Fault-scarp knickpoint recession in 10 years after Chi-Chi Earthquake in central Taiwan

Yuichi S. HAYAKAWA – Center for Spatial Information Science, The University of Tokyo, Japan
hayakawa@sk.is.t.u-tokyo.ac.jp  @hykwaaaa
Nobuhisa Matsuta – Earthquake and Volcano Research Center, Nagoya University, Japan
Akira Maekado – Faculty of Law and Letters, University of the Ryukyus, Japan
Yukinori Matsumura – Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan

Abstract  Surface rupture of the Chekungu thrust fault in central Taiwan has emerged with the Chi-Chi Earthquake on September 21, 1999. Bedrock knickpoints were formed in rivers crossing the fault and some of them have continued to recede upstream by fluvial erosion (the others were artificially modified and fixed immediately after their emergence). Recession of these knickpoints have been extremely quick, and inner channels were formed downstream of the receding knickpoints. The inner channels seem to expand their width after the passing of the knickpoints. Here we investigate temporal changes in the morphology of the bedrock rivers around the fault scarp after the earthquake by means of field topographic measurement and satellite imagery investigations. Rates of the knickpoint recession vary through the time. For instance, knickpoint in the Tachia River shows a recession rate of 3.3 m/y in the earlier 6 years (1999-2005) and 220 m/y in the following 4 years (2005-2009). Such variations in recession rates could be caused by variations in flood intensity and frequency, as well as some artificial modifications, rather than the variability in bedrock strength.

Keywords: knickpoint, bedrock erosion, field measurement, satellite imagery

The Tachia River

- 2005-2006: decrease in width, w = 160 ± 10 m
  - Bedrock erosion at the knickpoint could have been enhanced due to the narrowing of its width.
  - However this change does not correlate with lithological structures.
- Heavy rainfall induced by typhoons may have caused enhanced erosion of the knickpoint especially in case of the typhoon Morkot in 2006.
- However in 2008, there has been more rainfall event but less change in the knickpoint location. In contrast the knickpoint abruptly receded in 2007 without such extreme rainfall.
- Averaged rainfall amount in the latter period (2005-2009) is significantly higher than that in the former period (1999-2004).
- A harder sandstone layer (R = 25-29%) and an adjacent weaker mudstone layer (R = 15-20%) seem to have captured the incision in 2007-2008, but the path of knickpoint is not affected by the other layers.

The Tachia River – Satellite image analysis

- 2006-09
  - 2009-12

Study area

Highlights
- Field and remote sensing analyses revealed rapid recession of fault-scarp waterfalls over a decade after 1999 Chi-Chi-Earthquake.
- The increase in recession rate is affected by abrupt decrease in width and moderate increase in water discharge.
- Occurrence of rapid recession do not always correlate with heavy rainfall events and weaker lithology.
- Artificial modification of revetted could delayed recession of knickpoint.

Assessment of factors affecting recession rates by an empirical model

To quantify the effects of factors on the recession rate of the waterfalls, a quantitative model estimating the relationship between waterfall recession rate and relevant physical parameters by Hayakawa and Matsukura (2003) is used. Assuming that the rate of waterfall recession depends on the erosional force of the stream and the strength of the resisting bedrock, dimensional analysis finds a dimensionless index, FR, based on these variables:

\[ FR = \frac{A^2}{H^2} \left( \frac{P}{L} \right) \]

where A (L^2) is the upstream drainage area of a waterfall, P (L T^-1) is the mean annual precipitation in the drainage basin, so that the product of A and P accounts for the annual stream flow over the waterfall; W (L) and H (L) are the width (lip length) and height of the waterfall, ρ (M L^-3) is the water density (10^3 kg m^-3), and R (M L^-1 T^-2) is the unconfined compressive strength of bedrock. The dimensionless index FR represents the balance between the erosional force and bedrock resistance as a whole, where all these parameters are given in the S unit.

The relationship between the FR index and the waterfall recession rate, E, using data for waterfalls in the Boso Peninsula of eastern Japan, is given as follows (Hayakawa and Matsukura, 2003):

\[ E = 18.77 FR + 1.4 \]

This equation has been found to give good valid order-of-magnitude estimates of waterfall recession rates in many areas (e.g., Hayakawa and Wohl, 2005; Hayakawa et al., 2008a; Hayakawa et al., 2008b).

The Tall River

- Artificial modification of revetted could delayed recession of knickpoint.

Rock strength by Schmidt hammer

Sandstone gravels: R = 72.2% (n=6)
Bedrock sandstone: R = 15-20% (rounded, a = 53.8 cm (n=30, σ =19.9))
Bedrock mudstone: R = 25-29%

Sandstone gravels transported from upstream mountains are significantly harder than bedrock, which is mostly composed of vulnerable mudstone with several layers of sandstone. Gravels seem to be acting as effective tools of erosion.
断層崖にかかる渇の後退速度の変化：台湾、集集地震からの10年間

Recession rates of fault-scarp knickpoint s:
10 years after Chi-Chi earthquake in central Taiwan

Yuichi S. Hayakawa

1 Center for Spatial Information Science, The University of Tokyo, Kashiwa, Chiba 277-8568, JAPAN

1999年に集集地震で生じた断層崖にかかる渇は、生成後に急速な岩盤侵食により後退を続けた。本研究では、渇の位置の変化、およびその後退速度について、現地調査および衛星画像を用いた判読により明らかにし、河床の地質構造や降水量との対応を、規定要因の無次元パラメータを用いた経験モデル式により評価する。短期的（3y）な地形変化速度の変動に対する地質、気候の影響はそれぞれ経験モデル式によりパラメータの変化で説明可能であるが、より短期的（<1y）な変動は規則性が不明確である。また、侵食を抑制しようとする人行為的な影響が部分的にみられるものの、地震から10年を経ても岩盤侵食は選択点の維持・後退、また谷中谷の幅の增大として進行している。

1999年9月21日に生じた集集地震（Mw=7.6）にともなう断層崖断層の垂直変位により、断層を横切る多くの河川で選択点が生じた。選択点はその後、急速に侵食・後退し、発生から現在の位置までの時間からその後退速度を知ることができた。ただし多くの選択点では早い段階で人为的な工事など人の手が入り、その自然な地形変化を追うことは困難となった。本研究では人の手がすぐに入らなかった4つの河川における選択点において、その後退速度と侵食を規定する要因を検討する。

ここで、選択点における渇が来た渇の後退速度とその規定要因を無次元化した指標（FR）による経験モデル式（詳細は右欄に記載）を使用して、台中の渇の後退速度を評価する。2005年7月の時点で、現地調査および地形・気候の空間データから算出したFRに基づく予測値に対して、後退速度の実測値は1～2オーダー大きい値を示した（Hayakawa et al., 2009）。これは、台中の河水が上流から運搬する大量の堆積物が、軟質な河床の基盤若干が侵食を促進することが一大要因であると考えられる。

一方、選択点形成後の1999-2005年および2005-2009年の2時期についてそれぞれFRを計算し、後退速度の実測値と比較すると、渇の後退速度はいずれの時期でも予測値を大きく上回るか、その変化は3つの渇においてはFR、後退速度実測値ともに増加、1つの渇についてはFRが増加し後退速度が現象するという異なる傾向がみられた。そこで、前期と後期のFRに含まれるパラメータのうち、降水量はいずれの地点でも1.4%の増加、岩盤強度は大甲渇についてのみ変動、幅も大甲渇において1/10以下に減少したものの、後退速度が減少した大里渇については、人為的な影響により侵食が抑制された時期があることが示唆される。