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THE FORMATION MECHANISM AND CONSTITUENT ELEMENTS OF ROAD SINKHOLES AND THE RELATIONSHIP WITH SHEAR BANDING

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Abstract

Traditional scholars assert that in the development of road sinkholes, the tunnels and caves required respectively for the passage and storage of spalled subgrade soil would have been formed by the dissolution of limestone by groundwater. However, road sinkholes only appear locally and can also appear in layers of hard-to-dissolve gravel and mudstone. Therefore, the authors propose a different formation mechanism and constituent elements for road sinkholes based on shear banding and draw four conclusions from the results of a simulation analysis and test and case study: (1) sinkholes only appear locally in shear banding areas; (2) the water required for the development of road sinkholes is rainwater that has infiltrated through cracks in the road surface course that are present in incomplete structural systems; (3) the reasons for the formation of road sinkholes is the

loss of integrity of the road structure system and the fact that seismic design codes do not fortify against shear banding; (4) if the inclination angle of a retaining wall is less than 3°, deep excavation construction will not induce the shear bands in the backfill region that are required to develop sinkholes. Based on the above four conclusions, it is suggested that the integrity of road structure systems should be maintained and seismic design codes should also specify fortification against shear banding. Only in this way can the formation of road sinkholes be avoided.

Keywords: sinkhole, tunnel, cave, shear banding, rainwater, excavation.

Introduction

Figures 1 to 3 show that there are groups of sinkholes in the beach road of Zhuoshui Creek in Nantou, Taiwan, the earth dam in the Renyitan Dam in Chiayi, Taiwan, and the road and community area in Zhubei, Taiwan. They have appeared in groups with steep sidewalls.

(a) The first road sinkhole

(b) The second road sinkhole

(c) The third road sinkhole

Figure 1. The group of sinkholes in the road at Zhuoshui Creek, Nantou, Taiwan.

(a) The first sinkhole

(c) The second and the third sinkholes

Figure 2. The group of sinkholes at the Renyitan Dam, Chiayi, Taiwan.

(a) The first road sinkhole

(b) The second road sinkhole

(c) The first community area sinkhole

(d) The second community area sinkhole

Figure 3. The group of sinkholes in the road and community area, Zhubei, Taiwan.

Because the constituent elements of the road sinkholes have not yet been investigated, the causal relationship between the local occurrence of tunnels and caves and the sinkholes has not been discussed in the literature (Benson and Yuhr, 2016; Kohl, 2001; Parise and Gunn, 2007; Waltham, 2008; Waltham, Fred , Culshaw, Martin, 2006; Wikipedia, 2023), even for the sinkholes that have appeared locally in limestone areas. If there is no construction near a road sinkhole, the cause of its formation has been attributed to natural factors; on the other hand, when there is construction near a road sinkhole, the cause of its formation has been attributed to the construction. Due to the consistency of the causes for the formation of the road sinkholes, the authors of this paper found that sinkholes only appear locally in shear banding areas. Therefore, this paper will first present the results of a simulation analysis of the formation of shear bands, then propose the mechanism and constituent elements for the road sinkholes on the basis of the shear banding effect, and finally present the results of the simulation test for the phenomenon of shear bands forming in the backfill region of a retaining wall for deep excavation construction. The conditions required for deep excavation construction to create the shear bands in the backfill region of the retaining wall and induce road sinkholes are also deduced and examined to determine whether the road sinkhole in Zhubei, Taiwan, were caused by the adjacent deep excavation construction.

Numerical Simulation Analysis for the Formation of Shear Bands

Figure 4 shows the initial finite element mesh for the simulation analysis of a plate continuously subjected to lateral compression, and Figure 5 shows that when the strain goes deep into the plastic range, the plate loses its ellipticity under strain softening and localization of deformation occurs, thereby inducing shear bands.

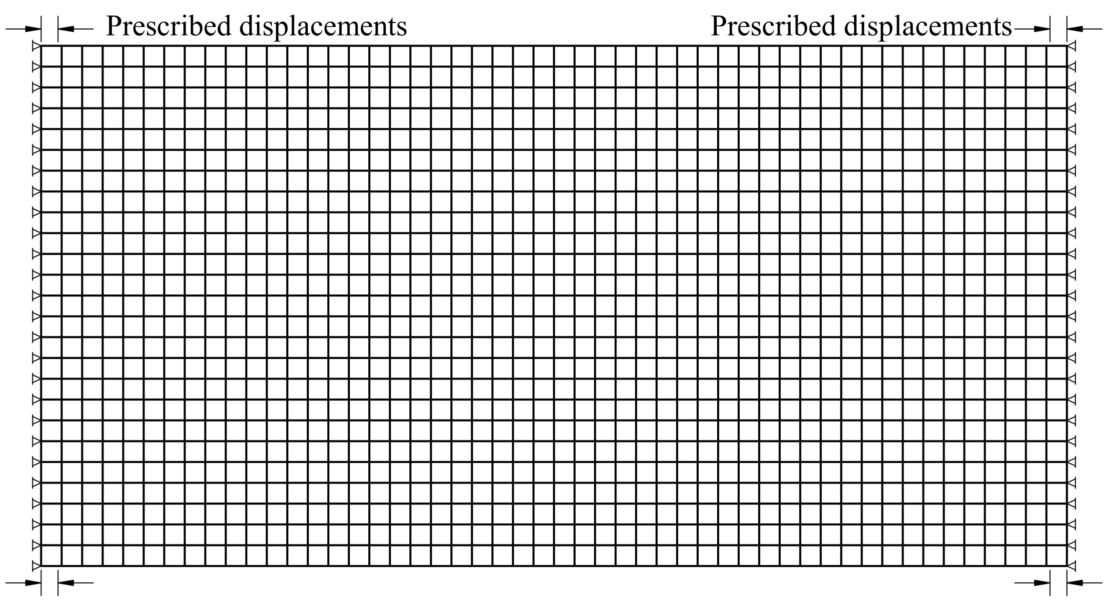


Figure 4. The initial finite element mesh for the simulation analysis of a plate under lateral compression (Hsu, 1987).

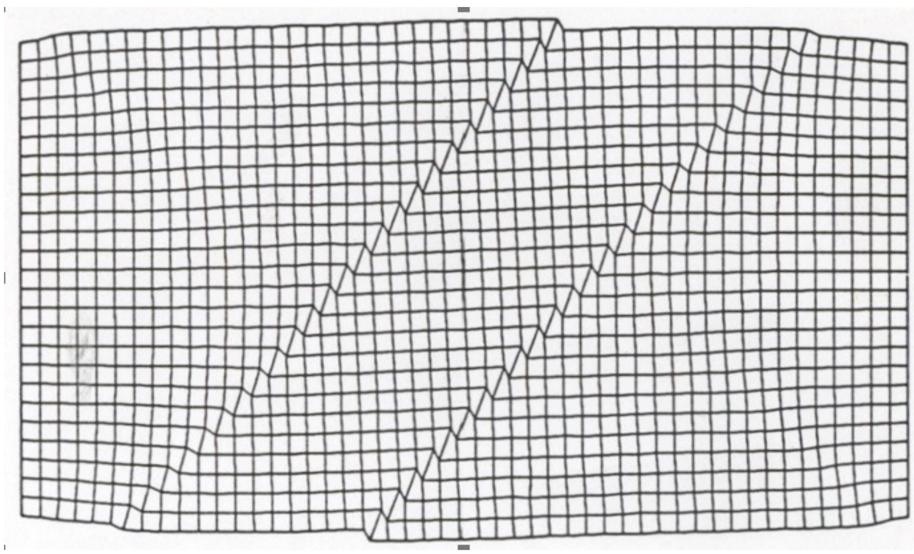


Figure 5. The deformed mesh showing shear bands that locally appear under the lateral compression of the plate (Hsu, 1987).

