Some attributes of road-slope failure caused by typhoons

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ABSTRACT: Taiwan is an island with two-thirds of its area located in mountainous zones. Because of the scarcity of usable land, many developments and roads have been built on the hillsides that were formed by relatively weak geological materials. During heavy rainfalls, these materials will be weakened and hence led to debris flows or landslides. The main purpose of this study is to explore some of the attributes of the 1567 road (excluding express/motor-ways) slope failures occurred after the heavy rainfalls that were brought by four intense typhoons in 2004 (Mindulle, Aere, Haima and Nock-Ten). This preliminary study statistically examined the significance of the types of geological material, slope angles, distance to the nearest active faults, and rainfalls intensity on road slope failures.

1 INTRODUCTION

Taiwan is an island where one-third of its total areas are plains with elevations below 100 m while the other two-thirds of the island are occupied by hills and mountains with elevations varying from 100 m to 4,000 m. Because of the scarcity of usable land, many developments and roads have been built at the hillsides that were formed by relatively weak geological materials. During heavy rainfalls, particularly those brought by typhoons, these materials will be weakened and led to natural hazards such as debris flows and landslides.

According to the Central Weather Bureau (CWB 2004), the island's average annual rainfall was about 2500 mm, in which approximately 70% of the precipitation occurred between May and September, i.e. during the typhoons season. Four intense typhoons: Mindulle, Aere, Haima and Nock-Ten struck the island and inflicted a total of 1567 road-slope failures along the island’s road networks. The road networks mentioned included all the roads on the island except the express/highways.

The main purpose of this paper was to identify the attributes of landslides generated after the heavy rainfalls that were brought by the four intense typhoons in 2004. The method of study was via statistical approach. Hopefully, area prone to landslides after heavy rain may be identified so that mitigation and contingency plans could be derived to minimize life and property losses in the event of another typhoon.

2 TYPHOONS IN 2004

Statistic between 1897 and 2002 shows that, of all the months, August is the month struck by the highest number of typhoons—about 29.3% of all typhoons (Chen 2004). 75.2% of all the typhoons struck in the months of July, August and September. The annual precipitation/rainfall also concentrated between these few months (Figure 1) as these typhoons brought along with them heavy rainfalls. There were four intense typhoons struck the island in 2004: typhoon Mindulle, typhoon Aere, typhoon Haima, and typhoon Nock-Ten.

2.1 Typhoon Mindulle

Typhoon Mindulle moved west after taking shape and landed on the east of Taiwan, about 20 km from the southeast of the island with a speed of 15 km/h on July 1, 2004 and left from the northwest of the island on July 2. The path of the typhoon Mindulle has been categorized as Path 4 (Figure 2). It brought heavy rains to the east, north, northeast and mountain regions of the island. The highest rainfall recorded was 1182 mm on Ali Mountain (usually called Alisan), the second

![Figure 1. Monthly and accumulated rainfalls through 2004.](image-url)
highest was 703 mm in Jade Mountain. Water levels at several reservoirs rose on July 2 and 3, with Jenwen Reservoir in Tainan County accumulated 419 mm of rain, while Nanhua Reservoir, which supplies water to Tainan, Kaohsiung and Chiayi, received 560 mm of rain. There were many rainfalls and landslides in the central regions of the island.

The death toll as a result of the typhoon and the flood was thirty-two. In addition, there were twenty persons wounded, thirteen missing, and one-hundred and forty houses damaged and over 80,000 electricity interruptions. Agricultural losses were estimated at more than NT$8,900 millions (US$278 millions).

2.2 Typhoon Aere

Typhoon Aere moved toward the northwest after taking shape on August 20, 2004 and landed on the northeast of the island with a speed of 15 km/h on August 25. The typhoon moved gradually southwest after entering the Strait of Taiwan and entered Fujian from northeastern side of Jinmen at 12:00 pm on August 25. Typhoon Aere weakened over the northern part of the island on August 25 after bringing heavy rainfall to the central and northern parts of the island. The path of typhoon Aere has been categorized as Path 1 (Figure 2). Thus, it rained a lot in the north and the central parts of the island. The highest rainfall encountered was 783 mm at Alishan and 774 mm at Zhuzihu, Taipei (CWB 2004).

Aere caused a total of fifteen deaths and fourteen people missing, three-hundred and ninety-nine wounded, one-hundred and sixteen houses damaged, more than 1.4 millions electricity interruptions, and about 380,000 tap-water interruptions. Agricultural losses were estimated at more than NT$180 millions (US$5.6 millions).

