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FORMATION MECHANISMS FOR VARIOUS FAILURE IN THE REAR-LINE REGION OF THE TAICHUNG PORT DOCK CAISSON

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Abstract

The current seismic design standards for dock caissons primarily focus solely on fortification against secondary ground vibration effects, making dock caissons susceptible to failure under primary shear banding effects. In view of this, this paper uses the case study of the damage to the rear-line region of the Taichung Port dock caisson during the 1999 Jiji earthquake in Taiwan to analyze the failure mechanisms. The analysis reveals the following findings: (1) Liquefaction in the rear-line region occurred only locally, and it was confined to areas of densely compacted backfill that had passed the compaction test prior to the earthquake, rather than in the loose sand zones as traditionally addressed by scholars. (2) The densely compacted backfill experienced plastic strain softening during the tectonic earthquake, which induced shear bands. This in turn caused the localized development of excess pore water pressure, leading to soil liquefaction. As a result, the dock caisson rotated or shifted significantly toward the seaward, causing substantial settlement in the rear-line region. (3) The direct placement of the caisson on the seabed, and the continued loss of shear band soils, both contributed to piping failure in the rear-line region. Based on these findings, the authors recommend that the seismic design codes for dock caissons be revised to clearly define the mechanisms for causing potential failures.

Furthermore, engineers should be required to conduct verification tests to ensure effective disaster prevention measures are incorporated into the design, thereby achieving the intended safety objectives for the rear-line region of dock caissons.

Keywords: rear-line region, dock caissons, shear band, soil liquefaction, piping failure.

Introduction

Earthquakes are generally classified into five types: tectonic, volcanic, collapse, reservoir-induced, and explosion-induced earthquakes. Among these, only tectonic earthquakes with a magnitude of 6.0 or higher are known to cause significant structural damage. The primary effect of tectonic earthquakes is the shear banding effect, which accounts for over 90% of the total seismic energy released. In contrast, ground vibration, which is the secondary effect, contributes less than 10% of the total seismic energy.

Research by Hsu (2018) indicates that shear banding is the primary cause of earthquake-induced structural damage. However, existing seismic design guidelines—such as the Seismic Design Guidelines for Port Structures by the International Navigation Association (2001), as well as Taiwan's Ministry of the Interior's seismic design guidelines for dock caissons, focus solely on mitigating ground vibration effects, overlooking the impact of shear banding effects. This gap in the guidelines has contributed to significant damage in the rear-line regions behind caisson docks during tectonic earthquakes. For example, Figure 1 shows the damage at Kobe Port, Japan, caused by the 1995 Hanshin earthquake, while Figure 2 illustrates the damage at Taichung Port, Taiwan, induced by the 1999 Jiji earthquake.

Figure 1. Damage to the rear-line region of the dock caisson induced by the 1995 Great Hanshin-Awaji Earthquake, Kobe Port (Kobe Geotechnical Collection, 2019).

Figure 2. Damage to the rear-line region of the dock caisson induced by the 1999 Jiji earthquake, Taichung Port (Lai et al., 2007).

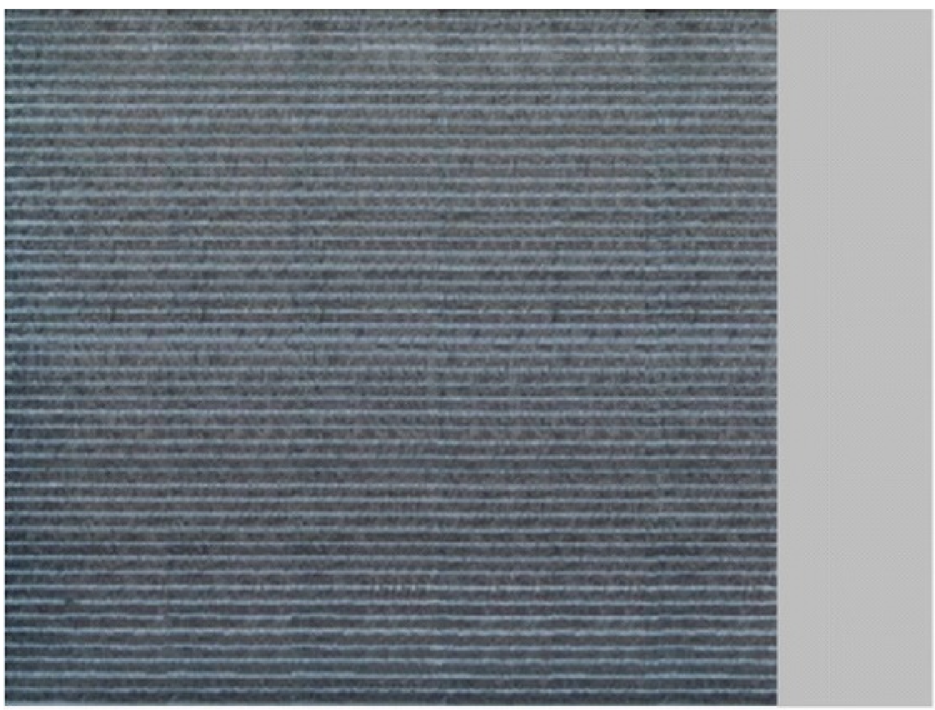
Because engineers must adhere to seismic design standards, they are required to design both dock caissons and the backfill in the rear-line region. The backfill in this region must be densely compacted and pass a site density inspection using the sand cone method.

