International Journal of Organizational Innovation

A STUDY ON THE CAUSES OF HIGH-RISE BUILDING FAILURE

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Abstract

In modern metropolitan areas, high-rise buildings have become ubiquitous, and their designs generally comply with existing seismic codes. However, because most current seismic design regulations worldwide are formulated primarily to address ground shaking, these buildings may still collapse or sustain severe damage when shear banding occur during major earthquakes. To address this issue, this study first examines three high-rise buildings in Taipei located within shear bands and shows that their failures can be attributed to ground conditions that meet the criteria for non–earthquake-resistant structures. The analysis then extends to four additional completed high-rise buildings. Although these structures are considered earthquake-resistant by their architects, the findings reveal that they actually meet the criteria for non–earthquake-resistant buildings. Given that high-rise buildings falling under such non-resistant criteria have a high likeli-

hood of collapsing during future major earthquakes, this study recommends that buildings be evaluated before construction to determine whether they satisfy the earthquake-`resistant conditions proposed by the authors.

Keywords: high-rise buildings, seismic design, rupture zones, earthquake-resistant structures.

Introduction

Figure 1 shows five active faults in northern Taiwan: the Sanchiao Fault, Kanchiao Fault, Taipei Fault, Hsintien Fault, and Chuchih Fault. When any of these active faults rupture, a total shear-zone width forms between the Kanchiao Fault and the Taipei Fault, as illustrated by the two shear bands D in Figure 2. Within this overall shear zone lie several structural elements: the principal displacement shear D, the thrust shear P, the Riedel shear R, the conjugate Riedel shear R′, and the compression fabric S (Tchalenko, 1968).

Figure 1. Active faults in north Taiwan (Taipei City Government)

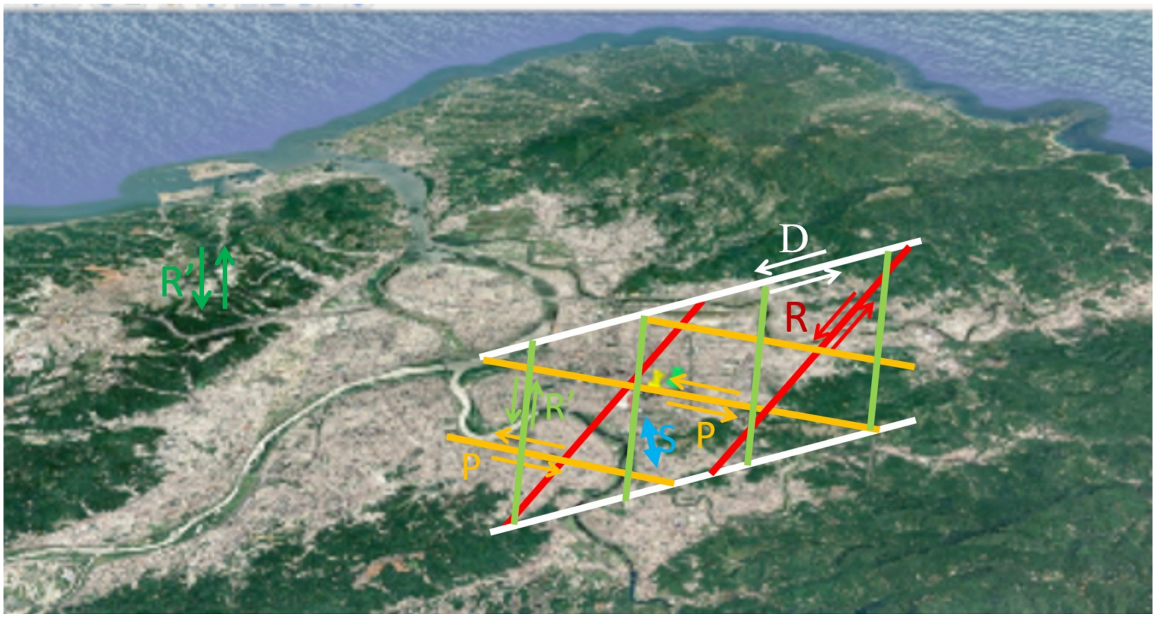


Figure 2. Soft region in the shear textures caused by five active faults in north Taiwan. (The background image is from Google Earth (2022)).

