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Impacts of the 921 Ji-Ji earthquake, Taiwan, on channel morphology and channel evolution

Y. H. HSU[1] & Y. S. HSU[2]

1 *Civil and Hydraulic Engineering and Construction and Disaster Prevention Research Center, Feng-Chia University, Taichung 407, Taiwan, Republic of China*
yuhsiung@mail2000.com.tw

2 *Department of Water Resources Engineering, Feng-Chia University, Taiwan, Republic of China*

Abstract On 21 September 1999, an earthquake, that measured 7.3 on the Richter scale, erupted with the epicentre located at Ji-Ji Township in central Taiwan. A large-scale landslide took place during the Ji-Ji earthquake. Landslide masses plugged the original channel of the Chingshui River and created an upstream dammed reservoir – the Tasoling Lake – with a water volume of 42 000 000 m^3. Subsequently, the area was affected by a series of typhoons and associated floods in 2001 and 2004. The newly formed channels show disparate patterns of channel evolution, and provide a rare opportunity for field observation and data collection. In this paper, the landslide-dammed lake was reconstructed using historic documents and geomorphic channel evolution. The result shows the channel is at a stage where the bed-slope is going through self-adjustment. Backward erosion at the spillway notch leads to lowering of the longitudinal bed slope.

Key words landslide-dammed lake; channel evolution; Ji-Ji earthquake, Taiwan

INTRODUCTION

Landslide-dammed lakes are formed when a waterway is impounded by obstructions and floods the upstream area. Landslide-dammed lakes frequently occur in mountain areas around the world and cause severe damage. For instance, rivers in the Canadian Cordillera have been dammed by landslides and debris flows and formed large-scale dammed lakes 18 times since 1880 (Evans, 1986). The Yi-Gong River in southeastern Tibet has been known for the repeated incidence of landslide dams that blocked the channel course, with the latest one occurring on 9 April 2000. A landslide event of over 3×10^8 m^3, within 8 minutes, caused a landslide dam of 130 m in height and a dammed lake 1.5 km long, which breached on 10 June 2000, and induced large-scale damage to the downstream areas (Shang *et al.*, 2003). Similar to the Yi-Gong River geomorphology, the Taiwanese Tsaoling area studied here has undergone five major landslide events in the last century that impounded the Chingshui River and created dammed lakes. Both areas are characterized by frequent events of landslide-dammed lakes.

The Tsaoling landslide-dammed lake, initially formed by a massive landslide triggered by the 921 Ji-Ji earthquake, subsequently developed significant fluvial processes due to a series of typhoons/floods in the following years. It therefore became a rarely observed case of a dammed lake, including severe sedimentation in the upstream lake, gully erosion in the landslide dam, and alternating erosion–deposition patterns along the downstream reaches. Observation and analysis of topographic changes in the landslide-dammed lake, and of the downstream bed evolution, can help to understand the formation and disappearance of the dammed lake, as well as their effects on downstream channels.

METHODS

In this study, topographic changes, historical channel surveys, and past records of relevant investigations were gathered and applied in a geomorphic analysis to study channel evolution for the Tsaoling landslide dam and the Tsaoling dammed lake.

The Tsaoling landslide-dammed lake of 921 Ji-Ji earthquake

A mega earthquake of 7.3 occurred on 21 September 1999 in central Taiwan. The violent tremors caused a large-scale landslide on Tsaoling Mountain, located near the town of Gu-Keng in Yun-

Lin county; the mud and rocks from the landslide impounded the original channel of the Chingshui River, and formed a landslide-dammed lake upstream. The Chingshui River, flowing through central Taiwan, is the second largest tributary of the Zhuo-Shui River, the longest in Taiwan (Fig. 1). The Zhou-Shui River has an average channel slope of 1/56, and a length of 186.6 km. Based on historical records, there have been five incidents of landslide-dammed lakes in the area caused by earthquakes and typhoons/floods. Among them the dammed lake that had formed in 1942 and breached in 1951, caused 137 casualties and severe damage to more than 3000 ha of land and properties of 10 000 people. In 1999, the massive soil and rocks of the landslide event induced by the 921 Ji-Ji earthquake blocked a significant segment of the Chingshui River, approx. 4815 m in length and 50 m in height, the landslide mass was about 1.2×10^8 m^3 in volume, and created a dammed lake (Hsu *et al.*, 2004).