Under these conditions, experts have assumed that the rear-line regions of completed dock caissons and rear-line region would remain intact under the ground vibrating effects of the design-basis earthquake.

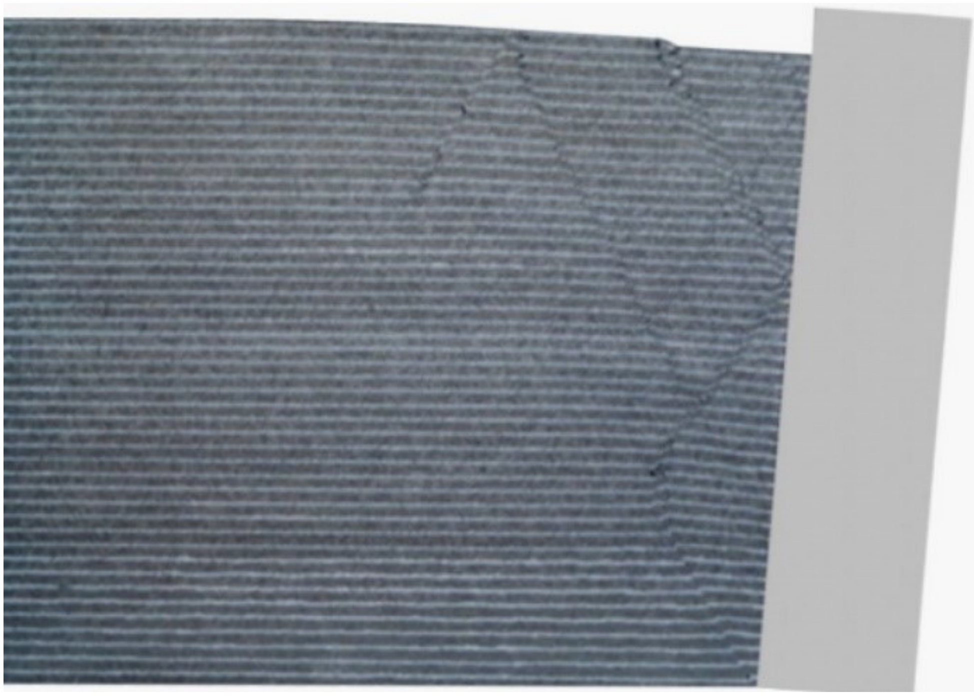
The Jiji earthquake was a catastrophic seismic event with a magnitude of 7.3. During the earthquake, engineers had not accounted for the effects of shear banding in the seismic design of the caisson dock and the rear-line region at Taichung Port. As a result, the rear-line region was compromised due to shear-banding effects. In view of the need for effective earthquake disaster mitigation, this paper explores the formation mechanisms for various failure observed in the rear-line region of the caisson dock at Taichung Port during the Jiji earthquake.

Formation Mechanisms of Shear Bands in the Rear-Line Region of Dock Caissons

Figure 3(a) presents a model of a dock caisson and a very densely packed sand backfill model in the rear-line region. As shown in Figure 3(b), when the dock caisson model undergoes a rotation of approximately 3 to 5 degrees about its bottom right edge, shear bands with different strikes are induced in the backfill model.



(a) Before the caisson rotation.



(b) After the caisson rotation.

Figure 3. Simulation of shear bands induced by the caisson and backfill model in the rear-line region.

The formation mechanisms of shear bands in the rear-line region of the caisson dock include the following:

1. The caisson rotates around its seaward bottom edge, resulting in horizontal displacements that increase proportionally with height above the caisson base.
2. When the caisson rotation reaches approximately 3 to 5 degrees, the densely packed sand layer in the rear-line region undergoes plastic strain softening, leading to a loss of stability.
3. The localizations of deformations in the rear-line region produces shear bands with different strikes.

Formation Mechanisms of Large-Scale Settlement in the Rear-Line Region of the Taichung Port Dock Caissons

Based on simulation experiments illustrated in Figure 3, the formation mechanisms contributing to large-scale settlement in the rear-line region of the Taichung Port caisson dock are as follows:

1. The rotation or movement of the dock caisson toward the sea side induces plastic strain softening in the densely compacted backfill within the rear-line region.

2. Highly concentrated excess pore water pressure locally occurs in the shear band groundwater.

3. The earth pressure and water pressure acting on the caisson increase significantly.

4. Significant rotation or movement of the dock caisson induces substantial settlement in the rear-line region.

Formation Mechanisms of Soil Liquefaction in the Rear-Line Region of the Dock Caisson

Figure 4 shows the structural analysis model for the finite element simulation of a plate continuously subjected to lateral prescribed displacements; Figure 5 illustrates the finite element deformation mesh after the plate goes deep into the plastic range; and Figure 6 presents the distribution of excess pore water pressure contours after the formation of the shear bands in the plate.

