0647, respectively.

For a square foundation on non-cohesive soil, the seismic bearing capacity of the foundation can be calculated from (Hsu et al., 2018):

$$q_{ult,E} = qN_{qs}s_q e_q + \frac{1}{2}B\gamma' N_{\gamma s}s_\gamma e_\gamma \tag{1}$$

where q represents the overburden pressure above the bottom of the foundation, γ' is the effective unit weight (or the submerged unit weight) of the soil, N_{qs} and $N_{\gamma s}$ represent the static bearing capacity factors of the strip foundation proposed by Meyerhof (1951), and e_q and e_γ represent the seismic bearing capacity correction factors proposed by Budhu and Al-Karni (1993).

For the square spread foundation of the Dazhi Market building, the width B is 3 m and embedded depth D_f is 1.5 m. The sandy silt layer in shear band zones, after shear banding due to strong tectonic earthquakes, tends to be compacted under the vibrational effect of subsequent weak earthquakes. Therefore, as shown in Table 1, the internal friction angle φ of sandy silt remains at 34° during normal times and during earthquakes, whether in a non-shear band zone or a shear band zone without shear banding. However, the internal friction angle in shear banding zone decreases to 30° due to strain softening.

When φ is equal to 30° or 34°, the shape factor for a square foundation s_q is equal to 1.577 or 1.675, respectively, and s_γ is equal to 0.6. As indicated by the data in Table 1, when the static load of the foundation reaches 537 kN/m^2, the foundation bearing capacity safety factor FS_S is 3.0, and this safety factor satisfies the requirements of the design specification.

When the acting pressure of the foundation is 537 kN/m^2 during a tectonic earthquake, where the foundation soil is unaffected by shear banding in the shear band zone, the seismic ultimate bearing capacity of the foundation is 879 kN/m^2. When the foundation earthquake safety factor FS_E is 1.64 (i.e., >1.0), the foundation does not subside. However, during a severe tectonic earthquake, when the foundation soil is affected by shear banding, the ultimate seismic bearing capacity of the foundation is 510 kN/m^2. When the foundation earthquake safety factor FS_E is 0.95 (i.e., <1.0), the foundation subsides.

Table 1. Safety factor of foundation bearing capacity of Dazhi Market building during normal times and earthquake periods.

		φ	q_{ult} (kPa)	FS_S	FS_E
Normal times	Non-shear band zone Shear band zone without shear banding	34°	1611	3.00	---
Earthquake periods	Non-shear band zone Shear band zone without shear banding	34°	879	---	1.64
	Shear band zone with shear banding	30°	510	---	0.95

Richards et al. (1993) provided Equation 2 to calculate seismic subsidence S_E.

$$S_E = 0.174\frac{V^2}{Ag}\left(\frac{k_h^*}{A}\right)^{-4} \tan \alpha_{AE} \tag{2}$$

where V is the PGV (m/sec), A is the PGA coefficient (dimensionless), g is gravitational acceleration (9.807 m/sec^2), α_{AE} is defined in Figure 4, k_h^* is the critical horizontal seismic acceleration coefficient of foundation seismic subsidence, and $\tan \alpha_{AE}$ is determined by the relationship between k_h^* and φ.