When the ground water table is at the ground surface, the shear banding effect will induce highly concentrated excess pore water pressure u_e^*, as shown in Figure 6. Under the influence of shear banding, the friction resistance will induce the repeated slip-stick phenomenon shown in Figure 7.

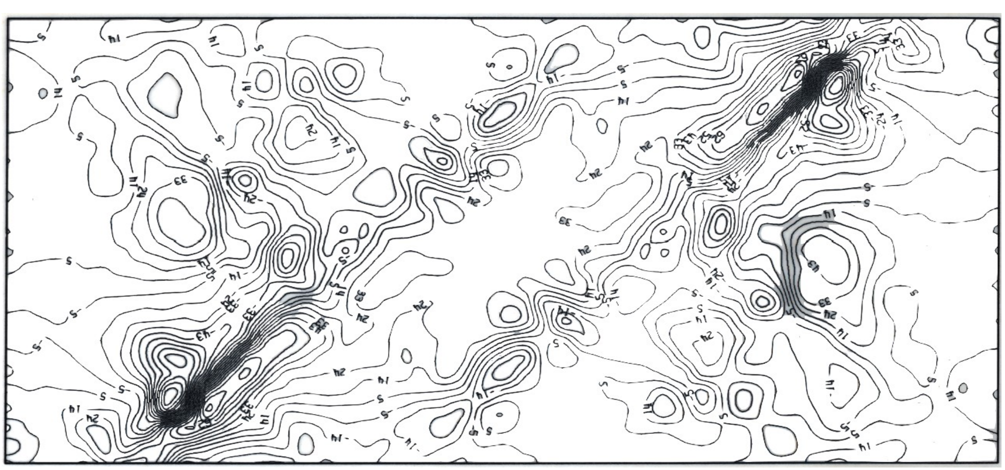


Figure 6. The contour lines of excess pore water pressure when shear bands are induced in the plate under lateral compression (Hsu, 1987).

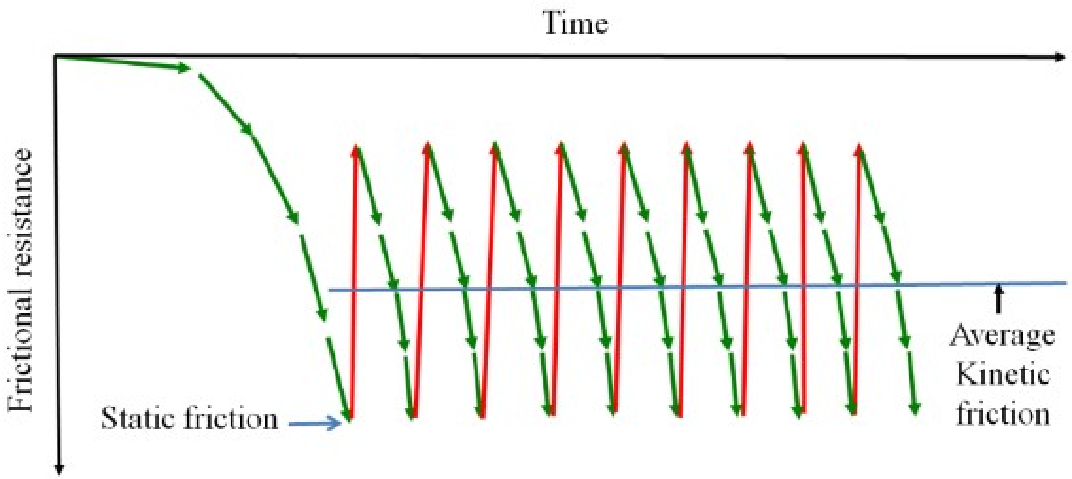


Figure 7. Repeated slip-stick phenomenon induced by frictional resistance during shear banding (Reproduced from Lambe, 1969).

Complete and Incomplete Road Structure Systems

Figure 8 shows a complete road structure system including the shoulder, wearing surface, base course, improved subgrade (if needed), and subgrade.

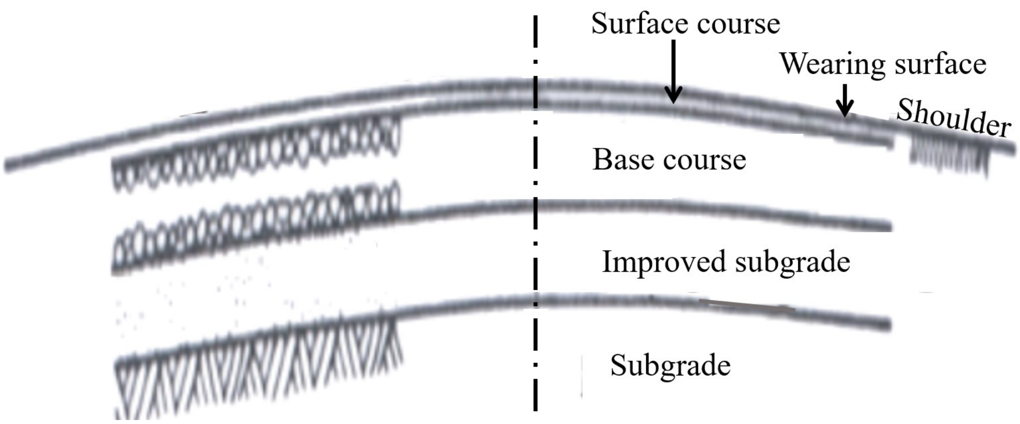


Figure 8. A complete road structure system (Lambe, 1969).

A complete road structure system is transformed into an incomplete road structure system under various conditions, including

1) when shear bands and shear textures appear in the road structure system (see Figure 9),
2) buried infrastructural pipelines occur in the system (see Figure 10),
3) when a low-elevation shoulder is changed into a higher-elevation landscape pedestrian walkway (detailed in Figure 11).

(a) Before the overlay of shear bands and shear structures.

(b) After the overlay of shear bands and shear structures.

Figure 9. Shear band and shear textures that have appeared in a road structure system.

Figure 10. Exposed pipelines under a road.

Figure 11. Changing of the shoulder of the road into a landscaped walkway.

Formation Mechanism of Road Sinkholes

When one end of a shear band is connected to a sinkhole and the other end is a water outlet, the stick-slip phenomenon shown in Figure 7 generates excess pore water pressure u_e^* during shear banding. The repeated positive-negative action of u_e^* provides a pumping action similar to that observed in the relaxation process of a sponge after being squeezed. Therefore, the soaked and softened subgrade in the sinkhole (see Figure 12) is drawn into the water outlet tunnels in the shear bands under negative values of u_e^* and discharged from the water outlet of the shear band outcrops under positive values of u_e^* (see Figure 13) during the pumping action. Therefore, the pumping action induced by shear banding continually increases the size of the sinkhole.

Figure 12. Subgrade soil soaking and softening after rainwater infiltration.

Figure 13. Groundwater entraining soil particles flowing out from a water outlet of the shear band outcrops (Nantou, Taiwan).

