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THE MAJOR CAUSE OF BUILDING FALL FAILURES DURING TECTONIC EARTHQUAKES

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

Hong-Chia Chang
Ph.D Program for Civil Engineering, Water Resources Engineering, and Infrastructure Planning, Feng-Chia University
Taiwan R.O.C.

Chao-Ming Chi
Department of Civil Engineering, Feng-Chia University
Taiwan R.O.C.

Abstract

All buildings in a seismic area must meet the requirements of the Seismic Design Specifications of Buildings. However, the building fall failures that have caused a large number of deaths in previous tectonic earthquakes continue to occur. The vibration resistance of columns, beams, plates and walls continues to increase, yet, the number of building fall failures has not been reduced. To this regard, in this paper, first, the conditions and mechanism of building fall failures in tectonic earthquakes are proposed, and then the major cause of building fall failures are discussed based on the example of the Tongshuai Building. It is found that the previous Seismic Design Specifications of Buildings do not include this failure cause. Therefore, it is suggested that only by including earthquake prevention methods for this cause in the Specifications can the number of building fall failures be reduced on a large scale.

Keywords: Earthquakes, Seismic Design, Building, Fall Failure, Mechanism, Shear Band.

Introduction

In the past 40 years, although the Seismic Design Specifications of Buildings in Taiwan have been revised continuously, buildings complying with the Seismic Design Specifications still suffered fall failures during the Jiji Earthquake and Jiayi Earthquake in 1999, and the Jiaxian Earthquake in 2010 and Meinong Earthquake in 2016 (as shown in Figure 1).

(a) Jiji Earthquake in 1999 (Nantou, Taiwan)

(b) Jiayi Earthquake in 1999 (Jiayi, Taiwan)

(c) Jiaxian Earthquake in 2010 (Tainan, Taiwan)

(d) Meinong Earthquake in 2016 (Tainan, Taiwan)

Figure 1. Cases of building fall failures induced by previous earthquakes in Taiwan

When a building begins to collapse in a tectonic earthquake, the height between the floors will be greatly reduced due to the severe fracture of the columns, which in return will result in a large number of deaths due to the "sandwich squeezing" effect. After the earthquakes listed, the investigation of the cause of the disaster began immediately, however, most of the experts participating in the investigation majored in structural dynamics and the investigation was also based on the Seismic Design Specifications of Buildings (Construction and Planning Agency Ministry of the Interior, 2005), thus, the causes of the disasters listed in the survey results were almost the same (Tainan Professional Civil Engineering Association, 2016; Shih, 2016; Lee, 2016). These causes included that the first floor was too high, a lack of walls, inadequate vibration-resistance in the upper structures, and incorrect methods of anti-vibration reinforcement, etc.

Experience shows that in the past, most of the revisions to the Seismic Design Specifications of Buildings were based on such investigation results. Therefore, they focused only on the improvement of the vibration resistance of upper structures such as columns, beams, plates, and walls. Since 1974, the vibration resistance of upper structures has been increased by 100% (Hsu, et al., 2015), but the fact that buildings still fell in tectonic earthquakes indicates that the investigation results did not address the major cause of building fall failures.

To this regard, in this paper, the major cause of building fall failures in tectonic earthquakes is discussed. Firstly, the conditions and mechanism of building fall failures in tectonic earthquakes are proposed, and then the building fall failure example of the Tongshuai Building during the 0206 Hualien Earthquake in 2008 is used to confirm that once the conditions and mechanism of fall failures occur in a tectonic earthquake, then the occurrence of building fall failures is inevitable. Finally, based on the major cause of building fall failure, some effective methods to reduce building fall failures are proposed.

The Conditions And The Mechanism For Building Fall Failure

The Proposed Conditions for Building Fall Failure

In the past 20 years, Taiwan has witnessed four tectonic earthquakes in a row. During these earthquakes, building fall failures were characterized by the fact that the columns on the bottom floors (or all floors) of the building were fractured, and before the fracture of these columns, the foundation had already witnessed seismic settlement, as shown in Figure 2.

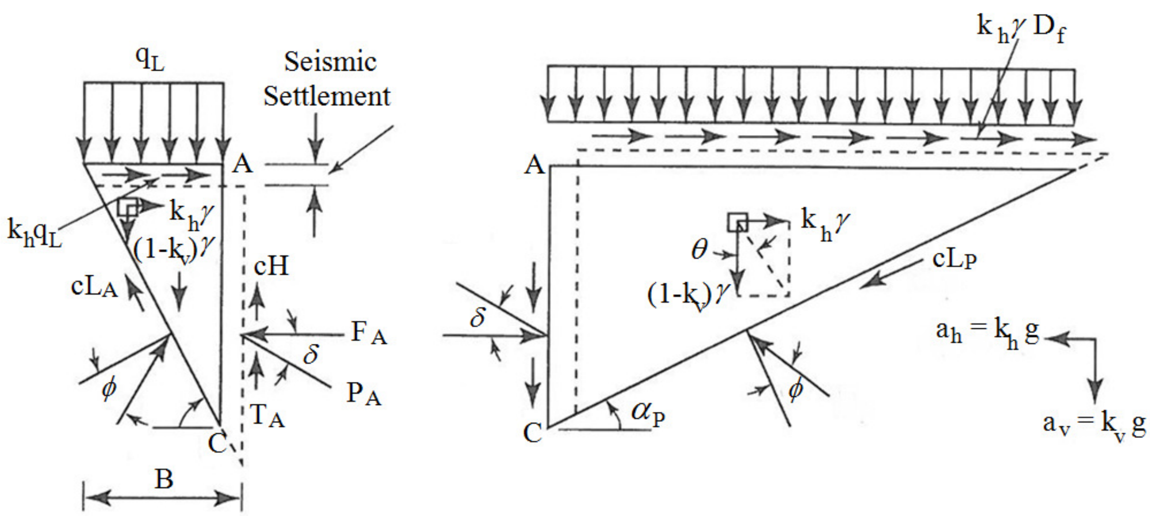


Figure 2. Seismic settlement and seismic-related forces acting on slip zone wedge (Richards, Elms, and Mudhu, 1993)

According to Richards, Elms, and Mudhu (1993), the condition that induces seismic settlement is the factor of safety for the foundation seismic bearing capacity $FS_E < 1.0$. However, according to the authors' experience, it is easy for $FS_E < 1.0$ to occur in a tectonic earthquake under the following conditions:

1. The factor of safety for the foundation static bearing capacity $FS_S \leq 3.0$;
2. The ground water table (GWT) is above the bottom of foundation;
3. The foundation soil in the tectonic earthquake contains shear textures of a shear band;
4. The horizontal and vertical ground acceleration coefficients k_h and k_v are adequately large.

