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Failures Associated with the 2004 Mindulle Typhoon in Taiwan

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Abstract On July 2, 2004, a 2000-km southwest air current following the Mindulle Typhoon caused serious damages to infrastructures in Taiwan. The disaster resulted in extensive geological and structural failures, mainly as a result of debris flow. Some of the sites were subjected to types of repeated failures compared to previous typhoons. Some structural failures were attributed to geotechnical failures. It is decided to document and identify causes for some of these major failures triggered by typhoons. The case history showed significant implications to future disaster prevention and management works. New challenges were posed in geotechnical engineering design in encountering rainfall-induced failures.

Keywords Case history · Debris flow · Geological failure · Structural failure · The Mindulle Typhoon

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1 Introduction

Taiwan is located in the west Pacific Ocean facing frequent attacking of typhoons. Besides, this small island is in the Cenozoic era with over 50 identified faults, and orogenesis is still working. These geological conditions coupled with land use schemes rendered Taiwan an area having very high risk of different types of disasters, such as earthquakes, flooding, debris flow (mud flow), etc. In recent years, both the abundant precipitation and unstable geological conditions led Taiwan to suffer from geotechnical hazards. In particular, debris flow has become the worst type of disaster in Taiwan that resulted in the most deaths, injuries, and property losses (Table 1). Typically, debris flows were induced by heavy rainfall in the season of typhoon (Table 2). According to the investigation by the Soil and Water Conservation Bureau (SWCB), which is the Agency in charge of the geological disasters, such as landslides and debris flow, there have been 1,420 potential debris flow areas after the Toraji Typhoon of 2001. Periodically, after typhoons and downpours, piles of gravels and boulders were carried and deposited by water that posed serious threats.

Mindulle Typhoon of 2004 led to one of the major disasters. It resulted in great loss of life and properties, and serious damages to the various infrastructures and public facilities. After the event, several research teams conducted reconnaissance and

Table 1 Property and life losses resulting from major Typhoons in Taiwan (1985–2004)

Year	Typhoons	Property	Life		Buildings	
		Economic losses (US$ Millions)[a]	Death/Missing (persons)	Injuries (persons)	Collapsed (households)	Semi-collapsed (households)
1985.09	Nelson	20.65	10	24	11	12
1986.08	Wayne	376.59	87	422	6624	31532
1989.1	Sarah	186.79	52	47	430	760
1990.06	Ofelia	53.68	38	10	88	139
1990.09	Dot	40.94	10	4	47	71
1991.09	Nat	10.87	7	11	29	52
1994.08	Tim	193.60	23	70	181	180
1996.08-09	Herb	1476.34	73	463	503	880
1998.1	Zeb	324.72	38	27	4	26
2000.08	Bilis	252.76	21	112	434	1725
2000.1	Xangsane	177.78	89	65	N/A	N/A
2001.07	Toraji	503.95	214	188	645	1972
2001.09	Nari	176.41	104	265	N/A	N/A
2004.07	Mindulle	240.69	4	4	270	0
2004.08	Aere	54.92	29	395	72	44
2004.12	Nanmadol	27.82	4	1	N/A	N/A
Total		4097.87	793	2084	9327	37381

[a] Includes losses of crop, livestock, fishery, forestry, and related losses of cultivated land, fishery facility, forestry facility, and soil and Water conservation, railway system, highway system and harbors, not including the losses of physical infrastructures, such as roads and bridges

Source: National Fire Administration

Table 2 Typhoons, from 1985 to 2004, with records of debris flow disasters in Taiwan

