The processes and rates of knickpoint migration in western Taiwan

Ming-Wan HUANG(1), Yii-Wen PAN(2) and Jyh-Jong LIAO(2)

(1) Disaster Prevention & Water Environment Research Center, National Chiao Tung University, Taiwan
E-mail: mwh@nctu.edu.tw
(2) Department of Civil Engineering and Disaster Prevention & Water Environment Research Center, National Chiao Tung University, Taiwan

Abstract

A knickpoint is a location with a sharp slope change in the longitudinal channel profile. Knickpoint migration is often a result in response to an abrupt base-level fall or a change in bedrock resistance. Many knickpoints have formed in river channels intersected by fault ruptures after the 1999 Chi-Chi earthquake. The migration processes and rates for these earthquake induced knickpoints were significantly different with the knickpoints formed in river junction or due to a difference in bedrock resistance. Based on the attitude of rock strata and the flow direction, the knickpoints could be classified into dip, strike, or anti-dip knickpoint. We carried out the site investigations for studying knickpoint migration process in western Taiwan. Also, the averaged migration rates in 10 reaches are derived from a series of chronological aerial photographs; among them, 5 reaches were verified with DEM data. The average rates of knickpoint migration were 57, 110, 83 myr^{-1} for dip, strike, and anti-dip knickpoint, respectively. Finally, the knickpoint migration processes were interpreted based on the results of field study.

Keywords: knickpoint, migration processes, migration rate, western Taiwan

1. Introduction

A knickpoint is a location with a sharp slope change in the longitudinal channel profile, and the channel is connected with an over-steepened reach. A plunge pool is often formed in the bottom of the knickpoint through toe scouring due to the accelerating flow of the knickpoint elevation drop. Knickpoint migration is an important process of bedrock channels in response to a base-level fall. The possible causes to induce a base-level fall include active tectonics, climate change, sea-level fall, river capture, resistant caprock, and differential incision in tributary junction, *etc*. (Frankel et al., 2007; Seidl and Dietrich, 1992; Whipple, 2004)

Several researchers have investigated the behavior of knickpoint migration based on flume tests (Frankel et al., 2007; Gardner, 1983; Holland and Pickup, 1976). Gardner (1983) proposed three types of knickpoint evolution models: inclination, parallel retreat, and replacement. The processes of knickpoint evolution are controlled by two primary factors: the actual shear stress and the critical shear stress of the channel bed. Frankel *et al*. (2007) proposed another knickpoint evolution model in a vertically bedded substrate; the model elaborated the processes of replacement and parallel retreat. Haviv *et al*. (2010) numerically simulated the evolution of vertical knickpoints with resistant caprock. They assumed the resistant caprock could only be removed through cantilever. Their results suggested that the knickpoint migration rate was closely related to downstream incision rate divided by channel gradient under the condition of a critical height for the sub-caprock failures.

The knickpoint migration rate is usually evaluated from the total retreat distance over the elapsed time period. Due to the scarce data of the average migration rate, the landscape change is often too small to realize. The knickpoint migration models considers the drainage area as a primary factor, other factors taken into account in the models may include channel slope, channel width, sediment transportation, lithology, geology structure, etc. (Berlin and Anderson, 2007; Bishop *et al.*, 2005; Crosby and Whipple, 2006; Hayakawa and Matsukura, 2003; Loget and Van Den Driessche, 2009; Valla *et al.*, 2010) Loget and Van Den Driessche (2009) compared average migration rate of knickpoints for variety ranges of rate (up to 1000 my^{-1} in alluvial rivers, and 0.001 my^{-1} in bedrock rivers), time scales (10^1 – 10^7 years), and drainage areas (10^{-2} – 10^7 km^2), and found that the longer the time scale, the lower the migration rate. From their data, the average migration rate of the bedrock knickpoints ranges from 0.001 to 30 my^{-1} and is mostly less than 1 my^{-1}.

