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INFLUENCE OF SHEAR BANDING ON BUILDING SAFETY AFTER URBAN RENEWAL

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Abstract

This study is based on the rebuilding of a four-floor building into a twenty-story building as part of a Taipei urban renewal project, which provided the opportunity for the landlords to obtain enormous benefits because of the high price of land in Taipei. This is also an example of the city government's active promotion of urban renewal plans to improve the city's appearance. Based on this case study and in order to help develop appropriate urban renewal plans, the authors of this paper present the following four conclusions: (1) Taipei has shear-band displaced landform features and the shear banding effect keeps the onsite low-plastic silt alluvium in a soft state; (2) the static and seismic ultimate bearing capacities of building foundations are seriously overestimated due to improper assumptions made in the deriva-

tion of the relevant formulas; (3) the old four-floor building would have remained safe during a tectonic earthquake; however, the new twenty-story building does not remain safe during a tectonic earthquake; and (4) landlords will benefit greatly from urban renewal but only if their buildings remain safe after reconstruction. In this case study, the new twenty-story building was found to be unsafe during a tectonic earthquake, and the landlord could therefore risk heavy losses. Therefore, the authors suggest that before a large number of urban renewal plans are promoted in Taipei, the seismic design codes for buildings should be revised so that the static and seismic ultimate bearing capacities of the proposed building foundations can be correctly calculated. This is the only way to ensure that buildings complying with seismic design specifications remain safe during tectonic earthquakes.

Keywords: urban renewal, shear banding, bearing capacity, tectonic earthquake, strain softening.

Introduction

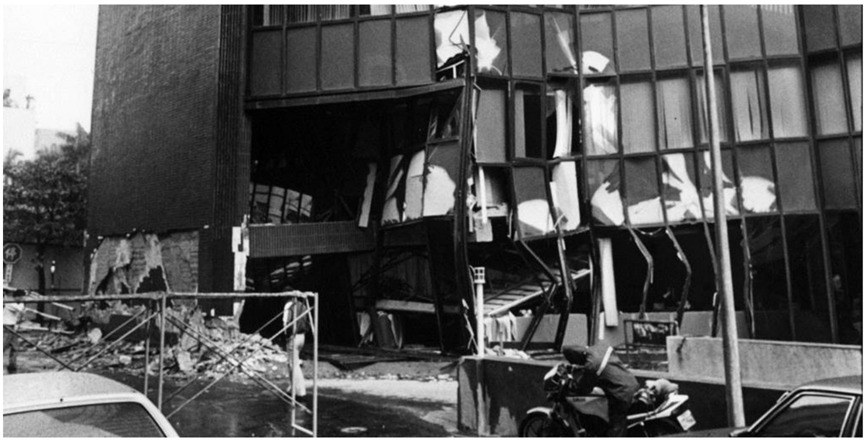
In Taipei, the capital of Taiwan, there are a large number of buildings that are more than 40 years old and have less than five floors. As the vibration fortification level prescribed in the building seismic design code has continued to increase, these buildings are now classified as dangerous. Since the building design and safety evaluations conducted by structural technicians are based on the building seismic design code, an important issue in urban renewal is whether buildings that comply with seismic design codes do in fact remain safe during tectonic earthquakes.

Examples of Taipei buildings that were damaged during previous earthquakes are the Dongshing Building that collapsed during the 921 Jiji earthquake of 1999 (detailed in Figure 1) and the Yutai Building that experienced tilt during the 1115 Hualien earthquake of 1986 and the 418 Hualien earthquake of 2019 (detailed in Figure 2). The Zhenong Building, shown in Figure 3, experienced cracking during the 418 Hualien earthquake of 2019, and is planned to be demolished and rebuilt.

Figures 1 to 3 show that the buildings that collapsed, tilted, or cracked during tectonic earthquakes were new buildings over ten stories high and not old buildings with fewer than five stories. Therefore, in order to provide the city government and landowners with important information relevant to urban renewal before an urban renewal plan is widely promoted, this paper conducts a case study of the safety and economy of an old Taipei four-story building after its restoration into a new twenty-story building.

Figure 1. The Dongshing Building in Taipei that collapsed during the 921 Jiji earthquake of 1999 (Chungshi News Network, 2016).

(a) Tilt failure



(b) Close-up of building leaning damage

Figure 2. The Yutai Building in Taipei that experienced tilting damage due to the 2019 418 Hualien earthquake (Chungshi News Network, 2019).

