Characteristics of hazards induced by extremely heavy rainfall in Central Taiwan — Typhoon Herb

M.L. Lin, F.S. Jeng *
Department of Civil Engineering, National Taiwan University, Taipei 106, Taiwan
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Abstract

In 1996, Typhoon Herb devastated Taiwan, moving across the northwestern part of the island. Historically, typhoons traveling such a route have frequently caused worse damage than typhoons on other routes. Herb brought record-breaking precipitation to Taiwan, especially the central part of the island. The heavy rainfall led to more than 1315 landslides and 20 debris flows. Seventy-three lives were lost, 463 people were wounded, and property losses of about 1 billion USD were sustained.

This study presents the distinct characteristics of Typhoon Herb as well as the induced hazards, including their extraordinary size and recurrent nature. The focus is on central Taiwan, where the severest hazards were encountered. Furthermore, the geological, geomorphologic and engineering factors, which may have magnified the consequences of the hazards, are also discussed. A comparison of hazards in other countries is also made and the results indicate that the extremely heavy rainfall encountered as well as the existence of a boundary fault in the study area are the most susceptible factors inducing the extraordinary hazards. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: debris flow; fault; hazard; landslides; rainfall; Taiwan; typhoon

1. Introduction

Typhoons are a part of life for Taiwanese. Almost every summer, from late June to late October, Taiwan is struck by one or more typhoons. Therefore, a typhoon striking Taiwan is not big news; rather, it is the summers where no typhoons occur that are newsworthy. Consequently, Taiwanese are well accustomed to typhoons. Most civil engineering facilities in Taiwan are designed to withstand typhoons, and even earthquakes.

In 1996, on 31 July and 1 August, Taiwan was struck by a strong typhoon named Herb. Herb was a strong typhoon with a highest sustained wind speed up to 60 m/s and a radius of 320 km. In fact, Herb was not the strongest typhoon encountered in terms of size and wind speed; therefore, it was not seen as a serious threat before it struck Taiwan. However, the damage caused by Herb ranked it as one of the severest typhoons to hit Taiwan in the past four decades. Table 1 summarizes the top five most destructive typhoon or cyclone events in Taiwan in the past four decades. In terms of casualties and property loss, the Herb event is the worst one since 1959. Herb caused 1315 landslides, more than 20 debris flows, 101 road closures and 49.6 km of embankment failure. Moreover, there were 73 deaths, 463 wounded, 1383 houses destroyed or damaged and one billion USD in property losses.

* Corresponding author. Tel.: +886-2-2363-0530; fax: +886-2-2363-0530; E-mail address: fsjeng@ce.ntu.edu.tw (F.S. Jeng)
These remarkably serious hazards brought by Herb resulted from one of its characteristics, its path across Taiwan. Herb went across northern Taiwan along a route shown in Fig. 1. The route was particularly unfortunate since the counter-clockwise air current brought abundant humidity from the southwest (indicated by solid arrows in Fig. 2b), which was then obstructed by the Central Mountain Range of Taiwan. The obstructed humidity current was then transformed into heavy rainfall on the mountainous range and the Western Plain, where the population and industry in Taiwan are concentrated.

Worse still, the southwest wind (Fig 2a) drove the tide toward the western coast, blocked the drainage of streams on the Western Plain and consequently induced 35 390 ha of flooding across the Western Plain.

However, if the typhoon had struck Taiwan through its southern part, the Central Mountain Range would have blocked the northwest wind (indicated by white arrows in Fig. 2c and d) and its humidity such that the magnitudes of the wind and the rainfall would be substantially reduced. Most of the typhoons went across Taiwan through its southern part. However, this did not occur for the Herb event.