Year	Name	The locations and conditions of debris flows
1985.09	Nelson	Debris flow disasters in Fengchiu, Nantou.
1986.08	Wayne	Debris flow disasters in Singyi, Nantou.
1989.10	Sarah	Debris flow in Ruisui, Yuli and Fenglin River in Hualien.
1990.06	Ofelia	Debris flow disasters in Tongmen, Chingfeng and Yuli, Hualien (The typhoon brought in 430 mm rainfall, with the maximum 106 mm/h rainfall intensity. The main causes for incurring debris flow included torrential rains, geological factors and man-made occupation of outlets of river valleys, etc. 29 deaths and 6 missing).
1990.09	Dot	Debris flow disasters in Hualien (All 10 neighboring residences were washed away in Hongye; bank breached near Fahuashan Temple upstream Chichiachuan River of Chi-an River, resulting in mountain torrent directly rushing into Taichang, four deaths).
1991.09	Nat	Debris flow disasters in Longchiao and Taimali, Taitung County (over 10 vehicles were rushed into the Pacific Ocean with debris flow, causing dozens of deaths), Sinfeng, Bachi and Lide, Hualien (debris fell into residences brought about disasters).
1994.08	Tim	Debris flow occurred around Fahua Mountain, Chi-an; In Sinshe, one residence was drowned by debris, 14 ones were all destroyed, and 3.05 ha farmland was lost; the banks north of Gaoliao, Hedong, and Yuli breached due to flash rise in Siouguluan River, with sand clays rushing to residential houses, bringing 10 collapsed and 40 partially collapsed.

Table 2 continued

Year	Name	The locations and conditions of debris flows
1996.08-09	Herb	Debris flow disasters in Singyi Town (Fengchiu, Chunkeng, Shenmu Village and Tongfu) alongside Chenyoulan River in Nantou, Majia Reservoir Watershed in Pingdong County and A'li Mountain in Chiayi County. According to the statistics from A'li Mountain Rain Gage Station, the rainfall accumulation reached as high as 1994 mm. Heavy rainfall with many causes, including geological factors, man-made occupation of outlets of river valleys, too small bridge culverts, improper land use, finally combined to bring in the catastrophic conditions with 27 deaths and 14 missing.
1998.10	Zeb	Mudflow in Lane 47, Sect. 1, Neihu Road, Taipei City buried two residences, and 5 residents were buried alive at No. 24 and No. 24-2. Debris flow disasters in Fengyikeng, Fenglin, Chianching, Wanrong, Sinshe, Fengbing and Shoufengchi in Hualien: while it came to the debris flow formed upstream Fengming Bridge, Fengyikeng, Fenglin, Hualien, the area of alluvial fan accumulated approximately 160,000 m^3 of debris. Downstream in Fengyili, there were five residences buried or semi-buried by debris; eight in Chianching, Wanrong, six in Sinshe, Fengbing, Dongxing, Sinshe, Fengbing, four in Chinan, Shoufeng and Fengtian.
2000.08	Bilis	Debris flow disasters in A'lishan Town, Chiayi County. Debris flow disasters in Yuli and Fengli, Hualien. Typhoon brought about heavy rainfalls. The catastrophic conditions of debris flow were also sent out of Yuli Area. Serious debris breakdown occurred at Ruigang Road, resulting in full-line interruption and totally six injuries and more than 200 buildings collapsed; three residences in Darong and Fengxinli, Fenglin were half destroyed.
2001.07	Toraji	Debris flow disasters in Nantou, Hualien and other places. Toraji Typhoon stayed in Taiwan for ten hours, bringing about excessive rainfalls and causing unprecedented large-scale debris flow and avalanche disasters. Debris flows broke out in 14 places, including Taichung, Hualien, Nantou and Miaoli. Throughout Taiwan, there were a total of 103 deaths, 111 missing, 189 injuries with heavy losses in agriculture and traffic and communication systems throughout Taiwan; in Dahsing, Hualien, nearly 150 residences submerged by debris flow; in Chianching, Hualien, buried 5 buildings and 300 m of roads. While in Fenglin, the water treatment plant was half destroyed with debris flow drowning three houses, resulting in three deaths, four missing, one injured and nearly 100 households evacuated.
2001.09	Nari	Debris flow disasters in many places. Nari typhoon set multiple records, including the longest duration, the most warnings issued by the CWB and new daily historical record of precipitation in many places, which met the 400-year frequency. Within duration of no more than a day and a half, the precipitation reached 820 mm according to Wudu Rain gage station and 679 mm according to Huoshaoliao Rain gage station. Massive rainfall resulted in 94 deaths, 10 missing, and 265 injuries. A lot of places were flooded, with debris collapsing in many locations, resulting in communication, water and power supply systems being cut off).
2004.07	Mindulle	Influenced by typhoon-surrounding circular flows and strong southwest air flow introduced during its northward movement, resulting in serious disasters. Many roads collapsed, and incurred serious debris flows in the mountain areas. During the typhoon and 7-2 flood, a total of 33 deaths and 12 missing. The losses in agricultural, forestry, fishery and pasturing fields were over US$ 30 million.
2004.08	Aere	Influenced by typhoon-surrounding circular flows, torrential rains occurred in the north, northeast, middle south, triggering off serious debris flow disaster conditions. The most serious case was Taoshan Village, Wufeng Town, Sinchu County. In Sanchong District of Taipei, improper MTS construction led to floodwater inwelling of Tansui River; and excessive turbidity of raw water in Shih-Men Reservoir resulted in large-scale water supply cutoff in Taoyuan area. There were a total of 15 deaths and 14 missing. The losses in agricultural, forestry, fishery and pasturing fields reached approximately US$ 60 million.
2004.12	Nanmadol	Influenced by typhoon-surrounding circular flows and accompanying effects of northeastern season wind, torrential rains occurred in the north and east half part. The amount of accumulated precipitation in Buluo Bay, Hualien reached 1090 mm. Roads in some areas collapsed. There were two deaths and two missing. The losses in agricultural, forestry, fishery and pasturing fields reached approximately US$ 2 million.