In general, foundation design often uses $FS_S = 3.0$, therefore, the foundation is not located in the loose sand layer or loose silty sand layer in which the peak angle of internal friction ϕ_p is smaller than 32°. For foundations located in the dense sand layer and dense silty sand layer in which ϕ_p is larger than 32°, once shear textures of a shear band start to form in a tectonic earthquake, the angle of internal friction will transfer to the residual angle of internal friction ϕ_r.

According to the experimental results of McCarthy (1997), ϕ_r in fine-to-medium sand is between 29° and 32°; ϕ_r in silty sand (SM) is between 27° and 32°; and ϕ_r in silt (ML) is between 26° and 30°. Therefore, based on the previous conditions where $FS_E < 1.0$ is easily induced, it can be seen that all fine-to-medium sand, silty sand (SM), and silt (ML) layers can induce ground settlement in a tectonic earthquake.

The Proposed Mechanism for Building Fall Failure

In general, the static load of the column in the structural design includes dead load (DL) and live load (LL). From the point of view of safety, both the Design Criteria for Concrete Structures (Construction and Planning Agency of the Interior, 2018) and Design Criteria for Steel Concrete Structures (Construction and Planning Agency of the Interior, 2018) require that the static resistance force of column is 1.2DL+1.6LL.

However, in a tectonic earthquake, when shear banding induces the repeated phenomena of stick-slip-stick-slip-… (Lambe and Whitman, 1969), a seismograph will monitor a time-domain-based curve of deceleration-acceleration-deceleration-acceleration-...; and at the moment when it accelerates to the peak and is about to decelerate, the whole building will bear an impact due to the sudden stop of ground settlement, and the magnitude of the impact is approximately twice the total static load (i.e. 2DL+2LL). In this case, from the foundation to the whole building, the columns on several floors or on all floors can break due to overloading, and then induce building fall failures as shown in Figures 3 to 5.

Figure 3. Fall failure of the 11-floor Tongshuai Building in the 0206 Hualien Earthquake in 2018 (Hualien City, Taiwan)

Figure 4. Fall failure of the 16-floor Longbang Wealth Celebrity Building in the 921 Jiji Earthquake in 1999 (Yuanlin Town, Changhua County, Taiwan)

Figure 5. Fall failure of the 11-floor buildings in the 1008 Kashmir Earthquake in 2005 (George Pararas Carayannis, 2012)

The Major Cause Of The Tongshuai Building Fall Failure

Figure 3 indicates that the Tongshuai Building suffered fall failure in the 0206 Hualien Earthquake in 2018. This paper will investigate the conditions and mechanism of building fall failures discussed above to discover the major cause of the fall failure of the Tongshuai Building.

The Required Conditions for the Tongshuai Building Fall Failure

Figure 6 shows that before the earthquake, the foundation of the Tongshuai Building consists of two similar strip foundations that are orthogonal to each other. Where the strip foundation width B is 15m, foundation depth D_f is 4.5m.

Figure 6. Stereoscopic image of the Tongshuai Building before the earthquake

(Google Earth, 2018)

Figure 7 shows the geological map for the area near the Tongshuai Building. From Figure 7, the Tongshuai Building is located on a quaternary alluvial layer, which is mainly composed of silty sand, but the geology of Meilun Mountain is Pleistocene Milun conglomerate.