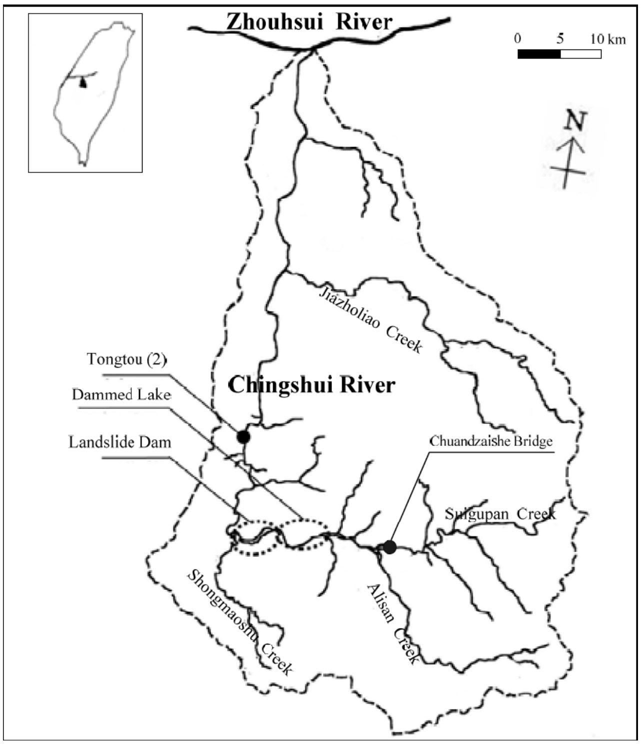

Fig. 1 The Chingshui River watershed and locations of the landslide dam from the Ji-Ji earthquake.

ANALYSIS OF MORPHOLOGICAL CHANGES IN THE LANDSLIDE AREA DOWNSTREAM OF THE DAMMED LAKE

Plan view of channel evolution

Flows passing through the spillway channel induce continuous erosion in the channel bed and downcutting downstream from the landslide-dammed lake. As the bed deepens, the riverbanks become unstable and may collapse due to undercut or excessive repose angle. The collapsed bank mass would block either the entire or partial flow paths, and force the flow path to alter and possibly swing over an area. Channel courses surveyed over four different years, together with locations of survey cross-sections, are plotted in Fig. 2. Except for some appreciable course changes at cross-sections 135, 140, and 144, the overall flow path remained stable. Chronologically, a larger amplitude of channel swing occurred mainly between May 2000 and December 2001, and major hydrological events were associated with typhoons Toraji and Nari.

At cross-sections 137 and 146, the pattern shows the bed becomes deeper and the channel wider. The cross-section at the spillway notch is narrower, forcing the passing flow to incise with

