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RAPID BEDROCK EROSION IN THE TAAN RIVER, TAIWAN

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Due to the results of high storm frequency, active orogeny, and frequent earthquakes bedrock erosion is very active in Taiwan, especially in soft rock. However, the researches on bedrock erosion in Taiwan were not paid much attention in the past. This paper presents a case study of rapid bedrock erosion in the Taan River, which is uplifted by the 1999 Chi-Chi earthquake and has a high erosion rate 4.5myr^{-1} in average. The erosion processes over the pop-up anticline structure are affected significantly by the bedding orientation. The rate of bedrock incision is dominated by plucking from the jointing planes induced by fold-bending.

Key Words : *Bedrock erosion, erosion process, erosion rate, soft rock, plucking*

1. INTRODUCTION

River incision into bedrock in Taiwan was not paid much attention in the past. However, several cross-river infrastructures and hydraulic facilities were suffered severely during the last decade. Hence, the problem of bedrock incision can no more be ignored. Bedrock erosion, especially in soft rock, is very active in Taiwan, which is the result in combination of high storm frequency, active orogeny, and frequent earthquakes[1, 2]. Regionally, Taiwan is located the boundary between the Philippine Sea Plate and the Eurasian Plate, with a relative convergence rate of more than 80mmyr^{-1} in a southeast – northwest direction[3]. Hundreds of mountains are more than 3 kilometers in height, though the island is roughly north-south for a length of 385 kilometers and east-west width of 143 kilometers, which results from being in a modern mobile belt, and accounts for the complex geological formations and structures[4]. With subtropical weather, mean annual precipitation is about 2,500mm, and an average 3.7 typhoons (standard deviation 1.7, 1897-1996) hit Taiwan[5], thus floods often dominate the fluvial bedrock incision.

Bedrock erosion is complex interaction comprising of geography, tectonics, lithology, channel hydraulics, sediment transportation, and climate[6, 7]. The understanding to these phenomena still was not sufficient to have a robust and quantitative description[6, 8, 9, 10]. The processes of river incision into bedrock including abrasion (bed load saltating, suspensions wearing), plucking (hydraulic wedging and quarrying), cavitation, weathering, knickpoint propagation, and scour by debris flow, etc[6, 7, 8, 9, 11, 12]. For erosion rate of regional scale, abrasion is probably the major influencing process whereas of rate limited, in contrast with plucking, which is efficient in small reaches with similar joint and bedding planes. Whipple et al.[9] denoted the most lacking understanding was the relative contribution of various processes under different conditions. Indeed, the results of bedrock erosion would be hardly caused as simply one process; it is also difficult to measure directly because of accessibility during floods.

The published data related to bedrock erosion of Taiwan in both spatial and time distribution is very limited. In the Western Foothills thrust belt, the range of erosion rate is 1 – 54 mmyr^{-1} from the records of river suspended-sediment discharge; the bedrock strath incision rate by dating 14C at Holocene strath terraces is over 15 mmyr^{-1} [1]; and the rate is grater than 125 mmyr^{-1} measured with erosion pins at 4 locations near upstream of the Chelungpu fault scrap[13]. The Liwu River in Eastern Taiwan, which underlain by metamorphic rock, has been much more studied in details. Its erosion rate is 5 ± 1 mmyr^{-1} for frequently intermediate size floods, and the rare large floods contribute mainly in widening channel[2]. Its long term average rate is 26 ± 3 mmyr^{-1} throughout the middle and late Holocene dating by cosmogenic nuclides[14]. Also, its lateral erosion characteristics can be adopted for explaining the shear stress distribution and cover / tool effects[15].

This paper aims to present a preliminary case study of the site in the Taan River, Taiwan, which was uplifted during the Chi-Chi earthquake, and sculpted just a few years to a gorge due to bedrock incision with the maximum depth up to 20 meters. The average rate of incision 4.5myr^{-1} from 2004-2008 is very rare worldwide. The work attempts to construct scenarios which could lead to know the reasons of rapid erosion more properly.