2.3 Typhoon Haima

Typhoon Haima was formed in the east of Taiwan Sea on September 11 with its center about 60 km to the east of the island. It passed through the north of the island with a speed of 14 km/h on September 12 and moved to the east of China. The path of typhoon Haima is Path 4 (Figure 2). It brought a lot of rains to the north of Taiwan and the highest rainfall area was in Anbu with rains of 706 mm, the second highest was 516 mm in Taipei. Rock and earth were loosened by the continuous downpours.

There were four deaths, two missing, thirty-four electricity interruptions, and 44,400 tap-water interruptions (National Fire Agency, 2004). Agricultural losses were estimated at more than NT$15 millions (US$0.47 millions).

2.4 Typhoon Nock-Ten

It started raining on October 24 as a result of typhoon Nock-Ten. It was a mild typhoon between October 18 to 25. The typhoon landed in Yilan on October 25 and left Taiwan a few hours later from Danshui with a speed of 19 km/h. The path of typhoon Nock-Ten is Path 4 (Figure 2). It rained heavily in the north of the island with the highest rainfall in Anbu with 496 mm of rain, the second highest was in Zhuzihu with 372 mm of rain. Accumulated rainfall from midnight of October 24 to 5 pm of October 25 exceeded 300 mm in many places in the northern part of the island. In northern Taiwan, the water surface of Danshui, Dahan and Xindian Rivers exceeded the alarming levels. The worst situation was reported in Taipei County, where the Keelung River suddenly rose from 42.09 m (1:00 October 24 2004) to 47.23 m (12:00 October 25 2004) due to the heavy rains.

Around the island, a total of four deaths, one-hundred and four wounded, two missing, 383,752 electricity interruptions and 12,566 tap water interruptions were reported. In addition, many agricultural facilities were also ruined. Financial losses in the agricultural sector reached NT$35 million (US$1.1 millions).

Among the four typhoons, the most serious disaster in 2004 was caused by typhoon Mindulle. The associated maximum accumulated rainfall was 1182 mm at Alishan between 29th of June and 2nd of July.
3 TYPES OF SLOPE FAILURES

According to Varnes (1978), slope failures can be classified into: (1) fall, (2) topples, (3) slides, (4) lateral spreads, (5) flows, and (6) complex. As they were not specifically related to our study, we have defined the following five types of failure instead:

1. **Type-1**: the upper slope failed and caused damage to the retaining wall supporting it [Figure 3(a)]. Soil/rock and broken retaining wall were seen on the road. This is the type with the least failure; only 86 failures, or 5.5% of all the 1567 failures, were reported compared to the other types of failures.

2. **Type-2**: the upper slope was stable but the retaining wall on the crest of the down slope was damaged due to the washing out of the down slope (Figures 3(b)). It was the second common failure among the five failures. The number of failures was 324 or 20.7% of all failures.

3. **Type-3**: Among all the types of failure, it was the greatest failure in terms of landslide volume because both the upper and lower slopes failed together, either with (Figure 3(c)) or without the retaining wall (Figure 3(d)). It accounted for 13.8% of all the failures.

4. **Type-4**: the natural upper slope failed with soil/rock debris fallen on to the road (Figure 3(e)). This was the type with the second fewest disasters, albeit only slightly less than the Type 3 failure. About 13.1% of the failures were belonging to this category.

5. **Type-5**: there were pits on the surface of the road together with the failure of the natural down slope (Figure 3(f)). This was the most common failure among all the five failure types. Close to half, or 46.9%, of all the failures reported were of this type of failure. The damaged of the upper slope drainage channels normally causes erosion on the down slopes, which may fail subsequently (Hung 1996).

4 ATTRIBUTES OF SLOPE FAILURES

All the above road slope failures occurred after the heavy rainfalls brought along by the typhoons. However, it was noted that these failures occurred not necessarily at places with the highest accumulated rainfall or highest rainfall intensity. There should be some other possible attributes of road slope failures, for example topography, geology, slope angle, distance to the nearest active fault and so on. As a result, we have statistically linked the attributes of topography, geology, slope angle, and distance to the nearest active fault with the number of slope failures. The results are presented in the following subsections.

4.1 Rainfalls

Landslides triggered by rainfall are the cause of thousands of deaths worldwide every year; and a large variety of landslides occur as a consequence of heavy rainfall in tropical and temperate climates (Jakob et al., 2003). There have been many studies on the relationship of rainfalls and landslides (Finlay et al. 1997, Lin and Jeng 2000, Collins & Znidarcic 2004, Alleotti 2004, Rahardjo et al. 2005, Cheng et al., 2005, Chang et al. 2005).