Figure 3 shows the locations of three buildings that were damaged during the 1999 Jiji (921) Earthquake, all situated within two soft-soil regions of Taipei. These damaged buildings include: (a) the Zhenong Building, which exhibited floor cracking (Figure 4); (b) the Yutai Building, which experienced tilting and subsidence (Figure 5); and (c) the Dongshing Building, which collapsed (Figure 6) (Hsu, 2022).

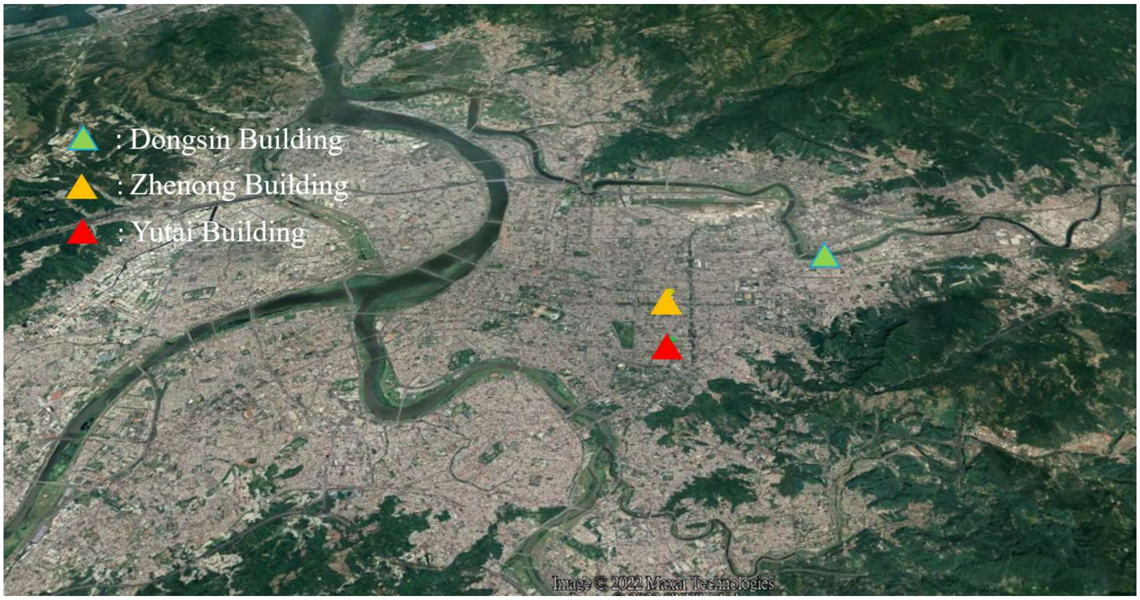


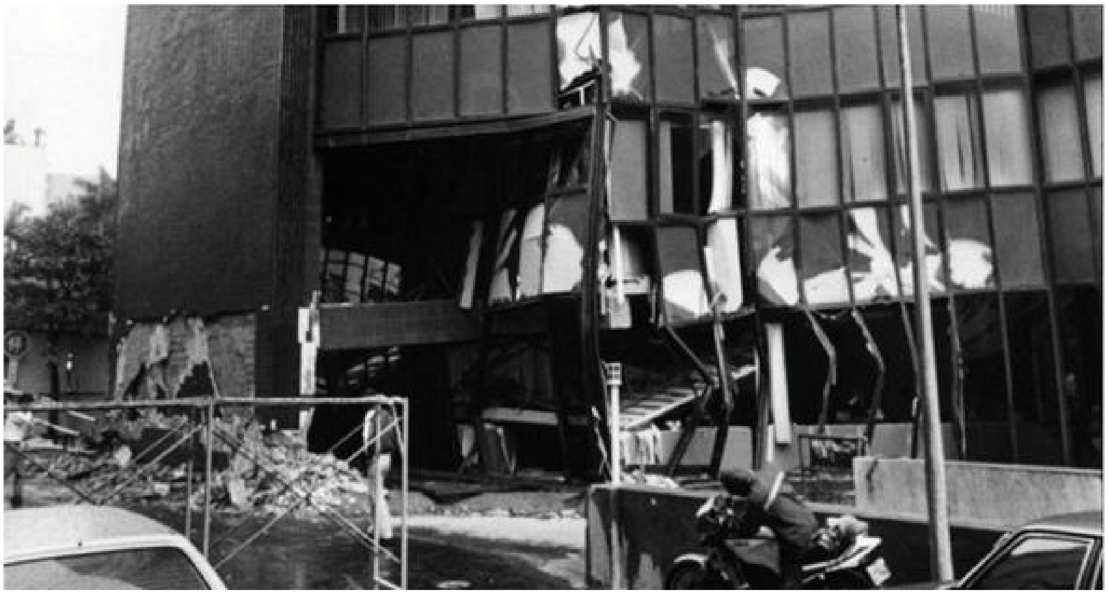
Figure 3. The three buildings damaged in the 921 Jiji earthquake in the two soft regions in Taipei (The background image is from Google Earth (2022)).