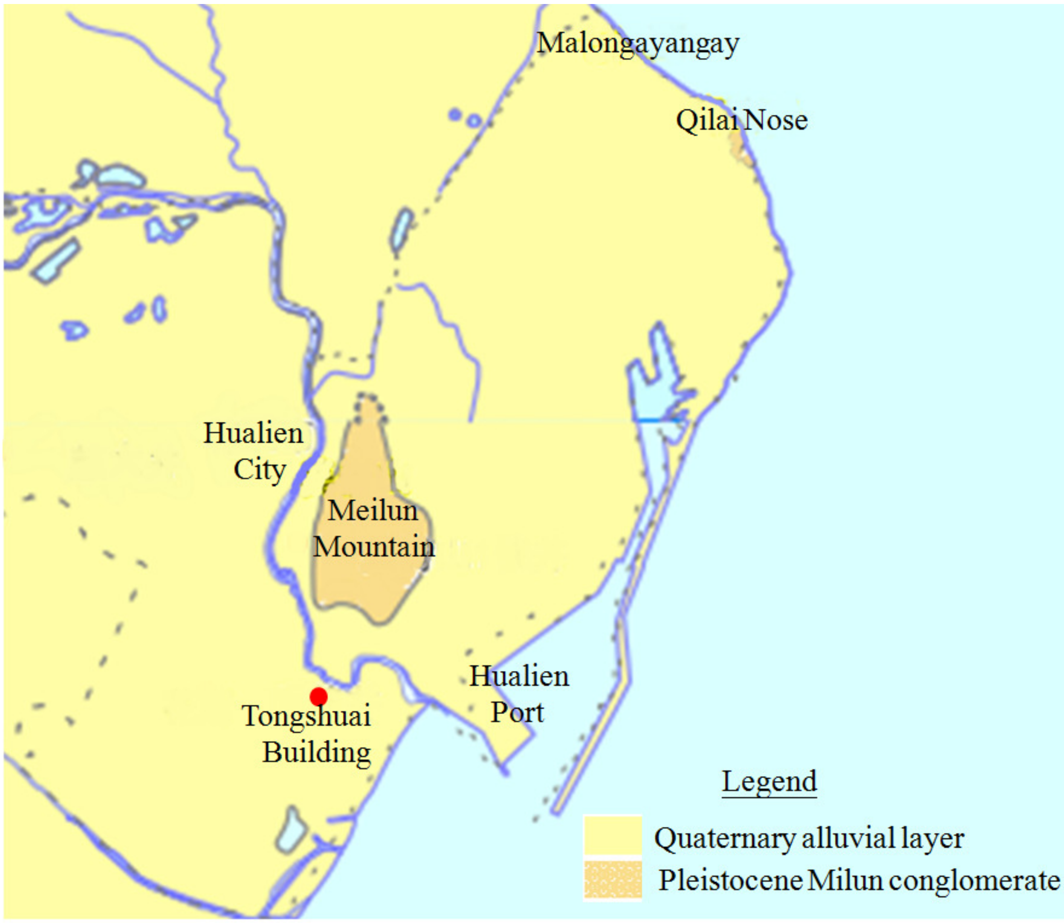


Figure 7. The geological map for the area surrounding the Tongshuai Building (Central Geological Survey of Taiwan, System of Geology in Taiwan, 2018)

Figure 8 shows the boring log next to the foundation of the Tongshuai Building. According to Figure 8, the GWT in this area is 3m below the ground surface. Based on the unified soil classification system, the ground layer above the foundation floor is composed of poorly graded gravel (GP); its average unit weight γ_{ave} is 22kN/m^3. However, the ground layer below the bottom of foundation is silty sand (SM), with an average saturated unit weight γ_{sat} of 20.5kN/m^3, an average ϕ_p of 32°, and an average ϕ_r of 30°.

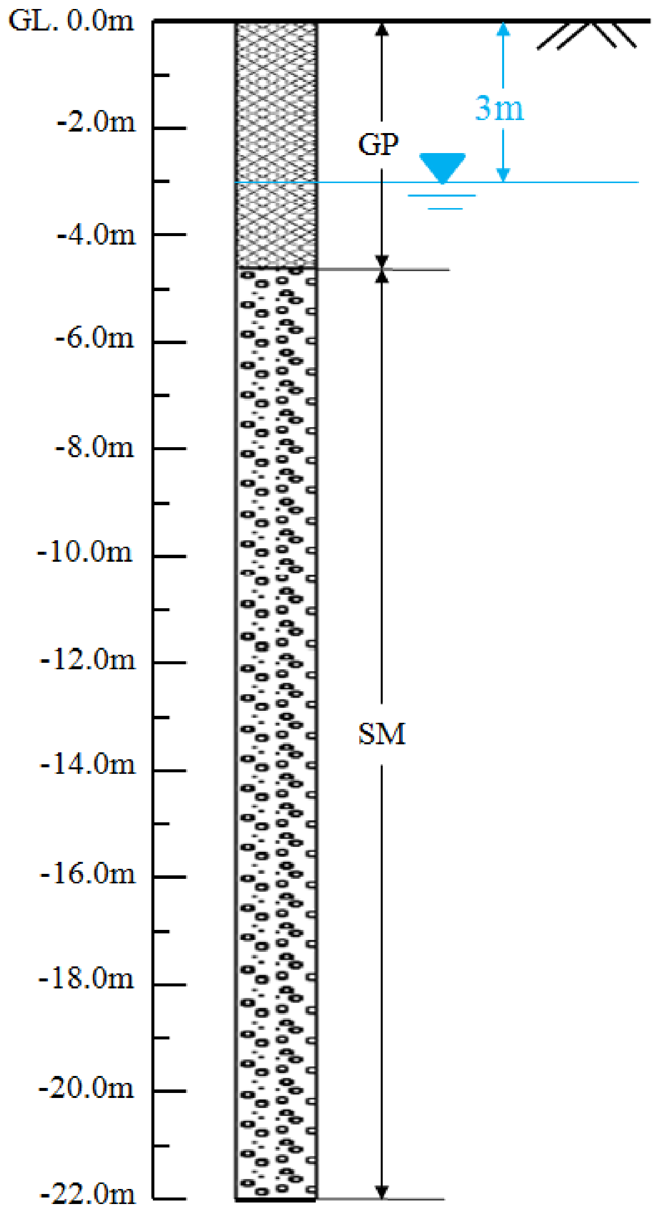


Figure 8. The boring log next to the foundation of the Tongshuai Building

Table 1 shows the recorded E-W direction, N-S direction, and vertical direction peak ground acceleration (PGA) at the Hualien Station in Hualien Earthquake, which are 0.405g, 0.443g, and 0.213g respectively, thus, the maximum PGA is 0.443g.

Table 1. PGA recorded from the Hualien station during the 0206 Hualien earthquake (NARLAB, 2018)

	PGA	PGV
E-W direction	0.405g	0.5396m/sec
N-S direction	0.443g	0.4043m/sec
Vertical direction	0.213g	0.1436m/sec

Secondly, according the corresponding relationship between PGA and the seismic acceleration coefficient (Ministry of Economic Affairs, 2008) in Table 2, it can be derived that the horizontal and vertical seismic acceleration coefficients k_h and k_v corresponding to the maximum PGA 0.443g are 0.153 and 0.0765, respectively.

Table 2. Corresponding relationship between PGA and seismic acceleration coefficients (Ministry of Economic Affairs, 2008)

PGA	k_h
<0.12g	0.10
0.12g~0.18g	0.10~0.12
0.18g~0.50g	0.12~0.16
0.50g~0.80g	0.16~0.24
>0.80g	0.24
Note: $k_v = k_h \times R$, $R \geq 0.5$.	