2. SITE DESCRIPTION OF THE TAAN RIVER

The Taan River located in west-central Taiwan (**Fig.1**), is one of the major rivers in Taiwan. It is 96 km in length and flows northwestward into the Taiwan Strait. The drainage area is about 758 square km. The Taan River originates in the western Hsuehshan Range (elevation near 3,500 meters). Its upstream above the Shuang-Chi creek (**Fig.2**) is in mountain area (elevation > 500 meters), and the average slope is about 1/50. From the Shuang-Chi creek to 12.7km in longitudinal distance, the average slope decreases to 1/76, and is about 1/90 from 12.7km to estuary. Mean annual precipitation is between 1,200 – 1,800 mm and distributed mainly during the summer for about 80%.

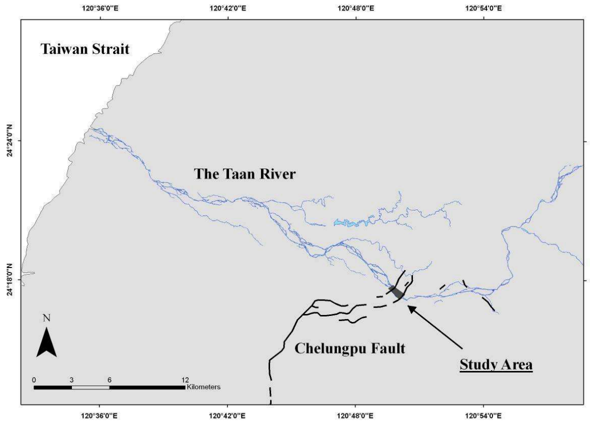


Figure.1 Study area of the Taan River, Taiwan.

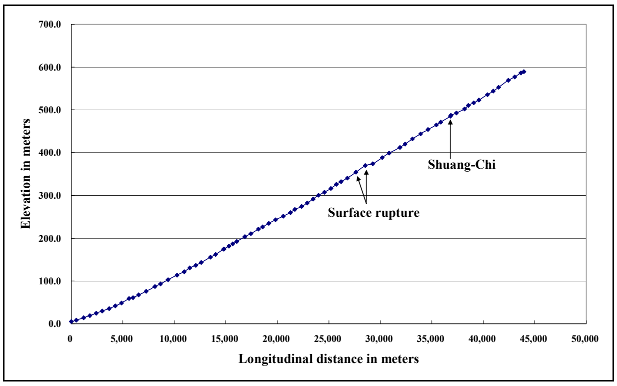


Figure.2 Longitudinal profile of the Taan River, 2004.

3. THE EFFECTS OF THE 1999 CHI-CHI EARTHQUAKE IN THE TAAN RIVER

On 21 September 1999, the Chi-Chi earthquake of magnitude Mw 7.6 took place and ruptured the preexisting 100-km-long Chelungpu fault in central western Taiwan. It is the largest inland earthquake in the twentieth century. In the north of the Chelungpu fault, the rupture turns to the east, diverges into several sub-paralleling branches, and extends northeastward to the Taan River. There are two fracture structures across the Taan River near the villages of Shanshin and Neiwan (**Fig.3**). The surface ruptures trend approximately parallel in northeast direction, and create a pop-up anticline structure. The length of the pop up structure is about 1 kilometer along the river. The vertical slip (i.e. the height of a fault scarp) was measured by the Taiwan Central Geological Survey, at CLB03 is about 5 meters and 6 meters at CLD05[16] (**Fig.3**). Based on the coseimic displacement data of Taiwan Global Positioning System network (established in 1989), the vertical displacement is less than 1 meter in adjacent to the Taan River valley[17]. Yue et al.[18] have developed structure models for whole region to explain this thrust-belt earthquake.

As the result of surface deformation, the pop-up anticline structure has blocked flow into a lake at the

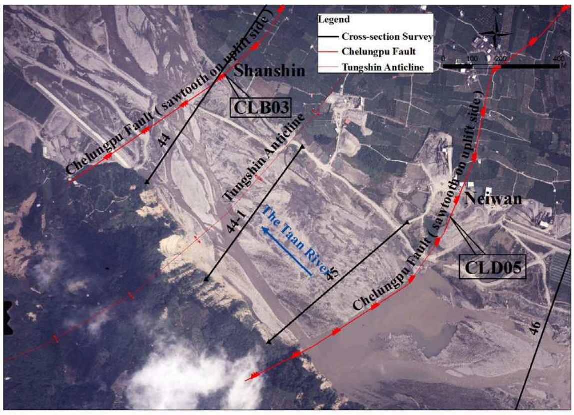


Figure.3 Aerial photo of the Taan River valley (1999/9/22, Aerial Survey Office, Forestry Bureau, Taiwan), showing the uplifted boundaries and a small lake at upstream. CLB03 and CLD05 are the vertical slip measured positions.

