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A NEW METHOD FOR DAM FAILURE POTENTIAL EVALUATION BASED ON SHEAR BAND DISPLACED LANDFORM FEATURES

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Abstract

Many countries in the world have adopted dam design and safety assessment methods that only focus on the effects of ground vibrations, which ignore shear banding effects and cannot always obtain results that meet actual needs. Therefore, current dam safety assessment results may indicate that a dam is safe, even when it can be severely damaged. In this study, seven types of shear-band displaced landform features that significantly affect dam failure potential are summarized by using the examples of the Shigang Dam in Taiwan, which was damaged in an earthquake, and the Banqiao Dam in China and the Malpasset Dam in France, which were both destroyed during rainy seasons. These features are used to evaluate the failure potential of the Feitsui Dam in Taiwan and the Three Gorges Dam in China. The results show that the Feitsui Dam has six different shear-band displaced landform features, while the Three Gorges Dam has only one. It is thus reasonable to speculate that the failure potential of the Feitsui Dam is much higher than that of the Three Gorges Dam. Based on the results of this research, it is suggested that future codes adopt this new method for dam failure potential evaluation to accurately guide dam design and evaluation procedures.

Keywords: tectonic earthquakes, shear banding, ground vibration, safety evaluation, failure potential evaluation.

Introduction

Most countries in the world build dams to meet the needs for people's lives, for economic development, and for tourism. Notably, China has built approximately 98,000 dams (Wang, 2017) and the United States approximately 91,000 dams (BBC News, 2017).

Although more than 200 dams failed from 2000 to 2009 in various countries (Wikipedia, 2021a), the failure rate was quite low. However, it is worth noting that when dams were on the verge of destruction, scholars and technicians were helpless and could only witness the ensuing destruction.

This dilemma stems from the fact that, in the past, scholars and technicians did not understand that there are five types of earthquake: tectonic earthquakes, volcanic earthquakes, subsidence earthquakes, earthquakes induced by reservoir storage, and earthquakes induced by artificial explosions (China Earthquake Disaster Prevention Center, 2017). Most earthquakes are tectonic earthquakes, and their main effect is shear banding, which accounts for more than 90% of the total earthquake energy. The secondary effect of tectonic earthquakes is ground vibration, which accounts for less than 10% of the total earthquake energy (Coffey, 2019).

Hsu (2018) pointed out the following results through simulation analysis of shear banding: (1) Under lateral compression, when the strain goes deep into the plastic range, the structure loses its ellipticity due to strain softening, and localizations of deformations occur, from which shear bands are derived (Figure 1, process 1). (2) When the ground water table is close to the ground surface, shear banding induces a high local concentration of excess pore water pressure (Figure 1, process 2a). (3) Within the shear bands, a stick-slip phenomenon is repeated due to frictional resistance (Figure 1, process 2b), which causes the tectonic plate to vibrate due to the repeated deceleration-acceleration phenomena (Figure 1, process 3).

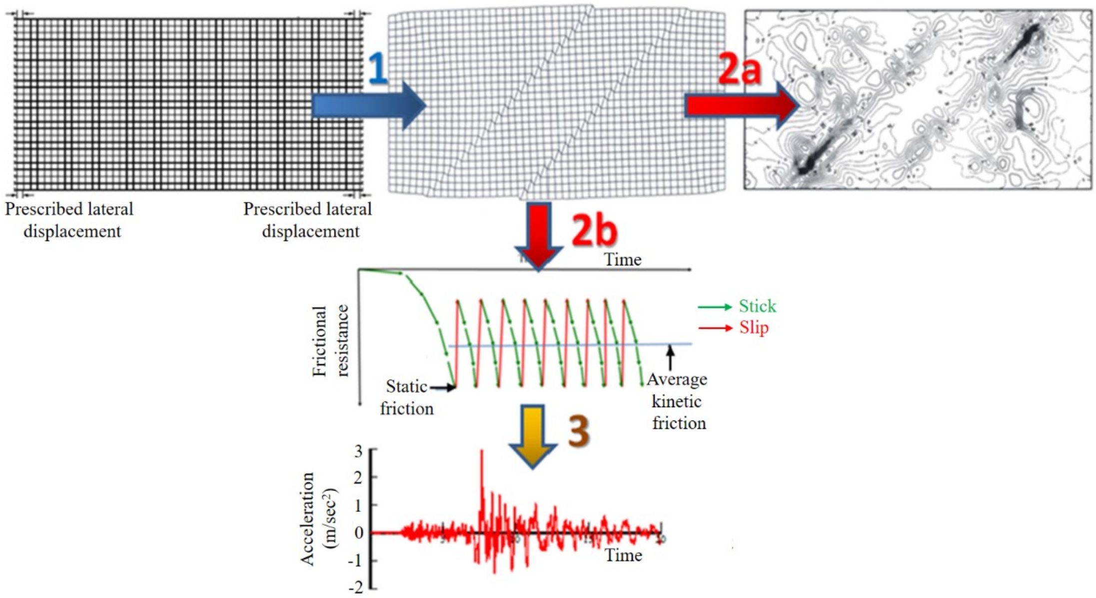


Figure 1. Tectonic plate-induced shear band formation process and ground vibration under lateral compression (Hsu, 2018).

Figure 1 clearly shows that the ground vibrations originate from shear banding. In the shear band, the site will have a local tilting effect, and a local tilted slope will appear (Figure 2).

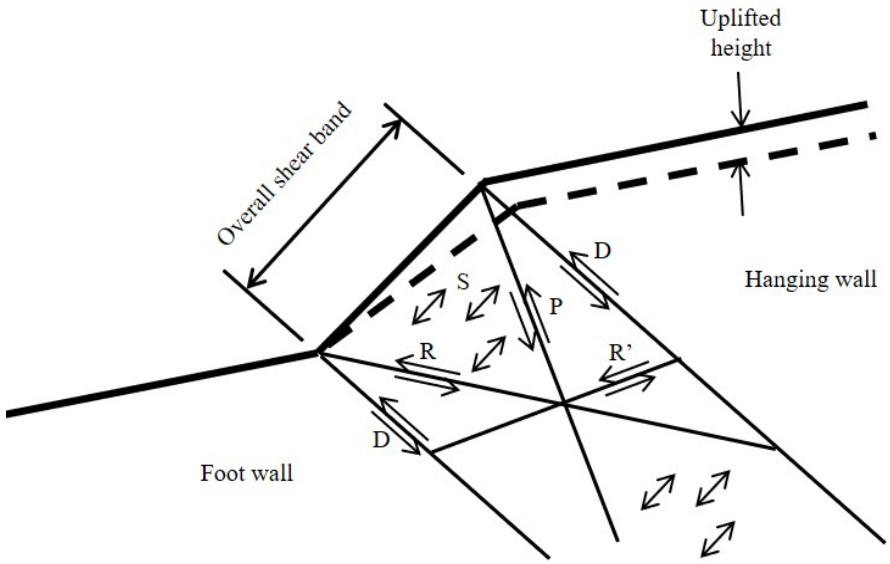


Figure 2. A shear-band tilted slope derived from a tectonic earthquake (Hsu et al., 2021).

Table 1 shows 18 previous tectonic earthquakes with the top death tolls globally (Wikipedia, 2021c). The highest death toll from a single tectonic earthquake was 830,000. The country with the highest level of ground vibration fortification is Japan, but Japan accounts for three of the top 18 deadliest tectonic earthquakes. Although the levels of vibration fortification in countries around the world have been increasing every year, the death tolls from tectonic earthquakes are still high.

Table 2 shows dam failure events during rainy seasons that caused more than 500 deaths in various countries around the world. The most serious incident occurred during the failure of the Banqiao Dam in China in 1975, causing 240,000 deaths and the displacement of 11 million people.