(a) Building appearance

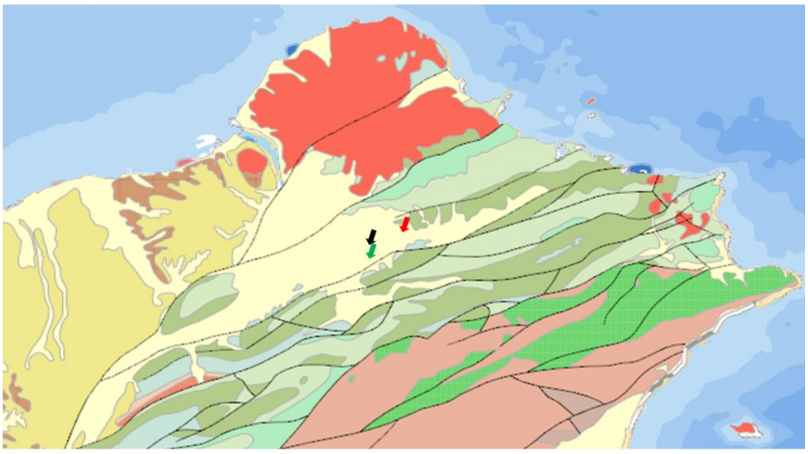
(b) Cracks in the floor slab

Figure 3. The floor slab of the Zhenong Building in Taipei that cracked during the 418 Hualien earthquake of 2019.

Case Study

Geology

Figure 4 shows that the predominant geological formation surrounding the Dongshing, Yutai, and Zhenong Buildings and adjacent areas in Taipei is modern alluvium. Borehole data provided by the Central Geological Survey of Taiwan (2022) shows that the soil is soft, gray, low-plastic silt (ML) from the ground surface to a depth of 35 m. The N values obtained from standard penetration tests are all less than 15. During the long rainy season, the groundwater table in Taipei rises close to the ground surface. For the Taipei low-plastic silt, laboratory test results have shown that the saturated unit weight (γ_{sat}) is equal to 17 kN/m^3, the liquid limit (LL) is equal to or less than 32, the plastic limit (PL) is equal to or greater than 22, the plasticity index (PI) is equal to or less than 10, the ultimate cohesion (c_{ult}) is equal to 24 kPa, the ultimate internal friction angle (ϕ_{ult}) is equal to 33^o, the residual cohesion (c_r) is equal to 0 kPa, and the residual internal friction angle (ϕ_r) is equal to 31^o. Of these, the ultimate shear strength parameters are used for the non-shear banding area and the residual shear strength parameters are used for the shear banding area.



Legend

: Modern alluvium

: Pleistocene-modern terrace accumulation

: Eocene-Oligocene sandstone

: Miocene Daliao and Mushan layers

: Oligocene Wuzhishan layer

: Miocene Nangang layer

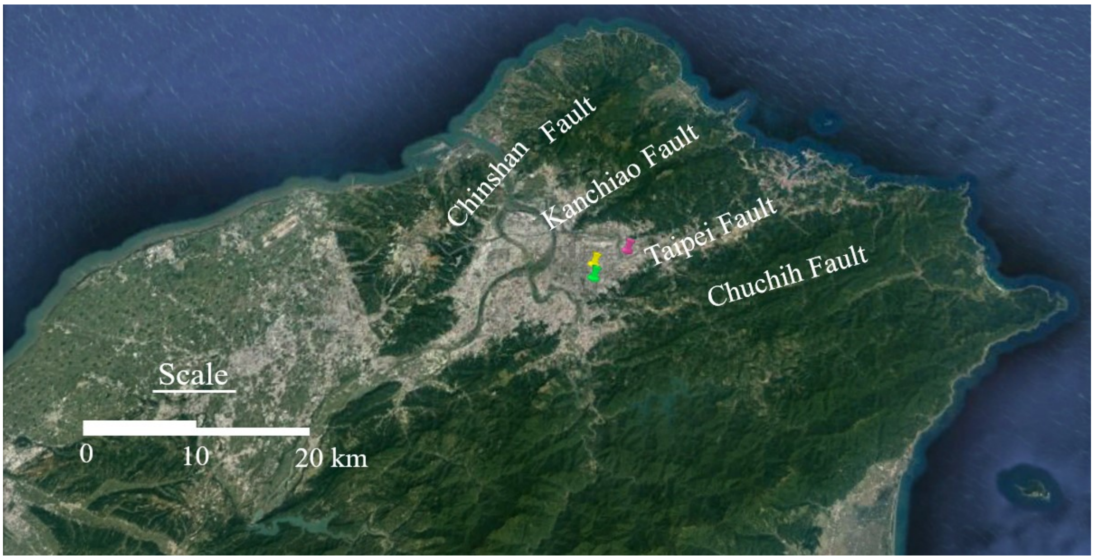
: Pliocene-Pleistocene andesite

Note: The red arrow points to the location of the Dongshing Building, the black arrow points to the location of the Zhenong Building, and the green arrow points to the location of the Yutai Building.