(a) Failure of tilting and subsidence.

(b) A close-up view of the damage resulting from tilting and ground subsidence.

Figure 4. The Zhenong building damaged in the April 18, 2019 Hualien earthquake (Hsu, 2022).

(a) Failure of tilting and subsidence.



(b) A close-up showing damage caused by tilting and subsidence.

Figure 5. The Yutai building damaged during the April 18, 2019 Hualien earthquake (Hsu, 2022).

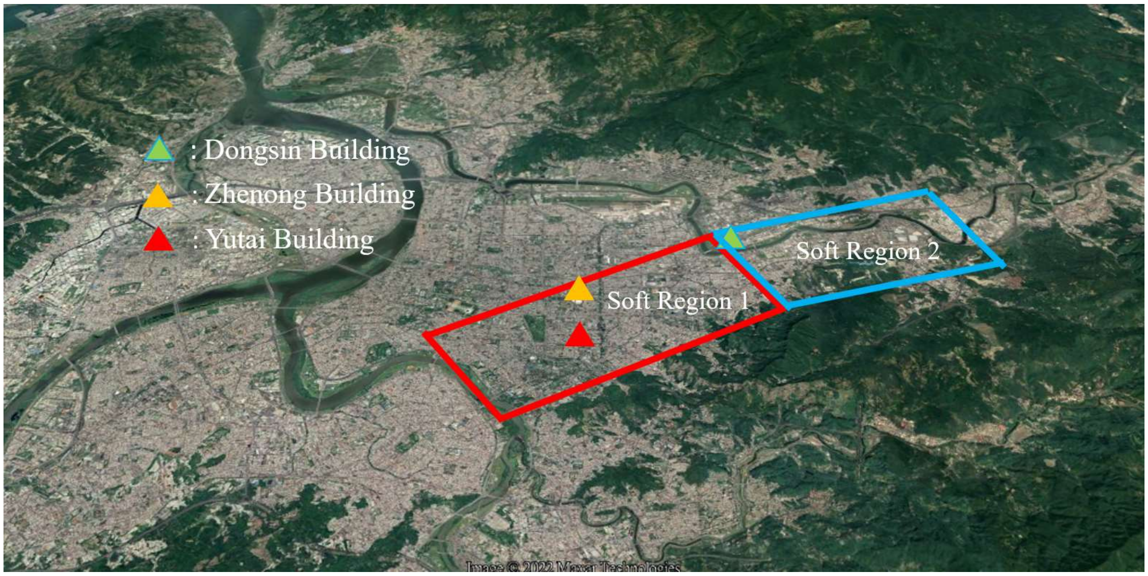
Figure 6. The Dongshing Building collapsed during the 1999 Jiji (921) earthquake (Hsu, 2022).