The soaked and softened subgrade will be discharged from the water outlet of the shear band outcrop after it has been drawn into the water outlet tunnels, and the punching shear failure of the road surface course and base course above the crown of the sinkhole will become more obvious. Therefore, the road sinkhole formation mechanism is as follows:

1) When rainwater infiltrates through the cracks of the surface course, the clay particles in the subgrade soils of size (D) less than 0.002 mm will begin to float and discharge from the water outlet of the shear band outcrops (see Figure 13).
2) As the clay exits, the volume of the pore space in the shear band increases, as does the flow velocity of the groundwater. Therefore, silt (particle size 0.002 mm □ D < 0.075mm) will begin to float and discharge from the water outlet of the shear band outcrops.
3) As the silt exits, the volume of the pore space in the shear band continues to increase, as does the flow velocity of the groundwater, and sand (0.075 mm □ D < 4.75mm) and/or gravel (4.75mm □ D < 7.62cm) will start to float, accompanied by the discharge of the groundwater from the water outlet of the shear band outcrops.
4) As the particles of the subgrade gradually change from small to large, the size of the road sinkhole becomes larger and larger. When the shear stress on the potential penetration surfaces in the surface course and the base course remaining above the crown of the sinkhole is greater than the shear resistance strength, the remaining surface course, base course, and any vehicles above the crown of the sinkhole will fall into the road sinkhole.

Constituent Elements of Road Sinkholes

The formation of road sinkholes requires the following three constituent elements:

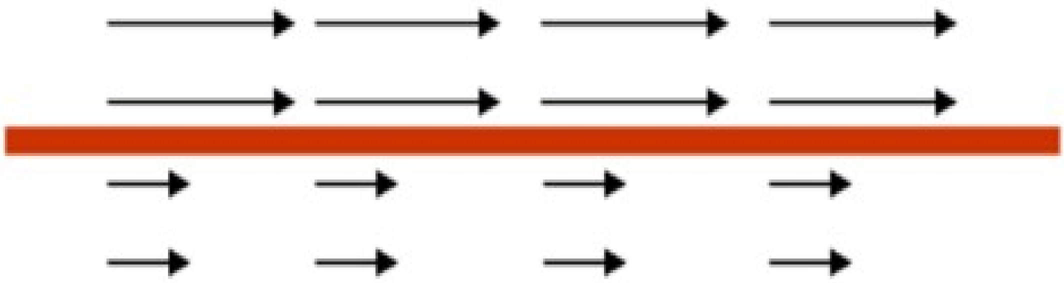
1) the existence of shear bands or shear textures in an incomplete road structure system,
2) infiltration of rainwater through cracks in the incomplete road structure system, and
3) soaking and softening of the subgrade soil and subsequent removal of soil particles, from small to large, which gradually float in the flowing shear band water before being discharged from the water outlet of the shear band outcrops.

Identification of Shear Bands or Shear Textures Required to Form Road Sinkholes

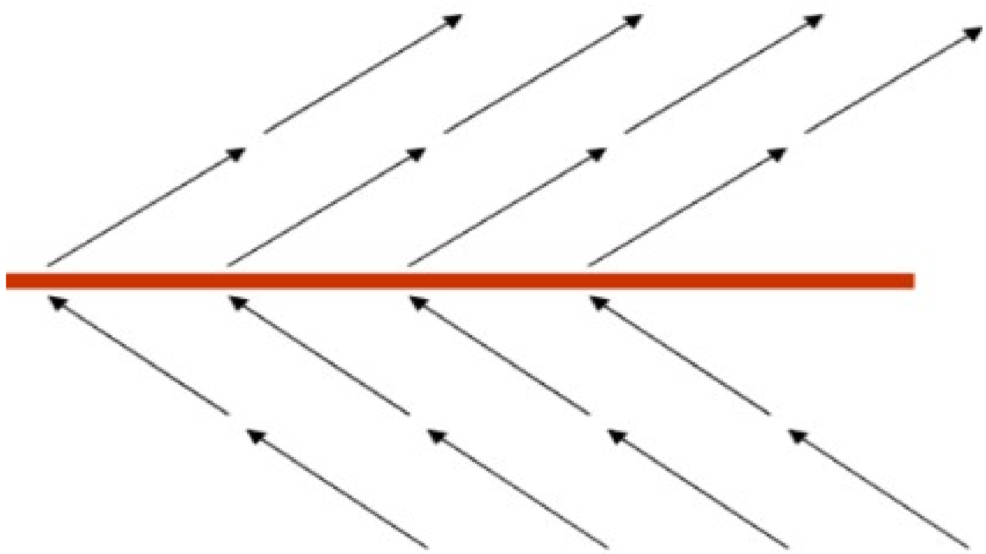
Identification of Shear Bands Using GPS Velocity Vector Distribution Maps

Hsu (1987) defined a slip-type

shear zone as one characterized by two adjacent points whose displacement velocity vectors have the same direction but different magnitudes and a twinning-type shear zone as one with two adjacent points whose displacement velocity vectors have different directions but the same magnitude (see Figure 14).



(a) Slip type



(b) Twinning type.

Figure 14. Definition of different types of shear bands (Hsu, 1987).

Figure 15 shows the distribution of GPS velocity vectors in northern Taiwan. For the sinkhole that appeared in Zhubei, Taiwan on April 27, 2023, the GPS velocity vector is 30 mm/year. Based on the distribution of GPS velocity vectors in north Taiwan as shown in Figure 15, and supplemented by an understanding of the definition of different types of shear bands, a group of slip-type shear bands and a group of conjugate shear bands with strikes of $N70^{\circ}W$ and $N20^{\circ}E$, respectively, can be identified in the vicinity of Zhubei.

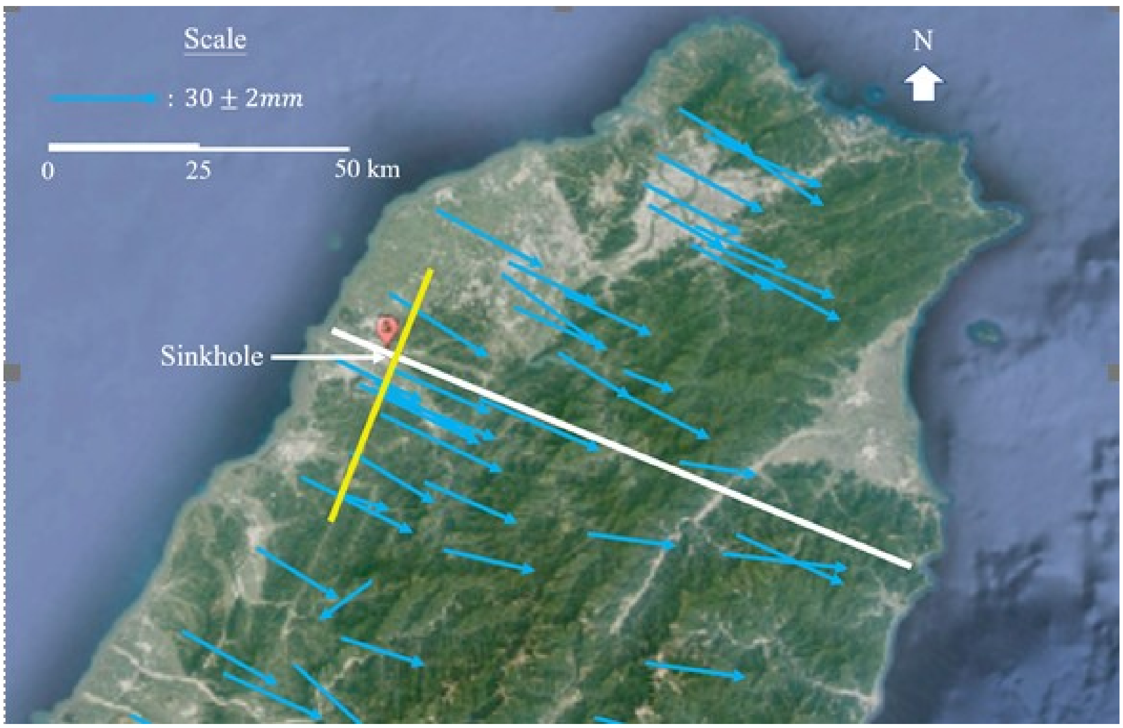


Figure 15. Using the GPS velocity vector distribution map to identify shear bands in the vicinity of Zhubei, Taiwan (Google Earth, 2023; GPSLAB, 2007).