According to Abramson et al (2002), during heavy rainfall, rain water seeps into the ground and travels across the top layer of the soil in the slope which is often unsaturated. Results of field measurements at various sites indicated that the unsaturated gradient was generally directed vertically downward during the steady rainfall and the water may perch on lower permeability materials or on a drainage barrier such as bedrock and highly impermeable clays, and so on, creating a temporary, localized saturated zone (Abramson et al., 2002). The water then continues downward and down-slope, eventually seeping into gullies or reaching the lower groundwater table and entire slope will be dangerous because of infiltration and erosion (Abramson et al., 2002).

Finlay et al. (1997) studied the number of slope failures and the rainfall intensity in Hong Kong Island between 1984 and 1993. They used the relationship of accumulated rainfall and number of slope failures to predict the number of slope failures. Hence, the number of slope failures reported here could also be linked to the rainfalls. For this study, we tried to relate the average rainfall, maximum hourly-rainfall, 24-hour rainfall, and accumulated rainfall to the number of slope failures.

4.1.1 Average rainfall

The average rainfall during each typhoon has been taken as the average rainfall value of 25 rain-stations throughout the island. The average value was then...
compared with the total number of slope failures during each typhoon.

Figure 4 shows the relationship of the average rainfall during each typhoon and the number of slope failures. The number of slope failures during typhoon Mindulle was 462, during typhoon Aere was 961, during typhoon Haima was 113, and during typhoon Nock-Ten was 31. In general, the distribution indicated that higher average rainfall was associated with higher slope failures, except for the case of typhoon Nock-Ten.

4.1.2 Maximum hourly-rainfall
From the records made by 133 rain-stations around the island, it was possible to derive a more representative value of the maximum hourly-rainfall for each failed slope. This method of study shows that the intensities that associated with the highest and second highest numbers of slope failures were 60 and 30 mm/hour, in which they accounted for 754 and 706, or 48.1% and 45.1%, of all failures, respectively. The intensities of 90 mm/hour and 120 mm/hour only accounted for 4.5% and 2.3% of all failures, respectively.

4.1.3 24-hour rainfall
The 24-hour rainfall was obtained by summing the rainfall record measured from a consecutive 24 hour’s period during the typhoon. The maximum value was then used to compare with the number of road slope failures and it was found that 53.6% of the slopes failed when there were less than 300 mm of 24-hour rain while 38.4% failed between 300 and 600 mm of 24-hour rain.

According to Hung (1992), each slope may be associated with a rainfall threshold, if exceeding it, the slope will fail. He suggested a rainfall threshold of 300 mm/day for some of the weak slope areas (crest of higher mountain, mudstone, lateritic terrace slope, residual slope, cataclinal slope, filled slope, over-used slope) in Taiwan. However, using the threshold suggested by Hung (1992), the 53.6% of failed slopes would not have had failed at all. This is clearly not the case and therefore the stability of a slope could not be correlated to a single rainfall threshold value.

4.1.4 Accumulated rainfall
The relationship between the accumulated rainfall and number of slope failures was also examined. A total of 1316 failures occurred in places with less than 600 mm of accumulated rainfall, or equivalent to an accumulated percentage of 84.0%; the failures percentage for accumulated rainfall of over 1500 mm was only 0.5%. Presumably, most of the weak slopes have already failed at accumulated rainfall of 600 mm or less.

Gabet et al. (2004), who studied the suspended sediment concentrations and discharge in a catchment in the High Himalayas of Nepal during the monsoon seasons of 2000 to 2002, found that landslides in Himalayas of Nepal were not triggered until 860 mm of accumulated rainfall have fallen. Their observations suggested that sufficient antecedent rainfall is necessary to bring the regolith up to field capacity (the soil moisture beyond which gravity drainage will ensue) such that future rainfall may produce positive pore pressures and trigger landslides (Campbell 1975, Crozier 1999).

4.2 Topography
Taiwan mountain belt is located at the oblique convergent boundary of the Eurasian Plate and the Philippine Sea Plate. The Central Mountain Range (comprising the Hsuehshan Range and the Backbone Range), which was resulted from active mountain building process, is up-heaved with elevations exceeding 3000 m, and about 70% of the island is mountainous area (Lin et al. 2000) with steep slopes. Due to society developments, many of these slopes were excavated for the purpose of roads building.

Figure 5 shows that 75.3% of all the slopes failures occurred on slopes located at elevation 600 m and below, in which 26.7% of all the failures concentrated between elevations 200 m and 400 m where most of the roads were built.