Different Seismic Conditions Produced by Various Types of Forces Acting on Geological Formations

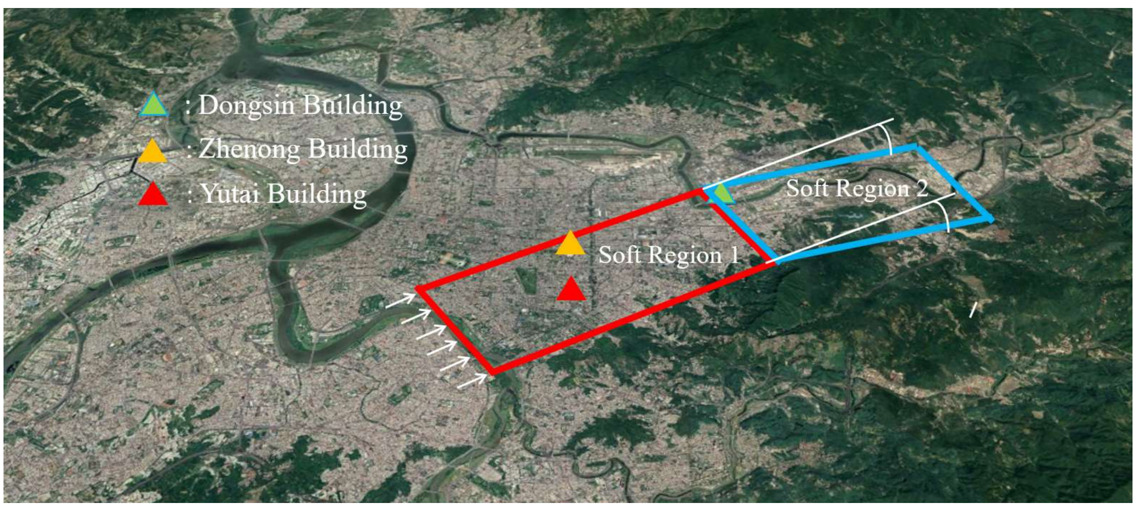
For the three buildings located at different sites in Taipei (Figure 7), the Zhenong Building and the Yutai Building are situated in Soft Region 1, as shown in Figure 8, while the Dongsing Building is located in Soft Region 2. Figure 8 also illustrates that Soft Region 1 is subjected only to compressive forces, whereas Soft Region 2 is subjected to both compressive and torsional forces.

Because the Zhenong Building is located in Soft Region 1—an area affected solely by compression—its floor cracking suggests that the structure was in a lightly non–earthquake-resistant state. For the Yutai Building, also within Soft Region 1, the observed tilting and subsidence indicate a moderately non–earthquake-resistant state. In contrast, the collapse of the Dongsing Building, located in Soft Region 2, reflects a highly non–earthquake-resistant state.

Figure 7. Geographical locations of three buildings damaged in Taipei during the 921 Earthquake. (The background image is from Google Earth (2022)).



(a) Locations of the two soft regions in Taipei.