Figure 15 shows the distribution of GPS velocity vectors in northern Taiwan. For the sinkhole that appeared in Zhubei, Taiwan on April 27, 2023, the GPS velocity vector is 30 mm/year. Based on the distribution of GPS velocity vectors in north Taiwan as shown in Figure 15, and supplemented by an understanding of the definition of different types of shear bands, a group of slip-type shear bands and a group of conjugate shear bands with strikes of $N70^{\circ}W$ and $N20^{\circ}E$, respectively, can be identified in the vicinity of Zhubei.

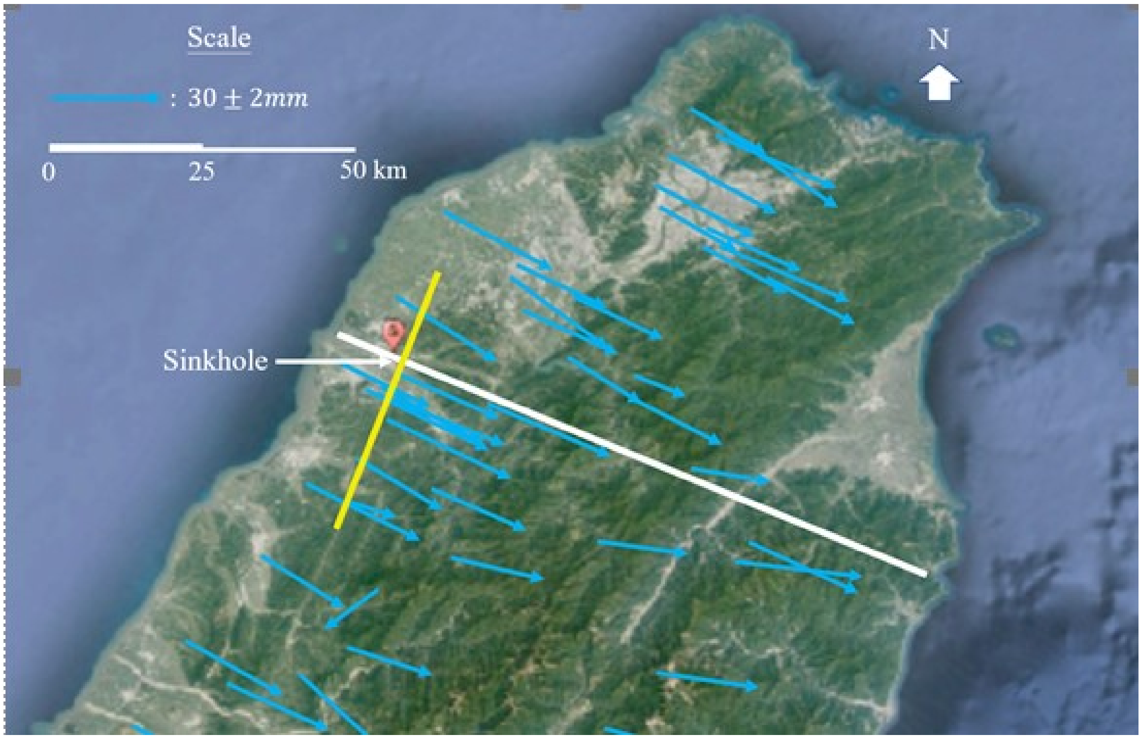


Figure 15. Using the GPS velocity vector distribution map to identify shear bands in the vicinity of Zhubei, Taiwan (Google Earth, 2023; GPSLAB, 2007).

Identification of Shear Bands Using the Historical Epicenter Distribution Map

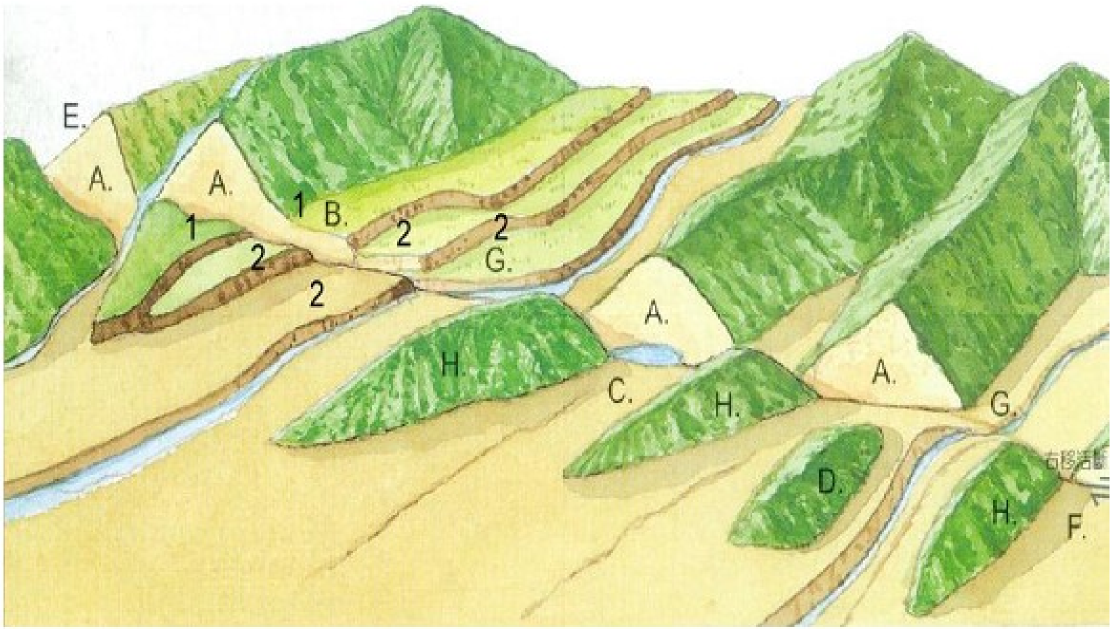
The hypocenter of an earthquake is located in a shear band, which is the starting point of shear banding, and the epicenter is the point where a line connecting the hypocenter and the center of the Earth extends to the ground surface. Therefore, the locations of shear banding in tectonic earthquakes can be approximately represented by the epicentral locations.

From the distribution of historical epicenters in the vicinity of Zhubei from 1995 to 2016 shown in Figure 16, two groups of shear bands with strikes of $N70^{\circ}W$ and $N20^{\circ}E$ can be identified in the vicinity of Zhubei.

Figure 16. Identification of shear bands existing in the vicinity of Zhubei, Taiwan using the historical epicenter distribution map (Google Earth, 2023; Central Weather Bureau, 2016).

Identify the Shear Band and Shear Textures Using the Satellite Imagery

Based on the satellite images and the shear-band displaced landform features (see Figure 17), various shear textures within the overall shear band as shown in Figure 18 can be identified.



Legend: (A) triangular facet, (B) low fault scarp, (C) fault sag, (D) bulge, (E) fault saddle, (F) horst, (G) beheaded stream, (H) shutter ridge, (1-1') offset of piedmont line, (2-2') offset of terrace

Figure 17. Shear-band displaced landform features (Cai and Yang, 2004).