The Calculation of the Factor of Safety for the Foundation Seismic Bearing Capacity of the Tongshuai Building

For strip foundations on cohesionless soils, Equation 1 can be used to calculate the foundation seismic bearing capacity:

$$q_{ult,E} = qN_{qs}e_q + \frac{1}{2}B\gamma' N_{\gamma s}e_\gamma \qquad (1)$$

where q is the overburden pressure above the bottom surface of the foundation; γ' is the effective unit weight of soil; N_{qs}, and $N_{\gamma s}$ are the bearing capacity parameters of soil under static conditions for strip foundations provided by Meyerhof (1951); and the seismic correction factors of e_q and e_γ, provided by Budhu and Al-Karni (1993), are calculated as:

$$e_q = (1-k_v)\exp\left[-\left(\frac{5.3k_h^{1.2}}{1-k_v}\right)\right] \qquad (2)$$

$$e_\gamma = (1-\frac{2}{3}k_v)\exp\left[-\left(\frac{9k_h^{1.1}}{1-k_v}\right)\right] \qquad (3)$$

For the strip foundation of the Tongshuai Building, Table 3 indicates the calculated factors of safety for the foundation seismic bearing capacity FS_E. According to Table 3, when FS_S is 3.0 and ϕ_p is 32°, the designed static bearing capacity of the foundation q_{design} is 1308kN/m^2.

In addition, when the foundation soil does not contain shear textures of a shear band in a tectonic earthquake, the shear resistance strength is controlled by ϕ_p. In this case, the calculated FS_E is 1.21 (see Table 3 for details), so seismic settlement will not occur. However, when the foundation soil contains shear textures of a shear band in a tectonic earthquake, shear resistance strength is controlled by ϕ_r. In this case, the calculated $FS_E < 1.0$ (see Table 3 for details), so seismic settlement will occur.

Table 3. Analysis results of the seismic bearing capacity safety factors for the strip foundation of the Tongshuai building attacked by the 0206 Hualien Earthquake

ϕ_p	ϕ_r	k_h	k_v	q_{ult} (kPa)	FS_S	FS_E
32°	---	0	0	3924	3.00	---
32°	---	0.153	0.0765	1577	---	1.21
---	30°	0.153	0.0764	1212	---	0.93

The Adopted Equation for the Determination of Seismic Settlement for the Tongshuai Building

In this study, the following equation proposed by Richard, Elms, and Mudhu (1993) for the determination of the seismic settlement (refer to Figure 2) is to be adopted.

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

Where

V = the peak velocity of the ground motion (m/sec);

A = the coefficient of the ground acceleration (dimensionless);

g = the gravitational acceleration (9.807m/sec^2);

α_{AE} = as the angle α_{AE} shown in Figure 9;

k_h^* = the critical seismic acceleration coefficient for foundation seismic settlement (refer to Figure 10);

$\tan \alpha_{AE}$ = determined by using the relationship between k_h^* and the soil internal friction angle ϕ (refer to Figure 11).

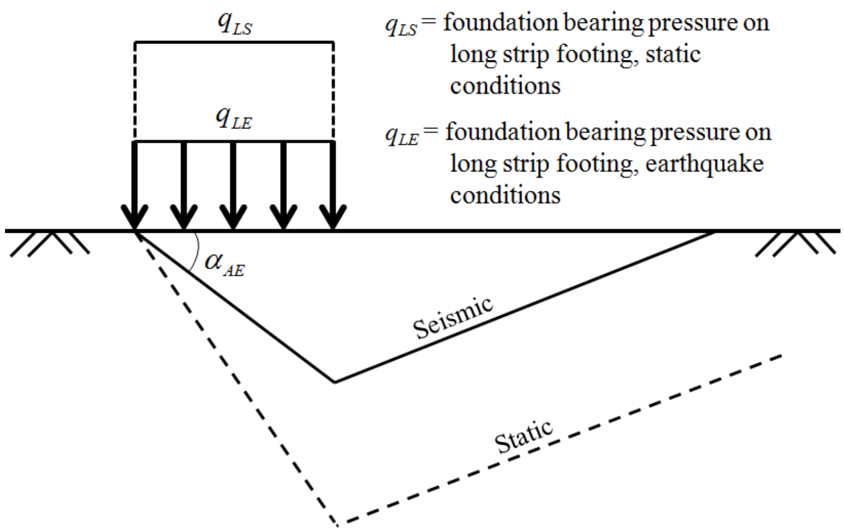


Figure 9. Foundation shear failure zones for static and seismic conditions

(Richards, Elms and Mudhu, 1993)

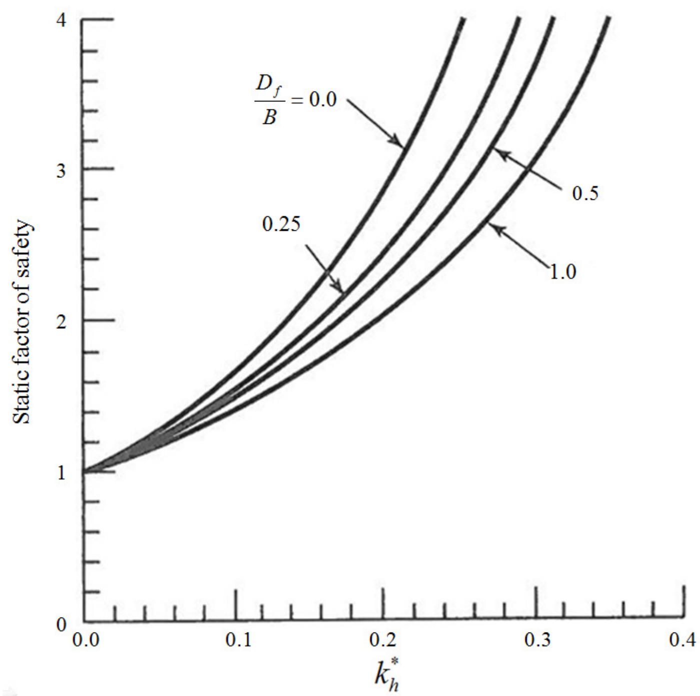


Figure 10. The relationship between the critical seismic acceleration coefficient k_h^* and the static factor of safety for $\phi = 30^\circ$ (Richards, Elms and Mudhu, 1993)