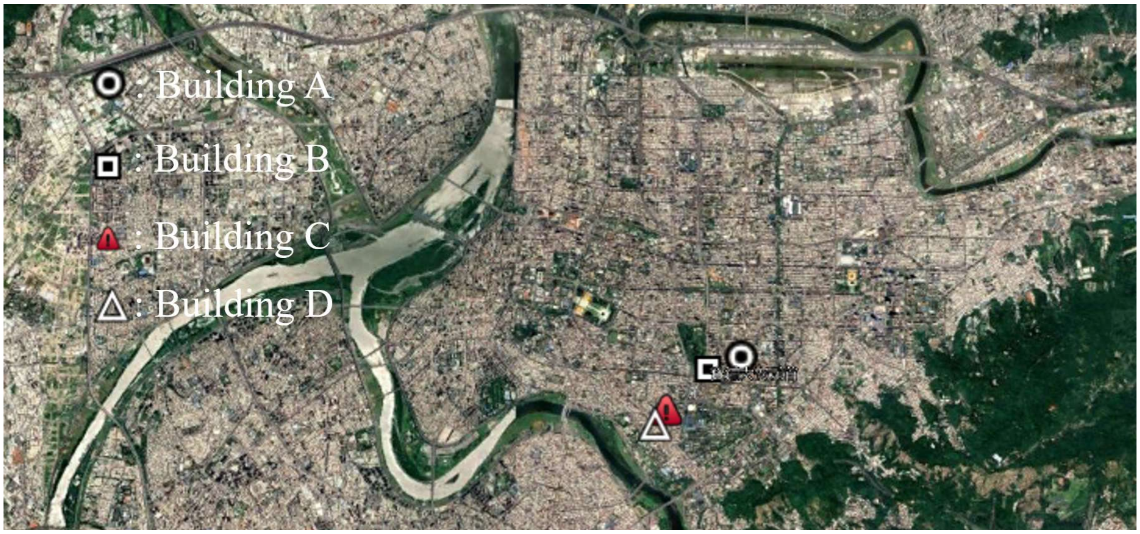
(b) Compressive and torsional forces acting on the two soft regions in Taipei.

Figure 8. Compressive and torsional forces acting on the two soft regions in Taipei. (The background image is from Google Earth (2022))

Seismic-Resistance Conditions of the Four Selected Buildings.

Figure 9(a) shows the geographical locations of the four buildings examined in this study. Figure 9(b) provides their specific addresses: Building A is located at No. 146, Section 2, Fuxing South Road, Da'an District, Taipei; Building B at No. 209, Section 2, Jianguo South Road, Da'an District, Taipei; Building C at No. 214, Section 3, Roosevelt Road, Zhongzheng District, Taipei; and Building D at No. 8, Alley 7, Lane 283, Section 3, Roosevelt Road, Da'an District, Taipei..

(a) The locations of the four selected buildings.



(b) Close-up of the locations of the four selected buildings.

Figure 9. Geographical locations of the four existing buildings.
(The background images are from Google Earth (2022)).

Non–Seismic Conditions of the Four Selected Buildings.

Figure 8 shows that all four buildings selected for this study—Buildings A through D—are located within Soft Region 1.

Figure 10. The four buildings selected from the soft region 1 shown in Figure 8.
(The background image is from Google Earth (2022))

Figures 11 to 14 show the current conditions of the four selected buildings located in Soft Region 1, as illustrated in Figure 8. Building A has 4 stories, Building B has 14 stories, Building C has 10 stories, and Building D has 16 stories.

Figure 14 shows that the first floor of the building on the left is nearly in contact with the first floor of the building on the right. However, gaps appear between the upper floors of the two buildings, and these gaps increase progressively with height. As a result, at the top floors, the gap between the left and right buildings widens to more than 10 centimeters. This phenomenon clearly indicates that the building on the left has tilted and subsided relative to the one on the right. If the building on the right meets seismic-resistance requirements, then the building on the left can be classified as a moderately non–seismic-resistant structure.

Figure 11. Building A (Google Earth (2022)).

Figure 12. Building B (Google Earth (2022)).

Figure 13. Building C (Google Earth (2022)).