Figure 4. Geological map of northern Taiwan (Central Geological Survey of Taiwan, 2022).

Geological Structure

Figures 4 and 5 show that the faults in Taipei and its adjacent areas include the Chinshan Fault, the Kanchiao Fault, the Taipei Fault, and the Chuchih Fault. The faults adjacent to the Dongshing, Yutai and Zhenong Buildings are the Kanchiao Fault and the Taipei Fault.



Note: The red needle points to the location of the Dongshing Building; the yellow needle points to the location of the Zhenong Building; and the green needle points to the location of the Yutai Building.

Figure 5. Distribution of the faults in the areas adjacent to the buildings of interest (background image from Google Earth, 2022).

Shear Textures

Various shear textures with different strikes between the Kanchiao Fault and the Taipei Fault can be identified using the satellite image of the adjacent areas in northern Taiwan (shown in Figure 6), supplemented with displaced landform features. These shear textures include the principal deformation shear (D) with a strike of N67°E, thrust shear (P) with a strike of N89°W, Riedel shear (R) with a strike of N42°E, conjugate Riedel shear (R') with a strike of N1°E, and compression texture (S) with a strike of N23°W.

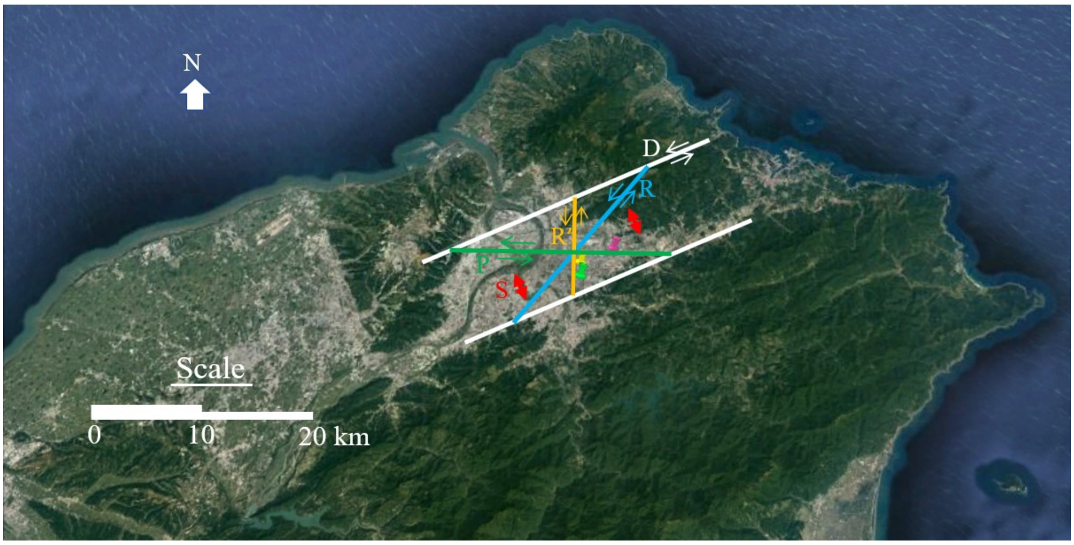


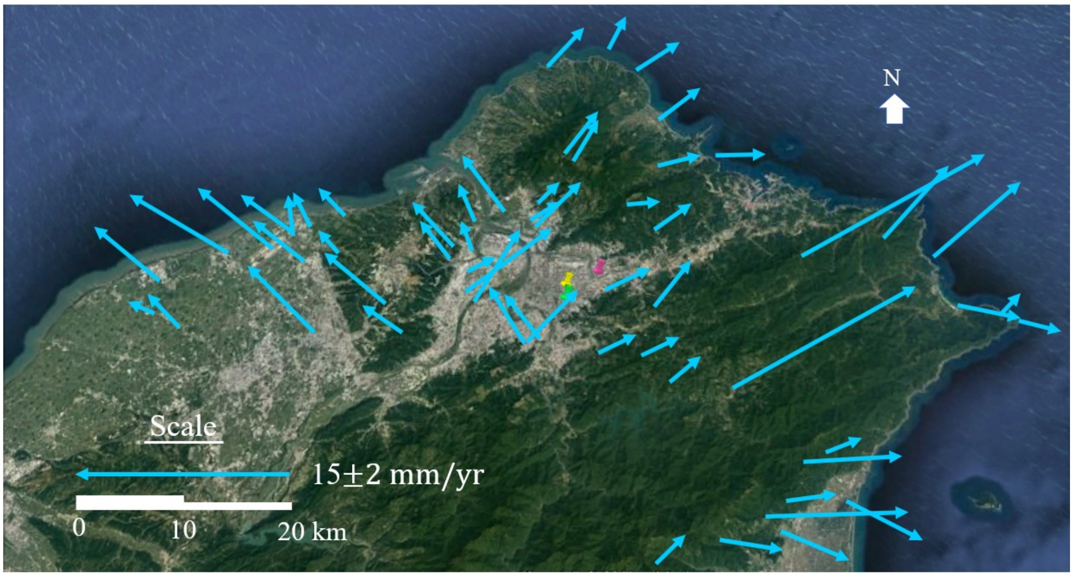
Figure 6. Shear textures within the overall width of a shear band in the vicinity of Taipei (background image from Google Earth, 2022).