The 1999 Chi-Chi earthquake (Mw=7.6) took place in central Taiwan; a 100 km surface rupture along the Chelongpu fault was generated by thrust faulting with fault scarps or pop-up deformations across four major rivers in central Taiwan (including the Taan River, the Tachia River, the Wu River, and the Choshui River). The earthquake induced riverbed deformations and formed knickpoints in these rivers and their tributaries. The knickpoint migration rate of the Taan River derived from multistage annual longitudinal profiles was up to a few hundred meters per year (Huang *et al.*, 2013). The knickpoint migration rates in the Tachia River and three main branches of the Wu River were from 3.3 to 220 meters per year (Hayakawa *et al.*, 2012; Hayakawa *et al.*, 2009). The migration rates of the Chi-Chi earthquake induced knickpoints were considerably much higher than worldwide data.

Due to the complicated geological structures and the meandering channels in central western Taiwan, the relationship of the attitude of rock strata and the flow direction varies with the channel location. From the field observation, the migration rate and the migration process are different for the different knickpoints.

This study aims to investigate the influence of rock orientation (relative to the flow direction) on the migration processes and rates of different types of knickpoints in western Taiwan. The channel erosion of the surface deformation reaches and the processes of knickpoints migration along the Chelongpu fault are examined. The averaged migration rates were derived from a series of chronological aerial photographs. The types of knickpoints migration are discussed based on their processes and migration rates.

2. Site background

The Chelongpu fault in western Taiwan is a major thrust fault with the north-south strike and the dip toward east (Chen et al., 2003). The fault thrusts the Pliocene-Pleistocene strata over modern sediments approximately along the mountain front of the Western Foothills (Fig. 1). Table 1 lists the 19 locations of fault scarps of pop-up deformations across the mentioned four major rivers and their tributaries, according to the geological survey report of Taiwan Central Geological Survey (Central Geological Survey, 1999). The channel bedrocks are young sedimentary rocks mainly composed of sandstone, shale, thin-interlayered sandstone and shale.

3. Aerial photo interpretation and field investigation

The changes of the 19 knickpoints were firstly examined through historical aerial photographs including channel geometry, sediment/bedrock distribution, possible knickpoint locations (locations of rushing flow or water spray) and knickpoint retreat distances, *etc*. Then, the field investigations for knickpoints erosion processes and surface geology were carried out based on the results of aerial photographs interpretations. The results are compiled in Table 1. The unconfined compressive strength of the bedrock tested via Schmidt hammer (using a Silver Schmidt type BN hammer with a mushroom plunger) are typically less than 10 MPa.

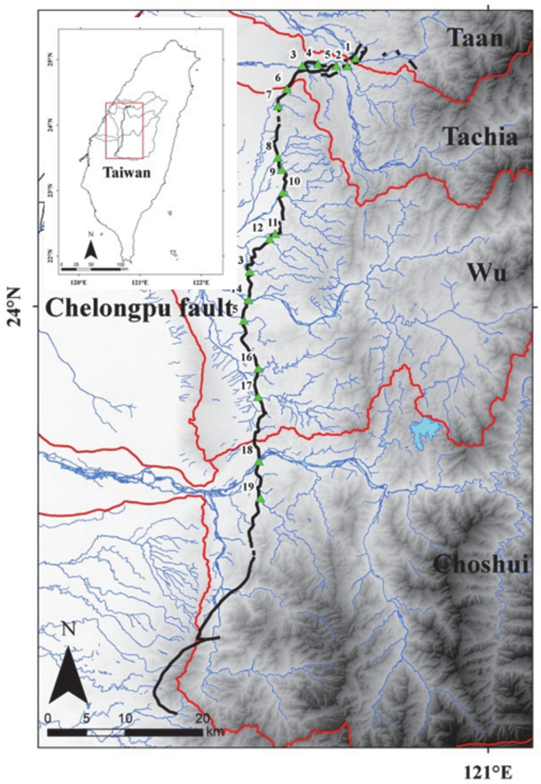

Fig. 1 Location of the surface ruptures of the Chelongpu fault in the 1999 Chi-Chi earthquake. The green triangles with site numbers indicate the investigation reaches with data listed in Table 1.

