

## Studies of High-resolution Morphodynamics with Special Reference to River Bank Erosion

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### Synopsis

Many alluvial rivers in Japan have recently undergone effects of degradation due to such factors as river training for flood control, excessive riverine sand mining, or reservoir sedimentation. This study focuses on bank erosion in clayey sediments of the Uji River floodplain that has occurred over a period of several decades or longer. It applies digital photo-theodolite surveying to precisely measuring the rate and extent of erosion on a 250m-long section of the left bank of the main channel of the Uji River. The maximum rate of erosion proved to be as high as 6m over a 9-month period. The volume of erosion (or sediment supply) over the 250m-long section was estimated to be equal to 3000m<sup>3</sup>. Notably, the erosion took place even under relatively mild stream conditions. An important consideration is the presence of intercalated granular soil layers in an otherwise thick deposit of clayey sediments. Our field observations point to the following progressive nature of erosion: 1) A granular soil layer is scoured by stream flows, forming caves; 2) The overlying clayey sediment then collapses in blocks; 3) The fallen clay blocks stay as a kind of talus at the foot of the bank wall for some time; 4) Stream flows drift such natural protections downstream over a period of time, then process 1) resumes, allowing the river bank to retreat by an amount.

**Keywords:** river bank erosion, high-resolution geomorphometry, sedimentary environments

### 1. Introduction

According to a recent report by Intergovernmental Panel on Climate Change (IPCC, 2007), the annual mean temperature on a global scale has risen at a noticeable rate and global warming is largely due to human activities. Global warming is likely to increase the frequency of occurrence of extreme meteorological events. This trend will certainly intensify flood disaster risks in floodplains that have witnessed extensive urbanization.

Alluvial rivers in Japan have particular runoff characteristics. A flood stage is featured by a significant peak flow rate with a short duration, as compared with

ordinary much milder flow stages. Due to this rapid flooding, it is one of the most important requirements to fully understand the performance of river banks through careful field observational studies. Floodplains of alluvial rivers are mainly a product of flood-related sediments, and bank materials in middle-to-lower reaches are fine-grained and cohesive sediments. Note in this regard that laboratory test results with reconstituted clayey materials are difficult to apply to field clayey deposits that have stood several thousand years or longer. Thus, it is fundamentally important to observe evolution of bank erosion for a prolonged period of time, if no immediate safety problems to flood-control levees are involved.

Fujita *et al.* (1983) undertook invaluable field

observations of bank erosion in Uji River in early 1980s. They discussed the correlation the extent and frequency of floods and the eroding velocity of the bank. They evaluated the tractive force which acted on the river bank from the gradient of the water surface at the flood stage, and concluded that the magnitude and duration of tractive force during the flood stage were the major factors that controlled with the eroding velocity of the river bank.

The purpose of this study is to make a revisit to the bank erosion problem in Uji River, with the aim of presenting an overview of evolution of the river morphology over past 70 years or so. Also, the present study focuses its discussion on the performance of a “hot segment” regarding bank erosion, in terms of digital photo-theodolite surveying with high-resolution.

In what follows, we will first outline the study area of bank erosion. This is followed by a discussion of results from the digital photo-theodolite surveys that were performed on January 17, 2006 and October 17, 2006. Moreover, based on cross-sectional profiles of the river segment over past, we will provide a perspective for the trend in the degradation of the river bed associated, along with implications of sedimentary environments. Also, the dynamical nature of the bank erosion process will be

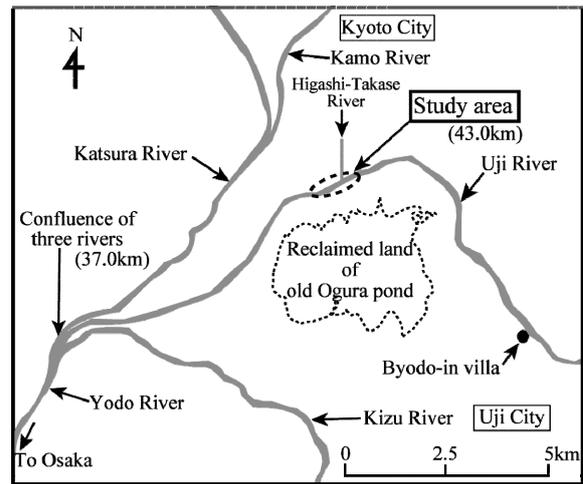


Fig. 1 A map showing the location of the study area

examined in light of the hydrograph available and snapshots of the bank wall that underwent recession in a progressive manner.

## 2. Study area of bank erosion

The Uji River runs through Uji City and southern part of Kyoto City and drains into Osaka Bay as Yodo River. Our study area is a segment several hundred meters long and includes the 43.0km cross section as