Table 1. The world's top 18 deadliest tectonic earthquakes (Wikipedia, 2021c).

Time	Location	M	Death
1556-01-23	China	$8.0M_w$	830,000
2004-2-26	Indonesia	$9.3M_w$	280,000
1976-07-28	China	$7.6M_w$	242,000
1920-12-16	China	$8.5M_w$	200,000
856-12-22	Iran	$7.9M_s$	200,000
1948-10-6	Turkmenistan	$7.3\ M_s$	160,000
1290-09-27	China	$6.8M_w$	100,000
1755-11-01	Portugal	$9.0M_w$	100,000
1923-09-21	Japan	$8.2M_L$	93,000
2008-05-12	China	$7.9M_w$	87,587
2005-10-08	Pakistan	$7.6M_w$	85,000
1908-12-28	Italy	$7.1M_w$	82,000
1667-11-25	Azerbaijan	$6.9M_s$	80,000
1721-4-26	Iran	$7.7M_s$	80,000
1970-05-31	Peru	$8.0M_L$	74,194
1693-01-11	Italy	$7.4M_w$	60,000
1949-09-20	Japan	$6.6M_w$	26,000
2011-03-11	Japan	$9.0M_w$	15,500

Table 2. Dam destruction events during rainy seasons that caused more than 500 fatalities in countries around the world (Wikipedia, 2021b).

Piping Failure of Dam	Year	Location, Country	Fatalities
Puentes Dam	1802	Lorca, Spain	608
Iruka Lake Dam	1868	Inuyama, Japan	941
South Fork Dam	1889	Johnstown, USA	2,209
Tigra Dam	1917	Gwalior, British India	1,000
St. Francis Dam	1928	Santa Clarita, USA	600
Möhne Dam	1943	Ruhr, Germany	1,579
Kurenivka Mudslide	1961	Kiev, Ukrainian SSR	1,500
Panshet Dam	1961	Pune, India	1,000
Vajont Dam	1963	Monte Toc, Italy	2,000
Sempor Dam	1967	Central Java Province, Indonesia	2,000
Banqiao Dam	1975	Zhumadian, China	240,000
Machchu-2 Dam	1979	Morbi, India	5,000

Since dam failures, either due to an earthquake or to heavy rain, are caused by shear banding (Hsu, 2018), the fact that current design and safety assessment specifications for dams only focus on the effects of ground vibrations may mislead safety assessment. In this paper, we first use the Shigang Dam (in Taiwan), which was damaged in an earthquake, and the Banqiao Dam (in China) and the Malpasset Dam (in France), which failed during rainy seasons, as examples to summarize the various shear-band displaced landform features that induced their failure. Such features are then used to evaluate the failure potential of two dams that have attracted worldwide attention: the Feitsui Dam (in Taiwan) and the Three Gorges Dam (in China).

The Shear-Band Displaced Landform Features For The Failed Dams

The Shigang Dam

1) The main reason for failure

In the past, safety assessments of the Shigang Dam were based on the technical specifications for inspection and safety assessment methods for water conservancy structures (Water Resources Agency, Ministry of Economic Affairs, 2003, 2008).

Although the amplitude of the ground vibration will disappear after a tectonic earthquake, the amount of shear banding will continue to accumulate with each earthquake occurrence. Therefore, when methods and codes only fortify against ground vibrations, the adopted geology, geological structure, designed earthquake scale, acceleration duration curve, dam material strength, and structural analysis model are all assumed to be the same in safety assessments conducted every five years. The riverbed is also assumed to be continuous, rigid, and steady (Figure 3), and the groundwater flow at the bottom of the dam is assumed to have steady-state seepage. Because the structural analysis model only contains the dam body, the bottom end of the dam adjacent to the riverbed is assumed to be fixed. Since there is no relative displacement and no relative rotation between each two fixed ends, stress distribution diagrams of the dam body obtained from previous vibration response analyses are the same, and the conclusions obtained from the safety assessments determine that the dam body is safe.

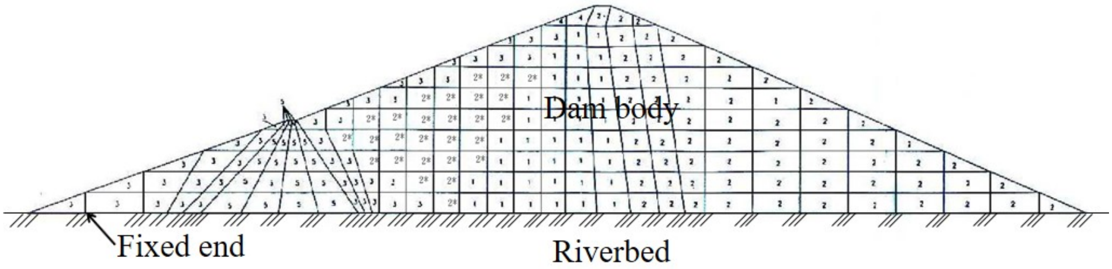


Figure 3. Schematic diagram of a dam structure analysis model, where the riverbed is assumed to be continuous, rigid, and steady-state.

In reality, the riverbed where the dam is located has deep grooves in the shear bands with brittle fractures (Figure 4), the amount of which increases year after year. Therefore, every analysis condition used in the safety assessments of the dam body carried out cannot be the same every five years. The shear-band riverbed with discontinuous, brittle, and unsteady conditions will also extend towards the dam body, thus weakening it and inducing damage (Figure 5). The groundwater flowing through the shear-band riverbed at the bottom of the dam is actually an unsteady pipe flow, which will induce piping failure.

Figure 4. The Shigang Dam, constructed on a riverbed with deep troughs and discontinuous, brittle, and unsteady shear bands (Google Earth, 2021).

Figure 5. The 921 Earthquake; the shear band extending obliquely upward from the riverbed into the dam body induced the failure of the Shigang Dam.

When the upward tilted shear band (Figure 5) or the horizontal displaced shear band (Figure 6) extends into the dam body, it will undergo shear-band fracture damage. Therefore, local fracture damage in the dam body is caused by shear banding derived from localizations of deformations, rather than by ground vibration.

Figure 6. The 921 Earthquake; the horizontal shear banding of the riverbed extended into the dam body and induced damage to the Shigang Dam.

2) Dam design and safety assessment cannot only focus on ground vibrations

When selecting the site for the Shigang Dam, it was announced by the government to be located in a weak vibration zone, and that the horizontal seismic coefficient (k_h) in weak vibration zones is 0.1. In the design of the Shigang Dam, based on code regulations, the selected k_h was increased by 50% and the vertical seismic coefficient (k_v) was half of k_h; in other words, the k_h used in the design of the Shigang Dam was 0.15 and the k_v was 0.075 (Liming Engineering Consulting Co., Ltd., 2012). In addition, the design fault selected for the Shigang Dam was the Sanyi Fault and the least distance (r_{rup}) between them was 4.5 km (Figure 7).