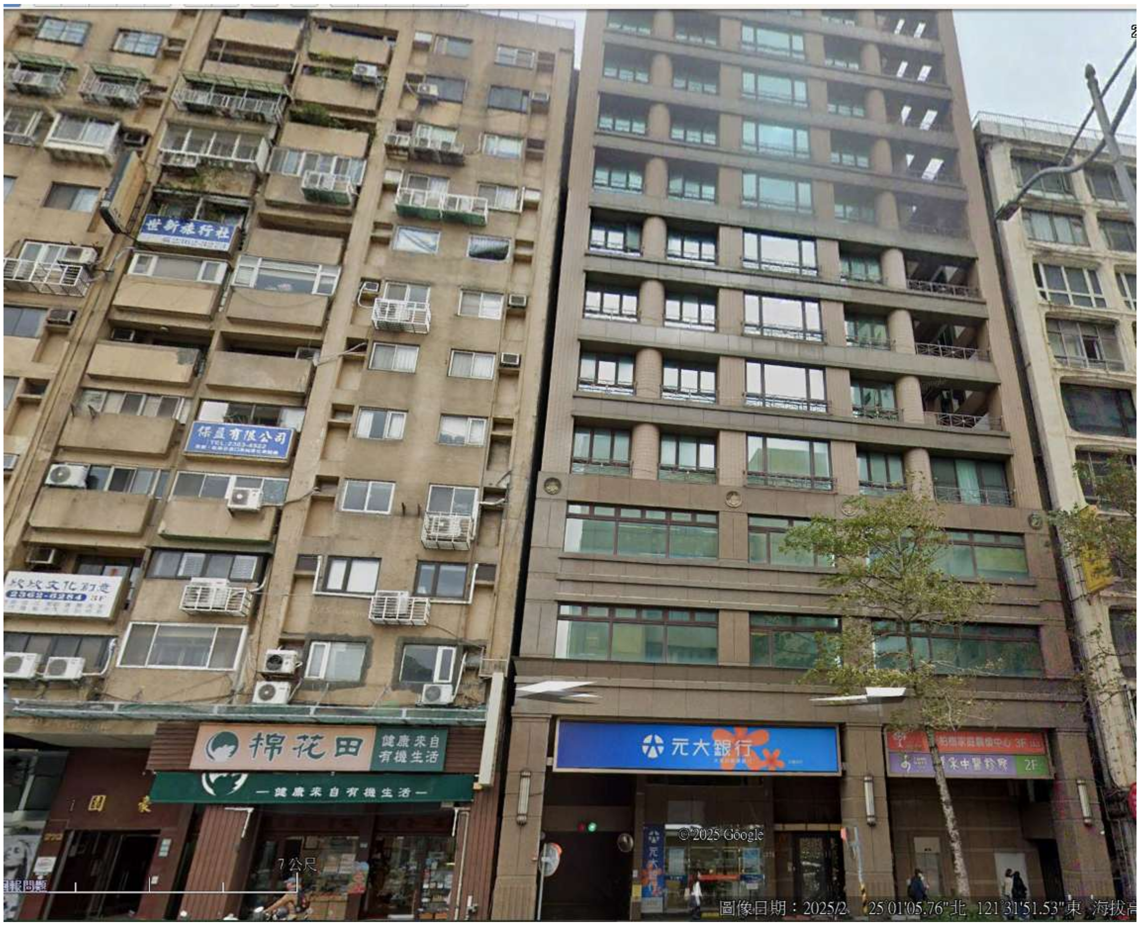


Figure 14. Building D (Google Earth (2022)).

The non–earthquake-resistant condition of a building can be classified into three levels of seismic vulnerability: slight, moderate, and severe. A building that is slightly non–earthquake-resistant typically exhibits cracks on exterior walls or floors, or shows uneven coloration. A moderately non–earthquake-resistant building displays floor tilting and subsidence. A severely non–earthquake-resistant building may undergo partial or complete collapse (Hsu, 2022).

Figure 15 shows floor cracking in Building A, indicating that it is in a slightly non–earthquake-resistant state. Figure 16 shows damage to the exterior wall tiles of Building B—including cracking, spalling, and uneven coloration—suggesting that Building B is also slightly non–earthquake-resistant. Figure 17 presents cracking of the walls and floors in Building C, likewise indicating a slightly non–earthquake-resistant condition. Figure 18 shows uneven settlement of the road adjacent to Building D and cracking of the asphalt concrete (AC) surface layer, indicating that Building D is in a moderately non–earthquake-resistant state.

Figure 15. Floor cracking between Building A and the adjacent building (Google Earth, 2022).

Figure 16. Cracking, spalling, and uneven coloration of Building B's exterior wall tiles (Google Earth, 2022).