Consequently, Herb brought a record-breaking precipitation to Taiwan. Fig. 1 illustrates the distribution of rainfall over Taiwan and indicates two major rainfall centers. The heaviest rainfall during Herb, with a 2 day rainfall intensity of 1987 mm, was located in central Taiwan. Next to this rainfall center was the area (indicated by a box in Fig. 1) that suffered from the severest hazards, including...
Fig. 2. Schematic illustration of the impact of typhoons traveling along two different paths. If the typhoon goes across northern Taiwan, the northwest wind will not be hindered by the mountainous range and drives the tide toward the western coast (a and b), followed by the southwest wind blocked by the central range (b), inducing extremely rainfall in the center Taiwan. If the typhoon sweeps through southern Taiwan, the northwest wind will be hindered by the central range (c), and most of the precipitation brought by the southwest wind will fall on the sea (d). The Chenyulan Stream area contains four weather-monitoring stations (Alishan, Hosheh, Shinyi and Shitou, Fig. 1). As shown in Fig. 3, the

landslides and debris flows, which took 27 human lives. Accordingly, this area, the Chenyulan Stream area, is selected as the study area of this paper.
precipitation recorded by these four stations during the typhoon strike indicates that the rainfall intensities (in 12, 18 and 24 h) at the Alishan station not only exceeds the previous maximum records of Taiwan, but is very close to the world record levels. The 12- and 24 h accumulated rainfalls in the mountainous Alishan area are 1158 and 1749 mm, respectively. Meanwhile, the rainfall collected in the Hosheh area during Herb was about 900 mm. In terms of regional annual rainfall, about 30% of the mean annual rainfall fell in only 2 days during Typhoon Herb in central Taiwan.

Based on a regression analysis, the return period for rainfall of this intensity far exceeds 200 years, as indicated in Fig. 4. This heavy rainfall collected in the watershed turns into overland flow or subsurface flow and directly impacts the stability of the slopes within the watershed.

Overall, Herb exhibited the following characteristics: (1) it was a strong typhoon with a huge...
radius and lots of humidity; (2) it traveled an unfortunate path across Taiwan; and (3) it brought a record-breaking rainfall.

In addition to the characteristics of Herb, the sensitive geological situation in central Taiwan accounts for the extraordinary landslides and debris flow in the study area. In the study area, a boundary fault separating the major geological units of Taiwan exists. This boundary fault, the Chenyulan Fault, not only intrinsically provides fractured rock strata that make hazards more likely but also makes hazards more likely to recur. This study examines the influence of the geographical, geomorphologic factors on the characteristics of the hazards. Furthermore, the engineering factors, which may have magnified the consequences of the hazards, are also discussed.

2. Regional geological condition

The Taiwan mountain belt is located at the oblique convergent boundary of the Eurasian Plate and the Philippine Sea Plate. Resulting from the active mountain building process, the Central Mountain Range (comprising the Hsuehshan Range and the Backbone Range) is up-heaved with elevations exceeding 3000 m, and about 70% of Taiwan is mountainous.

The local geological map of the Chenyulan Stream area is depicted by Fig. 5. The Chenyulan Stream is 42 km long with a mean gradient of 4°, and elevations ranging from 310 to 3952 m. The catchment of the Chenyulan Stream area is 443.6 km² with a mean annual rainfall of about 3000 mm. As Fig. 5 indicates, the Chenyulan Stream follows a major fault, the Chenyulan Fault, which is a boundary fault dividing two major geological zones of Taiwan: the Western Foothills (sedimentary rocks) and the Hsuehshan Range (light metamorphic rocks). In addition to the boundary fault separating geological zones, this area also contains many other faults, accompanied by fractured zones. Consequently, fractured rock mass prevails over the study area, accounting for enormous landslides and providing an abundant source of rock debris for debris flow.

3. Landslides

At least five major landslides, 13 debris flows and five locations of riverbank collapse were reported (Lin et al., 1996) along the section of highway Route 21 within the study area, as summarized in Table 2.

In fact, landslides are not unusual in this region, especially on the left bank of the Hosheh Stream, which possesses a dip slope with an angle of 25–38° and runs for about 1 km along Highway Route 21. After a major landslide at Hosheh area in August of 1994, this dip slope is still considered to be unstable as tensile cracks prevail over the slope, which enables quick infiltration of groundwater into the slope and to mobilize further landslides (Jeng and Lin, 1996; van Asch et al., 1996). Consequently, several landslides occurred in this dip slope during the Herb event, severely obstructing the traffic on Route 21 for 18 days.