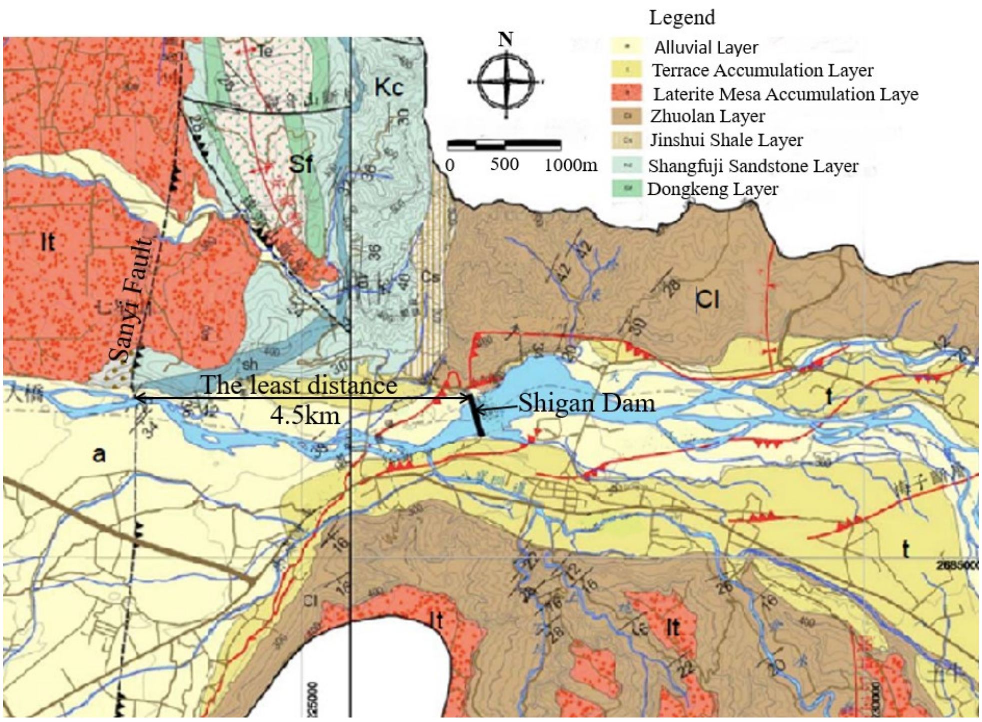


Figure 7. The least distance between the Shigang Dam and the Sanyi Fault (redrawn from Liming Engineering Consulting Co., Ltd., 2018).

Before the 921 Earthquake, the Shigang Dam had a safety assessment conducted every five years. Since it endured no earthquakes with large amplitudes after its completion, the safety assessments generally followed the conditions used in the design. Therefore, the safety assessment results over the years were generally the same, and the conclusions reached agreed that the dam body was safe.

However, in the 921 Earthquake, the Chelongpu Fault passed directly through the Shigang Dam (Figure 8), and the dam body was locally fractured and destroyed (Figures 5 and 6). This is sufficient to prove that the active fault and weak vibration areas announced by the government are inconsistent with reality, and seriously misled the design of the Shigang Dam.

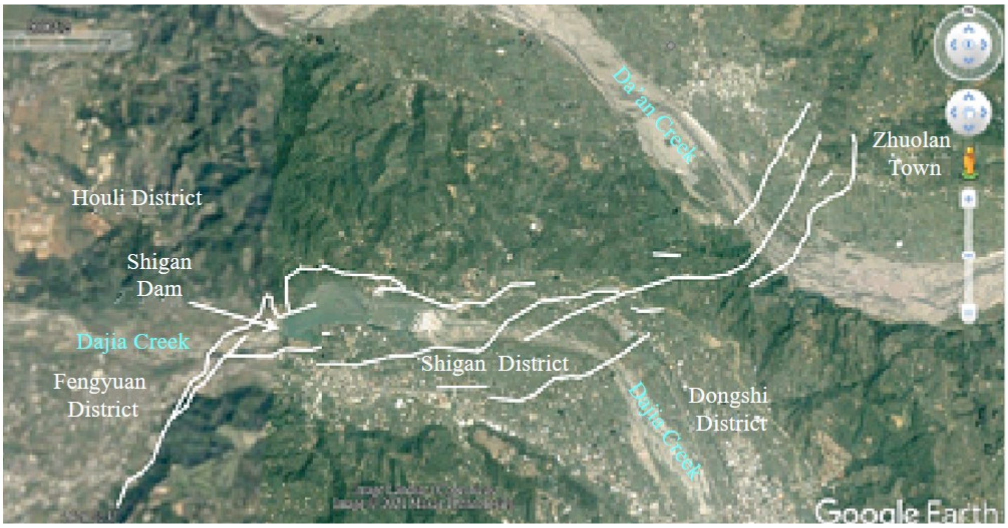


Figure 8. The Chelongpu Fault, which passes directly through the Shigang Dam (background image is from Google Earth, 2021).

Because the Chelongpu Fault clearly passed through the Shigang Dam and caused the fracture damage to the dam body, the design fault changed from the Sanyi Fault to the Chelongpu Fault. The least distance between the Shigang Dam and the design fault (r_{rup}) also changed from 4.5 km to 0.0 km, and the peak ground acceleration (PGA) calculated by the attenuation formula changed from 0.5 g to infinity.

However, after the 921 Earthquake, the seismic design code still only fortified against ground vibrations, and in the design of the Shigang Dam emergency restoration project, the selected values for the horizontal PGA and k_h were not infinite. According to the fourth safety assessment report (Liming Engineering Consulting Co., Ltd., 2018), the main basis for the safety assessments of the Shigang Dam after the 921 Earthquake was still the revised 2008 Technical Specification for Inspection and Safety Assessment of Water Conservancy Construction: Water Storage and Diversion Construction (Water Resources Agency, Ministry of Economic Affairs, 2008) which stipulates deterministic and probabilistic seismic hazard analyses as the methods for PGA determination. The estimated PGA under the maximum possible earthquake is thus 0.81 g, and the PGA under the design basis earthquake is 0.65 g.

3) Shear-band displaced landform features

Since the main cause of dam failure is shear banding, the following section summarizes various shear-band displaced landform features that can be used to assess dam failure potential.

Figure 9 shows that the maximum width of the riverbed sections upstream and downstream of the Shigang Dam are 755 m and 240 m, respectively. It is clear that the width of the downstream riverbed section is necked to 32% of that of the upstream riverbed. Since the degree of necking of the riverbed section downstream of the dam is a shear-band displaced landform feature, it can be used as an index for the evaluation of the dam failure potential.

Figure 9. The Shigang Dam is located at the necking position of lateral plate compression (background image is from Google Earth, 2021).

Figure 10 shows high-density triangular facets on the upper and lower slopes adjacent to the right bank of the Shigang Dam. Since triangular facets are a shear-band displaced landform feature, the density of the triangular facets on the slopes upstream of the dam can be used as an index for the evaluation of the dam failure potential.

The dam axis extension of the Shigang Dam is connected to the right bank ridge (Figure 10), where the thickness of the ridge decreases substantially. Since the change of ridge thickness is another shear-band displaced landform feature, it can also be used as an index for the evaluation of the dam failure potential.

Figure 10. High-density triangular facets on the right bank slope upstream of the Shigang Dam (Google Earth, 2021).

Figure 11 shows that the river upstream and downstream of the Shigang Dam has a high degree of meandering, which is also a shear-band displaced landform feature, so it can be used as an index for the evaluation of the dam failure potential.

In addition, Figure 12 shows that the Shigang Dam is located in an S-shaped bend of the river, which is another shear-band displaced landform feature that can be used as an index for the evaluation of the dam failure potential.

Figure 11. The meandering appearance of the river upstream and downstream of the Shigang Dam (Google Earth, 2021).

Figure 12. The Shigang Dam is located in an S-shaped bend of the river, and the ridgeline of the adjacent mountains is undulating and winding (Google Earth, 2021).

Finally, Figure 13 shows that there is a shear band on the slope next to the upper right bank of the Shigang Dam, and there are five different strike shear textures within the total width of the shear band. Since the displacement of the shear band and the shear texture increase the degree of brittle fracturing in the rock slope, the existence of shear bands and shear textures can be used as an index for the evaluation of the dam failure potential.