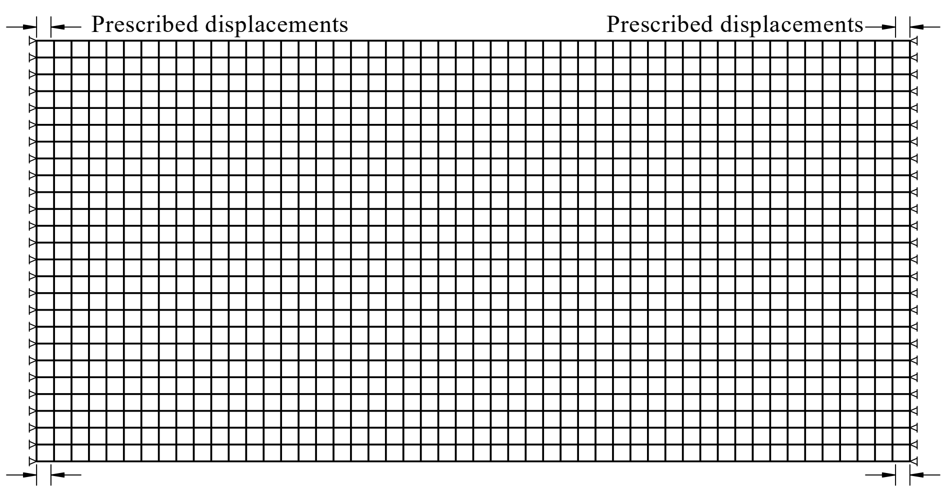


Figure 4. Initial finite element mesh and boundary conditions for numerical simulation analysis of a plate under lateral compression (Hsu, 1987).

As the strain goes deep into the plastic range, Figure 5 shows that the plate loses its stability and symmetry due to plastic strain softening, and shear bands are formed as a result of localizations of deformations. Figure 6 illustrates the distribution of excess pore water pressure contours of groundwater within the shear bands.

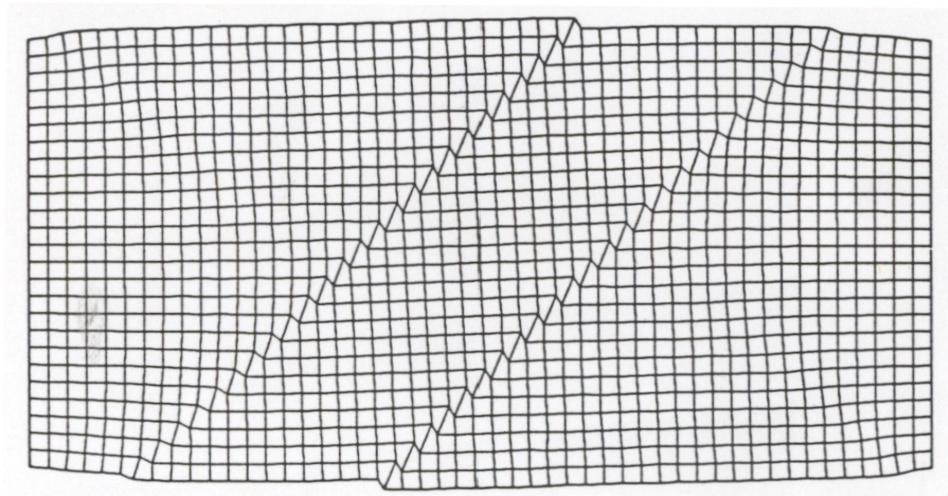


Figure 5. Finite element deformation mesh after the formation of shear bands in the plate (Hsu, 1987).

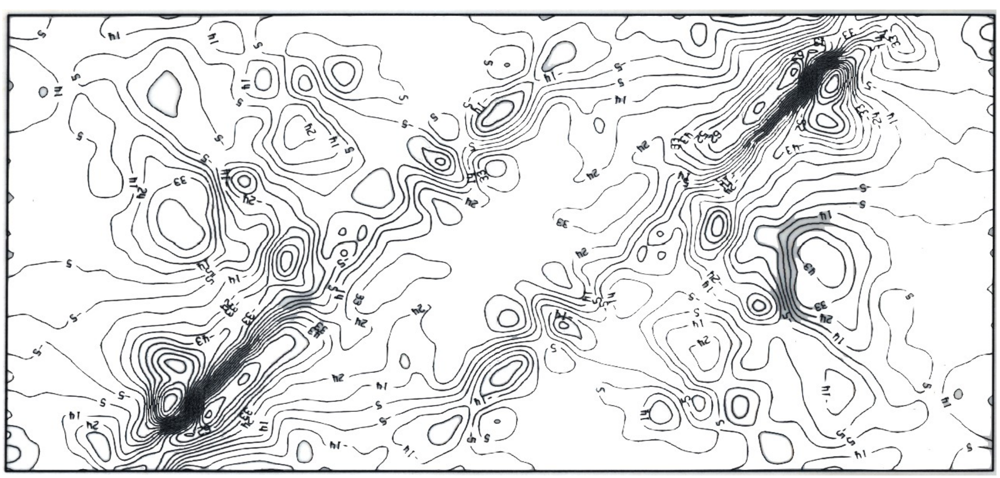


Figure 6. Distribution of excess pore water pressure contours after the formation of the shear bands in the plate (Hsu, 1987).

Combining the observations from Figures 5 and 6, the following conclusions can be drawn for the formation mechanisms of shear bands:

1. The plate can be divided into two regions: the non-shear band zone and the shear band zone.
2. The non-shear band zone is a stable elastic strain region.

3. The shear band zone is an unstable plastic strain-softened region.
4. Within the shear bands, the groundwater locally exhibits highly concentrated excess pore water pressure.

Therefore, the formation mechanisms leading to soil liquefaction in the rear-line region of the Taichung Port caisson dock are as follows:

1. After the caisson rotates or moves seaward, it induces shear bands, as shown in Figure 3.
2. Highly concentrated excess pore water pressure appears locally in the groundwater within the shear bands, as illustrated in Figure 6.
3. The soils within the shear bands undergoes brittle fracture. After the soil particles, ranging from fine to coarse, float in the groundwater, the groundwater, along with the suspended soil particles, sprays upward through the discharge tunnel formed along the fractured pore spaces of the shear band.