Shear Bands

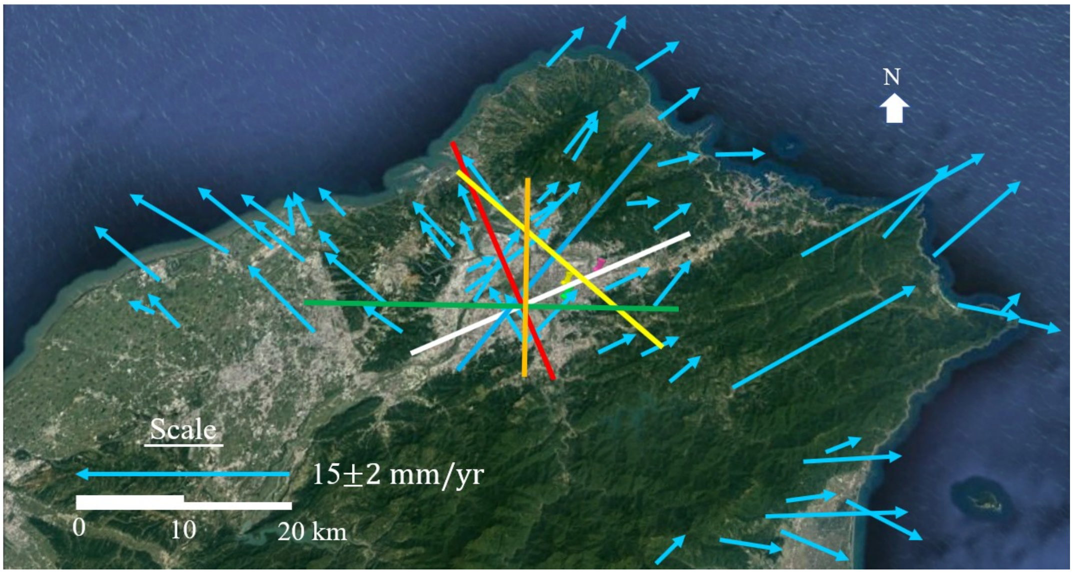
Six shear bands with different strikes can be identified using the GPS velocity vector distribution diagram shown in Figure 7 supplemented with the definitions of various shear bands (Hsu, 1987). These include the white shear band striking N67°E, the red shear band striking N23°W (which is conjugate to the white shear zone), the green shear band striking N89°W, the khaki-yellow shear band striking N1°E (which is conjugate to the white shear zone), the blue shear band striking N42°E, and the yellow shear band striking N48°W (which is conjugate to the blue shear band).

Shear Banding Effect

Figure 8 shows the distribution of epicenters of historical earthquakes that have occurred frequently in Taiwan during the period 1995 to 2016. Figure 7 shows that the average annual GPS displacement of each measuring point is approximately 5 mm. Since the amount of shear banding continues to accumulate, collapse, tilting failure, or floor slab cracks will be induced in buildings located on these shear bands or shear textures, as has been observed in the Dongshing Building (detailed in Figure 1), the Yutai Building (detailed in Figure 2), and the Zhenong Building (detailed in Figure 3).



(a) Before overlaying the shear bands



(b) After overlaying the shear bands

Figure 7. Identification of shear bands from the distribution map of GPS velocity vectors in northern Taiwan (background image from Google Earth, 2022; GPS velocity vectors from Researchgate.net, 2022).