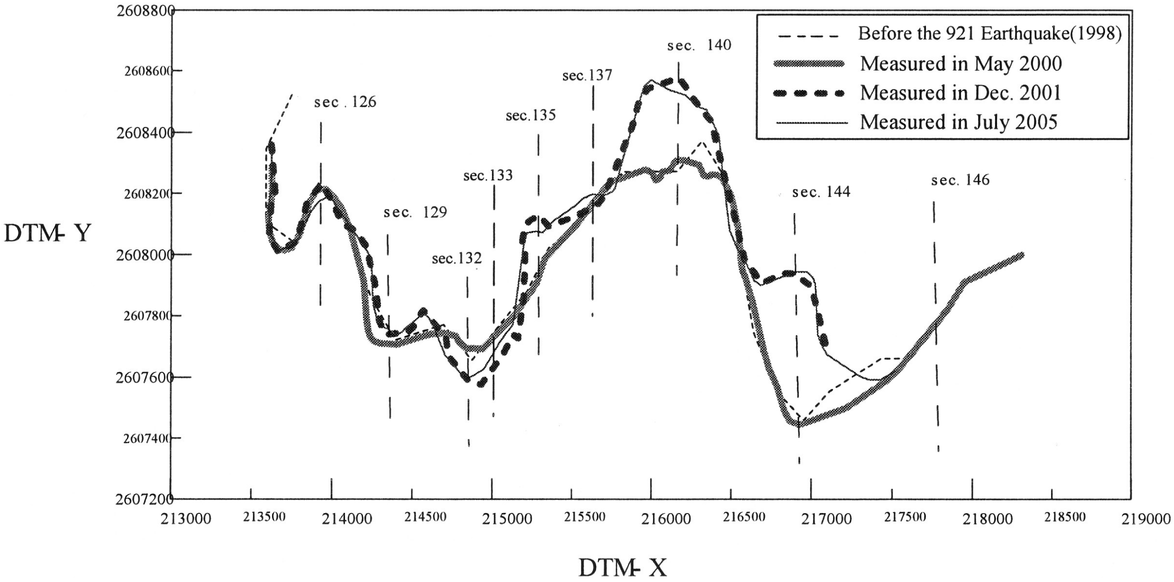

Fig. 2 Plan view of channel evolution of the Chingshui River after the Ji-Ji earthquake.

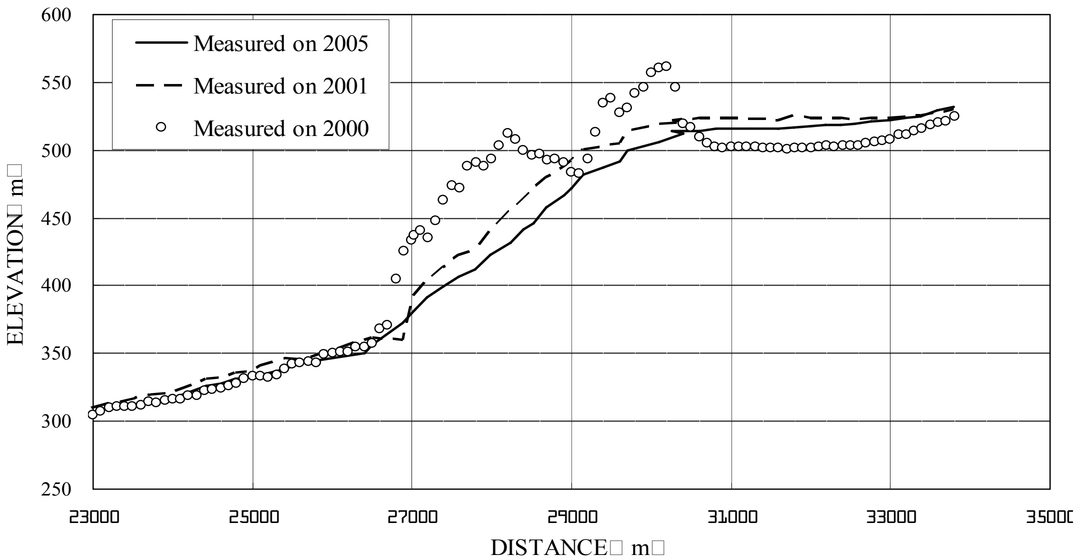

Fig. 3 Longitudinal bed profiles of the Chingshui River after the Ji-Ji earthquake.

force; therefore, the tendency of the channel in the overflow section is continuing to become wider. On the other hand, cross-sections 129 and 133 indicate narrowing. A possible cause may be its downhill location at the mass-wasting site where the channel slope changes from steep to mild. Continuous erosion at the toe of both banks may have broken the stability of the hills and induced localized landslides to fill the channel, depositing sediment of large cobbles in this area.

Longitudinal channel bed profile analysis

Longitudinal bed profiles surveyed during 2000, 2001, and 2005 are plotted in Fig. 3 for comparison. When the Tsaoling dammed lake and landslide area first formed, a natural furrow emerged on top of the landslide area that was cultivated into an emergency flood conveyance channel of about 4.5 km by the Water Resources Agency. The 921 earthquake plugged the Chingshui River with the landslide; debris piled in the channel with the thickest section reaching