Formation Mechanisms of Piping Failure in the Rear-Line Region of the Dock Caisson

Generally, dock caissons are directly placed on the seabed (as shown in Figure 7). Since the embedded depth D=0, and if the groundwater level in the rear-line region of the caisson is higher than the seawater level, piping failure occurs when the hydraulic gradient i at the water exit point E of the caisson (as shown in Figure 8) exceeds the critical hydraulic gradient i_c. Once piping failure occurs, large cavities, as illustrated in Figure 3, will appear in the rear-line region.

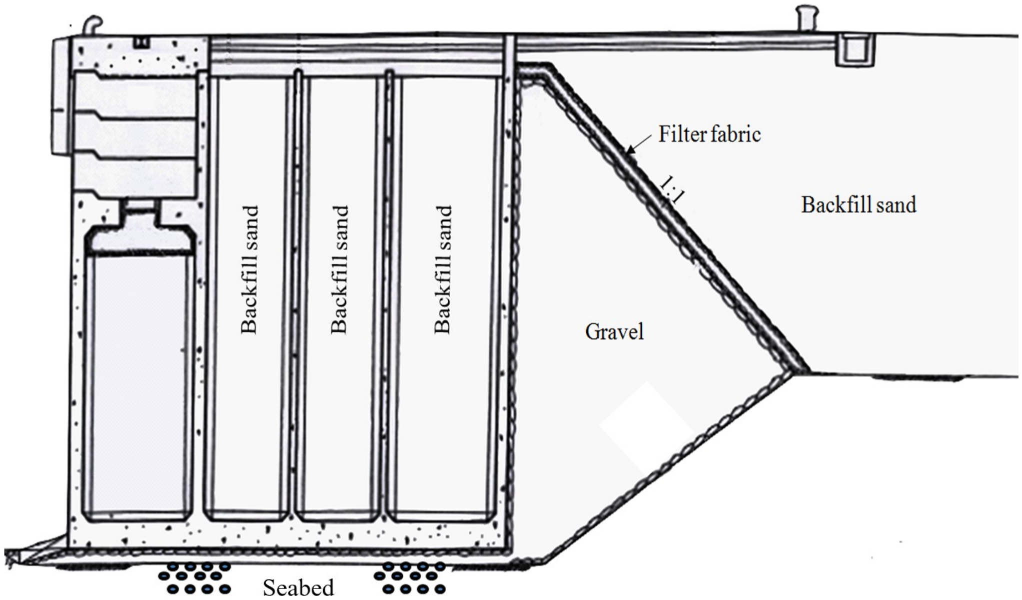


Figure 7. Schematic diagram of a dock caisson directly placed on the seabed without any embedded depth (Chang, 2019).

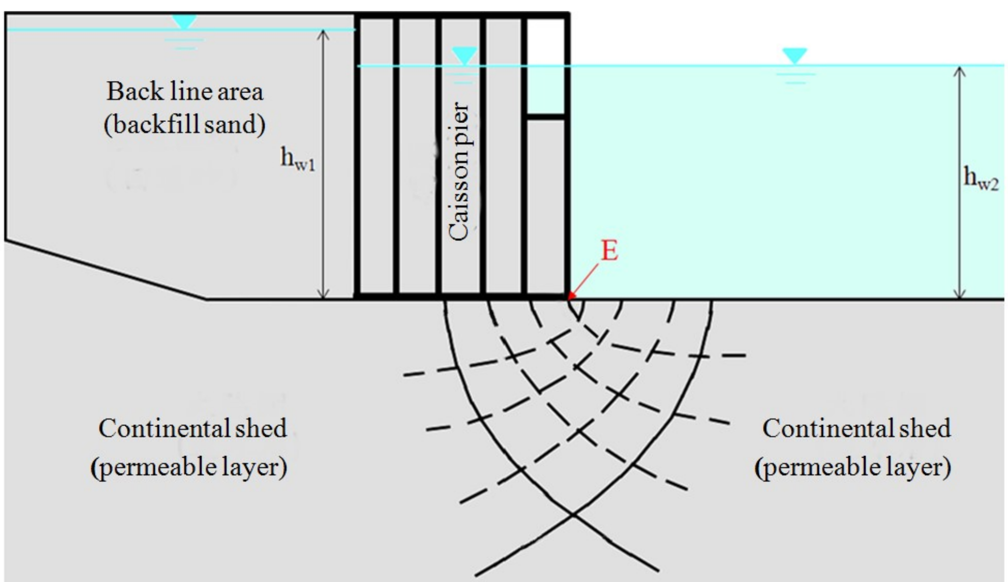


Figure 8. Dock caisson with an embedded depth of D = 0 (Chang, 2019).

Moreover, the formation mechanism of the piping failure in the rear-line region of the dock caisson is similar to that of piping failure in dams, where it follows the axis of intersection of shear bands with different strikes (see Figure 9). Therefore, for the rear-line region of the dock caisson at the Port of Taichung in Taiwan, piping failure is also likely to occur along the axis of intersection of shear bands with different strikes as shown in Figure 3.