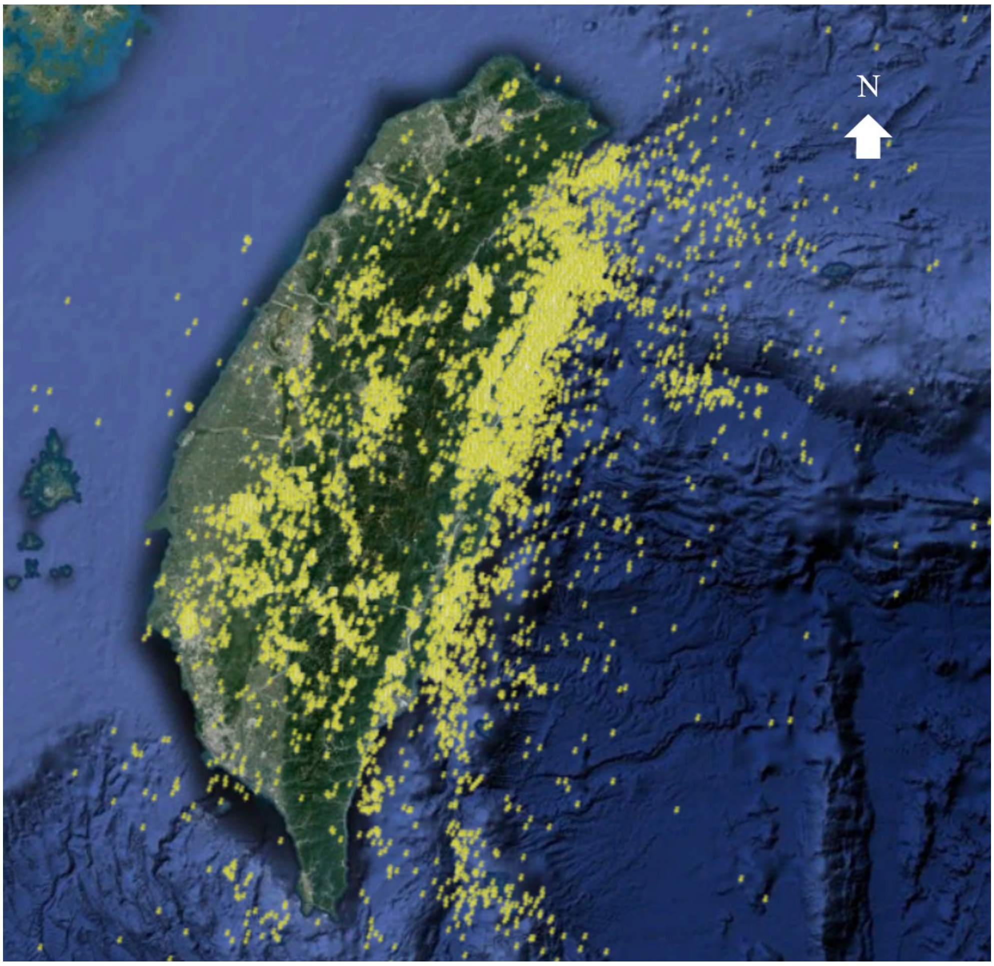


Figure 8. Distribution map of the epicenters of historical earthquakes in Taiwan from 1995 to 2016 (background image from Google Earth, 2022; the data for the epicenters of the historical earthquakes are from the Central Weather Bureau of Taiwan, 2016)

Evaluation of the Foundation Bearing Capacity Safety Factor

During tectonic earthquakes, shear banding can induce soil plastic strain softening and ground vibration (Hsu, 1987). When the soil plastic strain softens, the shear strength parameters decrease from their ultimate values (i.e., c_{ult} and ϕ_{ult}) to their residual values (i.e., c_r and ϕ_r), and the overall depth of the general shear failure plane becomes shallower with an increase in the ground vibration acceleration (Richard and Elms, 1993). Therefore, the static ultimate bearing capacity of the foundation is reduced.

To calculate the ground vibration effect of the tectonic earthquakes, we used a horizontal ground acceleration coefficient of k_h = 0.23 and a vertical ground acceleration coefficient of k_v = 0.115. The term “seismic condition” below refers to situations when a tectonic earthquake occurs and the term “static condition” refers cases when there are no such events.

First, a traditional analysis of the ultimate bearing capacity of a foundation was carried out for an old four-story building, using square spread footings with a length, L_1, of 2 m and a width, W_1, of 2 m, an embedded depth of $D_{f\,1}$ = 4 m, and design pressure of each spread footing of $q_{design\ 1}$ = 262 kN/m^2. In static conditions, the traditional static ultimate bearing capacity, $q_{ult\ 1S}$, for each spread footing of the old four-story building was calculated as 2904 kN/m^2 using the static ultimate bearing capacity formula of the foundation proposed by Meyerhof (1963). The corresponding traditional seismic bearing capacity safety factor, FS_{1S}, of each spread footing was calculated as 11.08. In seismic conditions, the traditional seismic ultimate bearing capacity, $q_{ult\ 1E}$, calculated for each spread footing of the old four-story building was calculated as 1258 kN/m^2 using the seismic ultimate bearing capacity formula of the foundation proposed by Budhu and Al-Karni (1993). The corresponding traditional seismic bearing capacity safety factor, FS_{1E}, of each spread footing was calculated as 4.80.