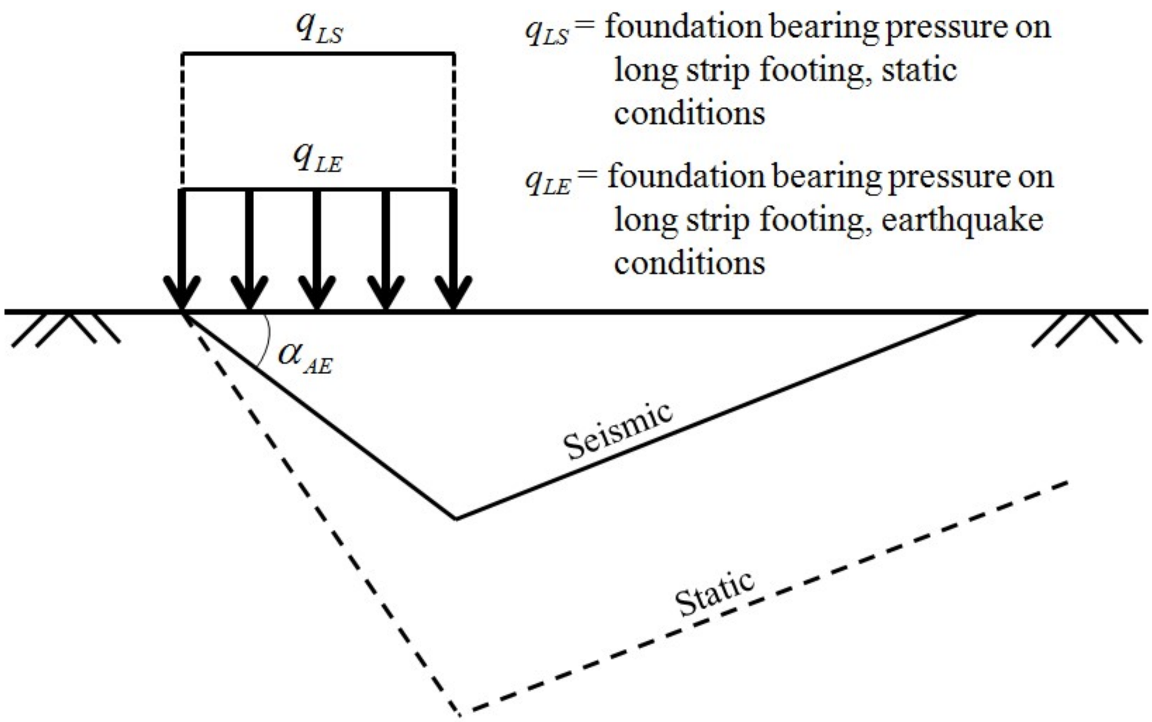


Figure 4. Shear failure surfaces of foundations for static and seismic conditions (Richards et al., 1993).

For the Dazhi Market building, under the influence of shear banding, the internal friction angle φ of the foundation soil is 30°, the static foundation bearing capacity safety factor is 3.0, and D_f/B is 0.2, yielding $k_h^* =$ 0.235 and $\tan\alpha_{AE} = 0.83$. Data recorded at the Tainan station during the Meinong earthquake yield the following parameters: the peak ground acceleration coefficient $A = 0.255$ and the peak ground velocity $V = 0.49$ m/s. The seismic subsidence S_E calculated using Equation 2 is 1.92 cm.

It is known from engineering ethics (Fleddermann, 2012) that the structure of the Dazhi Market building is complex and the professional cause of disaster is a process rather than a single factor. Therefore, the simple factors proposed by different scholars and professional engineers are not the sole cause of the fall failure of the Dazhi Market building.

For the Dazhi Market building, the process of fall failure can be described as follows:

1) Under static conditions, the safety factor of the bearing capacity of the building foundation is FS_S =3.0.

2) During a severe tectonic earthquake, regardless of whether the foundation is located in a shear band zone or non-shear band zone, the earthquake does not cause subsidence as long as the foundation soil is not affected by shear banding, and the safety factor of the bearing capacity of the building foundation is greater than 1.0.

3) During a severe tectonic earthquake, if the foundation soil softens under shear banding and the internal friction angle φ decreases to 30^{o}, the earthquake does cause subsidence because the safety factor of the bearing capacity of the building foundation is less than 1.0.

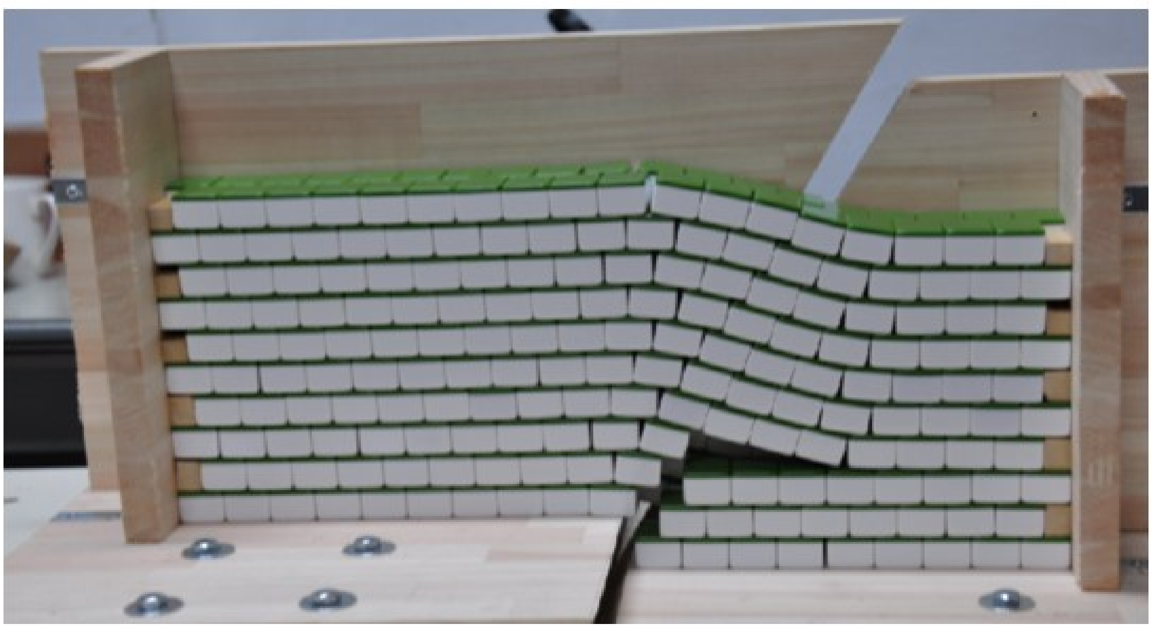
4) Because the phenomenon of stick and slip occurs alternately in ground vibration, an earthquake causes subsidence when slip occurs, and then subsidence suddenly stops when stick occurs; further, at the moment of sudden cessation, the columns on the first floor of the building bear an impact force twice the live load LL and dead load DL (i.e., 2LL + 2DL).

5) When the impact force of the columns on the first floor of the building is greater than the ultimate bearing capacity of the columns, all columns on the first floor of the building break.