No knickpoint retreatment was observed in 9 rivers which are crossed by the Chelongpu fault; the possible reasons for no retreat could be the following one.

1. Certain protection work was constructed in the channel shortly after the earthquake so that has prevented further erosion to occur, e.g. the Han River (Photo 1a), the Wuniulan River, the Puzikeng River and the Ailiao River.
2. The uplift height was small, and the armor layer was thick enough to compensate the earthquake uplift, e.g. the Wu River (Photo

1b), the Changping River, and the Maoluo River.
3. The earthquake rupture was nearly parallel across the channel and was unlikely to form a knickpoint, e.g. the Caohu River (Photo 1c) and the Dongpurui River.

The knickpoints in the other 10 reaches triggered significant bedrock erosion by knickpoint retreatment noticeable from aerial photographs. The locations of knickpoints were carefully identified on series of aerial photographs (Fig. 2). We also used the DEM data to identify the knickpoint locations in five reaches including the Taan River, the Tachia River (Meizi Bridge), the Toubiankeng River, the Gan River, and the Choshui River (Fig. 3). The average recession rates for these knickpoint were evaluated from the total retreat distance over the total time period of the respecting photographs. Based on the stream direction and the rock bedding attitude, the knickpoints can be classified into three types, dip, strike, and anti-dip.

Table 1 Compiled data of the investigated reaches along the Chelongpu fault

River	Site No. in Fig. 1	Uplift height [a] (m)	Stratum dip and flow direction	Fault strike and flow direction	Recession duration [e]	Average recession rate (m/yr)
Taan	1	6	dip, ~strike, and anti-dip knickpoint (migration cross an anticline)	~ perpendicular	1999-2010	dip: 53 ~strike: 93 Anti-dip: 294
Shalien [b]	2	5	anti-dip knickpoint	~ perpendicular	1999~2007	17
Tachia (Pifong Bridge)	3	6~7	anti-dip knickpoint	~ perpendicular	1999~2007	6
Tachia (Shigang Dam)	4	6~7	strike knickpoint	oblique	2005[f]~2010	50
Tachia (Meizi Bridge)	5	4	strike knickpoint	~ perpendicular	1999~2006	186
Han [c]	6	4	anti-dip knickpoint	~ perpendicular	(protection works)[g]	-
Wuniulan [c]	7	0.9	anti-dip knickpoint	~ perpendicular	(protection works)	-
Puzikeng [c]	9	1	anti-dip knickpoint	~ perpendicular	(protection works)	-
Dali [c]	8	1.5~2	anti-dip knickpoint	~ perpendicular	1999~2010	51
Toubiankeng [c]	10	2~3	dip knickpoint	~ perpendicular	1999-2004	60
Caohu [c]	11	2	anti-dip knickpoint	parallel	(protection works)	-
Beigou [c]	12	1	anti-dip knickpoint	~ perpendicular	1999~2006	58
Gan [c]	13	1.5	anti-dip knickpoint	~ perpendicular	1999~2009	38
Wu	14	1	anti-dip knickpoint	~ perpendicular	-	-
Ailiao[c]	15	3	anti-dip knickpoint	~ perpendicular	(protection works)	-
Changping [c]	16	0.5	anti-dip knickpoint	~ perpendicular	-	-
Maoluo [c]	17	0.2~0.3	anti-dip knickpoint	oblique	-	-
Choshui	18	1.2	anti-dip knickpoint	~ perpendicular	1999~2005	120
Dongpurui [d]	19	1.5	strike knickpoint	parallel	(protection works)	-

a: Data from Central Geological Survey (1999).
b: Tributary of the Tachia River.
c: Tributary of the Wu River.
d: Tributary of the Choshui River.
e: Recession duration is the interval of the data (DEM or aerial photographs) used for analysis.
f: Shigank Dam knickpoint is located upstream of the Pifong Bridge (site 3). The knickpoint was formed around 2005.
g: (protection works) indicates that the reach was protected by sill works.

a. Han River (Jun. 2015)	b. Wu River (Mar. 2010)	c. Caohu River (Nov. 2012)

Photo 1 The photographs of the reaches which did not exhibit features of knickpoint retreatment.