Taan river channel (**Fig.3**). Note that the initial outflow from the lake is close to the left bank on 1999/09/22, later the main channel changes to the middle after engineering excavation. The channel slope has also been changed due to the uplift. From cross-section 44 to 44-1 (**Fig.3**), the channel slope increases from 1/76 to 1/36, but decreases to 1/88 from cross-section 44-1 to upstream about 3 km.

4. GEOLOGICAL BACKGROUND

The study area was an alluvial channel before the Chi-Chi earthquake. The D10, D50, and D90 of bed materials at cross-section 44 (**Fig.3**) are 1, 142, and 400 mm, and at cross-section 45 are 0.7, 165, and 420 mm respectively[19]. The alluvium underlay the Pliocene Cholan Formation, which is composed of sandstone, siltstone, mudstone, and shale in a monotonous alternating sequence. The bed thickness of sandstone is ranging from tens centimeters to 2 meters, yet some can be greater than 5 meters. The shale and mudstone are generally in beds 20 to 50 centimeters thick, and locally thicker[4]. The pop-up anticline, named as Tungshih anticline, trends in NE-SW direction (**Fig.4**).

The Tungshih anticline is a fault bend fold induced by the Chi-Chi earthquake[20]. Hence, the anticline exhibits a smooth flexure on the west limb and a sharp rupture on the east limb. Based on the field measurements of bedding orientation, this pop up structure can be divided in to 3 zones (**Fig.4**). Zone1 is the west limb with dip angle being 22° in west increasing to over 38° in east. Zone 2 is the fold axis area with nearly horizontal bed. Zone 3 is the east limb with dipping angle being 12° in west increasing to 68° in east. Also from the field observations, there are two types of fractures accompanied the process of fold bending. One is the tension fractures set caused by layer-parallel stretching on the outer folded layer. The other is the conjugated shear fractures set caused by the forces from fault thrusting.

5. EROSION PROCESSES

(1) Longitudinal profiles

In **Fig.5**, the longitudinal profiles of year 1993,

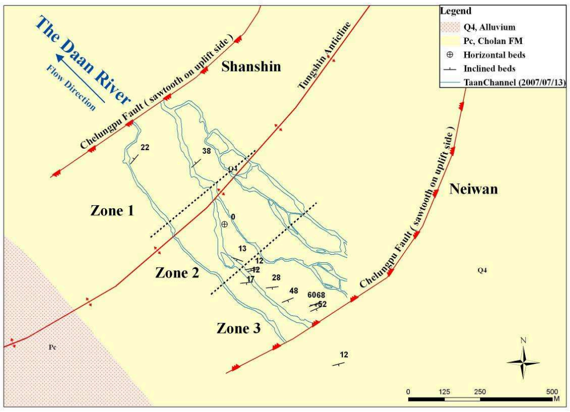


Fig.4 Geological map of uplifted area in Taan Valley.

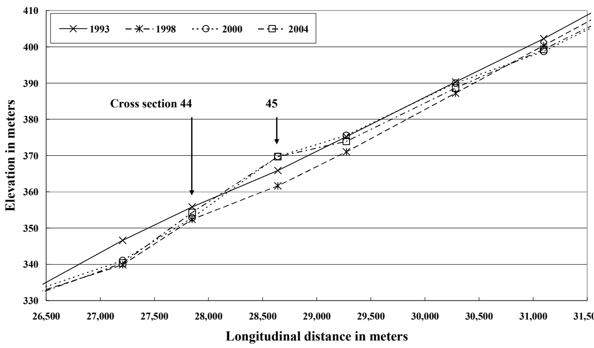
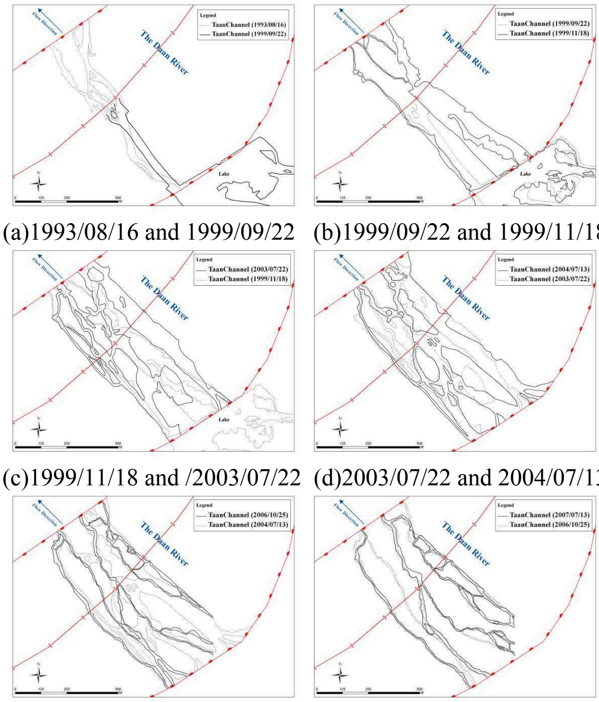