Comparison and Discussion of Results

1) Figure 5 shows the model test results of the tilting and lifting effect of shear banding. Figure 5(a) shows the horizontal stratum before tilting and lifting, and Figure 5(b) shows the strata after the effect of tilting and lifting. As shown in Figure 5(b), the tilting and lifting effect is accompanied by brittle fracture in the shear band, and the brittle fracture effect is accompanied by an increase in the void space within the shear band, thus resulting in strain softening.

(a) Before tilting and lifting.



(a) After tilting and lifting.

Figure 5. Model test results of the tilting and lifting effect of a shear band (Hsu et al., 2023).

2) For market buildings in Taiwan, the number of partition walls per unit area on floors above the first floor is high. The first floor is an arcade without side walls, and the relative number of partition walls in the inner area is low. Therefore, the shear-band foundation soil is strained during a severe tectonic earthquake, inducing earthquake subsidence of the foundation, and the foundation impacts the soil layer at the moment earthquake subsidence suddenly stops, exerting excessive impact force on the columns on the first floor. As a result, the columns on the first floor are severely fractured under the influence of the excessive impact force (Figure 6).

(a) Fall failure of the first floor

(b) Close-up of the fall failure of the first floor (1)

(c) Close-up of the fall failure of the first floor (2)

Figure 6. Strain softening of shear band soil during a severe tectonic earthquake induces fall failure of a typical market building (Dazhi Market building, Tainan, Taiwan).

3) Before the pushover analysis and test, all the bottom ends of the columns of the market buildings are located on a continuous and horizontal ground; in other words, all column bases are set to sit on a rigid ground. After the pushover analysis and test, the horizontal ground surface remains horizontal, the continuous ground remains continuous, and the rigid stratum remains rigid (details Figures 7 and 8). Therefore, the failure mechanism of market buildings obtained by pushover analysis and test is completely different from the actual fall failure mechanism of market buildings in severe tectonic earthquakes. Therefore, it cannot be used as the design basis for seismic reinforcement of market building structures.

Figure 7. Typical results of pushover test (Huang, 2009).

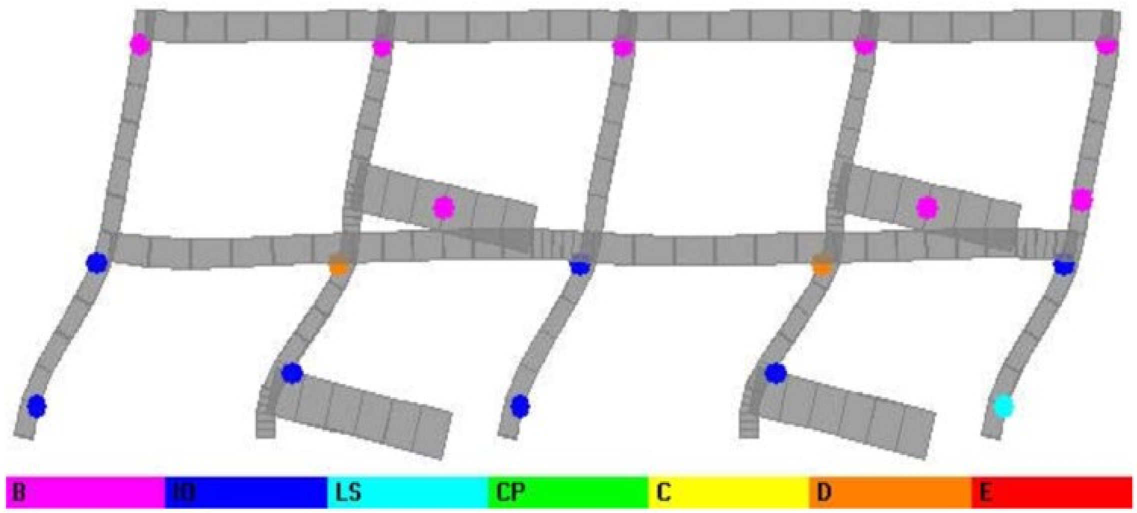


Figure 8. Typical results of pushover analysis (Huang, 2009).

4) When the strain goes deep into the plastic range, as shown in Figure 9, the capacity curves obtained from both the pushover test and pushover analysis indicate strain softening behavior; however, in the pushover analysis, strain hardening or a perfectly plastic capacity curve is utilized. In other words, the capacity curve employed in the pushover analysis does not correspond to the actual scenario.