Routing Route 21 along this dip-sloped section (left bank of the Hosheh Stream) was an unusual decision. The road was originally going to be located along the right bank. However, as most of the farms are located along the left bank, and because a previous road was there before Route 21 was built, the road authority chose the unstable left bank for the sake of convenience, disregarding experts’ advice against this (Wang, 1991). Consequently, enormous costs were incurred fixing the highway after 1994 landslide, and still more money (about 4 million USD) was spent after the damages caused by Typhoon Herb.

4. Debris flow

The debris flows in the study area accounted for many of the casualties of Herb, which warrants a thorough investigation over the study area to reveal the hazardous areas and to prevent any further losses of human life. Satellite images and techniques adopted in Geographical Information System (GIS) served as a useful means for preliminary investigation (Lillesand and Kiefer, 1994; Lee et al., 1996; Murai and Onat, 1997; Yu, 1997; Nagarajan, et al., 1998). In a satellite image, the
Fig. 5. Geological map of the Chenyulan Stream study area. The Chenyulan Fault is aligned along the Chenyulan Stream. The Chenyulan Fault is a major boundary fault in Taiwan, such that the strata to the west and the east of the Chenyulan Fault comprise sedimentary rocks and lightly metamorphic rocks, respectively.
Table 2
Major hazards induced along Route 21

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of hazard</th>
<th>Consequence</th>
<th>Deaths</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanpingkang (84.2K)</td>
<td>Debris flow</td>
<td>Roadway eroded</td>
<td>0</td>
<td>Transportation section of debris flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check dam damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Streambed eroded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shinshan Bridge (84.9K)</td>
<td>Debris flow</td>
<td>Streambed eroded</td>
<td>0</td>
<td>Transportation section of debris flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway eroded</td>
<td></td>
<td>Riverbank collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Invert blocked</td>
<td>4</td>
<td>Deposition section of debris flow</td>
</tr>
<tr>
<td>Junkengko (86K)</td>
<td>Landslide</td>
<td>Invert blocked</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Debris flow</td>
<td>Roadway eroded</td>
<td>5</td>
<td>Deposition section of debris flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Houses buried</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check dam damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Streambed eroded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junken Bridge (87.1K)</td>
<td>Debris flow</td>
<td>Roadway eroded</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Houses destroyed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check dam damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shinyi Bridge (90.5K)</td>
<td>Flood</td>
<td>Roadway eroded</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Houses buried</td>
<td></td>
<td>Deposition section of debris flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete channel damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Embankment eroded</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Pier washed away</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Part of streambed eroded/raised</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Roadway eroded</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Roadway buried</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Check dam damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Streambed eroded</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Houses buried</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Farm buried (14 ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway buried</td>
<td></td>
<td>Riverbank collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Streambed raised</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pier washed away</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway eroded</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bridge damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway collapsed</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Invert blocked</td>
<td>2</td>
<td>Dip slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>House destroyed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slope toe eroded</td>
<td>0</td>
<td>Riverbank collapse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway eroded</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway eroded</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dip slope</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Riverbank collapse</td>
<td>1</td>
<td>Baffle neck of stream</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bridge damaged</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway damaged</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Houses buried</td>
<td>0</td>
<td>Large landslide at upper stream</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bridge destroyed</td>
<td>0</td>
<td>Junction of two streams</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway destroyed</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Invert blocked</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roadway destroyed</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Houses destroyed</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
fresh deposits from recent landslides and debris flows are a lighter shade than the existing deposits.

### 4.1. Debris flow — regional characteristics of study area

Fig. 6 depicts the fresh deposits (with a light shade) existing after Typhoon Herb. Before Herb, plenty of fresh deposits already existed in the Chenyulan Stream and its major branch streams. However, after Herb, the quantity of fresh deposits along the Chenyulan Stream significantly increased, and these fresh deposits could even be found along minor branch streams. This indicates that: (1) this area has ample debris, which is likely due to its geological conditions, especially the fractured zone around the Chenyulan Fault; (2) the rainfall during Herb was sufficient to wash out this debris or to trigger landslides; and (3) these fresh debris are deposits of debris flows or landslides during and even after Herb, which provides sufficient conditions for a recurrent nature of debris flows.