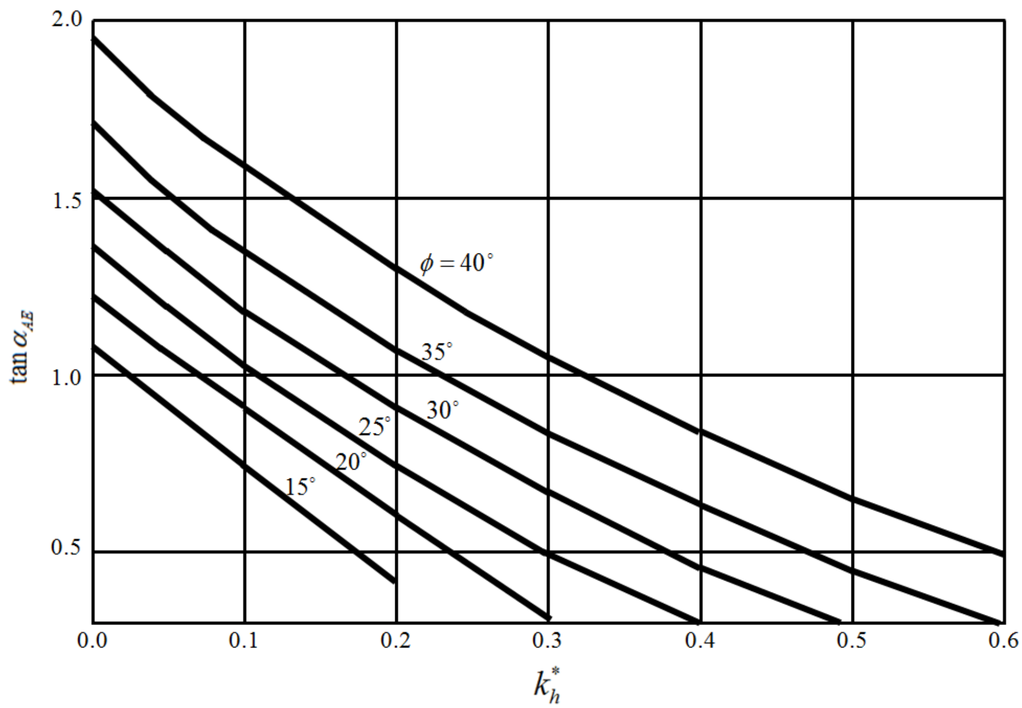


Figure 11. The relationship among k_h^*, $\tan \alpha_{AE}$, and ϕ

(Richards, Elms and Mudhu, 1993)

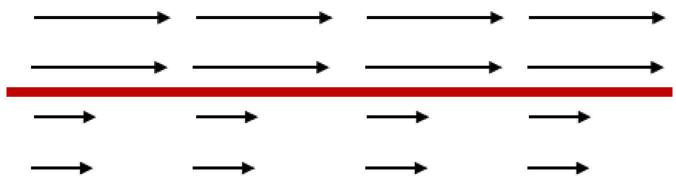
The Determination of the Seismic Settlement for the Tongshuai Building

Since ϕ_r for the foundation soil of the Tongshuai building is 30°, the adopted FS_S is 3.0 and the ratio between D_f and B is 0.3. Thus we obtain $k_h^* = 0.245$ from Figure 9 and $\tan \alpha_{AE}$ = 0.8 from Figure 10. For the event of the 0206 Hualien earthquake causing A = 0.443 and V = 0.5396 m/sec, therefore seismic settlement S_E can be calculated as follows:

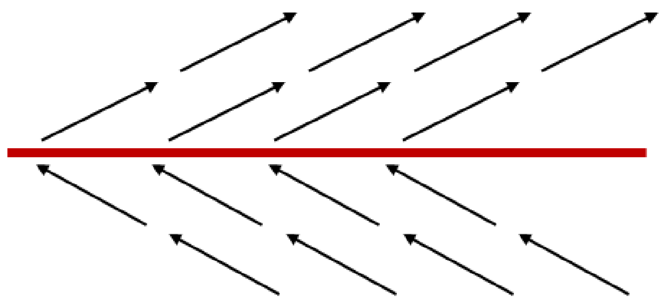
$$S_E = 0.174 \frac{0.5396^2}{0.443 \times 9.807} \left(\frac{0.26}{0.443} \right)^{-4} (0.76) = 0.078m = 7.9cm \qquad (6)$$

The Major Cause of the Building Fall Failure

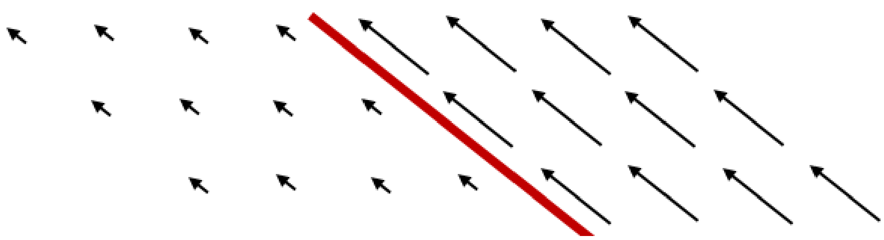
In general, there are four different types of shear bands, slip, twinning, thrust, and normal, as those shown in Figure 12.



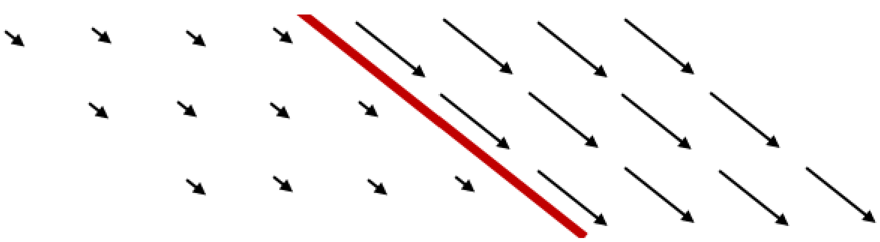
(a) slip type (Hsu, Tse-Shan, 1987)



(b) twinning type (Hsu, Tse-Shan, 1987)



(c) thrust type



(d) normal type

Figure 12. Four different types of shear bands

In addition, according to the GPS velocity vector diagram shown in Figure 13, there exists shear bands of slip type, twinning type, and thrust type in the area near the Tongshuai Building, their dips are N56^{o}W, N12^{o}W, and N21^{o}E, respectively.