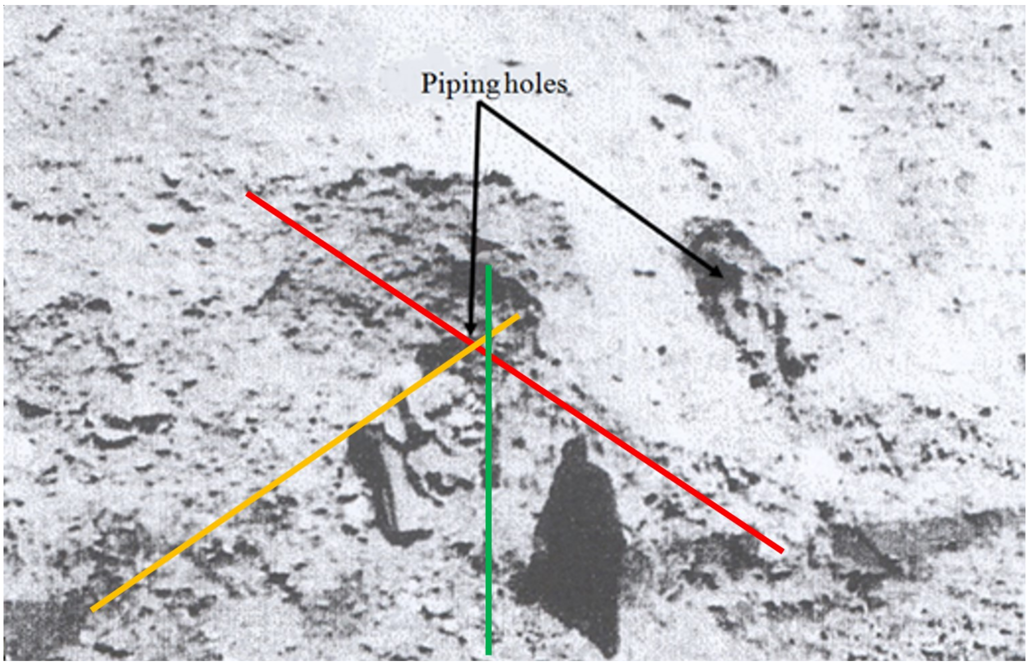


Figure 9. Piping tunnels induced at the intersection of shear bands with different strikes in a dam structure (Sinotech Foundation for Research and Development of Engineering Sciences and Technologies, 2008).

Regarding the discharge tunnel with a diameter of D_{p1} at the intersection of shear bands with different strikes, when the groundwater flow velocity v_1 in the shear band exceeds the critical velocity v_{bc1} required to float soil particles with a grain size D_1, the soil particles with size D_1 will be carried away along the discharge tunnel with diameter D_{p1}. Subsequently, as the diameter of the discharge tunnel in the shear band increases to D_{p2}, when the groundwater flow velocity v_2 exceeds the critical velocity v_{bc2} required to float larger soil particles with grain size D_2, soil particles with size D_2 will also be carried away along the discharge tunnel with diameter D_{p2}. This process continues, with progressively larger particles being transported, leading to the gradual loss of the backfill in the rear-line region. Ultimately, this continuous loss of material results in the formation of a large piping cavity, as shown in Figure 2.

Comparison and Discussion

1. Ports are typically located in Ω-shaped bays, where features of the displaced landform are evident in the bay's topography. For the design of the caisson docks at Taichung Port, Taiwan, it is crucial not only to consider earthquake-resistant measures based on existing seismic design codes for ground vibration, but also to prioritize protection against shear banding along shear bands.
2. The traditional design of the caisson dock at Taichung Port involves placing the caissons directly on the seabed. Under this design, the rear-line region of the caisson dock experienced significant damage during the 1999 Jiji earthquake, including large-scale settlement, formation of large piping cavities, and sand boil-type soil liquefaction.
3. Table 1 summarizes the key factors that contributed to the three types of damage induced in the rear-line region of the Taichung Port caisson dock during the 1999 Jiji earthquake.

Table 1. Summary of the mechanisms for three types of damage in the rear-line region of Taichung port caisson dock

Failure Phenomenon	Formation Mechanisms for Failure
Shear bands with different strikes	1. Caisson rotation or movement. 2. The dense backfill undergoes plastic strain softening during the earthquake. 3. The dense backfill loses stability and undergoes localized deformation.
Large-scale settlement	1. The dense backfill undergoes plastic strain softening during the earthquake, triggering shear bands of Rankine active failure plane type. 2. Shear banding induces localized, highly concentrated excess pore water pressure. 3. The caisson rotates or moves toward the seaward side due to increased soil and water pressures.
Soil Liquefaction	1. The dense backfill undergoes plastic strain softening during the earthquake, triggering shear bands of the Rankine active failure plane type. 2. Shear banding results in localized, highly concentrated excess pore water pressure. 3. The groundwater within the shear band carries soil particles, ranging from fine to coarse, which float along the shear band's pore spaces and form outflow conduits, causing upward ejection.
Piping Cavity	**The first type:** 1. The caisson is directly placed on the seabed with an embedded depth of zero. 2. The groundwater level in the rear-line region is higher than the seawater level. 3. The hydraulic gradient i at the caisson exit point exceeds the critical hydraulic gradient i_c. **The second type:** 1. The dense backfill undergoes plastic strain softening during the earthquake, triggering shear bands with different strikes. 2. Shear banding causes highly concentrated excess pore water pressure. 3. Soil particles of varying sizes within the shear band are carried by groundwater and lost as they travel through the shear band tunnels.

4. Based on the need for earthquake disaster mitigation at Taichung Port's caisson dock rear-line region, future designs should incorporate a minimum embedment depth of 1 meter for the caisson. Only by doing so will the hydraulic gradient at the exit point E, as shown in Figure 10, remain below the critical hydraulic gradient, thereby preventing the occurrence of piping failure.