The Chenyulan Stream is in fact a branch of the Choshui River. Based on Fig. 6, the Chenyulan Stream clearly has more debris than the main stream along the upstream junction. After the junction with the Chenyulan Stream, the amount of debris in Choshui River significantly increases due to the abundant supply brought by the Chenyulan Stream.

The fact that there are more deposits in the Chenyulan Stream, indicating more landslides in this stream, is possibly due to two factors: (1) an existing fault and (2) more precipitation along this stream valley.

The valley of Chenyulan Stream is much wider than that of the upstream section of Choshui River, as shown in Fig. 6, possibly reflecting the influence of the Chenyulan Fault, which is aligned right along the Chenyulan Stream. As the rock strata are frequently fractured during the faulting process and subsequent displacement, the fractured rock mass along the fault line may be displaced more easily than the adjacent sound rock stratum. As a result, there are more alluvial fans in the Chenyulan Stream than in the upstream section of the Choshui River. Therefore, the existence of the Chenyulan Fault may serve as an underlying cause, which enables the development of a wide valley and an abundant supply of debris along this valley.

However, the humidity in the study area was obstructed by the ridge of Junkeng Mountain (El. 3005 m; Fig. 6) causing much greater rainfall in the area between Shinyi and Hosheh than in the adjacent area (Shitou). In addition to the existence of a major fault, this heavier rainfall resulting from the local orographic effect facilitated the occurrence of a sequence of landslides and debris flows.

### 4.2. Debris flow — Fonchu area

One of the major debris flows occurred in the Fonchu area, which has a catchment area of 1.7 km². The stream is 4.9 km long, with elevations ranging from 600 to 2200 m and a mean gradient of 20°. The deposit of the debris flow is about 500 m by 300 m, with an area of 10 ha and a volume of $5 \times 10^5$ m³, as shown in Fig. 7 (marked as debris flow A) and Table 3. The Fonchu village is situated on an alluvial fan, which is the deposit mainly from several previous debris flows. As Fig. 7 indicates, the Chenyulan Stream is forced to detour ahead of the Fonchu alluvium fan, implying a sufficient source of debris and possibly a quick depositing process. As a result of detouring, the left bank of Chenyulan Stream became a cut bank and was substantially eroded by the flooding caused by Herb, leading to several landslides and riverbank collapses along the left bank.

Furthermore, debris flows have occurred more than three times in and around the Fonchu area (1985/08/23, Typhoon Nelson; 1986/08/22, Typhoon Wayne; and 1996/08/01, Typhoon Herb). Fig. 8 shows the events of 1986 and 1996. The 1996 deposit ($5.0 \times 10^5$ m³) greatly exceeds that in 1986 ($3.3 \times 10^5$ m³; Yu and Chen, 1987). A geo logically fractured zone, a decade of debris accumulation in the upper valley, a major landslide in the upper stream and the extraordinary heavy rainfall are the major reasons for the huge debris flow in the 1996 Herb event.

The 1986 debris flow was deposited spread over the south of the stream outlet, as shown in Fig. 8a. However, during the 1996 event, most of the debris
Fig. 6. Rainfall distribution and debris deposit during the Herb event in the Chenyulan Stream area. The fresh deposits are shown in a light shade. The contours and the number (expressed in mm) indicate the amount of rainfall brought by Herb. The SPOT image was taken on 18 August 1996.
Fig. 7. Aerial photo of the Fonchu debris flow and its vicinity. A check dam located at the upstream was destroyed by the debris flow. Meanwhile, a bridge to the south of Fonchu was also damaged by the flood of the Chenyulan Stream. The aerial photo was taken on 4 August 1996.
Table 3
Morphometric parameters of major debris flows in the study area