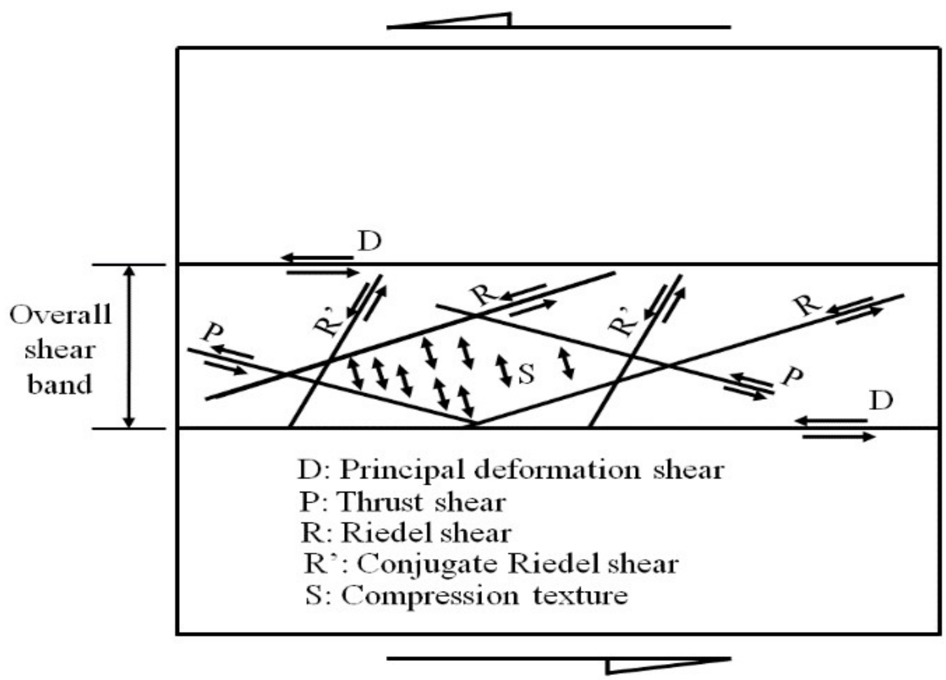


Figure 18. Various shear textures in the overall shear band (Tchalenko, 1968).

Based on the satellite imagery of the areas adjacent to Zhubei, and supplemented by considering the displaced landform features as shown in Figure 17, five groups of shear textures existing within the overall shear band in the adjacent areas of Zhubei can be identified as shown in Figure 19. These five groups of shear structures include principal deformation shear D with strike direction $N70^{\circ}W$, compression texture S with strike direction $N20^{\circ}E$, and three other groups of shear textures, namely, thrust shear P, Riedel shear R, and conjugate Riedel shear R'.

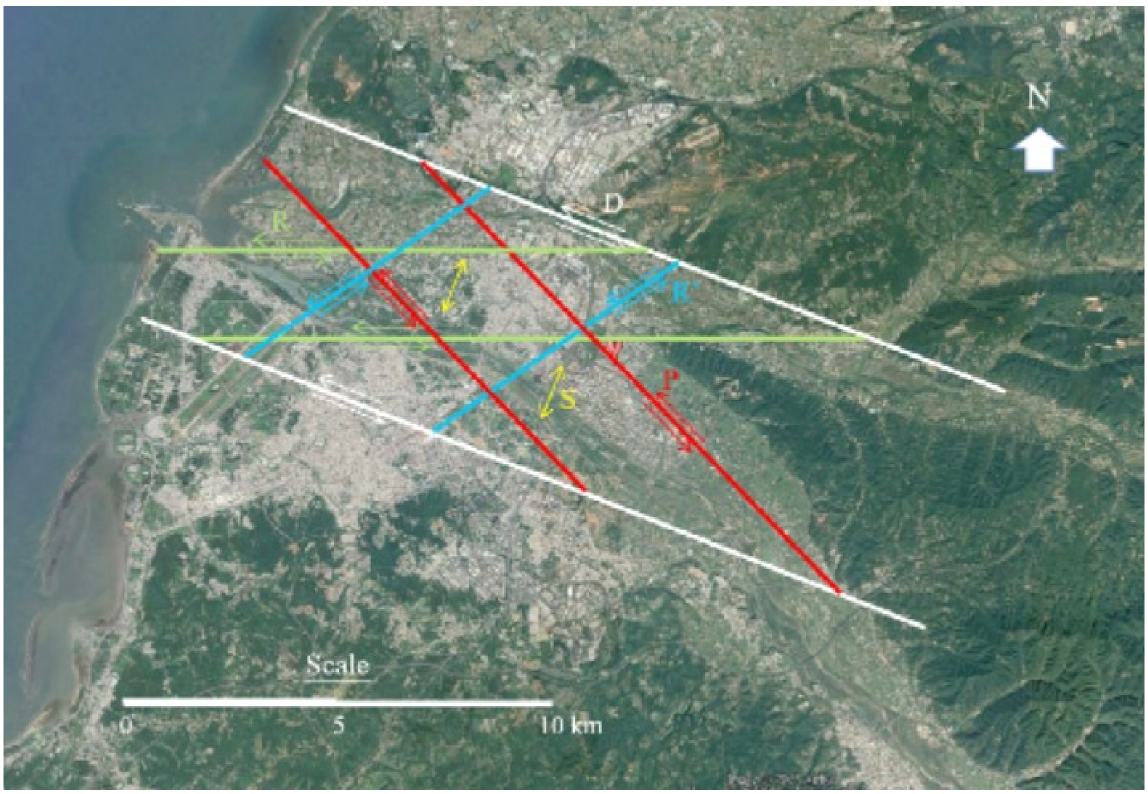


Figure 19. Identification of the shear band and shear textures existing in the vicinity of Zhubei, Taiwan using satellite imagery (Google Earth, 2023).

Simulation Testing of Shear Bands Required if Deep Excavation Construction in Adjacent Areas Induces Sinkholes

During deep excavation construction, tilting of the retaining wall will cause the formation of shear bands that induce sinkholes in the backfill. The simulation test results can therefore be used to quantitatively identify whether deep excavation construction in adjacent areas would create the necessary conditions to induce sinkholes in the area of interest.

Figure 20 shows the test model, which includes a 3.0 cm x 13.5 cm x 2.54 cm retaining wall model on the right-hand side and a 15.0 cm x 13.5 cm x 2.54 cm backfill model on the left-hand side. The backfill model is composed of sand modeled under the most compact conditions.