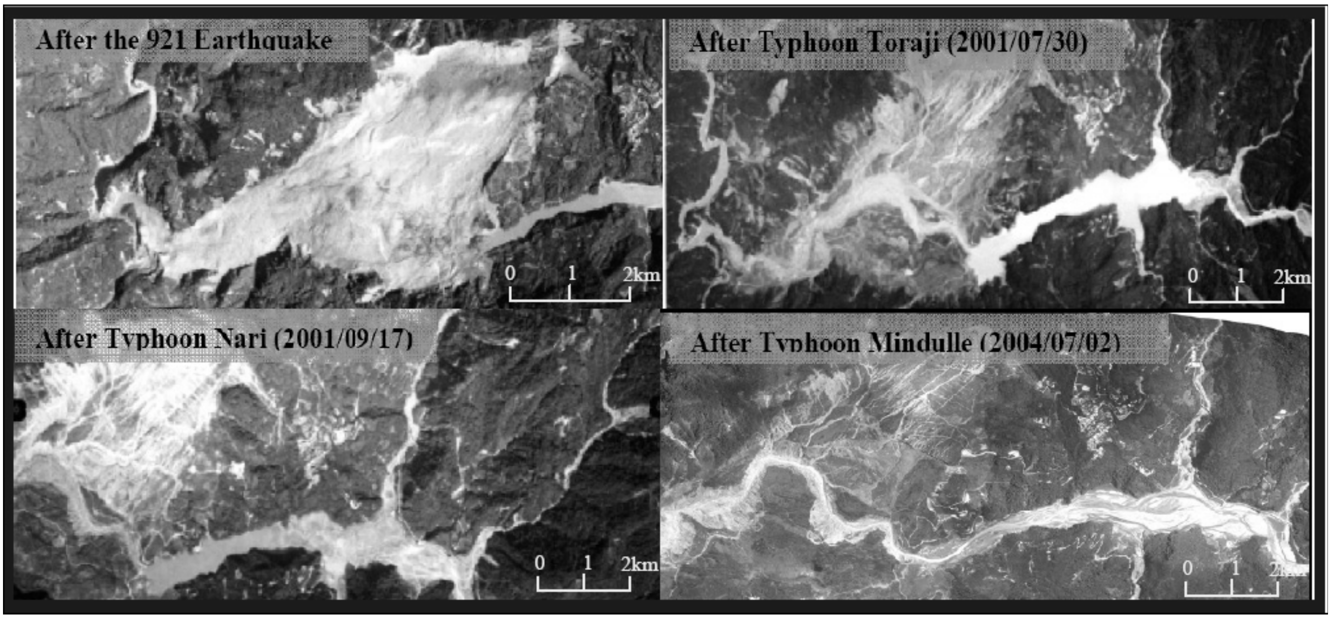

Fig. 4 Changes in channel morphology after selected typhoon events.

approx. 100 m and the average bed slope for the landslide area about 1/25 m/m. The landslide-dammed lake functioned as a check dam to trap sediment and the resulting clear water scoured downstream channels. Torrential rainfall during typhoons Toraji and Nari in 2001 caused vast topographic changes to the landslide area, where the hydrological characteristics also contributed to the severe channel bed incision. Surveys after the two typhoons of 2001 showed an approx. 35-m drop in the channel downstream and a 15-m incision in the spillway notch (Fig. 3). However, in 2005 the bed slope in the area showed a decrease, with sediment deposition of about 12–13 m. The new channel slope, now more slack, is at a self-adjusting stage, the average gradient in the landside section being about 1/30 m/m.

In general, from 2001 to 2005 the average incision depth at the spillway notch was about 8.5 m. The evolution of the channel section in the dammed lake showed the channel course to be degrading as the channel at the spillway notch and downstream incised, which indicated the deposition in the dammed lake had been transported downstream as a result of the typhoon/flood events. A survey conducted from 2001 to 2005 showed that the gully in the channel of the dammed lake, 2 km upstream from the spillway notch, dropped from about 4 to 8 m. Figure 4 shows a series of satellite pictures of the area after each typhoon event.

RESULTS AND DISCUSSION

The dammed lake reach

Field reconnaissance showed that braided channels are developing in parts of the dammed lake reach, some accompanied with river terrace landscapes. At the outlet cross-section, the channel width is only ¼ of the average width of the lake section. As the Chingshui River flowed into the dammed lake, with its flow velocity reduced and sediment carrying capacity weakened, it deposited most of the sediment carried from upstream in the lake.

Therefore, it can be stated that flood duration and peak discharge magnitude were the two factors determining the erosion depth at the overflow reach and the sediment volume in the dammed lake. The survey data from 2001 and 2005 show changes in bed elevation; the deposited sediment in the dammed-lake reach moved downstream following occurrences of extreme hydrological events, down-cutting the flow course in the dammed lake, where the lowest elevations of the deep gully dropped by between 4 and 8 m. Most notable is the continuing channel erosion that occurred in the segment between cross sections 147 and 161. During the four-year period, approx. 2.3×10^6 m^3 of sediment eroded away and the average channel bed elevation dropped 2.5 m.