<table>
<thead>
<tr>
<th>Location</th>
<th>Date (yy/mm/dd)</th>
<th>Typhoon</th>
<th>Rainfall (mm)</th>
<th>Length of stream (km)</th>
<th>Elevation (m)</th>
<th>Mean gradient (degree)</th>
<th>Area of catchment (km²)</th>
<th>Volume of debris (10⁵ m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fonchu</td>
<td>1985/08/23</td>
<td>Nelson</td>
<td>472</td>
<td>600–2000</td>
<td>19</td>
<td>1.68</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fonchu</td>
<td>1986/08/22</td>
<td>Wayne</td>
<td>321</td>
<td>600–2200</td>
<td>19</td>
<td>1.68</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Fonchu</td>
<td>1996/08/01</td>
<td>Herb</td>
<td>840</td>
<td>600–2200</td>
<td>19</td>
<td>1.68</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Shipachung Stream</td>
<td>1985/08/23</td>
<td>Nelson</td>
<td>472</td>
<td>670–2250</td>
<td>20</td>
<td>2.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shipachung Stream</td>
<td>1986/08/22</td>
<td>Wayne</td>
<td>321</td>
<td>670–2250</td>
<td>20</td>
<td>2.10</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Shipachung Stream</td>
<td>1996/08/01</td>
<td>Herb</td>
<td>840</td>
<td>670–2250</td>
<td>20</td>
<td>2.10</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>Longhwa Elementary School</td>
<td>1998/08/01</td>
<td>Herb</td>
<td>850</td>
<td>860–2100</td>
<td>19</td>
<td>1.67</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Junkengko</td>
<td>1996/08/01</td>
<td>Herb</td>
<td>400</td>
<td>370–1180</td>
<td>21</td>
<td>0.86</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Junkeng Bridge</td>
<td>1996/08/01</td>
<td>Herb</td>
<td>450</td>
<td>380–1310</td>
<td>17</td>
<td>1.93</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Shinyi Center</td>
<td>1998/08/01</td>
<td>Herb</td>
<td>800</td>
<td>440–950</td>
<td>18</td>
<td>0.39</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Tongfu Village</td>
<td>1996/08/01</td>
<td>Herb</td>
<td>850</td>
<td>700–1450</td>
<td>18</td>
<td>0.84</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Shennu Elementary School</td>
<td>1996/08/01</td>
<td>Herb</td>
<td>1150</td>
<td>1180–2710</td>
<td>13</td>
<td>9.10</td>
<td>2.2</td>
<td></td>
</tr>
</tbody>
</table>

Deposited over the northern end of the stream outlet because the 1986 deposit prevented it from moving south (Fig 8b). Unfortunately, the 1996 debris was thus deposited in a residential area and wiped out several houses. This highlights the importance of the existing topography when predicting where the debris will be deposited. Apparently, the existing topography of the deposition area has a significant influence on where new debris will be deposited. Therefore, the morphology of the potential deposition area should be considered when predicting the possible location of a new deposition, where necessary evacuating local residents or employing protective engineering solutions.

4.3. Debris flow — Shipachung Stream

About 2 km to the south of Fonchu debris flow and near the end of Shipachung Stream, another debris flow also occurred during Herb event, as shown in Fig. 7 (marked as debris flow B). This debris flow stream is 4.2 km long, with elevations ranging from 670 to 2250 m, a mean gradient of 20 and a catchment of 2.1 km² (Chen and Yu, 1988). Fig. 8 illustrates that this debris flow also has a recurrent nature.

Due to similar geological and morphometric conditions, and amount of rainfall, the patterns of debris flow in Fonchu and in Shipachung Stream areas are similar. The 1986 debris flow of the Shipachung Stream area was also accompanied by a landslide in the upper stream, as shown in Fig. 8a, which induced more debris than in 1996 event (Fig 8b and Table 3). As discussed by Iverson et al. (1997), landslides profoundly impact the occurrence, transportation and amount of deposition of a debris flow. The cases studied here also demonstrate that, whenever accompanied by a major landslide, a debris flow may deposit more than it would without a landslide.