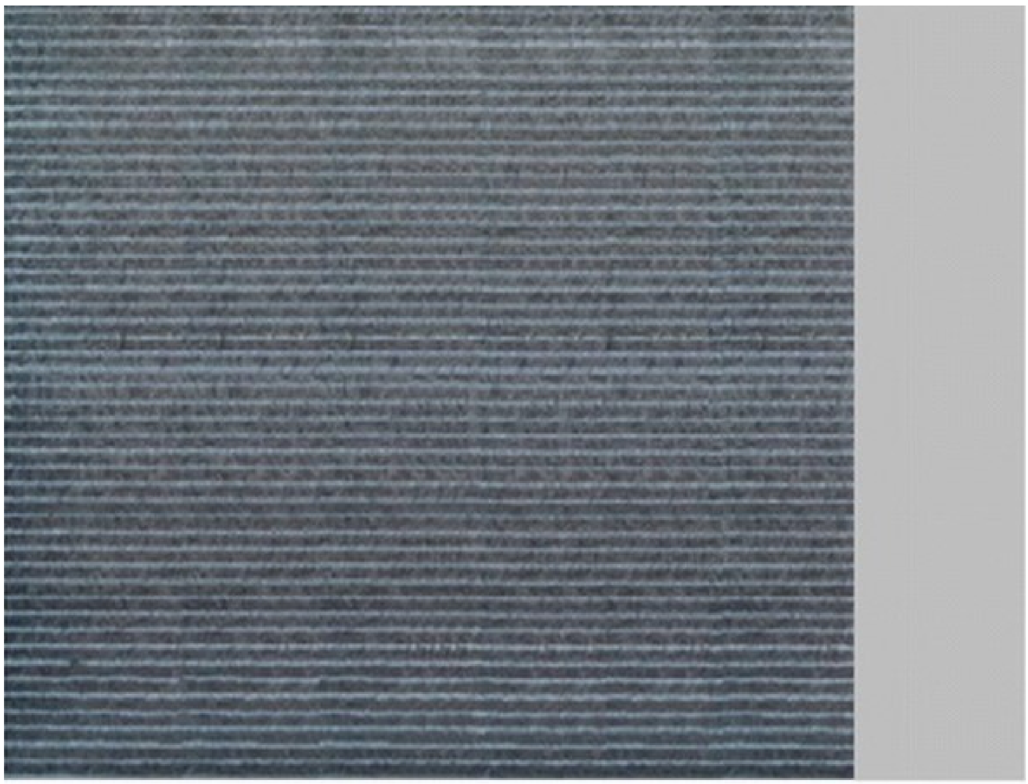
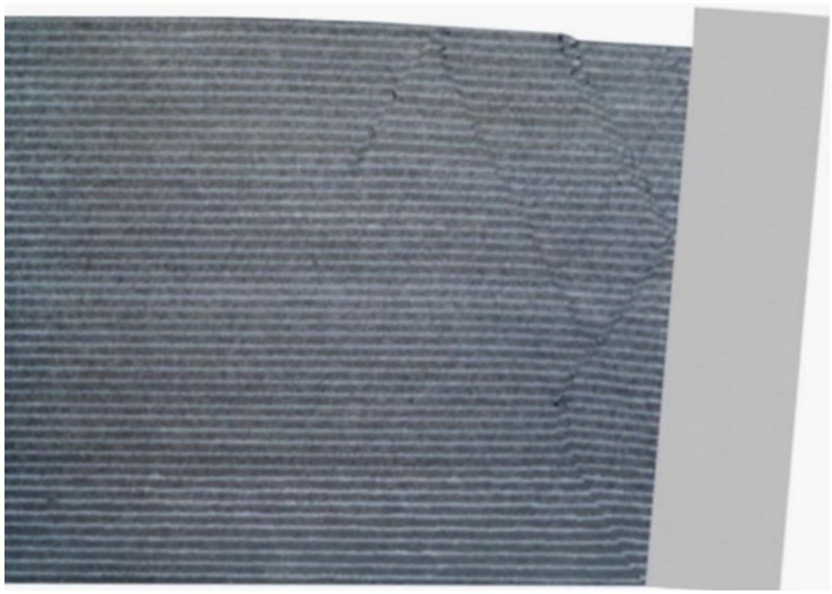
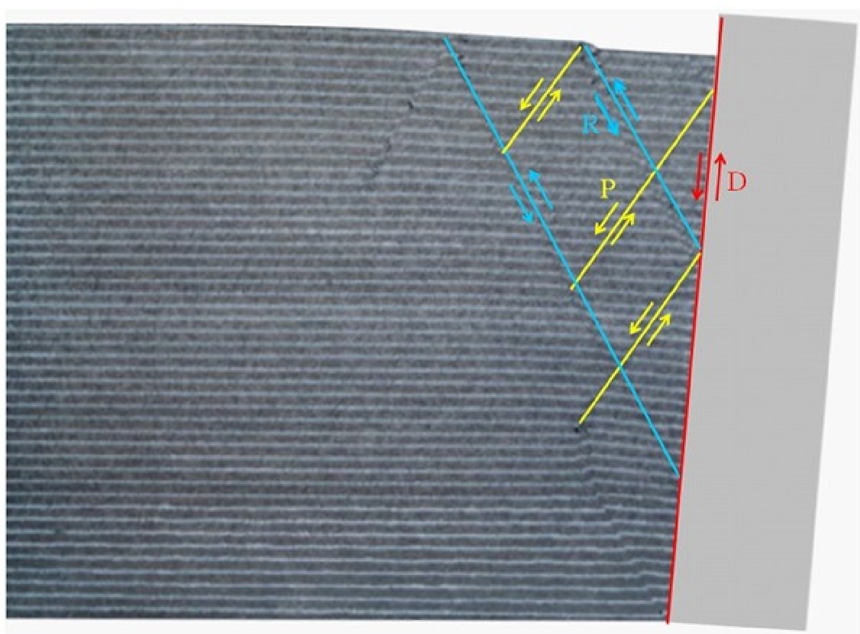


Figure 20. Experimental model of shear bands induced by tilting of the retaining wall (Hsu, 2022).

Figure 20 shows that when the retaining wall model has not been tilted, no shear bands or shear textures are present in the backfill model. When the retaining wall model is tilted clockwise along the bottom end of the model, shear textures in the backfill model becomes more and more pronounced as the tilting angle increases from 3° to 5° (see Figure 21). Over the course of the test, the shear textures propagate deeper and farther away from the retaining wall. Therefore, it can be deduced that when the tilting angle of the retaining wall model is greater than 3°, deep excavation construction will generate the shear bands required for road sinkholes to form in adjacent areas.



(a) Before drawing the shear textures



(b) After drawing the shear textures

Figure 21. Simulation test results of shear textures induced by tilting of retaining wall (Hsu, 2022).

Comparison and Discussion of Results

1) Sinkholes have appeared in many countries in the world. Scholars previously thought that the soil that peeled off during the formation of sinkholes would fall into tunnels and the caves below the sinkhole (see Figure 22) and that the tunnels and caves were created by the dissolution of limestone after soaking in groundwater.