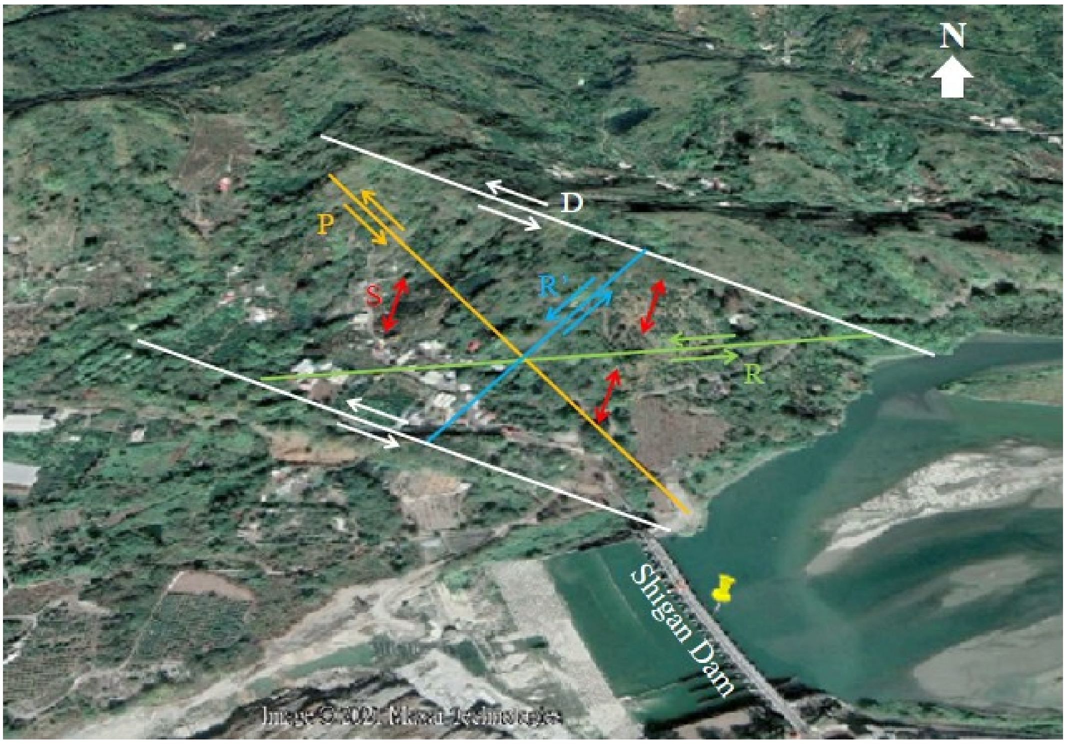


Figure 13. Shear band and shear textures on the right bank slope upstream of the Shigang Dam (background image is from Google Earth, 2021).

The Banqiao Dam

1) Dam body failure and cause

The Banqiao Dam is located 37 km west of Zhumadian City, Henan Province, China. Since the dam is located at the junction of the North China Block and the Yangtze Block, it is affected by the displacement of both blocks. The Banqiao Dam was destroyed on August 8, 1975 during Typhoon Nina (Figure 14). After that, 61 dams downstream continued to fail. The flood inundated 17.8 million acres of farmland in 30 cities, resulting in the collapse of 6.8 million houses, the death of 240,000 people, and the loss of 11 million homes. This is the worst dam breach in the world.

Figure 14. Destruction of the Banqiao Dam (Wikipedia, 2021a).

After the Banqiao Dam was destroyed, the causes of damage recorded in related documents emphasize water storage, flood control negligence, poor material quality, and cutting corners. However, some dams in other river basins built during the same period did not break, although the design specifications, technical level, and construction methods and materials were similar. Therefore, the above survey results may not reflect the main reason for the destruction of the Banqiao Dam.

2) The shear-band displaced landform features

Figures 15a and 15b show that the widths of the riverbed sections of the upper and lower reaches of the Banqiao Dam are 7740 m and 500 m, respectively. The width of the downstream riverbed section thus necks down to 6.5% of the upstream riverbed section width. Since the degree of necking of the riverbed section downstream of the dam is a shear-band displaced landform feature, it can be used as an index for the evaluation of the dam failure potential.

(a) Width of the riverbed upstream of the dam.

(b) Width of the riverbed downstream of the dam.

Figure 15. The Banqiao Dam, located at the necked position of lateral compression of the tectonic plate (background image is from Google Earth, 2021).

Figure 16 shows high-density triangular facets on the slopes of the right bank of the upper and lower reaches of the Banqiao Dam. Triangular facet density is another shear-band displaced landform feature, so it can also be used as an index for the evaluation of the dam failure potential.

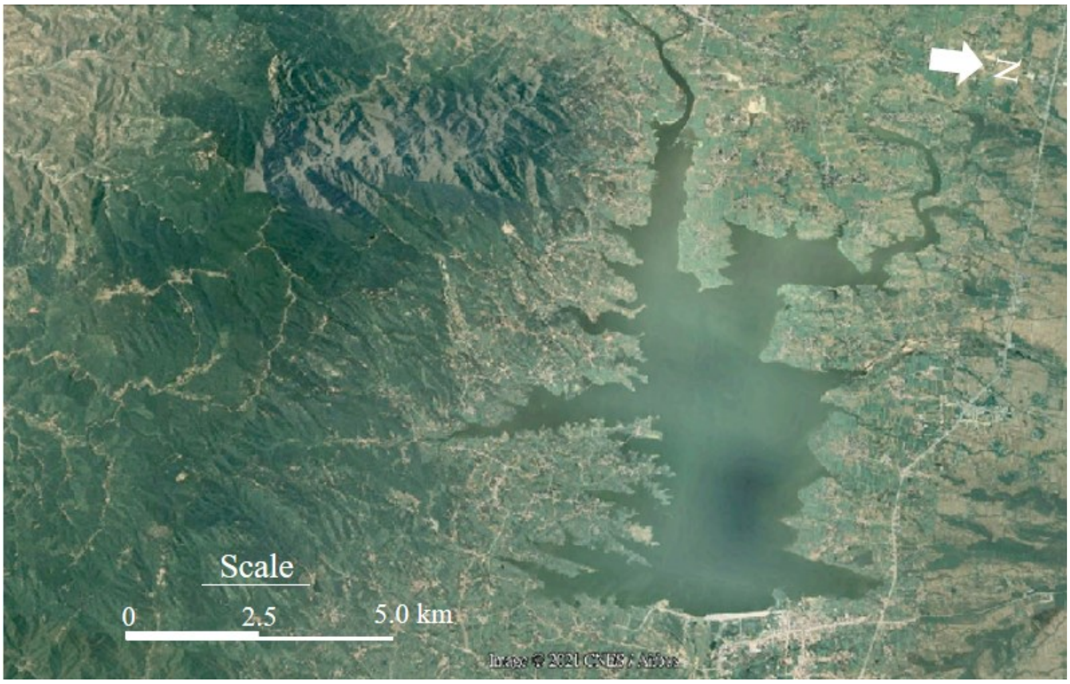


Figure 16. Triangular facets on the upstream and downstream slopes of the Banqiao Dam (Google Earth, 2021).

Figures 16 and 17 show that the river meanders significantly upstream and downstream of the Banqiao Dam, respectively. Since this is a shear-band displaced landform feature, it can also be used as an index for the evaluation of the dam failure potential.

Lastly, Figure 18 shows that a shear band and five different shear textures exist in the reservoir area and on the slopes of the left and right banks of the upper and lower reaches of the Banqiao Dam. Shear bands and shear textures are shear-band displaced landform features, so they are indices for the evaluation of the dam failure potential.

Figure 17. The appearance of the river meander downstream of the Banqiao Dam (Google Earth, 2021).