Source: Central Weather Bureau, Taiwan

assessed the damage and causes of failures. However, such emphases were mainly on the watersheds (CICHE 2004; Tsai et al. 2004) and on the response and recovery strategies (Lu and Wu 2005; NDPPC 2004; CICHE 2004). In fact, geotechnical studies have been mostly neglected in the past debris flow disasters, and thus repetition of similar types of failures and disaster sites have been reported.

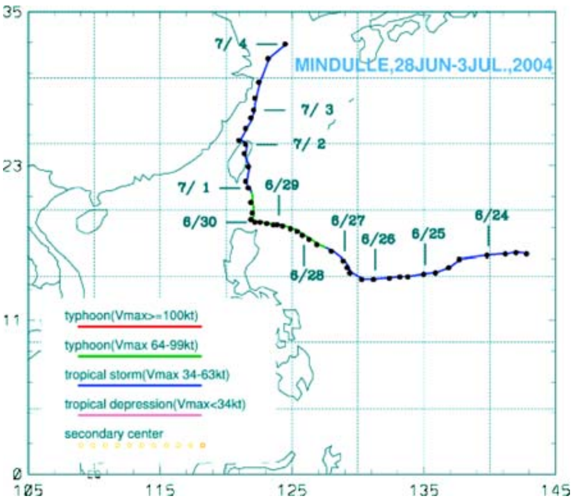


Fig. 1 Path of Mindulle Typhoon

This paper is focused on the discussions of geological and structural failures, which were documented from several sites in Taiwan following the 2004 Midulle Typhoon. It is one of the first publications that provided a comprehensive view of geotechnical failures associated with debris flows.