Second, a traditional analysis of the static ultimate bearing capacity of a foundation was performed for the restored twenty-story building. A rectangular mat foundation with a length, L_2, of 18 m and a width, W_2, of 12 m was used, with an embedded depth of $D_{f\,2}$ = 4 m and design pressure of $q_{design\ 2}$ = 980 kN/m^2. In static conditions, the traditional static ultimate bearing capacity, $q_{ult\ 2S}$, of the mat foundation was calculated as 3248 kN/m^2 using the formula proposed by Meyerhof (1963). The corresponding traditional seismic bearing capacity safety factor, FS_{2S}, was calculated as 3.31. In seismic conditions, the traditional seismic ultimate bearing capacity, $q_{ult\ 2E}$, of the mat foundation was calculated as 1004 kN/m^2 using the formula proposed by Budhu and Al-Karni (1993). The corresponding traditional seismic bearing capacity safety factor, FS_{2E}, of the mat foundation was calculated as 1.02.

In static conditions, the derivation of the traditional formula for the static ultimate bearing capacity of a foundation assumes that the asymmetrical general shear failure plane induced by destabilization is symmetrical and that the plastic strain softening model required to induce the general shear failure plane (Hsu, 1987) is a perfectly plastic model. When there is a tectonic earthquake, the derivation of the formula assumes that the general shear failure plane is asymmetrical, but the actual plastic strain softening model corresponding to the general shear failure plane is assumed to be a perfectly plastic model.

For the old four-story building, the design pressure, $q_{design\ 1}$, of each spread footing was calculated as 262 kN/m^2. In static conditions, the static ultimate bearing capacity, $q_{ult\ 3S}$, of each spread footing of the four-story building was calculated as 515 kN/m^2 using the formula proposed by Meyerhof (1963) and taking into account the asymmetrical general shear failure plane with the plastic strain softening model. The corresponding static bearing capacity safety factor, FS_{3S}, of each spread footing was calculated as 1.96. In seismic conditions the ultimate seismic bearing capacity, $q_{ult\ 3E}$, of each spread footing of the four-story building was calculated as 311 kN/m^2, using the formula proposed by Budhu and Al-Karni (1993) and taking into account the ground vibration effect and the asymmetrical general shear failure plane. The corresponding seismic bearing capacity safety factor, FS_{3E}, for each spread footing was calculated as 1.19.

For the rebuilt twenty-story building, the design pressure, $q_{design\ 2}$, of the mat foundation was calculated as 980 kN/m^2. In static conditions , the static ultimate bearing capacity, $q_{ult\ 4S}$, of the mat foundation of the twenty-story building was calculated as 709 kN/m^2 using the formula proposed by Meyerhof (1963) and taking into account the effects of the asymmetrical general shear failure plane. The corresponding static bearing capacity safety factor, FS_{4S}, of the mat foundation was calculated as 0.72. In seismic conditions the seismic ultimate bearing capacity, $q_{ult\ 4E}$, of the mat foundation of the twenty-story building was calculated as 336 kN/m^2 using the formula proposed by Budhu and Al-Karni (1993), taking into account the effects of the asymmetrical general shear failure plane and the ground vibration. The corresponding seismic bearing capacity safety factor, FS_{4E}, of the mat foundation was calculated as 0.34.

Comparison and Discussion of Results

1) At present, technicians must design a foundation according to the building seismic design code, and traditional static foundation ultimate bearing capacity calculation formulas (such as that proposed by Meyerhof (1963) are used in the design process. Shape and seismic force correction factors

are then used to modify the long strip static foundation ultimate bearing capacity into the static or seismic ultimate bearing capacity of foundations of various shapes. The shape correction factors s_c, s_q, and s_γ proposed by Hansen (1970) are:

$$s_c = 1.0 + \frac{N_q}{N_c} \cdot \frac{B}{L} \qquad \text{(Equation 1)}$$

$$s_q = 1.0 + \frac{B}{L} \cdot \sin\phi \qquad \text{(Equation 2)}$$

$$s_\gamma = 1.0 - 0.4 \cdot \frac{B}{L} \qquad \text{(Equation 3)}$$

In Equations 1 to 3, N_c and N_q are soil-bearing capacity factors, B is the width of foundation, L is the length of foundation, and ϕ is the angle of internal friction. The seismic force correction factors e_c, e_q, and e_γ proposed by Budhu and Al-Karni (1993) are:

$$e_c = exp\left(-4.3k_h^{1+D}\right) \qquad \text{(Equation 4)}$$

$$e_q = (1 - k_v)\, exp\left[-\left(\frac{5.3k_h^{1.2}}{1-k_v}\right)\right] \qquad \text{(Equation 5)}$$

$$e_\gamma = \left(1 - \frac{2}{3}k_v\right) exp\left[-\left(\frac{9k_h^{1.1}}{1-k_v}\right)\right] \qquad \text{(Equation 6)}$$