Channel reach in the landslide area

This channel reach was formed by flow directly carving into the soil mass in the landslide area. When the stream flowed through the spillway channel in the landslide area, and continued into the bed and bank toes, the undercut bank mass became unstable and eventually collapsed, which in turn blocked off or pushed the flow to alter its course, or to swing in the plan view. This could be explained by the field investigation showing that at the spillway notch, the cross-section was narrow and passing flow generally had higher velocity and energy for erosion, and therefore, stronger capability to cause bed undercut. The degree of down-cut at the outlet section increases with increases in incoming flow discharges. As the bed elevation lowered, the potential energy of the upstream flow increased and backward erosion was induced.

Therefore, we can conclude on the basis of hydraulic characteristics, that the landslide reach was in a stage of gradual bed erosion and widening, as illustrated in Fig. 5. Presently, the channel is at a stage where the bed slope is going through self-adjustment. Through the backward erosion at the spillway notch lowering the longitudinal bed slope, the flow would lower potential energy to incise. On the basis of these analyses, the study concluded that the current channels of the Chingshui River were gradually evolving towards the original course, i.e. before the 921 earthquake.

It is possible for the landslide to be reactivated in the near future, particularly due to the inherent seismic risks. The investigations of the channel evolution showed in this study can assist in improving management strategies for treating the mass of the landslide.

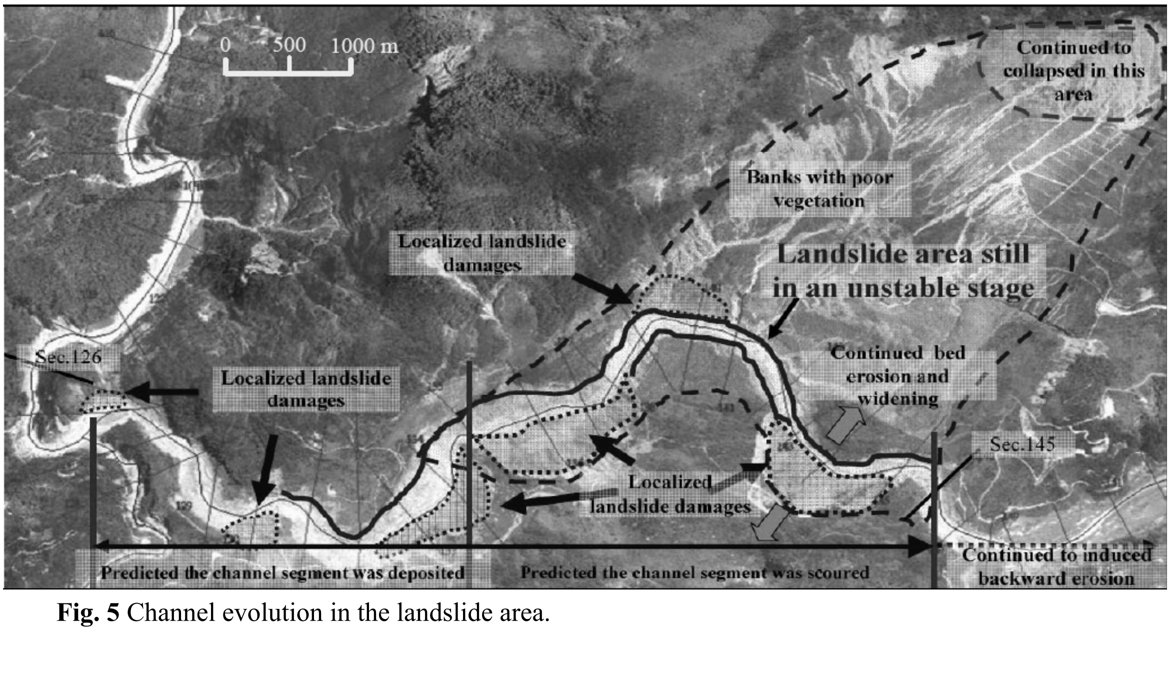

Fig. 5 Channel evolution in the landslide area.

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