Figure.5 Longitudinal profiles of the Taan River in uplifted area.

1998, 2000, and 2004 are drawn side by side for comparison. Note that the uplift zone is between cross-sections 44-45. From 1993 to 1998, due to gravel mining, the average height of riverbed was descended with 2-6 meters. After the 1999 Chi-Chi earthquake, the elevation of the river bed in 2000 is higher 1-8 meters than that in 1998. For year 2000 and 2004, the elevation was about the same at cross-section 45, but increased 1.4 meter at cross-section 44. In general, the uplift structure has slowed down the degradation upstream, and prohibits part of sediments transportation; as a result, the degradation of downstream channel is increased.

(2) Channel diversion

Fig.6 shows the Taan River channel adapted from orthophoto base maps in different periods. In 1993/08/16, the channel is slight curved toward one longitudinal bar, then expands from a diagonal bar, separates into two flows by an island (**Fig.6a**). Right after uplifted by the earthquake (1999/09/22), a lake forms in upstream of the pop-up structure, with slope increased, the channel became relatively straight (**Fig.6a**). Two months later, a wider channel was excavated at river center to prevent undercutting the left hillslope (**Fig.6b**). In 2003/07/22, the channels were still widened but parts of them were constrained by bedrock outcrop in downstream side of the anticline axis. Then, there were lateral channels existed along the stratum trending of west limb, also some narrow channels were formed along the dipping direction (**Fig.6c**). In 2004/07/13, the channels pattern did not change compared to the previous year. Implicating erosion progress along channels was relatively confined, but not deeply incised because the channels were still widened (**Fig.6d**). The width of channels had been changed greater in 2006/10/25 (**Fig.6e**) i.e., the channel was much narrower which represented a deeply down cutting. Following the erosion process proceeded downward, the banks were getting steeper accompany slope failure gradually; as the result of bank erosion, the channel was widened in 2007/07/13 (**Fig.6f**).



(a)1993/08/16 and 1999/09/22 (b)1999/09/22 and 1999/11/18

(c)1999/11/18 and /2003/07/22 (d)2003/07/22 and 2004/07/13

(e)2004/07/13 and 2006/10/25 (f)2006/10/25 and 2007/07/13

Figure.6 Comparisons of the Taan River channel in different periods..

(3) Channel cross-section

There were two cross-section surveys carried out in 2000 and 2004 respectively after the 1999 Chi-Chi earthquake. Refer to **Fig.7**, the entire cross-sections (44, 44-1, and 45) of the pop-up area did not show significant bedrock incision, which was agreed with the discussion in channel diversion. Since the cross-section surveys were not carried out at the same location, the shapes of riverbed in **Fig.7** are slightly different.