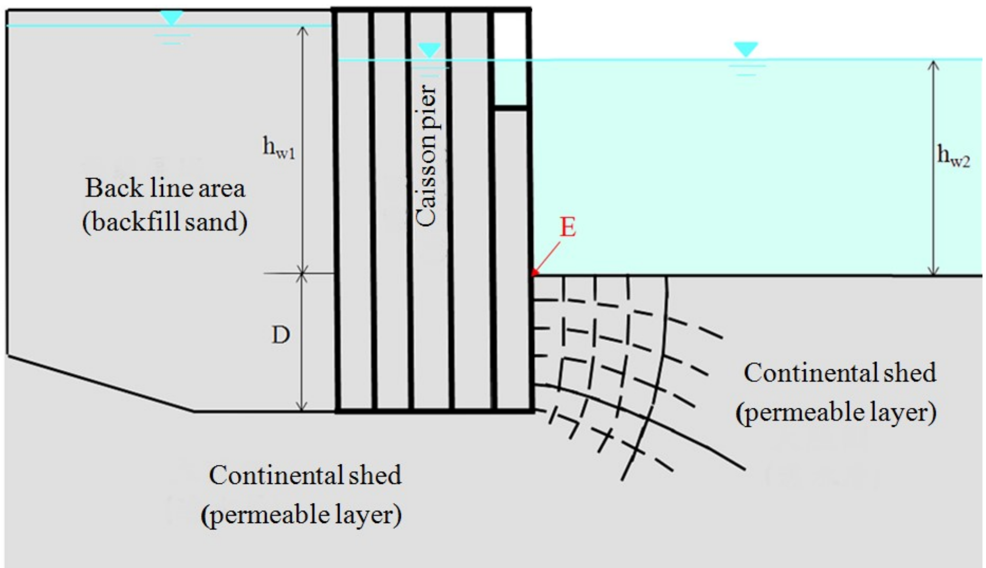


Figure 10. Caisson Dock with Embedment Depth D (Chang, 2019).

5. Due to the distinct features of shear band displaced landform at Taichung Port, and the fact that the caisson dock and rear-line region designs have not accounted for shear banding effects, the traditional scholars and experts involved in formulating and revising the caisson dock seismic design codes lack expertise in shear banding. As a result, they have not incorporated the increased active earth pressure and water pressure induced by plastic strain softening in the shear band backfill into the seismic design codes for the dock caisson.
6. Traditional soil liquefaction experts in Taiwan previously conducted a soil liquefaction assessment of the rear-line region of the Taichung Port caisson dock. However, the localized soil liquefaction phenomena observed on-site was assessed by Lai et al. (2007) as a widespread occurrence in the rear-line region. The primary reason for this discrepancy in the liquefaction assessment is the traditional definition of soil liquefaction, which occurs when the liquefaction resistance safety factor (FS_L) is less than 1.0. Here, FS_L=CSRRL/CSRE, where CSRRL is the cyclic stress ratio related to liquefaction resistance, and CSRE is the cyclic stress ratio under the design earthquake. From the perspective of plastic mechanics, the traditional definition of soil liquefaction occurs in stress spaces where the yield function $f > 0$ does not exist, and the farther the stress coordinate point is from the yield surface, the

higher the potential for soil liquefaction (see Figure 11). Since this definition of soil liquefaction and its potential contradicts plastic mechanics principles, the entire rear-line region of dock caisson for Taichung Port was incorrectly assessed as having soil liquefaction potential (Lai, 2007).

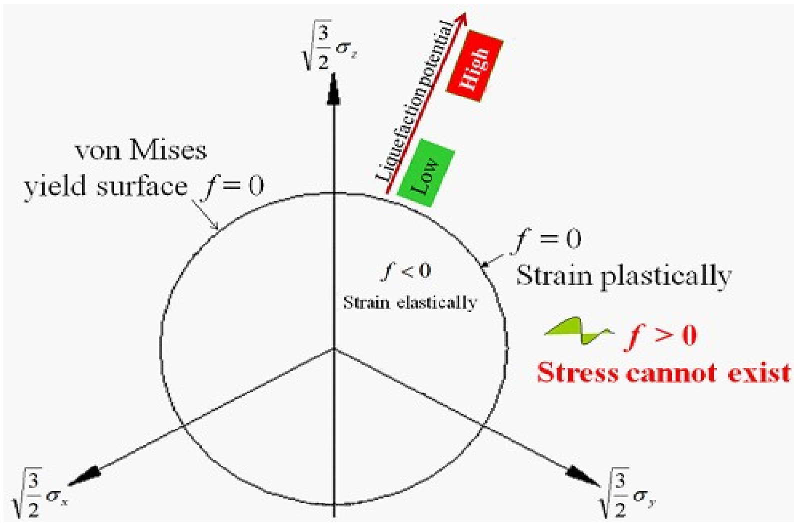


Figure 11. Stress space for the traditional definition of soil liquefaction potential, shown using the von Mises yield plane.

7. Figure 12 shows the soil liquefaction potential distribution map for Tainan City, Taiwan, while Figure 13 shows the same for Alameda, California, USA. Both Figure 12 and Figure 13 indicate that nearly the entire areas of Tainan City and Alameda, California, USA, possess soil liquefaction potential. However, Figure 12 also reveals that during the 2016 Meinong earthquake in Tainan, Taiwan, soil liquefaction only occurred locally at the positions marked by the black dots in the figure. Since the actual area of soil liquefaction accounted for less than 3% of the total area, this demonstrates that the soil liquefaction potential distribution maps in Figure 12 and Figure 13, which suggest nearly complete liquefaction potential throughout these regions, do not align with the observed facts.