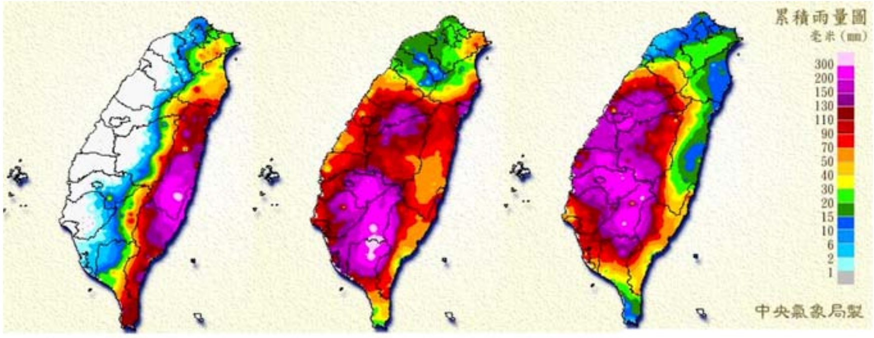
2 Mindulle Typhoon

The Mindulle Typhoon passed over Taiwan from June 29 to July 2, 2004. It left a 2000-km tail following the storm, which continued to attack Taiwan and wreak havoc for 2 more days (Fig. 1). The heavy rainfall (Fig. 2) induced flooding, debris flows, landslides, slope failures, and other various types of geological failures (Ling et al. 2004). For 7 days under the influences of the typhoon and the southwest current, two rain gage stations recorded over 2000 mm of rainfall accumulation, while 10 stations recorded over 1600 mm and 45 stations recorded over 1000 mm of rainfall. The heavy rainfall caused 134 landslides. 14 main bridges were destroyed, whereas 15 additional main bridges were damaged.

The disaster caused 26 deaths and 11 missing, and the losses were estimated at US$ 123 million in agriculture and US$ 1 billion loss in tourism (Table 1). Up to 210,000 households were without power and 440,000 households were without water supply for a couple of weeks after the typhoon. The recovery cost for such rainfall-induced failures has been extremely high. The failures have been repeated at many locations since the 1996 Herb Typhoon.

There were certain special features of Mindulle Typhoon that led to catastrophic events:

1. Unusually heavy rainfall–The average annual rainfall in Taiwan is about 2500 mm. However, for Mindulle Typhoon, two rain gage stations measured over 2000 mm of rainfall, and 10 measured over 1600 mm.
2. Soils, rocks and debris from upstream accumulated in the river channels that resulted in the rise of riverbeds of 10 to 20 m above adjacent roadways at some locations.
3. Rocks and debris buried villages. Communities located on the alluvial fans were most seriously damaged.
4. Riverbanks were destroyed by flooding and erosions. Communities located along riverbanks were also heavily damaged.
5. Erosion was particularly damaging in mountainous areas that had been converted into agricultural lands.



July 1 (00:00-20:00) July 2 (00:00-14:00) July 3 (00:00-08:00)

Fig. 2 Rainfall accumulation of Mindulle Typhoon (Source: Central Weather Bureau, Taiwan)

Fig. 3 Locations of failure sites

Fig. 4 Failure of foundation

3 Types of Failure

This section focuses on the issues of geological/geotechnical and structural failures. The sites that were seriously damaged after the Mindulle Typhoon included Tung-she, He-ping, Sung-he, Ku-kuang, Kuo-shing, Chiu-fen-er-shan, Jen-ai, Wu-shr, Chu-shan, Lu-ku, Shi-tou, Shan-ling-shi, Shui-li, Hsin-yi and Shen-mu-Village (Fig. 3). These hillslopes, which were more vulnerable to disaster histories by having undesirable geological conditions, were chosen in the reconnaissance to explore the features and failures associated with debris flow.

3.1 Geological/Geotechnical Failures

The geological/geotechnical failures were categorized as follows:

Foundation failure (Fig. 4): There were many factors that led to the failure of foundations, which accordingly resulted in damage of the superstructures. For instance, foundations were vulnerable to landslides and debris flows. Due to the increase in excess pore pressure through rainfall infiltration, the strength of the soil at the foundation decreased. The large and uneven settlements resulted from the loss of bearing capacity. The extent of damage depended on the types of soil and locations.

Landslide: The rainfall-induced landslides in this case included that of translational and rotational mechanisms. Some of the failures were surficial and shallow.

- Translational landslide (Fig. 5): The slides of the dip slope, often occurring among layers of rocks, have caused many tragedies in recent years, especially after heavy downpours. In these cases, the translational landslides were very common since the rainfall was not only torrential in intensity but also lasted for extended period of time.
- Rotational landslide (Fig. 6): This failure involved large scale of soil movement. The

Fig. 5 Translational landslide

Fig. 6 Rotational landslide

failure as seen in this particular site may lead to catastrophic failure in the events of future typhoons.