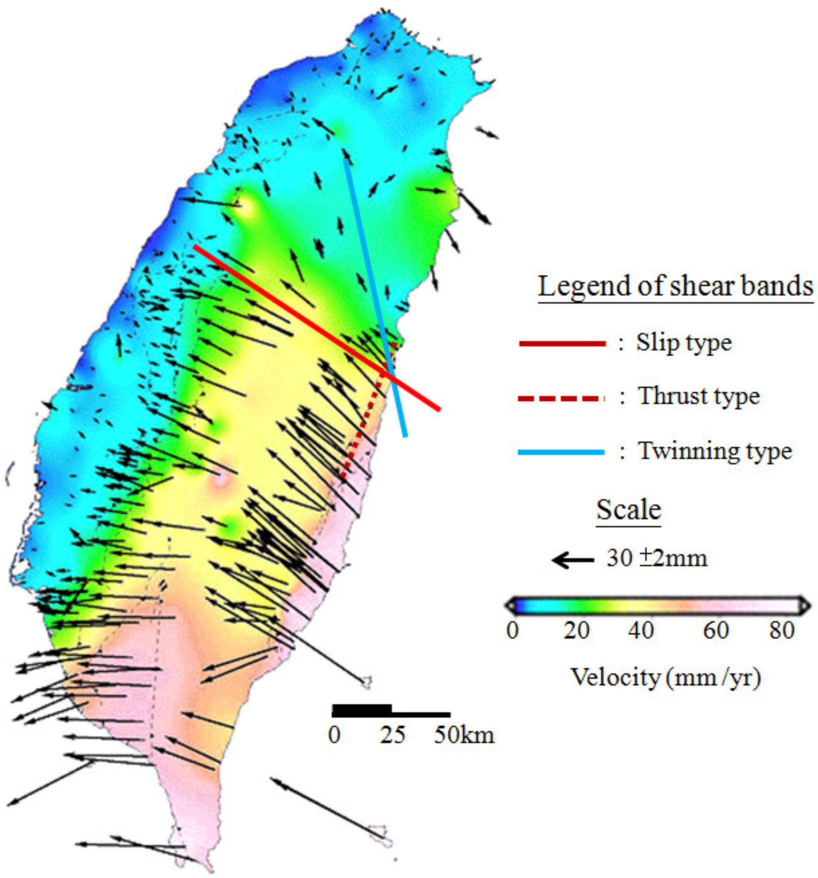
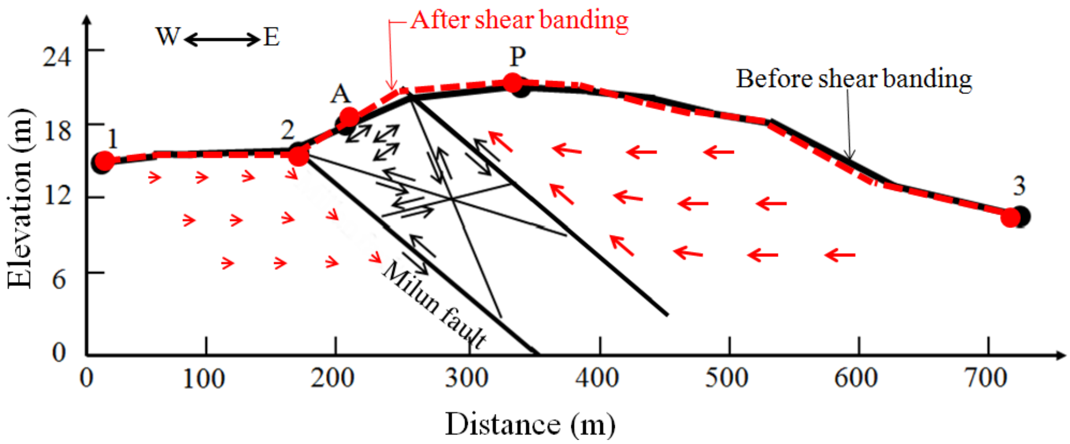


Figure 13. Three different types of shear bands identified near the Tongshuai Building by using the GPS velocity vector diagram of Taiwan (GPS LAB, 2018)

Since a shear band of thrust type can uplift hanging wall of the land, according to the shear band of thrust type shown in Figure 12 and Figure 13, it can be inferred that the Tongshuai Building is located on a tilted slope, in which the eastern side is higher than the western side. This inference can be confirmed by the elevation profile shown in Figure 14b.

Remark: A is the location of the Tongshuai Building; 2 is location of Milun Fault.

(a) Measuring line passing five points 1, 2, A, P, 3 (Google Earth, 2018)



(b) Shear band going through the Tongshuai Building

Figure 14. Shear textures in a shear band related to the Milun Fault (The profile before shear banding was obtained from Google Earth, 2018)

Figure 15 shows that when shear banding related to Milun Fault starts, apart from some building fall failures (details see Figure 3) and building leaning (details see Figure 15a) in Hualien City, there were hundreds of roads, bridges, tap water pipes, gutter covers, embankments, and piers, etc. that suffered local damage due to local shear banding effects.

(a) Building leaning induced by local shear failure of foundation

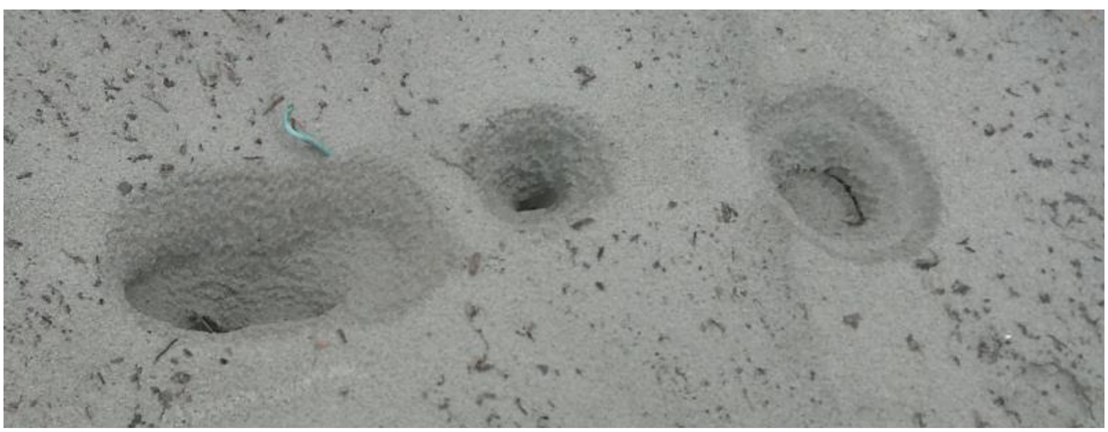
(b) Local uplifts of a road induced by local shear banding effects