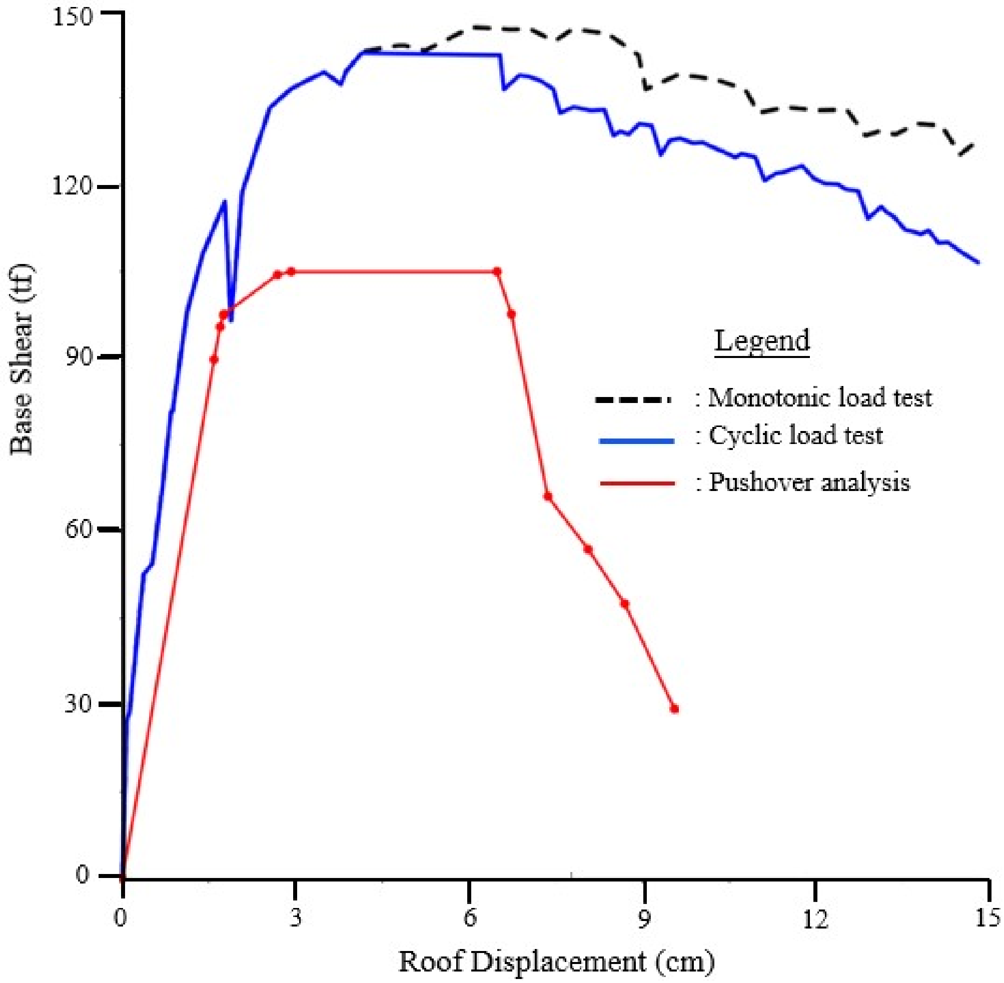
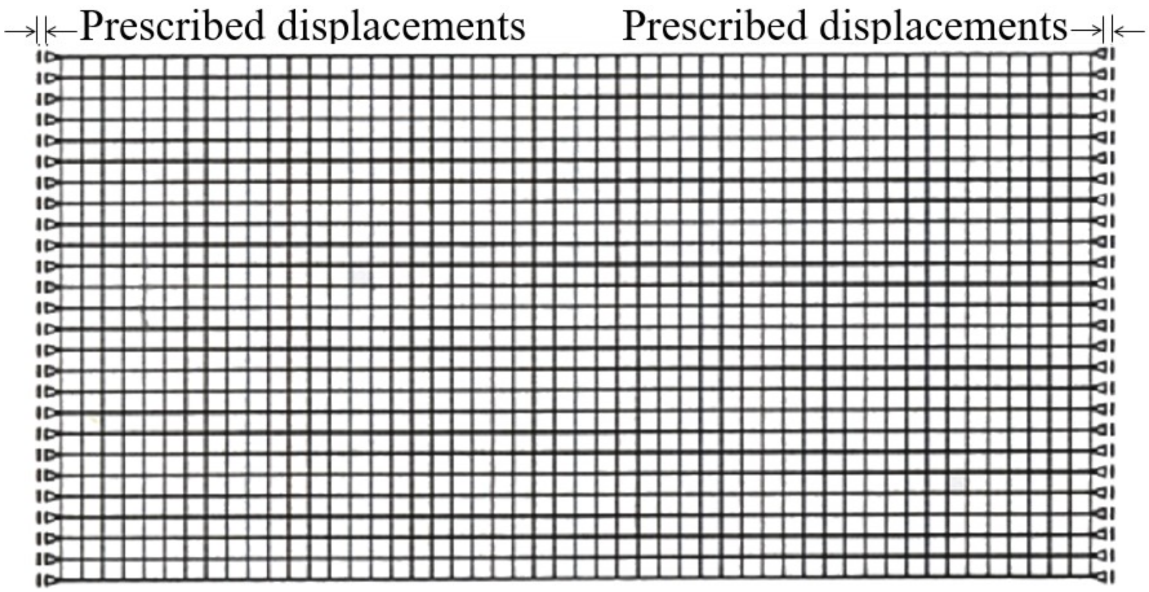
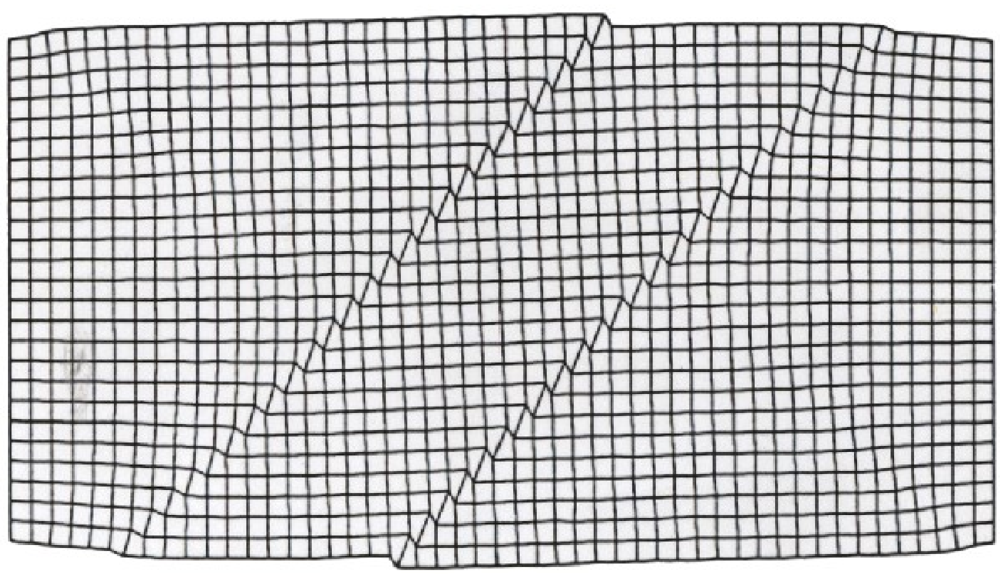