- Surficial Failures (Fig. 7): Numerous small-scale slope surface failures due to rainfall were seen. These failures were shallow and typically left unrepaired. Exposure of such failures may lead to large-scale failures with time.
- Debris Flow (Fig. 8): The massive mixture of solids and water moved down the streams as viscous fluid. The debris may be very dense, so flows occurred more slowly than water. It is perceived that debris flow is a destructive disaster in Taiwan since there are now up to 1420-documented potential debris flow areas.
- Rock Fall (Fig. 9): The downward movement of rocks that fell off after separating from the

Fig. 7 Surficial slope failure

Fig. 8 Debris flow

Fig. 9 Rock fall

bedrock. Geological structures in Taiwan are considered young and thus have a high risk of rock falls, and possibly providing sufficient sources of debris flow as they break down and disintegrate. Many near-vertical rock slopes that are susceptible to different types of failures were observed along the major roadways. (Fig. 10)

There are several main factors contributing to geotechnical failures as observed above.

1. Erosion: The main factors of flow that affected erosion included the discharge, flow rate, and sections of the channel. After the Mindulle typhoon, heavy rainfall raised the water level rapidly, and then erosion accompanied inasmuch as the soaring flow rate. Erosion increased the angle of the slope to a critical value, while the shear resistance of soil was also reduced in the presence of water flow, thus created unstable slope. The soil strength was reduced and thus the factor of safety of the slope decreased drastically. Thus, the buildings were washed away by debris flows (Fig. 5), the slope roots were washed out (Figs. 11 and 12), and the roads were destroyed (Fig. 12).
2. Sediment Deposition: The flow rate determines the shifting capability of sediments. The distribution of the flow rates varies with depth. Even though the higher flow rate is at the surface, the river bottom possesses slower flow rates due to frictional shear. That is why the observed sediments were deposited at the river bottom (Figs. 12, 19, 20 and 21).
3. Excess Pore Water Pressure: The low soil permeability and high intensity of rainfall resulted in a temporary rise of the water table. The cohesive soil beneath the water table became saturated; hence the pore water pressure increased. The increase in the total unit weight of soil due to the permeation of rainfall also promoted the sliding force and thus reduced the factor of safety. As a result, many roads were damaged (Figs. 13 and 18).
4. Chemical Reactions in Soils (Leaching): When large amounts of rain permeated into the rock joints, the increasing sliding moment, owing to lateral and bottom up water pressure, increased the risk of rock falls. Furthermore, clay minerals existed in the joints of rocks. The prolonged chemical interactions between water and clay minerals may have led to the separation of stones from the bedrock and thus the risk of rock fall increased (Fig. 9). The mechanism between mineral and water interaction is found in standard text, such as Mitchell (1976).

Fig. 10 Erosion increased the slope angle to critical conditions

Many geological materials disintegrated after reacting with water. In Taiwan, there are many tiny

Fig. 11 Scouring and failure of foundations

Fig. 12 Roadway failure due to scouring of road base

Fig. 13 Collapse of bridge and road

particle materials, such as shale, schist and clay, whose internal strengths reduced quickly after reacting with water. Moreover, the volume of clay changed (swelled) after mixing with water. The pressure resulting from swelling led to the geological failures as well.

3.2 Structural Failures

The main natural factors and mechanisms that caused damages to the physical structures are similar to that mentioned in the geological section. Generally speaking, the types of failure and possible factors contributing to the failures are classified as follows:

- Buildings: Impact and/or burial by debris, lack of bearing capacity of the foundations.
- Roadways: Erosion and lack of bearing capacity, rock impact, burial by debris and landslides, failure of retaining walls.
- Bridges: Lateral impact, lack of bearing capacity of the abutments and foundations.