(c) Lateral movement of the bridge girders caused by shear banding

(d) A finished repaired broken tap water pipe below the hill road caused by local shear banding effect

(e) Twisting of a gutter cover caused by lateral compression

(f) Local ruptures on a embankment induced by localizations of deformations



(g) Piped shaped soil liquefactions in the Meilun riverbed (Ke, 2018)

(h) Seismic settlement of a gravel-sand-filled pier (Ke, 2018)

Figure 15. All kinds of failures in different facilities caused by shear banding related to Milun Fault in 0206 Hualien Earthquake, 2018

Under the lateral compression of the tectonic plate, Figure 16 shows a shear band tilting slope. It is to be stressed that after each tectonic earthquake, shear banding effect is cumulated continuously while the ground vibration effect is zeroed. Thus when tectonic earthquakes happen continuously, the degree of fracture for the shear band soils becomes more and more significant.

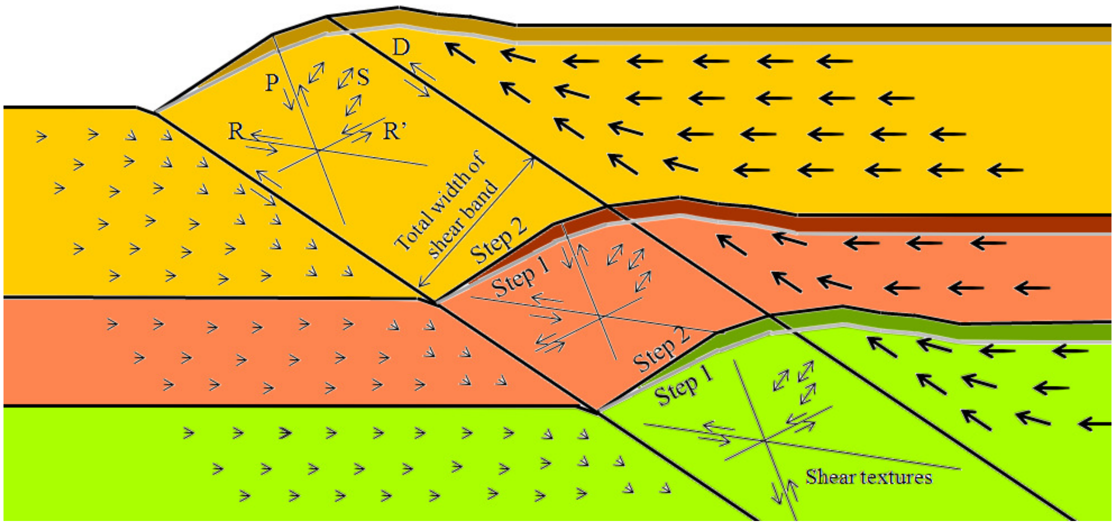


Figure 16. A schematic diagram for the shear band tilting slope

The effect of shear banding can not only reduce the cohesion of the soils or rocks to zero, but can also transfer the angle of internal friction from the peak value to the residual one. In addition, the elevation of the hanging wall relative to the foot wall induced by shear banding can also lead to local uplift in a construction site, which has been leveled by digging and filling previously.

Therefore, it can be deduced that in tectonic earthquake, the cause of a building fall failure is closely related to shear banding. In addition, since the energy of shear banding accounts for over 90% of the total energy in a tectonic earthquake, the energy of the ground vibration accounts for less than 10% of the total energy (China Earthquake Disaster Prevention Center, 2018), therefore, it has been further confirmed that ground vibration cannot be the major cause of a building fall failure in a tectonic earthquake.

Figure 14b indicates that the Tongshuai Building is located on the shear textures of a shear band related to the Milun Fault, and the 0206 Hualien Earthquake has been confirmed to be induced by Milun Faulting according to the geological investigation of the Department of the Economy; however, because the magnitude of the earthquake was only 6.0, the cumulated amount of shear banding in the urban area of Hualien city is not so significant. Therefore, the Tongshuai Building fall failure was triggered by combined conditions. These conditions include: (1) $FE_S = 3.0$; (2) the GWT is above the bottom surface of the foundation; (3) the foundation soil contains shear textures of a shear band; (4) ϕ_r for foundation soils is 30°; (5) k_h and k_v are 0.153 and 0.0765, respectively. Under such conditions, the calculated FS_E is less than 1.0, and when seismic settlement occurred and suddenly stopped, the whole building suffered an impact, all the columns from the bottom floor to several floors above (even all floors) were fractured due to overloading, which then induced a severe building fall failure.

In addition, since (1) the foundation soil did not contain any shear textures of a shear band; (2) ϕ_p for foundation soils is 32°; and (3) k_h and k_v were 0.108 and 0.054, respectively; such that the calculated FS_E is 1.70 (refer to Table 5). Therefore, without seismic settlement, the Tongshuai Building did not suffer building fall failure in the 921 Jiji Earthquake.

Table 5. The calculated FS_E for the Tongshuai building attacked by the 921 Jiji Earthquake

Conditions	c (kPa)	ϕ_p	k_h	k_v	q_{ult} (kPa)	FS_E
Without shear textures of a shear band in foundation soils	0.0	32^o	0.108	0.054	2149	1.70

Some Useful Methods for the Prevention of Building Fall Failure

As for the four conditions addressed for $FS_E < 1.0$ to be induced in a tectonic earthquake, engineers only need to alter one of the conditions to guarantee that $FS_E > 1.0$ in a tectonic earthquake, then building fall failure can be avoided.

1. Increase FS_S; since FS_S=3.0 regulated in conventional Design Specifications cannot guarantee FS_E>1.0, when designing foundations, the required FS_S must be decided by the back calculation to insure that $FS_E \geqq 1.2$.