In Equations 5 and 6, k_h and k_v are the seismic horizontal and vertical acceleration coefficients, respectively, $D = c/(\gamma H)$ in which c is the cohesion, γ is the unit weight of soils and H is the depth from the ground surface to the shear failure zone. The embedded depth of the foundation is D_f, and H can be determined from Equation 7:

$$H = \frac{0.5B}{cos\left(\frac{\pi}{4}+\frac{\phi}{2}\right)} exp\left(\frac{\pi}{2} tan\,\phi\right) + D_f \qquad \text{(Equation 7)}$$

2) The case study results of this paper are summarized in Table 1.

Table 1. Summary of the case study results of the old four-story building and the new twenty-story building in Taipei.

Number of floors	Size of foundation	Earthquake condition	Symmetry/ Asymmetry	Plasticity model	c (kPa)	ϕ_{ult} / ϕ_r	q_{design} (kPa)	q_{ult} (kPa)	FS
4	2m x 2m	Without earthquake	Symmetry	Perfectly plastic	24 (c_{ult})	33° (ϕ_{ult})	262	2904	11.08
4	2m x 2m	With earthquake	Asymmetry	Perfectly plastic	24 (c_{ult})	33° (ϕ_{ult})	262	1258	4.80
4	2m x 2m	Without earthquake	Asymmetry	Strain softening	0 (c_r)	31° (ϕ_r)	262	515	1.96
4	2m x 2m	With earthquake	Asymmetry	Strain softening	0 (c_r)	31° (ϕ_r)	262	311	1.19
20	18m x 12m	Without earthquake	Symmetry	Perfectly plastic	24 (c_{ult})	33° (ϕ_{ult})	980	3248	3.31
20	18m x 12m	With earthquake	Asymmetry	Perfectly plastic	24 (c_{ult})	33° (ϕ_{ult})	980	1004	1.02
20	18m x 12m	Without earthquake	Asymmetry	Strain softening	0 (c_r)	31° (ϕ_r)	980	709	0.72
20	18m x 12m	With earthquake	Asymmetry	Strain softening	0 (c_r)	31° (ϕ_r)	980	336	0.34

(1) By comparing the case study results of each 2 m x 2 m spread footing of the old four-story building (Table 1) it was found that:

(a) In static conditions, the traditional static bearing capacity safety factor of the foundation obtained in the case study was 11.08 when the symmetrical general shear failure plane and the perfectly plastic model were used, but when the asymmetrical general shear failure plane and the plastic strain softening model were used, the actual safety factor was 1.96.

(b) In seismic conditions, the traditional seismic bearing capacity safety factor of the foundation obtained in the case study was 4.80 when the asymmetrical general shear failure plane and the perfectly plastic model were used, but when the asymmetrical general shear failure plane and the plastic strain softening model were used, the actual safety factor was 1.19.

(c) In static conditions, the traditional static bearing capacity safety factor of the foundation obtained in the case study was 5.65 times the actual value, and in the event of a tectonic earthquake, the traditional seismic bearing capacity safety factor of the foundation obtained in the case study was 4.03 times the actual value.

(2) By comparing the case study results of the 12 m x 18 m mat foundation of the new twenty-story building (Table 1), it is clear that:

(a) In static conditions, the traditional static bearing capacity safety factor of the foundation obtained in the case study was 3.31 when the symmetrical general shear failure plane and the perfectly plastic model were used, but when the asymmetrical general shear failure plane and the plastic strain softening model were used, the actual safety factor was 0.72.

(b) In seismic conditions, the traditional seismic bearing capacity safety factor of the foundation obtained in the case study was 1.02 when the asymmetrical general shear failure plane and the perfectly plastic model were used, but when the asymmetrical general shear failure plane and the plastic strain softening model were used, the actual safety factor was 0.34.

(c) In static conditions, the traditional static bearing capacity safety factor of the foundation obtained in the case study was 4.60 times the actual value, and in the event of a tectonic earthquake, the traditional seismic bearing capacity safety factor of the foundation obtained in the case study was 3.00 times the actual value.

(d) The traditional static ultimate bearing capacity formula uses a symmetrical general shear failure plane and a perfectly plastic model in its derivation, whereas the traditional seismic ultimate bearing capacity formula uses an asymmetrical general shear failure plane and a perfectly plastic model in its derivation. The actual static and seismic ultimate bearing capacity formulas for a foundation should both use an asymmetrical general shear failure plane and a plastic strain softening model in their derivation. Therefore, both the traditional static ultimate bearing capacity formula and the traditional seismic ultimate bearing capacity formula have a serious overestimation problem.