Figure 9. Capacity curves obtained through pushover test analysis (Chung, et al., 2013).

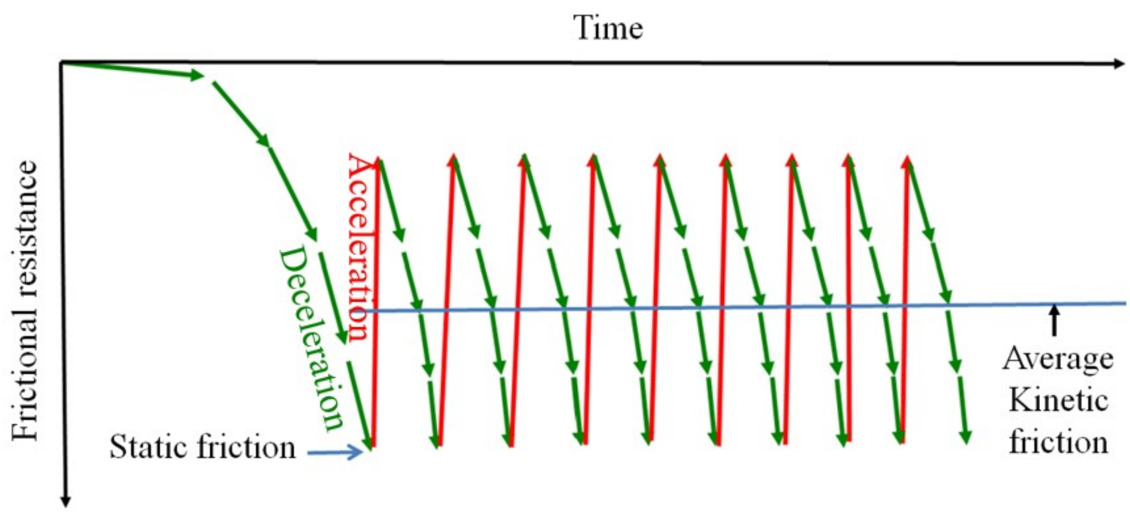
5) As shown in Figure 10(a), a tectonic earthquake originates from lateral plate compression. When the strain goes deep into the plastic range, the plate loses ellipticity because of strain softening, and localization of deformation occurs under the condition of instability, forming shear bands (Figure 10(b)). During shear banding, the stick-slip phenomenon persists because of frictional resistance fluctuations over time (Figure 10(c)). When stick occurs, the plate decelerates, and when slip occurs, the plate accelerates; therefore, the acceleration time history curve can be obtained from seismographs (Figure 10(d)).



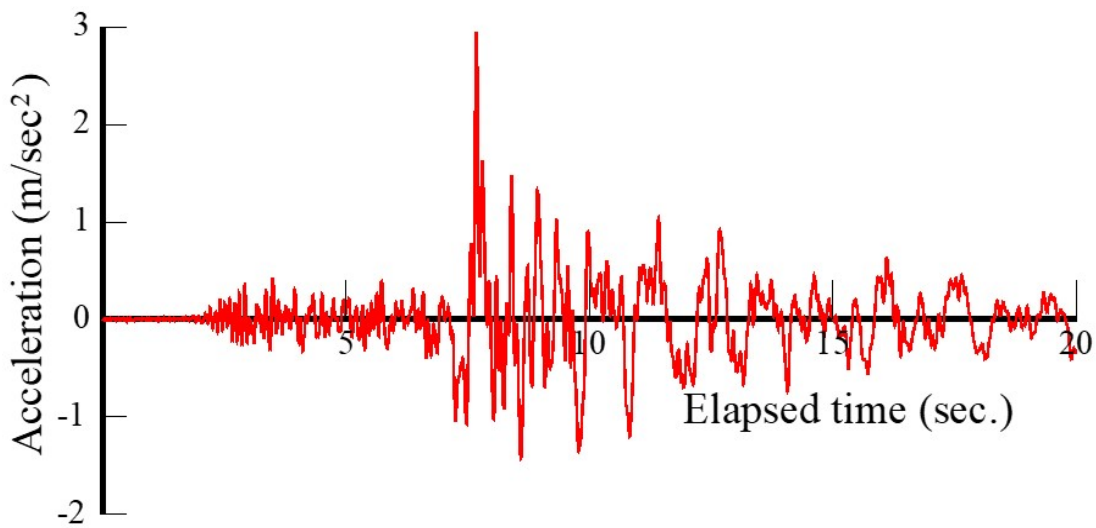
(a) Prescribed displacements for a tectonic plate (Hsu, 2018)