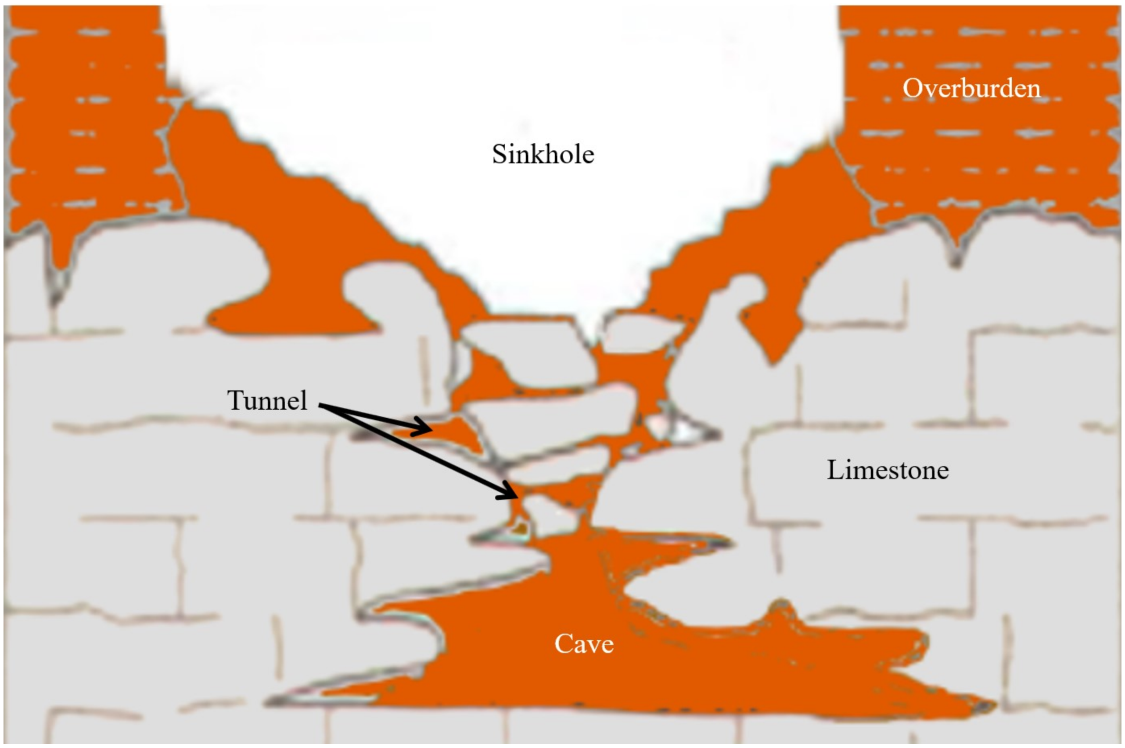


Figure 22. Soil that has peeled off the crown of a sinkhole and fallen into the tunnels and caves below (Reproduced from Wikipedia, 2023).

2) Figure 23 shows the shear bands excavated in Zhushan after the 921 Jiji earthquake. By comparing Figure 5 with Figure 23, it is found that the shear bands obtained by the numerical simulation analysis are very similar to the shear bands excavated in Zhushan. Since the shear bands are a failure phenomenon under unstable conditions, the numerical simulation analysis of the shear bands is appropriate for obtaining the solution under conditions of structural instability. Traditional structural scholars believe that there are no solutions under conditions of structural instability, so it is not easy to obtain a numerical solution for the shear bands that are consistent with the facts.

Figure 23. Shear bands excavated in Zhushan, Taiwan after the 921 Jiji earthquake (Hsu, 2018).

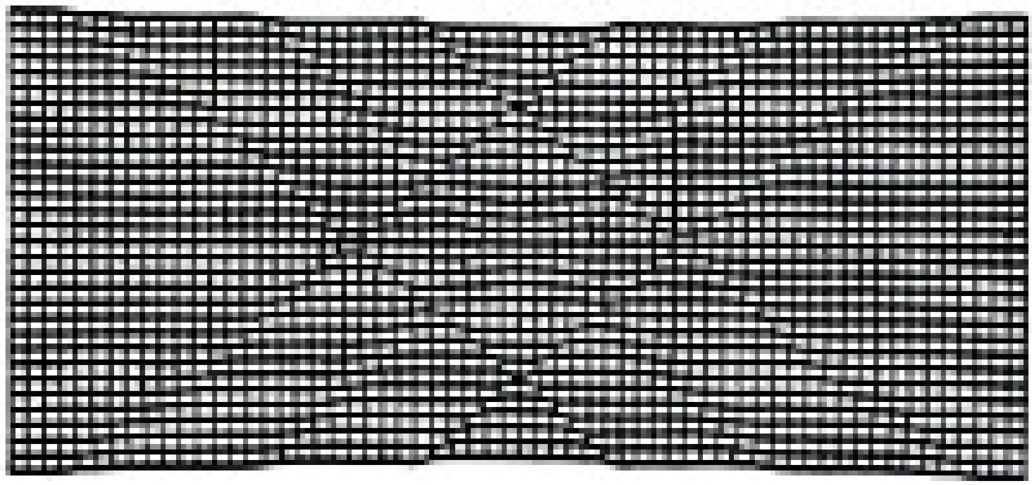
3) Under the load of a vehicle, the surface course of the incomplete road structure system will crack and peel off (see Figure 24).

(a) Local cracking

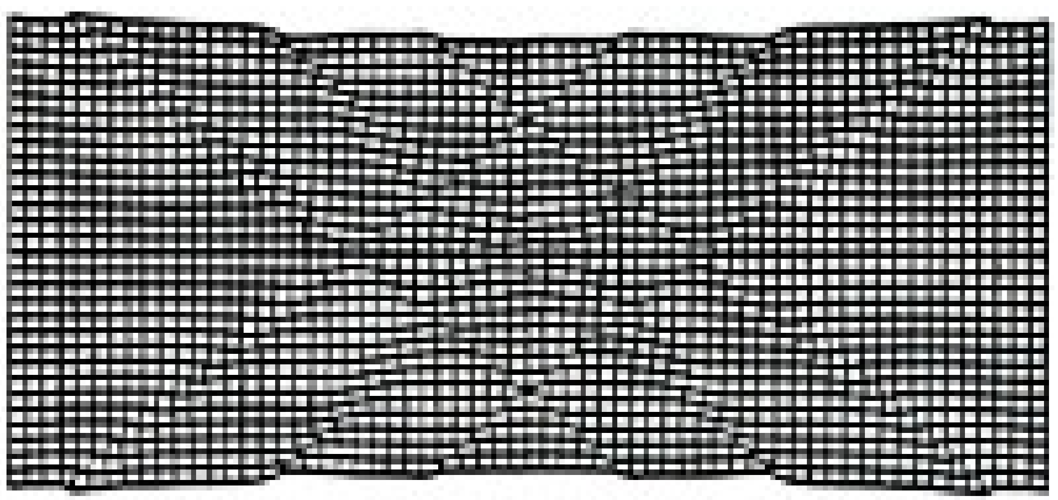
(b) Local cracking and spalling

Figure 24. An incomplete road structure system inducing local cracking and spalling of an asphalt concrete surface.

4) There are five types of earthquakes: tectonic earthquakes, volcanic earthquakes, subsidence earthquakes, earthquakes induced by reservoir impoundment, and earthquakes induced by explosions. The vast majority of earthquakes are tectonic earthquakes, and earthquakes that can induce structural damage are those with a scale of M □ 6.0. The main and secondary effects of tectonic earthquakes are:
   a) The main effect is the shear banding effect, whose energy accounts for more than 90% of the total energy of tectonic earthquakes, and the amount of shear banding accumulated with the increasing number of felt earthquakes.
   b) The secondary effect is the ground vibration effect, whose energy accounts for less than 10% of the total energy of tectonic earthquakes. The amplitude of ground vibrations disappears after the occurrence of felt earthquakes; thus, it does not continue to accumulate with an increase in the number of felt earthquakes.
5) Figure 24 shows that under n^{th}-order and $(n+1)^{th}$-order lateral compression, groups of shear bands that intersect appear in the plate. When felt tectonic earthquakes occur frequently, the degree of brittle fracturing of each shear band will become larger and larger. Since each shear band can induce a sinkhole, sinkhole groups (see Figures 1 to 3) are therefore more likely to appear in areas where groups of shear bands intersect.



(a) The n^{th}-order lateral compression



(b) The $(n+1)^{th}$-order lateral compression

Figure 25. Groups of shear bands that intersect in the plate under lateral compression (Hsu, 1987).

6) The ground vibration fortification level of the seismic design codes of various countries has been continuously increasing in recent decades, but the death toll from tectonic earthquakes is still significantly high. Hsu (2022) asserted that the main reason why earthquake disaster reduction has not been effective in the past is that the seismic design codes have not yet clearly defined the conditions for structures to become or be

considered "resistant" or "not resistant" to tectonic earthquakes. Therefore, the current available vibration isolation, vibration reduction, and vibration resistance technologies only have the effect of increasing the ground vibration resistance of stable structures but not of changing the non-seismic conditions for road sinkholes (under which they do occur) into seismic conditions (under which they do not occur).