The major factors contributing to above-mentioned failures are described as follows:

1. Riverside Roads and Erosion: Many expressways and villages are located at riverine areas, some of which are vulnerable to attack. After downpours, water levels rose quickly and flow rates increased dramatically. Gravel and boulders carried by floods led to erosion and transportation of soil particles; thus the foundations under the roads, bridges and building foundations became unstable and collapsed (Figs. 14–16).
2. Slope Failure: The failure of slope would harm the physical structure sitting upon it, especially since many structures were constructed above the failure surface within the sliding mass (Fig. 18). Similarly, the slope became less stable if the earth, which supported the physical structure, was damaged by the debris of the structure.
3. Debris Deposits, Lateral impact and Clearance: The river deposited the debris at certain areas. The gravels and boulders piled up and blocked the waterways, thus increased the water level (Figs. 17–20).

In this case, several constructions were unable to withstand the lateral impact from boulders or giant woods. Many riverside buildings were fully destroyed by the lateral forces of floods and their accompanying solids (Fig. 14).

The sediments from debris flow raised the riverbed. Insufficient buffer room or clearance beneath the bridge jeopardized the structural safety of bridges. When the rivers overflowed, the bridges not only lost the function but also threatened communities nearby, increasing the regional vulnerability (Figs. 17 and 21).

4. The Scouring of Bridge Foundation: The scouring of bridges is a common problem in Taiwan (Fig. 22). The effects of washout and erosion might have been underestimated. Aside from improving design and monitoring, it revealed the need of deepening and/or protecting the foundations if the situations keep occurring.

Fig. 14 School buildings damaged by impacts from wood debris carried by flooding river

Fig. 15 Building damage–Debris flow has buried buildings and transported large objects

Fig. 16 Bridge damage–Road surface on bridge has been destroyed (much of structure remained intact)

Fig. 17 Debris-flow deposit up to bottom of new arch-bridge

Fig. 18 Road damaged by slope failure

Fig. 19 Debris piled up and blocked waterway

Fig. 20 River channel filled with debris overflowed into adjacent roadway

Fig. 21 Bridge lacked lateral resistance. Only three piers remained

Fig. 22 Approximately 1 meter of bedrock (shale) removed beneath foundation

Fig. 23 Detail of failed unreinforced concrete retaining wall

Fig. 24 Open tunnel destroyed by landslides

Fig. 25 An example of reinforced concrete abutment withstanding debris flow. Bridge approach has been washed away

Fig. 26 Abandoned pier arrested debris on unreinforced concrete retaining wall

5. Lateral Resistance of the Retaining Walls: In many failure cases, reinforced concrete retaining walls either lacked lateral resisting force or reinforcements (Fig. 23), so that the retaining walls were unable to resist large lateral earth pressure. Several reinforced soil retaining walls with geosynthetic reinforcements were found to have performed well. Some of them were built after failure of conventional retaining walls.
6. Engineering Design Problems and/or Alternative Solutions: Open tunnels, used for protecting the slope and falling rocks, are often located at the sites of falling rocks or sliding zones (Figs. 24–26). Although constructions are often destroyed by debris flows or landslides, the problem may not be related to construction quality but rather the design and site selection. Alternative construction methods need to be sought in avoiding repeated failures.

4 Conclusions

The types and possible causes of geological/geotechnical and structural failures in the events of heavy rainfall, such as typhoon, were summarized as follows:

- Increasing discharge and flow rate resulting from typhoon accelerated the erosion process.
- Both the angle and washout of slope resulting from erosion led to slope instability.
- The interaction between water, soil and rocks (especially shale, schist and clay), not only reduced the strength of materials but also induced excess pore pressure and swelling that rendered slopes unstable.
- The pressure of ground water due to rainfall infiltration increased the risk of geological and geotechnical failures.
- Reinforced concrete structures performed well, while unreinforced concrete structures performed poorly. Modern reinforced soil structures have been successfully in resisting failure.
- Careful placement of structures is important in protecting bridge foundations or reducing its clearance with riverbeds. However, inexpensive and temporary structures may be good alternatives at high-risk locations with less critical applications.

Eventually, the aspects of geological/geotechnical and structural failures may lead to some suggestions for better future structural and geotechnical designs and/or construction methodologies. Different from traditional theories, high disaster frequency, serious disaster consequences and diversed nature of the disaster posed a new research field for Taiwan. Meanwhile, the experiences gained from this case study also provide opportunities for better future development of both disaster prevention research and practical works.

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