4.2.1 Geology
These slope failures were seen concentrating on the west side of the island. Relationship between the period of geology and number of slope failures is shown in Figure 6 and the highest number of failures was distributed between the geological period of Pliocene and Pleistocene to Middle Miocene. The highest failures occurred in Late Miocene group, also called the SanSia Group, with 398 failures; the second is Pliocene group with 267 failures; the third is Pliocene and Pleistocene group with 235 failures; and the fourth is Middle Miocene group with 235 failures.
These four geological groups made up of 72.6% of all slope failures. The reason why there were so many failures in the SanSia group was probably because SanSia Group is the youngest Miocene sedimentary cycle in western Taiwan. The group is distributed more extensively than any other Miocene groups in western Taiwan. This group is divided into a lower coal-bearing formation (Nanchuang Formation) and an upper marine unit (Kueichulin Formation). Both formations are composed predominantly of thick sandstones, which are tertiary weak rocks (also included are shale and mudstone) that are not strong enough to be classified as hard rock as a result of a relatively short rock forming period with a typical strength ranges from 10 to 80 MPa (Jeng et al. 1994).

4.3 Distance to the nearest active fault

Slope failures that occurred during typhoons Mindulle, Aere, Haima and Nock-Ten were mainly caused by the extremely high rainfalls. However, it should be noted that many slopes on the island had probably been severely disturbed by the September 21, 1999, Chi-Chi earthquake. The magnitude 7.5 September 21 Chi-Chi earthquake had triggered 25,845 landslides with a total area of 15,977 ha and severely disturbed mountainous slopes in central Taiwan, and setting the conditions for occurrence of more landslides and debris flows/debris floods in the future (Lin et al 2002).

Since, tectonic activities caused by the collisions of the Philippine Sea Plate and the Eurasian Plate have resulted in a series of Quaternary thrust faults trending north-south and dipping towards the east (Ho 1982, Lu et al. 2000), thus, it was decided to examine the relationship between the degree of disturbances and the number of slope failures by assuming that the closer a slope to a fault the more severe it was disturbed; hence, the relationship between the nearest distance of active faults and the failure locations was studied. The finding shows that only 145 cases, or 9.3%, of failures occurred within 1 km of active faults. There were 1077 cases, or 68.7%, of the failures occurred within 10 km of active faults; while almost all the failures (96.6%) located within 30 km from active faults. The number of slope failures within 3, 5, and 20 km were 444, 726, and 1343, respectively. So, it could be concluded that earthquake had played an important role in destabilizing the stability of these slopes.

4.4 Slope angles

The relationship between slope angles and the number of slope failures obtained from this study is shown in Figure 7. The slope angles were obtained from a 40 m × 40 m digital terrain map. The result indicated that 293 cases, or 18.7%, of the failures occurred on slopes with gradient ranges between 25° and 30°. A total of 937, or 60%, of all the failures occurred on slopes with gradient ranges between 20° and 40°. It was also interesting to observe that 29%, or nearly one-third, of the failures had occurred on slopes with slope angle of 20° or less, but there were only 11.2% of the failures occurred on slopes with gradient greater than 40°.
The reason why there were more failures observed on the gentle slopes than the steeper slopes was that during rainfalls, water was supposed to infiltrate into the slopes but the gradient of the slopes dictated the amount of the water infiltrating into these slopes. On one hand, a large amount of the rain water has sufficient time to infiltrate into the gentle slopes since it required a longer time for the rainfall to travel down the slopes. As the water content in the slope increases the shear strength of the slope reduces until a value equals to the mobilized shear stress of the slope, which is also increase due to the weight of water in the slope. At this point, the slope or a portion of the slope would fail. On the other hand, steeper slopes can not absorb all the rainfall quickly and therefore water travel as surface runoff down to the toe of slope by gravity. This has resulted that most of the steep slopes have failures near the toe of the slopes.

5 CONCLUSIONS

A statistical study has been carried to identify some of the attributes of road slope failures occurred after the heavy rainfalls brought by four intense typhoons that struck Taiwan in 2004. In total, there were 1567 road slope failures reported.

The study shows that the number of slope failures is generally proportional to the average rainfall, and that 84% of all failures occurred under an accumulated rainfall of 600 mm or less. In terms of geology, the highest number of failures occurred in the late Miocene group, which is the youngest Miocene sedimentary cycle on the island. The study also shows that 96.6% of all failures were located within 30 km of active faults, which had weakened these slopes during tectonic activities in the past. In addition, 60% of all the failures occurred on slopes with gradient ranges between 20° and 40°.

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