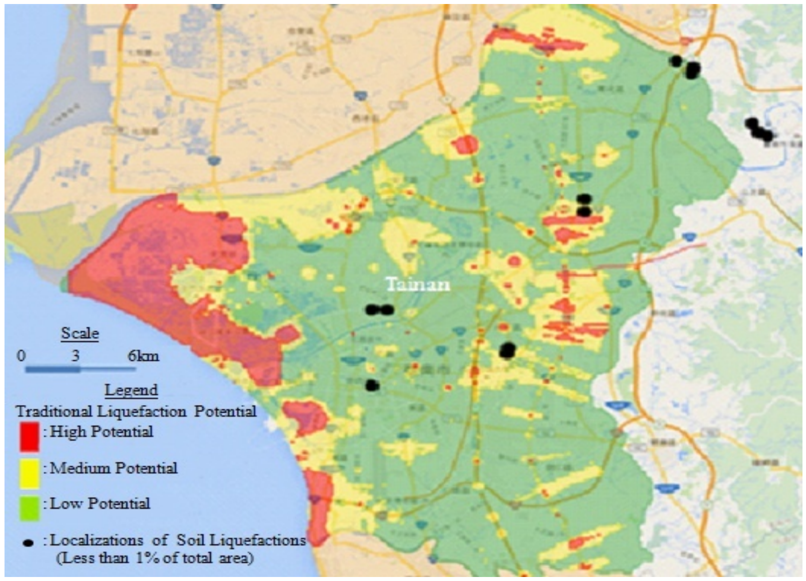


Figure 12. Distribution map of soil liquefaction potential of Tainan, Taiwan (Hsu et al., 2017; Central Geological Survey, MOEA, 2016).

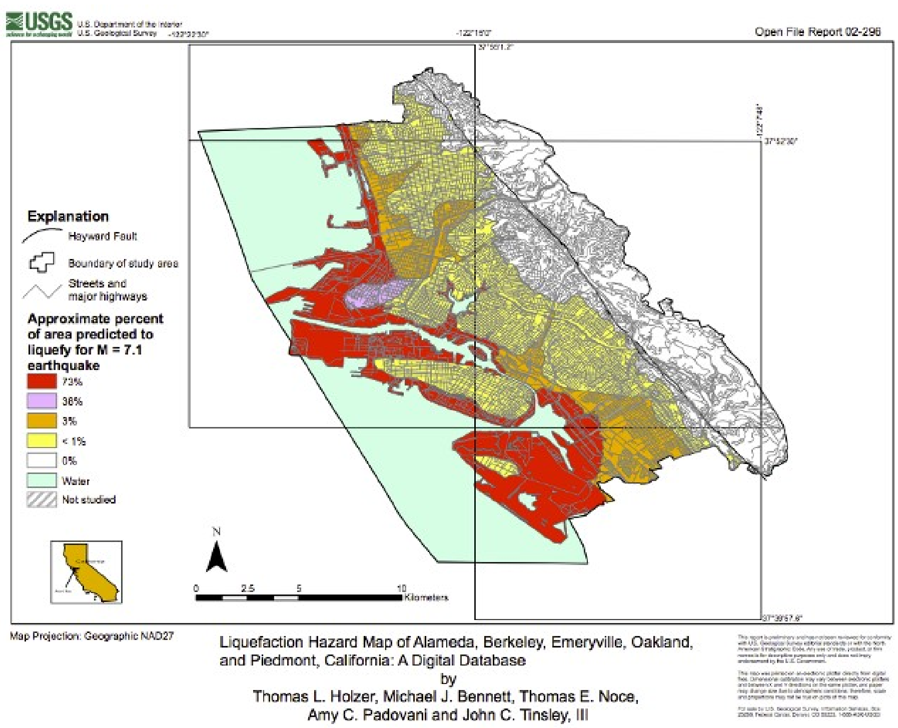


Figure 13. Distribution map of soil liquefaction potential of Alameda, California, USA (Holzer et al., 2019).

8. The soil liquefaction potential distribution maps shown in Figures 12 and 13, which do not match the actual observations, are based on the traditional definition of soil liquefaction. The traditional definition of soil liquefaction is primarily based on ground vibration, rather than shear banding. In traditional soil liquefaction assessments, when nearby locations have the same maximum ground acceleration (a_{max}), if one location is assessed as having liquefaction potential, then all other locations in the nearby area are also evaluated as having the same liquefaction potential. However, since soil liquefaction only occurs locally along shear bands, using maximum ground acceleration (a_{max}) is not an accurate method for assessing soil liquefaction potential.
9. Since actual soil liquefaction occurs only locally along shear bands, Table 2 presents the definition of the soil liquefaction potential that is required for accurate assessment:

Table 2. Definition of the soil liquefaction potential required for accurate assessment

Amount of shear banding	The phenomena observed on the ground surface during a tectonic earthquake.	Liquefaction potential
None	Ground surface remains without fracturing.	None
Mild	Groundwater carrying fine sand and fine-grained soils spouts from slightly fractured ground surface.	Mild
Moderate	Groundwater carrying sand and fine-grained soils spouts from moderately fractured ground surface.	Moderate
Severe	Groundwater carrying gravel, sand, and fine-grained soils spouts from highly fractured ground surface.	Severe

10. Soil liquefaction potential assessment method for the rear-line region of Taichung port dock caisson, aligned with actual needs:
    a. Prior to design, divide the rear-line region of Taichung Port dock caisson into non-shear band zones and shear band zones.
    b. In non-shear band zones, no soil liquefaction potential assessment is required.
    c. In shear band zones, soil liquefaction potential must be assessed based on the observed amount of

shear banding and the phenomena observed on the ground surface during a tectonic earthquake.