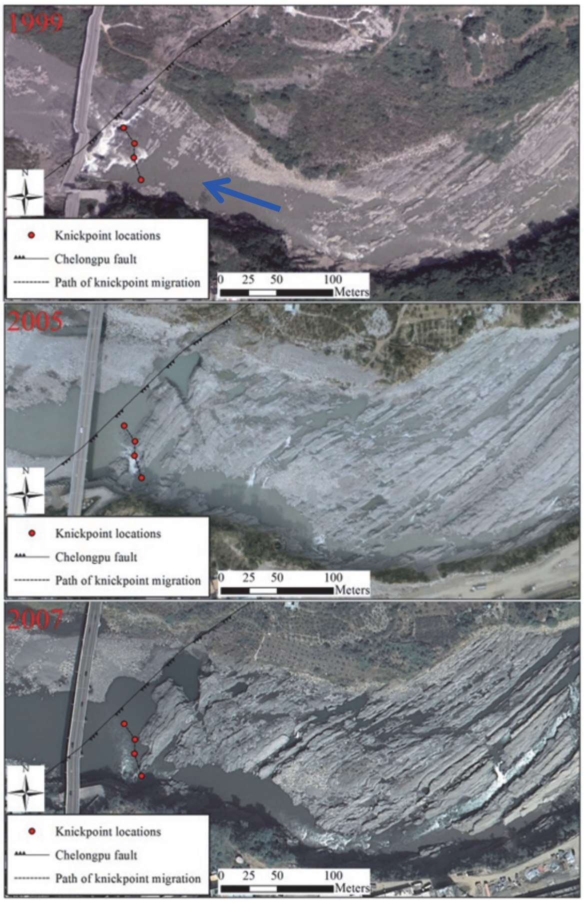

Fig. 2 The knickpoint locations are identified on a series of aerial photographs (the Pifong Bridge of the Tachia River).

4. Migration processes and rates of the knickpoints

In principle, both hydraulic and geological factors will affect the migration processes of knickpoint in a river. The drainage basins of the four rivers are relatively adjacent; their precipitation trends are also similar. In spite that the drainage areas (proxy of discharge) of various reaches are different and inevitably affect the maximum discharge, channel width and unit-width discharge, the focus of the following discussion is on the geological conditions at the knickpoints.

The average recession rates of knickpoint migration were evaluated according to the geometry relationship of stratum orientation and flow direction, which could be simply classified into dip, strike, and anti-dip knickpoints. The average recession rates range between 6 to 294 myr^{-1} which are significantly higher than the published knickpoint migration rates in bedrock channel all over the world (e.g., Hayakawa and Matsukura, 2003; Loget and Van Den Driessche, 2009). Our data show that the maximum rate was in the anti-dip knickpoint of the Taan River and the minimum rate was in the anti-dip knickpoint of the Tachia River. The knickpoints were further grouped into dip, strike, and anti-dip types to calculate average rate for each group regardless rivers. The grouped average rates are 57, 110, 83 myr^{-1} for the dip, strike, and anti-dip knickpoint respectively. The group average rate in the strike knickpoint is about 2 times higher than that in the dip knickpoint. The difference in the grouped average rate of knickpoint migration could be explained from the erosion processes based on field observations.

The migration processes in the dip knickpoint of the Taan River observed from Fig. 4a shows that the discharge flows over the strata top and down along the over-steepened reach of the knickpoint. The major erosion occurred along the over-steepened face, which is the bedding plane of bedrocks in dip knickpoint. The knickpoint could migrate once the underneath rock layers were eroded away; hence the migration rate would be controlled by the resistance of the rock layers sequentially. Once the strata contained a competent rock layer, the knickpoint migration rate could be lowered down significantly.