(b) Shear bands induced by localizations of deformations (Hsu, 2018)



(c) Repeated stick-slip phenomenon induced by shear banding (Lambe, 1969).



(d) Deceleration-acceleration time history induced by repeated stick-slip (Hsu, 2018)

Figure 10. Shear bands induced by continued lateral compression and ground vibration induced by shear banding of a tectonic plate.

6) For the alluvial soil layer of silty sand or sandy silt in Tainan, when the groundwater table is close to the ground surface, shear banding induced by a severe tectonic earthquake locally induces highly concentrated excess pore water pressure (Figure 11). In such instances, the ultimate bearing capacity of the foundation is reduced by a positive excess pore water pressure during the compression of the shear band. Then, the bearing capacity increases due to negative excess pore water pressure during the relaxation of the shear band. Therefore, when shear banding occurs during a severe tectonic earthquake, the occurrence and instantaneous cessation of the seismically induced subsidence of the foundation continues, causing the column to fracture under an impact force that is twice the live load and dead load.

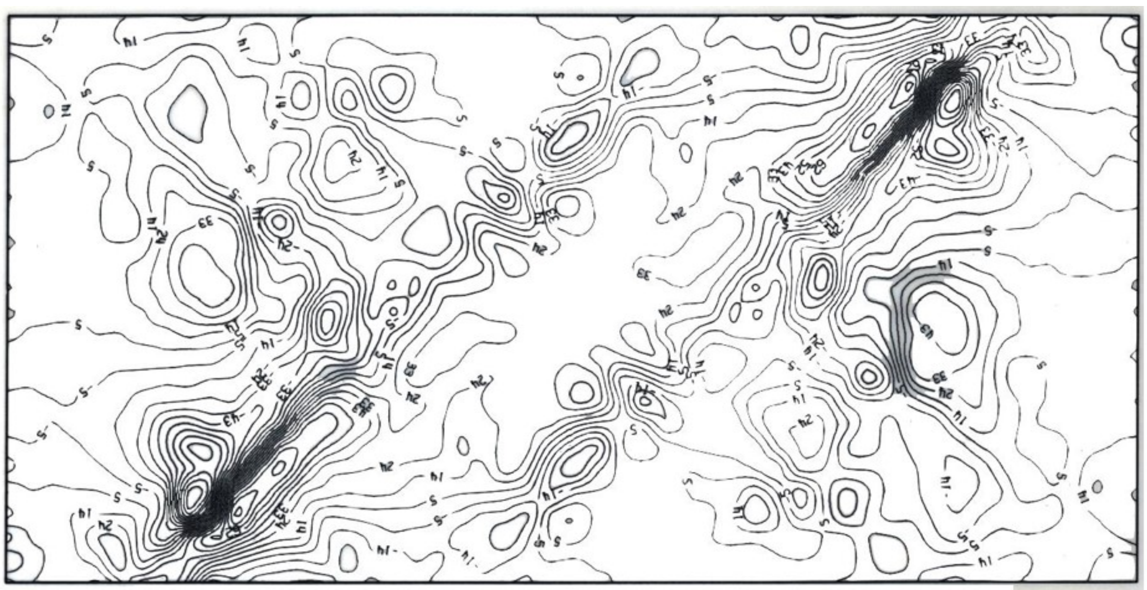


Figure 11. Highly concentrated excess pore water pressure induced by shear zone dislocation (Hsu, 2018).

7) Historically, the formulation and revision of seismic design codes for buildings were overseen by scholars specializing in structural dynamics. Therefore, although buildings collapsed because of shear banding, the inadequate vibration resistance of superstructural elements (columns, beams, slabs, and walls) has been misidentified as the primary cause of disasters under unproven conditions. This misidentification has led to a continuous increase in the vibration fortification level of these superstructural elements.

8) Figure 12 shows the failure of Olive View Hospital in the United States, accompanied by the shear-band tilt and uplift effect, resulting in an uneven uplift of the ground where the bottom ends of the columns on the first-floor are located. Therefore, when the horizontal ground surface could not maintain its level, the continuous stratum could not maintain continuity, and the rigid stratum could not maintain its rigidity, resulting in the breakage of columns on the first floor of the hospital. However, Figure 13 shows the structural dynamic analysis model presented by Chopra (2007), where the bottom ends of the first-floor columns are uniformly set as fixed ends. In this structural dynamic analysis, while ensuring that the horizontal ground surface, the continuous stratum, and the rigidity of the stratum all remain unchanged, the failure pattern of the Olive View Hospital obtained through the analysis is entirely different from the actual failure pattern observed for the hospital.