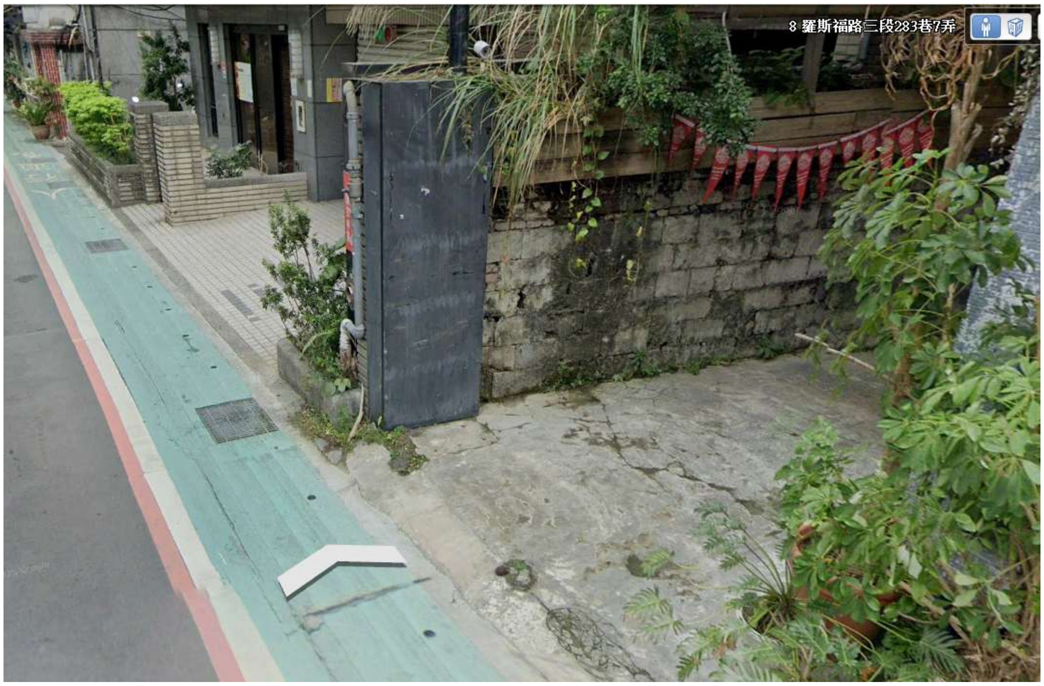


Figure 17. Cracking observed in the walls and floors of Building C (Google Earth, 2022).

Figure 18. Uneven settlement of the road adjacent to Building D and cracking of the AC pavement (Google Earth, 2022).

Conclusions and Recommendations

1. Current seismic design codes define a building's slight, moderate, and severe non–earthquake-resistant conditions on the basis of light, moderate, and severe ground shaking, respectively. Consequently, even buildings that comply with these codes may still experience localized collapse along shear bands. In light of this limitation, the slight, moderate, and severe non–earthquake-resistant conditions of a building should instead be defined according to the corresponding light, moderate, and severe displacements that occur along shear bands.
2. During the 921 Earthquake, some buildings in Taipei—located more than 180 kilometers from the epicenter—still experienced floor cracking, tilting and subsidence, and structural collapse. Analysis revealed that these buildings corresponded to slight, moderate, and severe shear banding effect, respectively.
3. In non–earthquake-resistant buildings, adjacent walls may develop localized cracks, while nearby asphalt concrete (AC) pavement may undergo localized settlement and cracking.
4. During an earthquake, less than 10% of the total seismic energy is associated with ground shaking, while more than 90% is concentrated along shear bands. Therefore, if seismic design codes focus solely on ground shaking, they may significantly underestimate the dominant effects of shear bands, potentially leading to unforeseen failures and even building collapse.
5. Effective seismic retrofitting of buildings relies on preventing the propagation of shear bands from the ground beneath the foundation into the foundations, columns, beams, and slabs, rather than merely reducing the transmission of ground shaking to these structural elements.
6. Based on the five conclusions above, the authors recommend that future seismic design codes account for potential shear-band displacements. Designers and architects should be required to consider both shear-band displacements and ground shaking when planning buildings. Only by addressing these combined effects can completed structures maintain stability and safety during a major earthquake.

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