11. Due to the fact that ground vibration effects are much lower than shear banding effects, after tectonic earthquake disasters, scholars and experts have mistakenly attributed earthquake damage to insufficient seismic vibration resistance. As a result, they have continuously revised seismic design codes to increase the level of fortification against ground vibration, even when there was no need to increase seismic vibration resistance. Therefore, engineers in future design projects must simultaneously account for both shear banding and ground vibration fortification. When addressing ground vibration, the design can only comply with the maximum ground acceleration of design earthquake specified in the first edition of seismic design regulations.

Conclusions and Recommendations

In general, disaster-causing earthquakes are tectonic earthquakes with a magnitude greater than 6.0. The shear banding effects of tectonic earthquakes account for more than 90% of the total energy of the earthquake, while the ground vibration effects account for less than 10%. Currently, the seismic design of the dock caissons only addresses ground vibration fortification, which leads to failure under the effects of shear banding. Thus, the authors of this paper have conducted a study on the formation mechanisms of various types of damage to the rear-line region of the Taichung Port dock caisson during the 921 Jiji earthquake. The findings of the study are as follows:

1. Before the 921 Jiji earthquake, the rear-line region of the Taichung Port quay was a densely compacted gravel backfill area that passed compaction tests; during the 921 Jiji earthquake, the area underwent plastic strain softening, resulting in the formation of localized shear bands.

2. The area of shear band zone accounted for less than 3%, with locally concentrated excess pore water pressure in the groundwater in the shear bands, causing localized soil liquefaction. The government-issued soil liquefaction potential distribution maps, which show soil liquefaction as a widespread phenomenon across Taiwan, are clearly inconsistent with the actual observations.

3. The effect of shear banding significantly increased the rotation or lateral movement of the dock caisson towards the seaward side, leading to substantial subsidence in the

rear-line region. Furthermore, both the direct placement of the dock caisson on the seabed and the continuous loss of shear-band soil could induce piping failure in the rear-line region.

Based on the three conclusions mentioned above, for effective earthquake disaster prevention in the rear-line region of the dock caisson at the port, the authors suggest the following:

1. The seismic design regulations for dock caissons should clearly define the formation mechanisms of various possible damages in the rear-line region of the dock caisson, based on the findings of this study.

2. Seismic design should be carried out separately for the shear band zones and non-shear band zones, according to the results of shear band surveys. After completion, the dock caisson and the rear-line region at Taichung Port should be verified to meet the design objectives.

References

Central Geological Survey, MOEA, "Soil Liquefaction Potential Sytem," Website:http://www. geologycloud.tw/map/liquefac tion /zh-tw, 2016

Central Institute of Geological Survey, Ministry of Economy, Soil Liquefaction Query System: Zoning Map, Website: https://www.liquid.net.tw/CGSSL/Public/process/MainPage.aspx, 2019

Chang, Hong-Chia, *A Study of the Major Cause for the 2018 Hualien Earthquake Disasters*, Ph.D. Dissertation, Advisor: Professor Dr. Tse-Shan Hsu, Feng-Chia University, Taiwan, 2019.

Holzer, Thomas L., Bennett, Michael J., Noce, Thomas E., Padovani, Amy C. and Tinsley, John C. III, "Liquefaction Hazard Map Alameda, Berkeley, Emeryville, Oakland, and Piedmont, California," USGS, Webite: http://www.earthquakesafety.com/_pdf/of02-296_2liq-sg.pdf, 2019

Hsu, Tse-Shan, *Capturing Localizations in Geotechnical Failures*, Ph. D. Dissertation, Civil Engineering in the School of Advanced Studies of Illinois of Technology, 1987

Hsu, Tse-Shan, *The Major Cause of Earthquake Disasters: Shear Bandings*, A Chapter in "Earthquakes-Forecast, Prognosis and Earthquake Resistant Construction," Edited by Valentina Svalova, IntechOpen, pp. 31-48, 2018

Hsu, Tse-Shan, Chang-Chi Tsao, and Chihsen T. Lin, "Localizations of Soil Liquefactions Induced by Tectonic Earthquakes," *The International Journal of Organizational Innovation,* Vol.9, No. 3, Section C, pp. 110-131, 2017

Kobe Geotechnical Collection, Earthquake Engineering Research Center, University of California, Berkeley, Website: https://depts.washington.edu/liquefy/selectpiclique/kobe95/portgraben.jpg, 2019

International Navigation Association, Seismic Design Guidelines for Port Structures, MARCOM, Report of Working Group 24, 2001

Lai, R. Y., Lai, S. Y., Hsieh, M. Z., & Lin, Y. W., *Study on the impact of liquefaction on the stability of port structures* (2/4), Transportation Research Institute, Ministry of Transportation and Communications, 96-22-7274, MOTC-IOT-94-H1DA002-3, 2007

Ministry of the Interior, Republic of China, "Seismic design of caissons," *Building foundation design standards,* 2023

Sinotech Foundation for Research and Development of Engineering Sciences and Technologies, "Summary of Accident for Gouhou Dam, Qinghai Province, China," Special Report for Large Dam Accidents, SFRDEST E-02-DE-02-10, pp. 1-22, 2008