7) The conditions under which deep excavation construction causes the formation of road sinkholes in adjacent areas are that shear bands or shear textures are induced in the backfill of the retaining wall when the retaining wall is inclined greater than 3°. In the case that the height of a retaining wall is 25 m, for example, if the horizontal displacement of the top end of the wall relative to the bottom end is greater than 1.31 m, then road sinkholes will form in Zhubei. When the horizontal displacement of the retaining wall for the deep excavation constructions under in-situ conditions is significantly less than 1.31 m, deep excavation construction will not create the necessary conditions for the formation of road sinkholes in adjacent areas.

8) In order to avoid conducting deep excavation construction under water, the groundwater table is generally lowered to a depth of one meter below the excavation surface by pumping. As for road sinkholes in Zhubei, since the groundwater tables are located below the road sinkhole before and during construction, lowering of the groundwater table has no relation to the formation of road sinkholes in that location.

9) Since there are no tunnels and caves under the road sinkhole in Zhubei, the formation mechanism of limestone sinkholes is not applicable.

10) Figure 12 shows that there are a number of infrastructural pipelines buried beneath the road and no vehicle weight limits; therefore, the road surface course will crack due to the uneven subsidence. Rainwater can then infiltrate through the cracks and, after the road base course and subgrade are submerged, the road bearing capacity will be reduced by approximately 50%, and the subsidence will be doubled under the same vehicle load conditions. Such conditions will intensify the uneven subsidence of the road surface course and cause more rainwater to infiltrate through the cracks.

11) Table 1 shows the monthly rainfall in Zhubei from January 2019 to April 2023. It can be seen that there is rainfall in Zhubei every month. Therefore, the groundwater needed for the formation of road sinkholes will be continuously supplied.

Table 1. Monthly rainfall in Zhubei, Taiwan from January 2019 to April 2023.

	2019	2020	2021	2022	2023
January	25.5	36.0	4.5	72.0	9.5
February	67.9	55.0	51.5	213.0	21.5
March	279.7	105.0	100.0	247.5	23.5
April	217.0	72.5	62.5	108.0	141.0
May	515.0	353.2	123.8	522.5	---
June	482.7	46.0	200.5	346.0	---
July	48.5	0.7	142.0	31.5	---
August	211.4	219.5	300.0	61.5	---
September	92.0	80.5	15.0	220.5	---
October	11.5	5.0	84.5	101.0	---
November	6.9	7.5	45.0	112.5	---
December	140.2	44.5	54.5	26.0	---

12) Since the tunnels and caves required respectively for the passage and storage of spalled soil exist in limestone layers but not in the gravel layer and mudstone layer below the road sinkhole in Zhubei, the path through which the spalled subgrade soil passes is in fact the water outlet tunnels in the shear bands. The subgrade soil after water soaking and softening is drawn into the water outlet tunnels in the shear bands when u_e^* is negative and then discharged from the water outlet of the shear band outcrops (see Figure 13) when u_e^* is positive.

Conclusions and Suggestions

Since there are no tunnels and caves in the gravel and mudstone layers below the road sinkhole in Zhubei, Taiwan, using the limestone sinkhole formation mechanism to identify the cause for its formation will yield incorrect results. Therefore, the authors proposed a new formation mechanism and constituent elements for road sinkholes that involve shear banding and consider the road sinkhole in Zhubei as an example case. Four conclusions were drawn:

1) The traditionally applied formation mechanism of sinkholes formed in limestone areas is not applicable to the road sinkholes in Zhubei because they are located in the road subgrade layer formed by the original surface soil, and the gravel and mudstone layers below the road subgrade layer do not dissolve in water.
2) Shear bands or shear textures are required for the formation of sinkholes according to the simulation analysis and test results, and these shear bands or shear textures can be identified by three different methods.

3) The proposed shear-band sinkhole formation mechanism and constituent elements can be used for areas with high rainfall where tectonic earthquakes often occur, and the reason for the formation of road sinkholes are the loss of the integrity of the road structure system and that the seismic design codes do not fortify against the shear banding effect.
4) It is deduced from the simulation test results that shear bands can be formed in the backfill region only if the inclination angle of a retaining wall is greater than 3°. Therefore, when the inclination angle of the retaining wall is significantly less than 3°, the formation of the road sinkholes is not related to any adjacent deep excavation.

Based on the above four conclusions, the following two suggestions are made in order to achieve the performance design goals for road sinkholes.

1) Since road sinkholes can form due to the incompleteness of a structural system, it is suggested that the integrity of road systems must be maintained during the road use stage after completion of construction.
2) Since road sinkholes are formed by the shear banding effect, it is suggested that in addition to seismic design codes specifying fortification against the ground vibration effect of tectonic earthquakes, the seismic design regulations must also specify fortification against the shear banding effect of tectonic earthquakes.

References

Benson, Richard C., Yuhr, Lynn B., "Site Characterization in Karst and Pseudokarst Terraines: Practical Strategies and Technology for Practicing Engineers," Hydrologists and Geologists, Springer, 2016

Cai, Heng and Yang, Jianfu, Taiwan's Fault and Earthquake, Teacher Hou Culture Co. Ltd., 2004

Central Weather Bureau, Ministry of Transportation and Communications. "Monthly Rainfall," Website: https://www.cwb.gov.tw/V8/C/L/Agri/Agri_month.html, 2023

Central Weather Bureau, Ministry of Transportation and Communications. "Disastrous earthquakes," Website: http://www.cwb.gov.tw/V7/earthquake/damage_eq.htm, 2016

Google Earth, Website: http://www.google.com.tw/intl/zh-TW/earth/, 2020

GPS LAB, Website: http://gps.earth.sinica.edu.tw/, 2007.

Hsu, Tse-Shan, Capturing Localizations in Geotechnical Failures, Ph.D. Dissertation, Civil Engineering in the school of Advanced Studies of Illinois Institute 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, "Seismic Conditions Required to Cause Structural Failures in Tectonic Earthquakes," A Chapter in "Natural Hazards - New Insights," Edited by Mohammad Mokhtari, ISBN 978-1-80355-850-9, IntechOpen, 2022

Kohl, Martin. "Subsidence and Sinkholes in East Tennessee: A Field Guide to Holes in the Ground," State of Tennessee, Department of Environment & Conservation, Division of Geology, Public Information Series No. 1, 2001

Lambe, T. William and Whitman, Robert V., Soil Mechanics, John Wiley & Sons, New York, pp. 10, 1969

Parise, M.; Gunn, J., "Natural and Anthropogenic Hazards in Karst Areas: An Introduction". Geological Society, London, Special Publications, Vol.279, No. 1, pp. 1-3, 2007

Tchalenko, J. S., "The evolution of kink-bands and the development of compression textures in sheared clays", Tectonophysics, Volume 6, pp. 159-174, 1968

Waltham, T., "Sinkhole hazard case histories in karst terrains". Quarterly Journal of Engineering Geology and Hydrogeology. Vol. 41, No. 3, pp. 291-300, 2008

Waltham, Tony, Bell, Fred G., Culshaw, Martin G., Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction," Springer Praxis Books (Praxis), 2005

Wikipedia, "Sinkhole," Website: https://en.wikipedia.org/wiki/Sinkhole, the Free Encyclopedia, 2023.