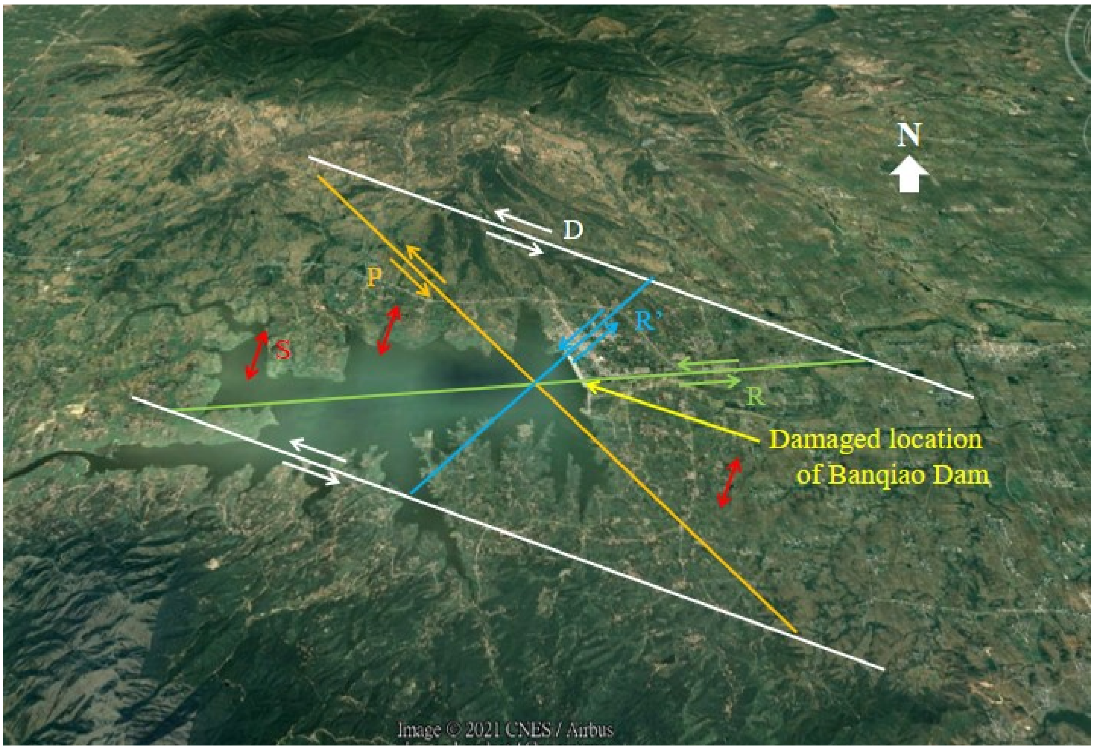


Figure 18. The shear band and shear textures in the reservoir area and on the left and right banks of the upper and lower reaches of the Banqiao Dam (background image is from Google Earth, 2021).

The Malpasset Dam

1) The process of dam failure

The Malpasset Dam was a concrete arch dam located on the Riviera in Southern France. Because the left abutment of the dam was higher, a large dihedral thrust block was placed below the dam to raise it to the necessary height. When the first dam filling was nearly complete (Figure 19), the Malpasset Dam failed (on December 2, 1959) after the area experienced heavy rain. Geological investigations that took place after the failure of the dam revealed that it had been built on a gneiss formation. In addition, a fault was discovered immediately downstream of the dam. Failure of the left abutment led to the ultimate failure of the dam as cracks propagated across the dam face (Association of State Dam Safety Officials, 1984).

2) The main reason for the dam failure

Since the design of a concrete arch dam uses the arch mechanism to spread the large water pressure to both banks of the valley, the conditions suitable for construction are only favorable when the rocks on both sides of the canyon are hard. Figure 20a shows that the left abutment of the Malpasset Dam is located in a geologically unstable landslide zone, and Figure 20b shows that there are shear bands and shear textures that pass through this landslide zone. Figure 20c shows a tilted four-step shear band slope on the left bank supporting the left dam abutment.

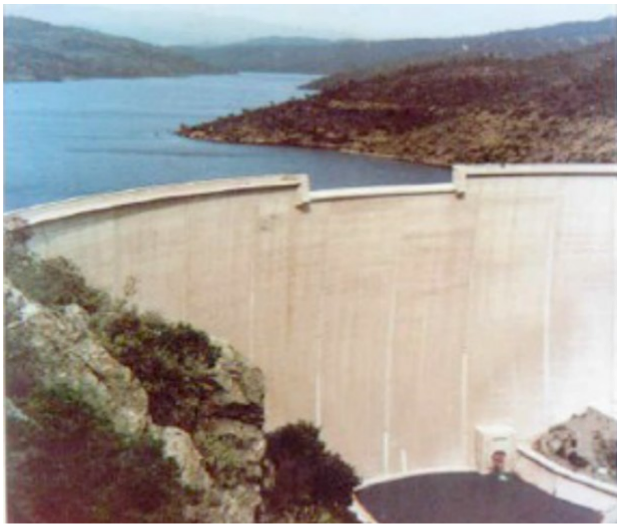
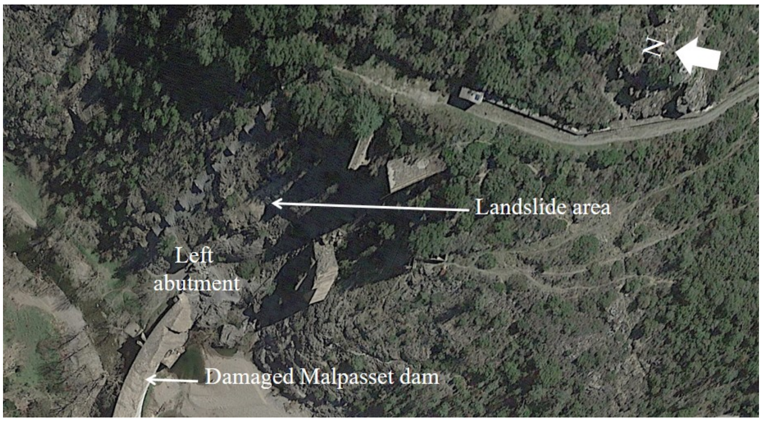
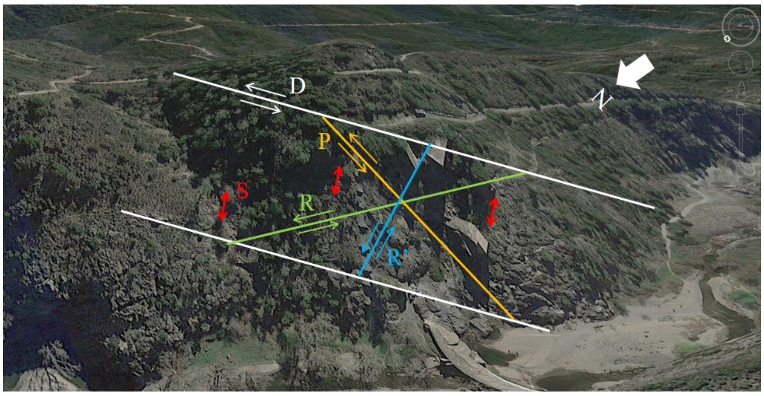


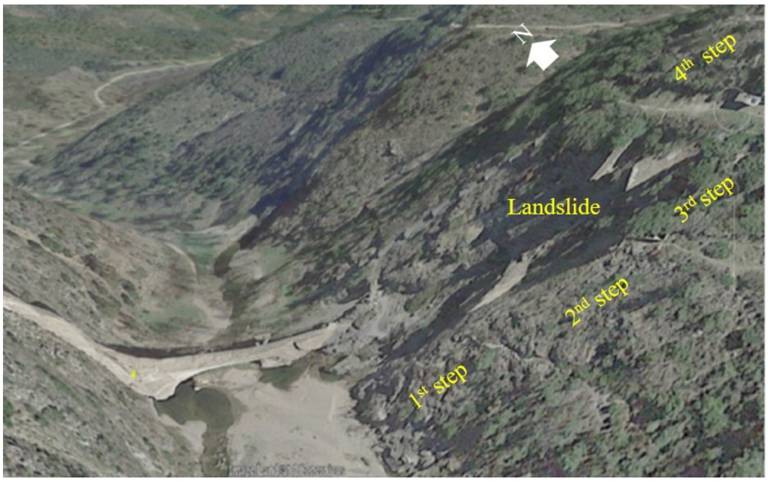
Figure 19. The Malpasset Dam prior to failure
(Association of State Dam Safety Officials, 1984).