2. Lower the GWT; according to the thumb rule, the foundation static bearing capacity can be doubled when the GWT is lowered from the ground surface to the lowest level of the shear failure surface caused by the ultimate load.

3. Foundation soil does not contain shear banding effect; the areas where shear band is present can be identified by the monitored diagram of GPS velocity vectors, by which the location of the foundation can be shifted away from the shear banding effect.

4. To insure $\phi_r \geq 32^\circ$ for the foundation soil; in the case where it is impossible to determine that the foundation soil does not contain shear banding effect, multiple methods can be applied to improve the foundation soil. For example, replace silt or fine sand with gravel or grit, use geosynthetics to reinforce silt sand, or use group piles to reinforce raft foundations, etc., by which $\phi_r \geq 32^\circ$ for foundation soil and then the calculated $FS_E > 1.0$ can be guaranteed.

Discussions

In a tectonic earthquake with M_L=6.0, Figure 3 shows that the columns in three floors of the 11-floor building all broke down; when M_L=7.3, Figure 4 shows that the columns in nine floors of the 16-floor building all broke down; when M_L=7.6, Figure 5 shows that all columns in the 11-floor building broke down. This is probably because under such combined conditions, the seismic settlement increases with the magnitude of earthquake.

In this regard, scholars who formulate or amend the Seismic Design Specifications of Buildings must be familiar with the conditions and mechanism of building fall failure induced by tectonic earthquakes, only then can it be guaranteed that the buildings complying with the Seismic Design Specifications of Buildings will not fall in tectonic earthquake.

At present, since the scholars who formulate or amend the Seismic Design Specifications of Buildings mostly focus on structural dynamics only, the columns in the first floor of a structural model permitted by the Seismic Design Specifications of Buildings are all set as fixed end or hinged end, globally. Therefore, no matter how large k_h and

k_v are, seismic settlement will not occur. In other words, although current the Seismic Design Specifications of Buildings keep increasing the vibration resistance of columns, beams, plates, and walls, yet it is impossible to foresee seismic settlement in their analysis results, they cannot completely predict whether fall failures could occur in a tectonic earthquake.

As for building fall failures in tectonic earthquakes, since the disaster identification is all based on the Seismic Design Specifications of Buildings, and these Specifications only focus on the vibration effect, no disaster identification results related to shear banding can be obtained, therefore, most disaster identification does not comply with the actual case.

Only by identifying the real disaster cause can the Seismic Design Specifications of Buildings be amended in the correct way; and only the Seismic Design Specifications of Buildings complying with practical needs, can provide effective prevention methods. Therefore, according to the types of prevention methods for building fall failures proposed by the authors of this paper and the seismic design and reinforcement methods proposed in the current Seismic Design Specifications of Buildings, it can be seen that only the prevention methods proposed in this paper can achieve the goal of preventing building fall failures. In addition, although current seismic design and reinforcement methods proposed in the Seismic Design Specifications of Buildings dramatically increase the vibration resistance of upper structures, as long as seismic settlement occurs in a tectonic earthquake, the occurrence of building fall failures is still inevitable.

Conclusions And Suggestions

Over the past 40 years, the Seismic Design Specifications of Buildings have increased the vibration resistance of upper structures after each earthquake, but buildings complying with the Seismic Design Specifications of Buildings have still experienced fall failures during tectonic earthquakes, resulting in many casualties. With this consideration, based on the needs of tectonic earthquake prevention, the conditions and mechanism of building fall failures are demonstrated, the example of the Tongshuai Building is used to analyze the major cause of building fall failures, and corresponding prevention methods are proposed. The results of this study can be summarized into the following six conclusions:

1. The major effect of a tectonic earthquake is localized shear banding, and the secondary effect is the all-around vibration of the ground; since building fall failures only occur locally in a tectonic earthquake, there is a highly positive definite relationship with the existence of shear banding.

2. The conditions of building fall failures in tectonic earthquakes include $FS_S \leq 3.0$, the GWT above the bottom surface of the foundation,

$\phi_r \leq 30^\circ$ for the foundation soil , and k_h and k_v are adequately large.

3. The mechanism of building fall failure in tectonic earthquakes when the foundation soil contains shear textures of a shear band is $FS_E < 1.0$ and then seismic settlement is induced. This kind of seismic settlement can suddenly stop at the moment when ground acceleration starts to decelerate, and thus the whole building suffers an impact, the columns in several floors or even all floors of the building can be fractured due to overloading, which then leads to fall failure.

4. The major cause of the Tongshuai Building fall failure was not the shear band effect only. It was induced by combined effects including adopting a FS_S of 3.0, the GWT being above the bottom surface of foundation, the foundation soil containing shear textures of a shear band, $\phi_r \leq 30^\circ$ for the foundation soil and a sufficient large k_h and k_v.

5. The prevention methods for building fall failures include increasing FS_S , lowering the GWT, ensuring that the foundation soil is free of shear banding effect, and in the case where the foundation soil contains shear textures of a shear band, ensuring that $\phi_r \geq 32^\circ$ for the foundation soil , which then guarantees $FS_E > 1.0$.

6. At present, the amendment of the Seismic Design Specifications of Buildings only focuses on increasing the vibration resistance of upper structures, so it cannot guarantee that the buildings complying with the Seismic Design Specifications of Buildings would not suffer fall failure in tectonic earthquakes.

According to the six conclusions above, the following two suggestions are proposed:

1. Since local building fall failures that occur in tectonic earthquakes are highly correlated with localized shear banding, it is suggested to take the shear banding effect into consideration when amending Seismic Design Specifications in the future.

2. The lateral compression of tectonic plates continues to occur, and only the amount of shear banding continues to accumulate. Thus, when engineers build the monitoring network for vibration, they should include a monitoring network for shear banding, and based on these monitoring results, the positions of all shear bands can be identified and the degree of weakening for soils or rocks with the increase in the cumulative amount of shear banding can be evaluated. Only in this way can we ensure that the seismic evaluation of building is compliant with real situations, and then the mitigation of earthquake disasters can be facilitated.

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