In the strike knickpoint of the Tachia River (downstream of the Shigang Dam, Fig. 4b), the major bedrock erosion occurred along the relatively weak rock layer, and the discharge flowed in the confined narrow channel. The erosive rate of the weak rock layer would be high and could effectively accelerate the knickpoint migration rate.

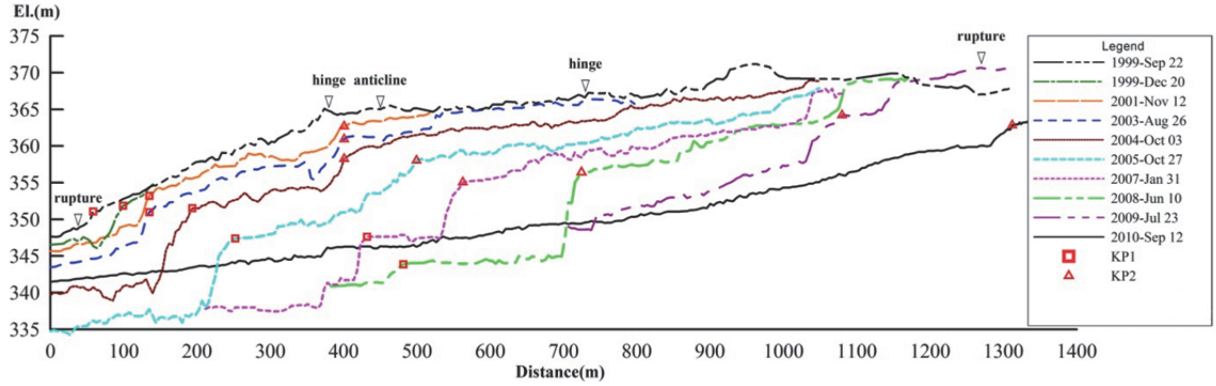

Fig. 3 The longitudinal profiles derived from DEM data for knickpoint locations identification (the Taan River).

Figure 4c demonstrated the anti-dip knickpoint in the Taan River. The knickpoint is located in a competent layer of massive sandstone and formed a waterfall. The height of the knickpoint gradually increased because of undercutting and resulted in an unstable overhung rock. The process of toe scouring enabled the knickpoint migration in case of a resistant rock layer.

5. Discussion and conclusion

The rock strata near a knickpoint created by fault rupture are generally fractured because of tectonic stresses. The young sedimentary rocks of the Pliocene-Pleistocene strata in the western foothills of Taiwan belong to soft rock and are generally not resistant to flow erosion. The rate scale of the knickpoint migration ranges in tens to a few hundred meters annually that is astonishingly high compared to worldwide data. The extremely high rate of knickpoint migration causes significant landform changes in the reaches adjacent to the co-seismic Chelongpu fault in the 1999 Chi-Chi earthquake and imposes great impacts on river environments and nearby infrastructures.

This study adopted both chronological aerial photographs and DEM data to assess the conditions of knickpoints induced by the Chi-Chi earthquake and to evaluate the average rates of knickpoint migration after the formation of these knickpoints. Among the formed knickpoints, some of them did not exhibit backward migration due to (1) prompt installation of protection works, (2) very thick armor layer, and (3) relatively small angle between the fault and the channel. In this study, the knickpoints were grouped into dip, strike, and anti-dip types to calculate average rate for each group. The average migration rates were 57, 110, 83 myr^{-1} for the dip, strike, and anti-dip knickpoint. Finally, the knickpoint migration processes were interpreted based on the migration rates and the results of field study.

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a. The dip-knickpoint reaches of the Taan River in 2004.

b. The strike-knickpoint reaches of the Tachia River in 2013.

c. The antidip-knickpoint reaches of the Taan River in 2008.

Fig. 4 Conditions of channel bedrock erosion.

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