(a) Left dam abutment located in the landslide zone.



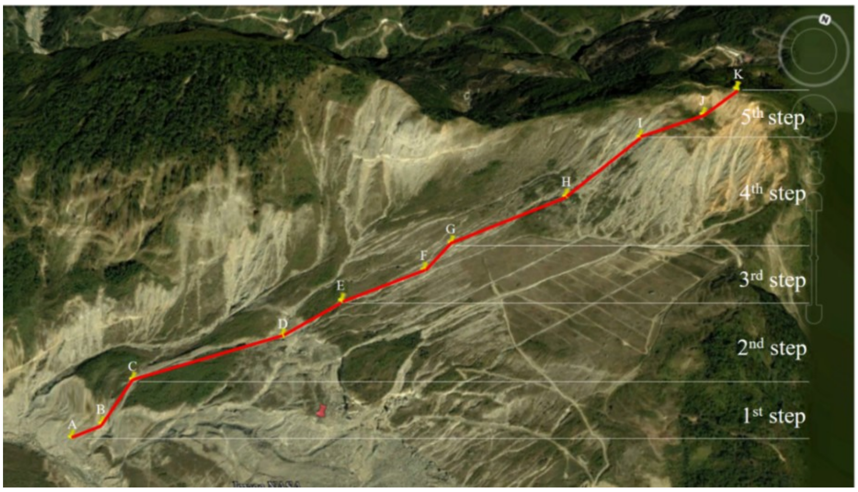
(b) Shear band and shear textures passing through the landslide zone.



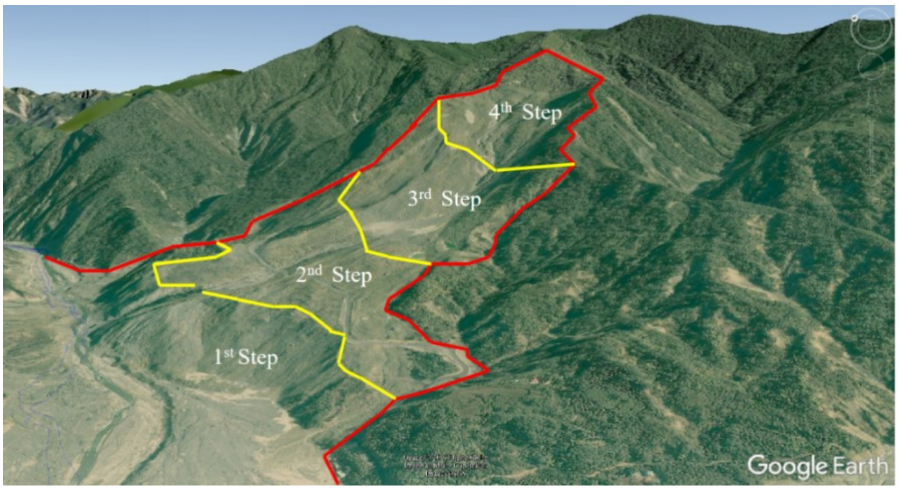
(c) Tilted four-step shear band slope.

Figure 20. The left bank slope supporting the left abutment of the Malpasset Dam (background image is from Google Earth, 2021).

Hsu et al. (2021) demonstrated that when there are tilted shear band slopes with multiple steps on the river bank, the slope will induce delamination and sliding failure under strain softening and shear band tilting effects. They cited two examples from Taiwan (Figure 21).The Malpasset Dam canyon wall is therefore unsound and unstable. Because a tilted slope is a shear-band displaced landform feature, it can be used as an index for the evaluation of the dam failure potential.



(a) Caoling landslide (921 Earthquake in 1999; Hsu, et al., 2021).



(b) Landslide of Siaolin village (Typhoon Morakot in 2009).

Figure 21. Large-scale landslides that happened on tilted multi-step shear band slopes in Taiwan (background image is from Google Earth, 2021).

Evaluation Of Dam Failure Potential

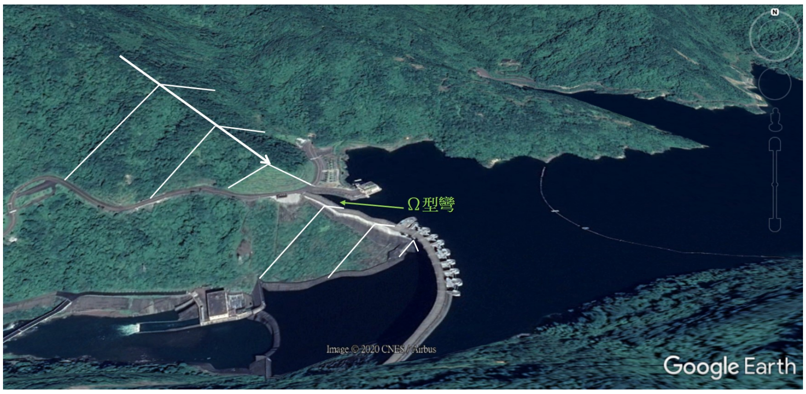
Evaluation of the failure potential of the Feitsui Dam, Taiwan

Figure 22 shows that the upstream riverbed section width of the Feitsui Dam is 550 m while the downstream riverbed section width is 145 m, which is therefore necked to 26.4% of the width of the upstream section.

Figure 22 Necking of the riverbed downstream of the Feitsui Dam (background image is from Lee, 2010).

Figure 23a shows high-density triangular facets in the mountains on the right side of the Feitsui Dam. There are also high-density triangular facets on the right bank (Figure 23b) and the left bank (Figure 23c) of a line extended along the dam axis.

(a) Mountains to the right of the dam.



(b) Right bank of the dam axis extension.

(c) Left bank of the dam axis extension.

Figure 23. The Feitsui Dam and the triangular facets on the left and right banks of the dam axis extension (background images are from Google Earth, 2021).

Figure 24 shows that the river upstream of the Feitsui Dam has a high degree of meandering, and the river downstream has a moderate degree of meandering.

Note: The white arrow indicates the location of the body of the Feitsui Dam.

Figure 24. The meandering river system upstream and downstream of the Feitsui Dam (background image is from Google Earth, 2021).

Figure 25 shows shear bands and textures in the reservoir area, on both banks, and upstream and downstream of the Feitsui Dam.