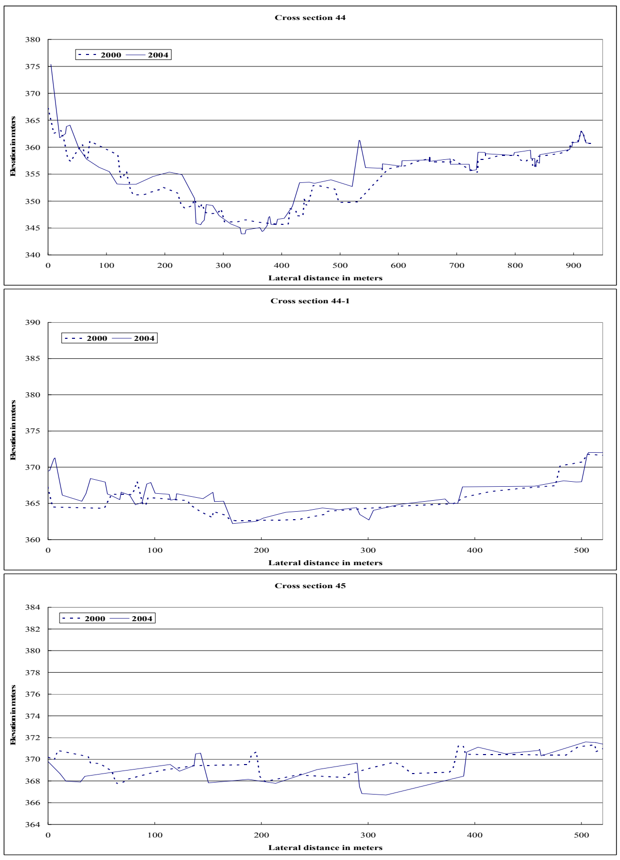


Figure.7 Comparison of cross-section 44(a), 44-1(b), and 45(c) in year 2000 and 2004

(4) Erosion processes

All the strata of anticline structure belong to the late Pliocene Cholang Formation, but strata attitude are different in three zones (**Fig.4**). According to the field observations, the erosion conditions in these zones are different. In zone 1, bedding planes are dipping downstream and the outcrop of sandstone stratum found here is relatively fresh (**Fig.8a** and **Fig.8b**) than in other zones. It maybe inferred that, while the weak siltstone, mudstone, or shale are eroded from the bedding planes, the strong sandstone will dislodge rapidly along the joint plane and displacing by gravity or flood. It is also noted that there is no flute or pothole in this zone. In zone 2, the bedding is almost flat; erosion processes are dominated by both abrasion and plucking. Dislodged blocks (**Fig.8e**), stages developed along sandstone layers (**Fig.8f**), large flutes and narrow incised channel (**Fig.8c** and **Fig.8d**) all exist in this zone. There is a knickpoint (waterfall, **Fig.8g**) in the border of zone 2 and 3, which shows the resistance to erosion is much greater when the bedding is dipping upstream (Zone 3). The resistive phenomena of zone 3 can be observed along the channel (**Fig.8h**).


(a)Outlet of zone 1, dipping downstream.


(b)The border of west limb and flatten top.


(c)Zone2, narrow deep channel.


(d)Zone 2, large flutes on thick sandstone.


(e)Zone 2, huge dislodged block.


(f)Stages formed by resistive sandstone.


(g) The border of zone 2 and 3, a knickpoint.


(h)Zone 3, more resistive dipping upstream.

Figure.8 Field photos of erosion processes

(5) Erosion rate

As mentioned above, the channel was not yet deeply incised into bedrock from the latest data of cross-section surveys in 2004. A narrow channel with gorge shape is found on the 2006 and 2007 orthophoto base maps due to a strong typhoon attacked the area in 2005, but there is no contour across those gorges due to the map resolution. The depth of the gorge was measured at two locations this year (2008). The depth from top of channel bank to the water surface at upstream side of zone 2 is about 12 meters and is about 23 meters at downstream side of zone 2, respectively. Assuming the channel incision from 1999 to 2004 can be neglected, the average erosion rate (2004-2008) is $4.5 myr^{-1}$.

6. CONCLUSION

In the Western Foothills of Taiwan, the Pliocene and Pleistocene formations with weak strength are vulnerable to erosion. Once the erosion process initiates, it continues and hardly ceases until new equilibrium is reached. The case of rapid incision in the Taan River is definitely a local condition due to uplift of faulting. The case shows that the river channel is sculpted just a few years to a gorge with the maximum depth up to 20 meters and the average rate of incision is larger than $4.5 myr^{-1}$ from 2004-2008. From this preliminary study, we also found the bed orientation is important to bedrock erosion. Plucking is the most efficient process of erosion while jointing condition is permitted. Finally, the bedrock erosion starts from incising into weak planes, proceeds with flute, narrow deeply channel, then channel widening.

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