(e) Hsu et al. (2022) argued that when scholars assume that the asymmetrical general shear failure plane is symmetrical, they will calculate the static bearing capacity safety factor of a foundation to be approximately twice its actual value. Thus, there is a 100% overestimation of the static bearing capacity safety factor.

(f) The seismic bearing capacity safety factor of each spread footing of the old four-story building was 4.03 times the actual value, and the seismic bearing capacity safety factor of the mat foundation of the new twenty-story building was 3.00 times the actual value. Therefore, the assumption that the plastic strain softening model is perfectly plastic leads to a 200% and 303% overestimation of the safety factor of the seismic bearing capacity of the foundation of the four-story and the twenty-story building, respectively.

3) When the seismic bearing capacity safety factor is less than 1.0, earthquake subsidence will be induced (Richard and Elms, 1993). This will cause problems such as building collapse, tilt and floor cracking. Therefore, technicians must ensure that the seismic bearing capacity safety factor is greater than or equal to 1.0 when designing the founda-

tion. The case study results displayed in Table 1 show that when the plastic strain softening model required to induce the general shear failure plane is used, the seismic bearing capacity safety factors for each spread footing of the four-floor building are greater than 1.0; however, the seismic bearing capacity safety factors for the mat foundation of the twenty-floor building are less than 1.0. Therefore, the four-floor building would have remained safe during a tectonic earthquake, but the twenty-floor building would be unsafe when earthquake subsidence is induced.

4) Since the landlord of each floor of the four-story building could obtain about twice the original building area after urban renewal, they could obtain enormous benefits from the process. The land area held by the landlord of each floor of the four-story building, however, was 33 m^2 before urban renewal but reduced to 13.2 m^2 after urban renewal. As we know from the above case study, the geology of Taipei is weak and it is possible for old four-story old buildings to remain safe during tectonic earthquakes if the seismic bearing capacity safety factor of their foundations is greater than 1.0. Newly built twenty-floor buildings, on the other hand, could experience earthquake subsidence during a tectonic earthquake if the seismic bearing capacity of their foundations is less than 1.0. If a twenty-floor building collapses during a tectonic earthquake, each landlord would own only the value of the land and so, without considering casualties, the percentage loss caused by urban renewal could be as high as 60% (i.e., [(33-13.2)/33] x 100% = 60%). If we estimate the price per 1 m^2 of land area at $40 000 USD, the total loss for each floor owner could be as high as $792 000 USD.

Conclusions and Suggestions

The soils in Taipei are mostly soft low-plastic silt from the surface to a depth of 35m. Despite meeting seismic design specifications, some high-rise buildings in Taipei have suffered from problems such as collapse, tilt, and floor cracks during past earthquakes. In this paper we draw the following four conclusions from a case study of a particular building that are relevant to planned urban renewal in Taipei.

1) It is clear that there are shear-band displaced landform features in Taipei and five groups of shear textures and six groups of shear bands with different strikes were identified. These shear textures or shear bands continue to dislocate

and the shear-band affected soil in Taipei continues to be in a soft state.

2) In the derivation of the traditional static ultimate bearing capacity formula for foundations, a symmetrical general shear failure plane and a perfectly plastic model are both assumed and both are different from the actual conditions. In our case study, the false symmetrical general shear failure plane assumption resulted in a 100% overestimation of the static bearing capacity safety factor of the foundation, and the false perfectly plastic model assumption resulted in a 200% and 303% overestimation of the its seismic bearing capacity safety factor for a pre-existing four-story and a twenty-story replacement building, respectively.

3) Assuming an asymmetrical general shear failure plane and plastic strain softening soils, the old four-floor building in Taipei would have remained safe during a tectonic earthquake because the seismic bearing capacity safety factor of its foundation was greater than 1.0; however, the new twenty-floor building would not remain safe during a tectonic earthquake because the seismic bearing capacity safety factor of its foundation is less than 1.0.

4) If buildings in Taipei remain safe during tectonic earthquakes after urban renewal that involves increasing their number of stories, then landlords will be able to reap enormous benefits. However, the soils in Taipei are weak and the new building designs will generally not remain safe under the shear-banding induced plastic strain softening condition. This may cause heavy losses for landlords.

Based on the above conclusions, in order to ensure that the building seismic design code provides the correct formulas for calculating the static and seismic ultimate bearing capacity of a building foundation, the authors suggest that the existing codes be revised according to the conclusions of this paper so as to correct all of the false assumptions made in formula derivations before pursuing an urban renewal plan in Taipei. Only in this way can the static and seismic ultimate bearing capacity of future foundations be correctly calculated and future new high-rise buildings be safe under both static and seismic conditions.

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