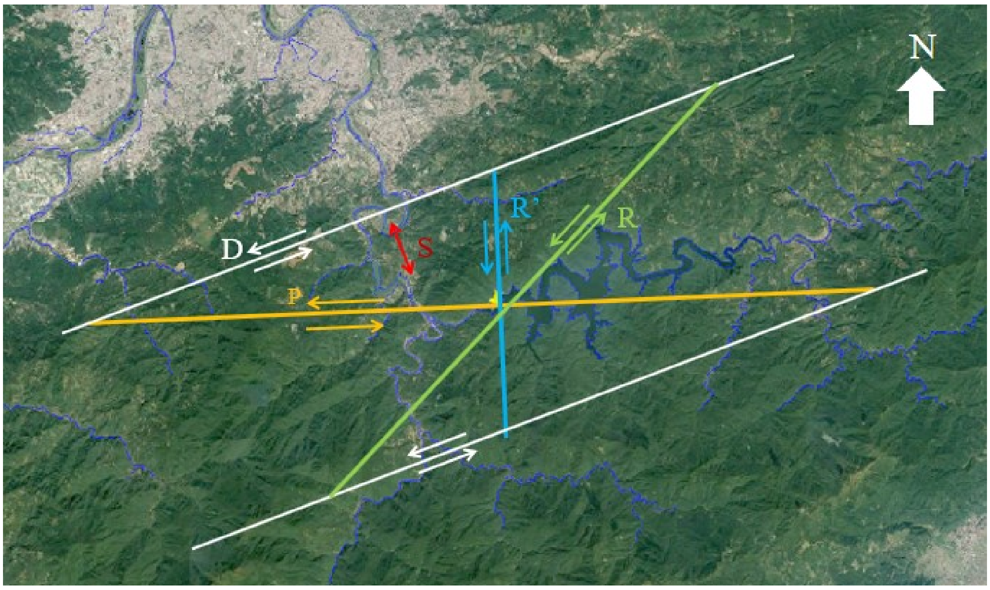


Figure 25. Shear bands and shear textures in the reservoir area, on both banks, and upstream and downstream of the Feitsui Dam (background image from Google Earth, 2021).

Figure 26 shows a tilted four-step shear band slope on the right bank immediately upstream of the Feitsui Dam.

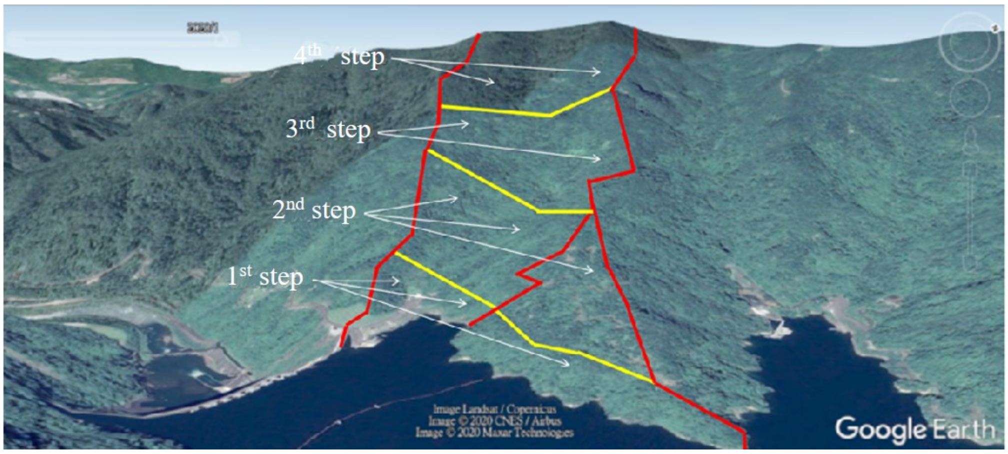


Figure 26. A tilted four-step shear band slope on the right bank upstream of the Feitsui Dam (background image is from Google Earth, 2021).

Evaluation of the failure potential of the Three Gorges Dam, China

Figure 27 shows that the Three Gorges Dam is a concrete gravity dam with a length of 2335 m, a top width of 40 m, and a bottom width of 115 m. It is currently the largest dam in the world (Wikipedia, 2021d).

Figure 27. The Three Gorges Dam and its adjacent areas (Google Earth, 2021).

Figure 28 shows the upstream and downstream sections of the Three Gorges Dam in 1986, before its construction. The width of the upstream and downstream sections of the Three Gorges Dam are nearly the same, so there is no necking of the riverbed.

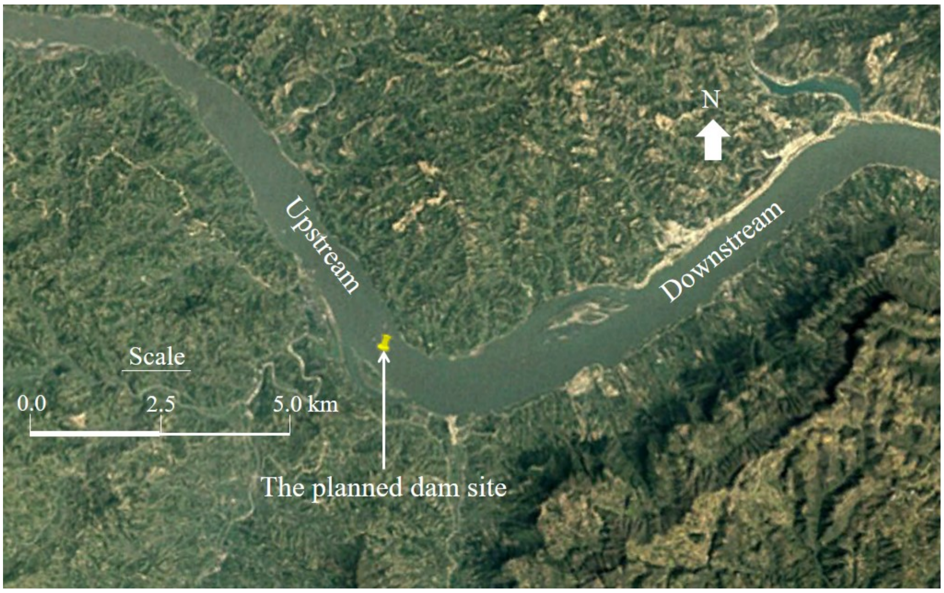


Figure 28. The upstream and downstream river sections of the Three Gorges Dam before its construction (Google Earth, 1986).

Figure 29 shows that the river upstream of the Three Gorges Dam has a low degree of meandering, and the river downstream has a moderate degree of meandering.

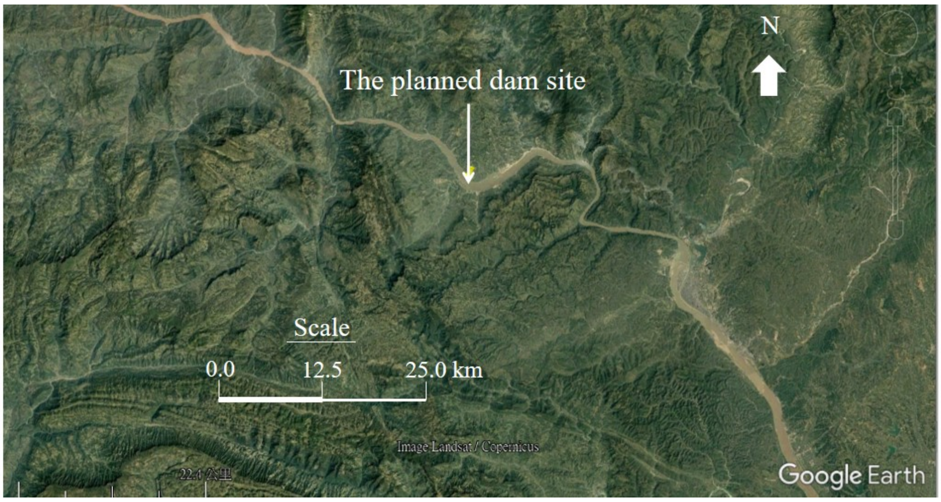


Figure 29. The meandering river upstream and downstream of the Three Gorges Dam (Google Earth, 1986).

Figure 30 shows the shear bands and shear textures that exist downstream of the Three Gorges Dam. These shear bands and textures are distant from the dam abutment, so they do not affect the safety of the dam.