4.4. Debris flow — Longhwa Elementary School

After the 1994 landslide in the Hosheh area, the inhabitants requested to be relocated to an alluvial fan near Longhwa Elementary School. However, this alluvial fan was identified to have high potential for debris flow due to the following concerns:
1. The catchment of the valley is huge (with an area of 1.7 km²), but drainage is very limited.
2. The gradient of the stream is steep. The stream is 3.6 km long, with an elevation ranging from 860 to 2100 m, resulting in a mean gradient of 19.
3. The Hosheh Stream is forced to detour in front of this alluvial fan. This detour implies a sufficient debris source and possibly a rapid deposit, exceeding the transport capacity of the Hosheh
Stream, formed this fan. Therefore, the possibility that this alluvial fan was formed by previous debris flows cannot be excluded. The above features are compatible with the conditions leading to debris flow (Johnson and Rodine, 1984; Vandine, 1985; Iverson et al., 1997) and make future debris flow a serious concern. Therefore, the local residents were warned against...
selecting this alluvial fan for relocation due to the possibility of debris flow (Jeng and Lin, 1996). As predicted, a major debris flow (with a volume of $10^5 \text{m}^3$) did occur during Herb event, and the Longhua Elementary School was seriously damaged.

5. Discussion and concluding remarks

5.1. Discussion — volume of debris flow

Based on Canadian cases of debris flow, Vandine (1985) observed that the greater the watershed, the greater the volume of debris flow, as Fig 9 illustrates. For comparison, Fig. 9 also plots the debris flows in the study area during the Herb event. The volume of debris flow deposit is estimated from the product of the depositional area with the mean depositional depth based on field investigation. When establishing the regressive relationship of Taiwanese cases, the cases that are accompanied by landslides at upstream, are excluded. Therefore, the regression line of Taiwanese cases only represents those debris flows initiating from steep creek channels, referred to as 'channelized' debris flow (Vandine, 1985; Slaymaker, 1988). As shown in Fig 9, the 'landslide-type' debris flows accompanied by major landslides yield a much greater amount of debris than those channelized debris flows.

A comparison of the Canadian cases with the channelized cases in Chenyulan Stream area reveals similar trends in that the greater the watershed, the greater the debris flow (Fig. 9). However, the Chenyulan Stream area cases have much larger deposits than the Canadian cases (by a factor of about 2.5). This discrepancy possibly results from the differences in geological conditions, amount or intensity of rainfall or other factors.

5.2. Discussion — genesis of fans

An alluvial fan can be formed by flood (a fluvial fan), debris flow (a debris flow fan) or both mechanisms (a mixed fan), depending on geomorphic features and other factors (Melton, 1965; Marchi et al., 1993; Jackson et al., 1987). In general, given the same watershed area, a stream with a steeper slope tends to have a greater potential for a debris flow fan. In contrast, a stream with a relatively flat slope tends to have a fluvial fan (Melton, 1965; Marchi et al., 1993; Jackson et al., 1987). Accordingly, Melton (1965) combined the morphometric parameters, $H_b$ (basin high) and $A_b$ (basin area), and defined a rugged-
Fig. 10. Fan angles formed from various Melton ruggedness numbers. The Italian cases were obtained from the eastern part of north Italy (the eastern Italian Alps) by Marchi et al. (1993). The Canadian cases were obtained from Bow Valley, Kananaskis Valley, Spray Lakes Reservoir and Crowsnest Pass in Canada by Jackson et al. (1987).

Fig. 10 charts the variation of the slope angles of fans located in the study area, Canada (Jackson et al., 1987) and Italy (Marchi et al., 1993) with Melton’s ruggedness number ($R$). As revealed by Fig. 10, streams with a greater $R$ generally have greater fan slope angles. Two boundaries, herein referred to as ‘the lower boundary’ and ‘the upper boundary’, can be drawn to distinguish conditions in favor of the occurrence of respectively fluvial fans, debris flow fans or mixed fans. For the combination of fan slope and $R$ to the right-hand side of the upper boundary, only debris flow can be observed. Similarly, for the combinations of fan slope and $R$ to the left-hand side of the lower boundary, only fluvial fans can be observed. For the intermediate cases between the upper and the lower boundaries, both fluvial fans and debris flow fans, namely mixed fans, are possible.