Figure 12. Shear banding induced failure of Olive View Hospital (Chopra, 2007).

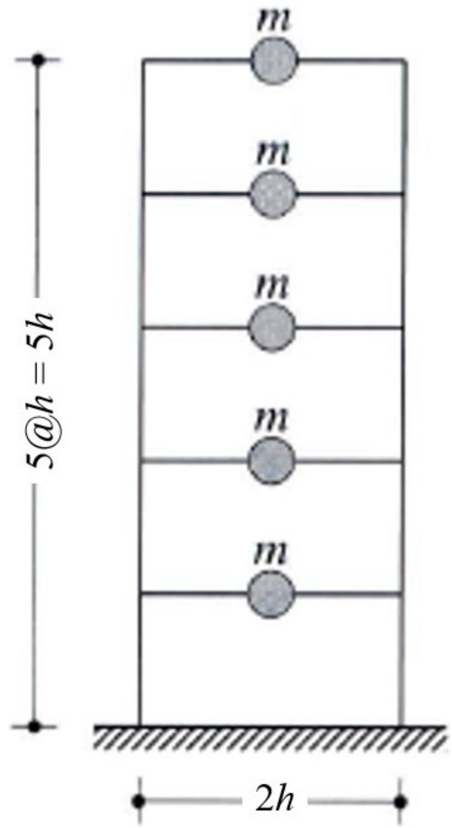


Figure 13. Dynamic analysis model of uniform five-story frames (Chopra, 2007).

9) Figure 14 presents a schematic diagram of the mutual generation and mutual restraint between buildings and shear bands in the strata. As shown in Figure 14, the major cause of the collapse of buildings is shear banding, and there are many local tilt-uplift slopes in the elevated land and hillsides, where shear bands outcrop. When the construction site is leveled using cut-and-fill balance techniques during the construction period, this may obscure shear bands and tilt-uplift slopes, which may cause the collapse of buildings during severe tectonic earthquakes.

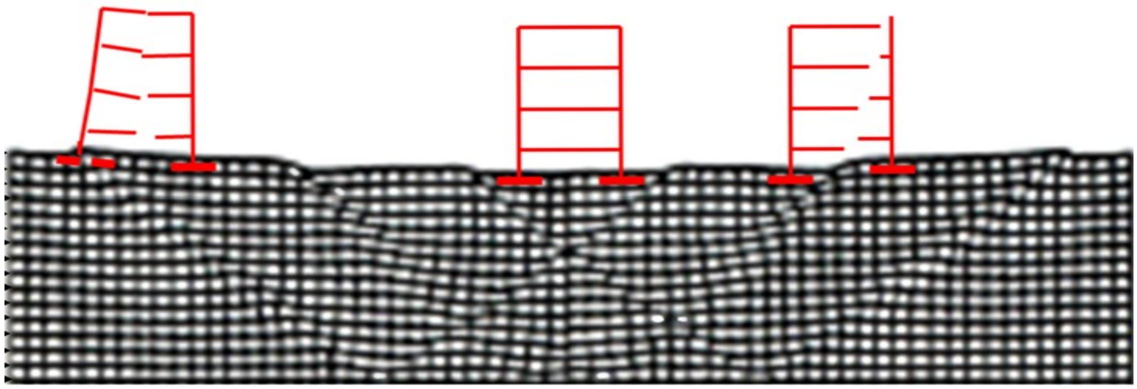


Figure 14. Schematic diagram of the mutual generation and mutual restraint between buildings and shear bands in strata (Hsu, 2022b).

10) When the left and right sides of a building are adjacent to shear bands (the building in the middle of Figure 14) or when the two sides of a shear band are adjacent to the building (as detailed in Figure 15), stability during severe tectonic earthquakes is maintained when the horizontal floor on which all the columns on the first floor of the building are located remains horizontal, the rigid stratum maintains its rigidity, and the continuous stratum remains uninterrupted. Buildings conforming to any version of the seismic design code can thus remain stable during severe tectonic earthquakes (Lin et al., 2022).

Figure 15. The buildings on both sides of the shear band that was tilted and uplifted in the 921 Jiji earthquake continued to remain stable.

11) Because of the continuous lateral compression of the tectonic plate, the horizontal ground surface may become a curved surface (Figure 14), and a building equipped with vibration isolation pads may lose its necessary stability conditions when the ground surface is inclined during a severe tectonic earthquake (Figure 16).