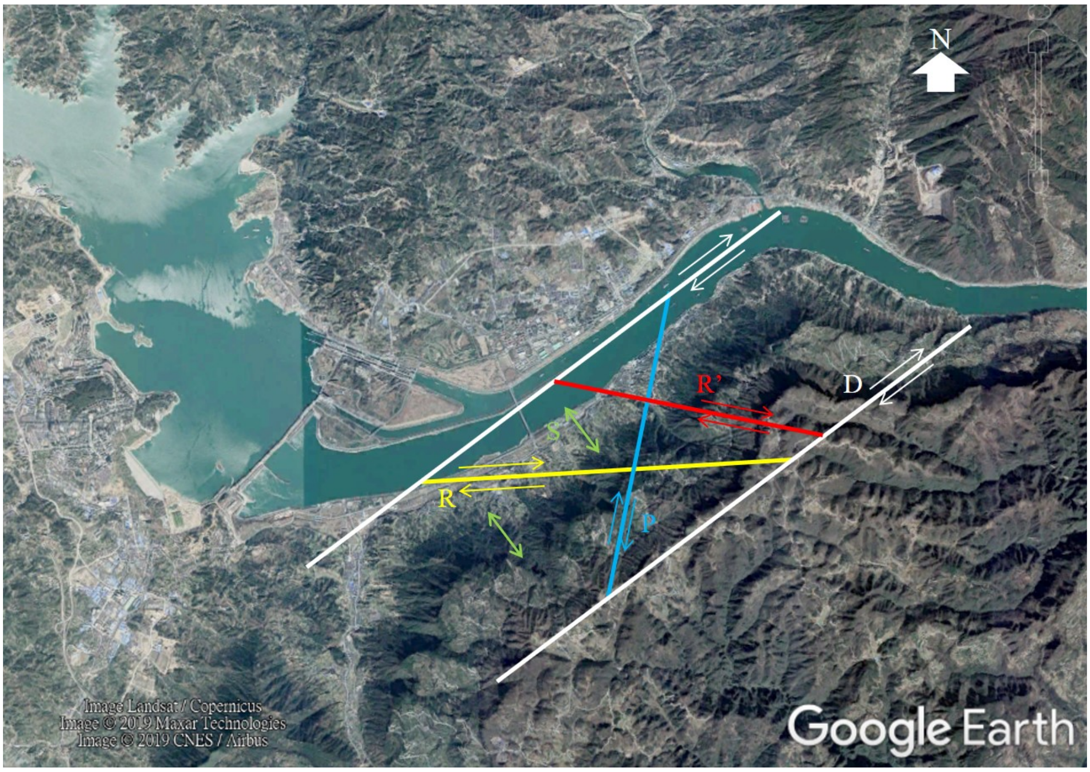


Figure 30. Shear bands and shear textures downstream of the Three Gorges Dam (background image is from Google Earth, 2021).

Figures 28 and 30 both show that a tilted multi-step shear band slope exists downstream of the Three Gorges Dam. However, this type of slope does not affect the safety of the dam.

Comparison Of Failure Potential Of Feitsui And Three Gorges Dams

Table 3 compares the shear-band displaced landform features of the Feitsui Dam and Three Gorges Dam. The Feitsui Dam has six features that significantly affect the failure potential of the dam: (1) The downstream river-bed section has a large degree of necking; (2) There are high-density triangular facets on the right bank; (3) The ridges on the left and right banks are connected to the dam axis, and the thickness of the ridge changes greatly; (4) The upstream river course meanders significantly; (5) Shear bands and shear textures simultaneously exist on both upstream and downstream river banks; (6) There is a tilted multi-step shear band slope upstream of the river bank that is used to support the dam abutment. The Three Gorges Dam, on the other hand, only has one shear-band displaced landform feature that significantly affects the failure potential of the dam: the dam is located in an S-shaped bend. Therefore, it can be reasonably concluded that the Feitsui Dam has much greater potential for damage than the Three Gorges Dam.

Table 3. Comparison of the different shear-band displaced landform fractures of Feitsui Dam and Three Gorges Dam.

Shear-band displaced landform features	Feitsui Dam	Three Gorges Dam
The degree of necking of the downstream riverbed section	The section width of the downstream river course necks to 26.4% of that of the upstream	No necking
The location and density of triangular facets	Right bank, high density; Left bank, medium density	Downstream of the right bank, medium density
The location and thickness of the ridge connected to the dam axis	Both the left and right banks have changed significantly	Not exist
The degree of meandering of the river	Upstream, high Downstream, moderate	Upstream, low Downstream, moderate
Whether the dam is located in an S-shaped curve	No	Yes
The location of the shear band and shear textures	Reservoir area, both banks, upstream and downstream	Right bank, downstream
The location of the multi-step shear-band tilting slope	Close to the dam abutment, upstream	Away from the dam abutment. downstream

Conclusions And Suggestions

Although the design and safety assessments of dams must follow the specifications announced by government, the current specifications only fortify against ground vibrations. Whether in the original design or in the safety assessments conducted every five years after dam construction, most of the conditions and data used remain similar, the assessment results obtained tend to be consistent, and the conclusions are that the dams are safe.

However, dams that have been continuously evaluated as safe can be vulnerable to earthquakes or heavy rains. For this reason, we investigated the examples of the failed Shigang Dam, Banqiao Dam, and Malpasset Dam. The main cause of dam damage was shown to be shear banding, and various features that have a significant influence on the failure potential of dams were summarized. These features were then used to assess the failure potential of the Feitsui Dam in Taiwan and the Three Gorges Dam in China. The four most important conclusions are summarized below:

1) Traditional design codes are all based on ground vibrations, and the addressed design and safety assessment methods cannot ensure the safety of the dam when subjected to shear banding.

2) In the dam body ground vibration response analysis, the end points of the structure analysis model adjacent to the riverbed are all set as fixed ends. In other words, the riverbed is assumed to be continuous, rigid, and steady. However, where there are local deep grooves in the shear bands, the riverbed is actually discontinuous, brittle, and unsteady.

3) The summarized shear-band displaced landform features required for evaluation of dam failure potential are as follows: the degree of necking of the downstream river course section, the location and density of triangular facets, the location and thickness of the ridge connected to the dam axis, the degree of meandering of the river, whether or not the dam is located in an S-shaped curve, the location of shear bands and shear textures, and the location of tilted multi-step shear band slopes.

4) Based on the various types of shear-band displaced landform features, the failure potential of the Feitsui Dam and the Three Gorges Dam were evaluated, and the results are summarized below.

(1) Six shear-band displaced landform features significantly affect the failure potential of the Feitsui Dam: a high degree of necking of the downstream river course section, a high density of triangular facets on the river bank slope, the existence and thinning of ridges connected to both ends of the dam axis, the extent to which upstream rivers meander; the existence of shear bands and shear textures in the reservoir area and the upper and lower river banks; and the existent of the multi-step shear band tilting slope immediately upstream of the dam abutment on the right bank. Therefore, the failure potential of the Feitsui Dam is very high.

(2) The only shear-band displaced landform feature that significantly affects the failure potential of the Three Gorges Dam is that the dam is located in an S-shaped curve, so the failure potential of the Three Gorges Dam is low.

Since the amount of shear banding continues to increase with the occurrence of tectonic earthquakes, once shear-band displaced landform features that significantly affect the failure potential of the dam are initiated, their amount will increase annually. Therefore, the data and conditions cannot be the same for the dam safety assessments every five years, and the assessment results cannot continuously be regarded as safe. Therefore, we recommend that the governments of various countries prioritize shear banding effects when revising codes, and replace the existing dam safety assessment methods with the dam failure potential assessment method proposed in this paper. In this way, the stability and safety conditions of dams can be ensured.

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