According to Fig. 10, the lower boundary, distinguishing fluvial fans and mixed fans, is almost identical for all Taiwanese, Italian and Canadian cases. However, the upper boundary of Taiwan cases ($U_b$) is very much to the left of the Italian cases ($U_a$), as indicated in Fig. 10. That is, the streams in the study area, with geomorphic conditions between the two upper boundaries, can have fluvial fans in addition to debris flow fans.

One possible explanation for this discrepancy is that Taiwan has intense rainfall annually during July and September, which may wash off the debris rested along the riverbank. Given a heavy rainfall event and a valley prone to debris flow, if sufficient debris already exists, debris flow would be expected to occur. However, if the debris accumulated in the valley is not sufficient, only the fluvial transport and deposition, namely fluvial fan, can take place. Therefore, the frequent intensive rainfall (or insufficient debris) possibly leads to the occurrence of fluvial fans in the valleys prone to debris flow.

5.3. Discussion — hydrology condition triggering hazards

Both shallow and deep landslides (as defined by van Asch et al., 1996) have occurred during the Herb event. All landslides occurred not long after the initiation of heavy rainfall (within 30 h or shorter). The surface deposits in this area are either alluvium or colluvium (composed of silt, sand and gravel), which allows easy infiltration of water into the soil body or rock joints. Therefore, infiltration of water and accumulated pore pressure

$$R = H_b A_b^{0.5}.$$
may account for the instability of slopes and triggering of shallow and deeper landslides. It has been observed that all bank collapses occurred at cut banks, which is caused firstly by bank (terrace edge) erosion, followed by failure (landsliding) of the bank. Therefore, the stream flow dominates the collapse of riverbank. All debris flows have also occurred during the heavy rainfall period. As the deposit of the riverbed is shallow (commonly less than 10 m) and highly permeable, it is speculated that both overland flow and subsurface flow have accounted for the occurrence of debris flow.

5.4. Discussion engineering factor

The hazards induced by Herb have influenced design codes and governmental policy. As the heavy rainfall of Herb washed debris down from the upstream, followed by blocking of culverts and floods with a recurrence period of 50 years, instead of the previous 25 years standard. Meanwhile, a single-span bridge, instead of a multi-span bridge, has been made the standard for most small highway bridges.

Additionally, a nation-wide inspection of streams with a high potential of debris flow has been conducted. The inspection has screened out 485 streams with high debris flow potential for further investigation (Council of Agriculture, 1996). A comparison of these ‘high debris flow potential’ locations with the tectonic map (Fig. 11) shows that these locations cluster around the major structural lines of Taiwan, namely the major faults. In fact, the heaviest rainfall encountered in the Chenyulan Stream area (48 h rainfall of 800 mm) but in the Alishan area (48 h rainfall of 1700 mm), about 5~20 km from the Chenyulan Stream area (Fig. 6). The Alishan area should have more hazard events than the Chenyulan Stream area, provided all other factors are equal. However, more hazard events were induced in the Chenyulan Stream area. The geological condition of the Chenyulan Stream (being a major boundary fault) is the main cause for this discrepancy. The fact that the Chenyulan Stream has more alluvial fans than adjacent streams again
reflects the fractured, easily eroded nature of this stream.

To predict the location and quantity of debris deposition, which is essential to protect the inhabitants of an alluvial fan, the following characteristics of a debris flow should be cautiously considered:

1. The size of debris flows can be significantly increased by the occurrence of landslides in addition to the volume resulting from the other factors (watershed area, existence of fault, etc.).

2. The location of deposits varies, depending on the existing morphology resulting from previous debris flows.

Since alluvial fans are favored by local inhabitants for cultivation and housing, and since a debris flow is recurrent, protecting the local inhabitants is a problematic challenge. Meanwhile, the extent to which society should expend resources on protecting a very small minority living in a disaster prone area is also controversial.

References