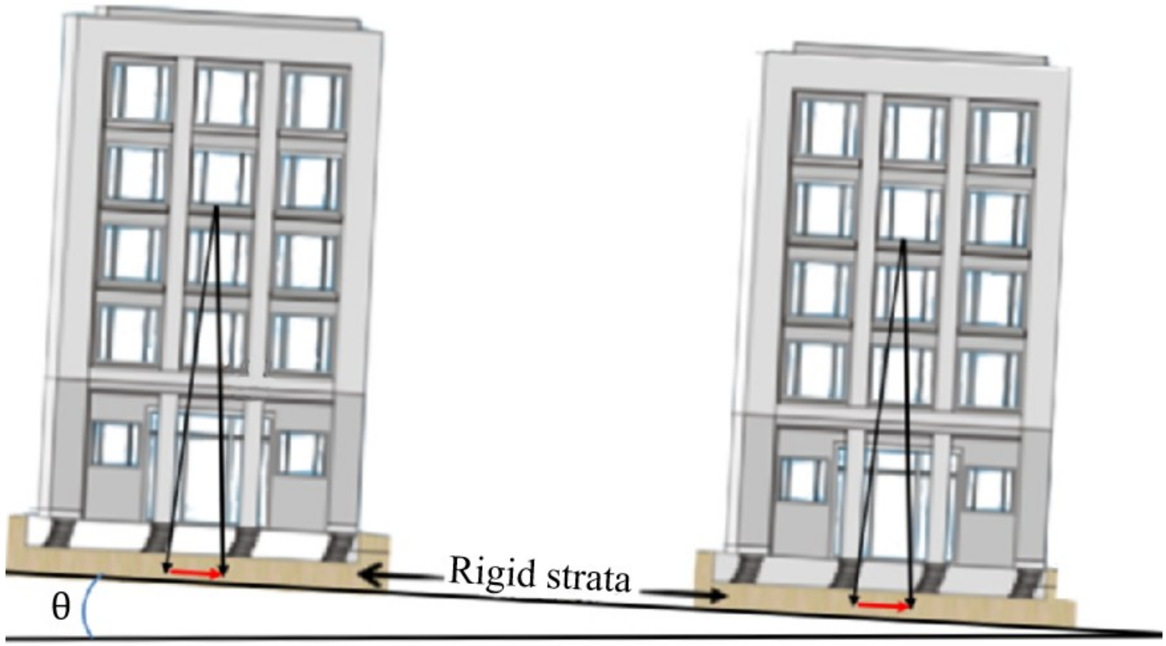


Figure 16. Vibration-isolated buildings tend to be unstable on a rigid stratum inclined during a severe tectonic earthquake.

12) For the alluvial sandy silt layer, in the non-shear band zones or in the shear band zones without shear banding, Table 1 shows that if there is no strain softening phenomenon during the tectonic earthquake, the safety factor of the foundation bearing capacity will be reduced from FS_S =3.0 to FS_E=1.64>1.0, so under the circumstance that the foundation earthquake subsidence will not occur, the market building will not collapse. On the contrary, if there is strain softening during the tectonic earthquake, the safety factor of the foundation bearing capacity will be greatly reduced from FS_S =3.0 to FS_E=0.95<1.0, so under the circumstance that the foundation earthquake subsidence will occur, the market building will collapse. Therefore, it is known that during tectonic earthquake, the strain softening effect of alluvial sandy silt layer is the major cause for the fall failure of Dazhi Market building.

Conclusions and Suggestions

Tectonic earthquakes in Taiwan are frequent and may result in local collapse of many buildings, as occurred during the 921 Jiji earthquake. In order to safeguard people's lives, the National Center for Research on Earthquake Engineering has developed an evaluation method, which employs various techniques, for determining whether structural seismic reinforcement is necessary. Subsequently, the Ministry of Education initiated seismic reinforcement of school buildings, and the Ministry of Economics followed closely with the structural seismic reinforcement of market buildings. Given that the major cause for the fall failure of market and school buildings affect the effectiveness of the seismic reinforcement of structures, this study reached the following five conclusions:

1) The major cause for the fall failure of market buildings in tectonic earthquakes is shear banding, not ground vibration.

2) The shear bands or shear textures in the vicinity of the Dazhi Market building in Tainan, Taiwan, can be identified based on historical epicenter distribution maps, satellite imagery, and GPS velocity vector distribution maps, and the area adjacent to Dazhi Market building can be delineated into shear band zones and non-shear band zones.

3) For a market building located in an alluvial sandy silt layer in a non-shear band zone or in a shear band zone without apparent shear banding, the building foundation soil is solely subjected to ground vibration. When the seismic design is reinforced against ground vibrations, market buildings do not collapse under the influence of ground vibration.

4) For a market building located in the alluvial sandy silt layer in a shear banding zone, the building foundation soil is simultaneously affected by shear banding and ground vibration. When the seismic design code exclusively addresses ground vibration, market buildings collapse under the combined influence of strain softening and tilting-lifting induced by shear banding.

5) Market buildings situated in non-shear band zones or shear band zones where shear banding is absent did not collapse during the 921 Jiji earthquake because of ground vibration. Provided that the buildings pass the physical verification of ground vibration, enhancing the level of ground vibration fortification through structural seismic reinforcement is not necessary.

Based on the above five conclusions, the authors make the following two suggestions:

1) The major cause for the fall failure of buildings must be included in the seismic design codes for buildings in the future.

2) Because seismic design codes focus only on ground vibration fortification, professional engineers can adopt any version of the seismic design code, in addition to consideration of the shear banding effect, in order to achieve the performance design goal while taking into account economy.

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