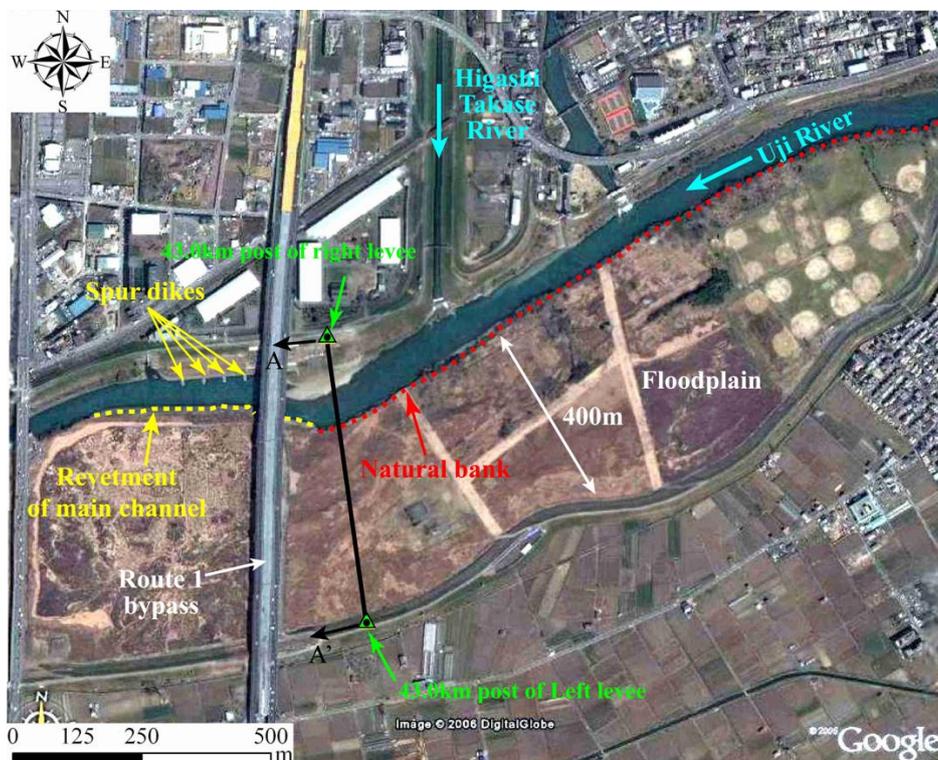


Fig. 2 Satellite image of study area (adapted from Google earth)



(A) A section of natural bank that extends upstream of the section protected with revetment



(B) Natural-bank section extending further upstream

Photo 1 Panoramic views of river bank taken from crown of right levee on January 17, 2006 in Survey 1

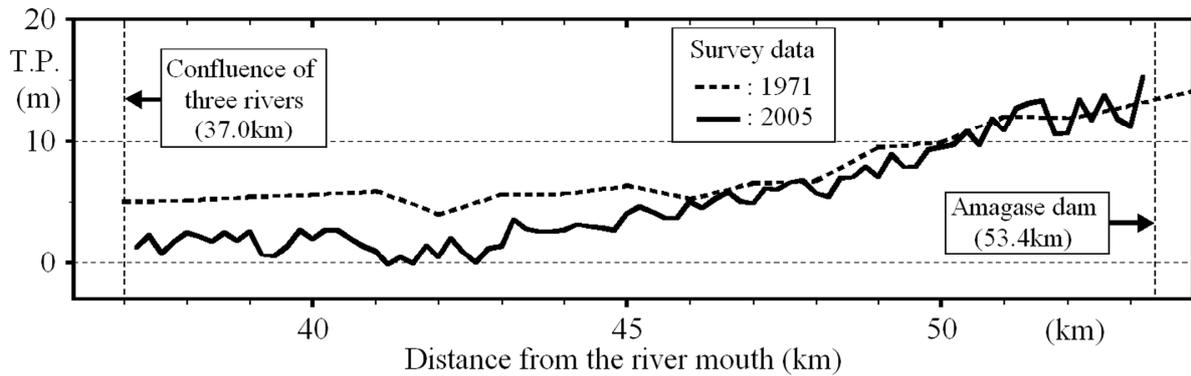


Fig. 3 Longitudinal profile of the deepest channel bottom in Uji River (adapted from survey results of Yodogawa River office, MLIT)

indicated in Figs. 1 and 2. Note that the study area is a part of low-lying area that develops upstream of the confluence point of the three major rivers (Katsura, Uji and Kizu Rivers). The Ogura pond shown in Fig. 1 located to the south of this study area was reclaimed in 1941.

A satellite image adapted from Google earth is shown in Fig. 2, with a few geographical features for reference. In the downstream section from 43.0km post, revetment was constructed at the left bank of main channel in order to protect the bridge pier at the time of construction of the Route 1 bypass because Uji River has a gentle bend at this site. Spur dykes on the right bank was installed at the same time as above construction. Note that a natural river bank extends from immediately upstream the 43.0km post. A view of the natural river bank slightly upstream of 43.0km post is presented in Photo 1. In order to protect the bridge pier of the Route No. 1 bypass road, the revetment works were performed from 43.0km to the downstream section (Photo 1 (A)). The bank without revetment works was eroded and the outcrop was formed (Photo 1 (B)). Note that erosion has

made a very steep face of the river bank.

Fig. 3 shows the longitudinal profile of deepest point in the channel bottom of Uji River in which survey data in 1971 and 2005 were adapted from Yodogawa River office, MLIT. What has to be noticed is that degradation of channel bottom is significant in the section from 46.0km to 41.0km. The study area falls into this hot section regarding erosion.

### 3. Digital photo-theodolite surveys of bank erosion

#### 3.1 Features of the digital photo-theodolite survey

The digital photo-theodolite survey has superior features, such as non-invasive, remote and three-dimensional measurement and preservation as an image of the field condition. These features are crucial for field survey in view of the fact that we can not approach closely to erosional bank. This system is effective for high accuracy and resolution survey of flood stricken topography (Azuma *et al.*, 2006).

The digital photo-theodolite consisted of a digital camera that was mounted on a theodolite (Fig. 4). The

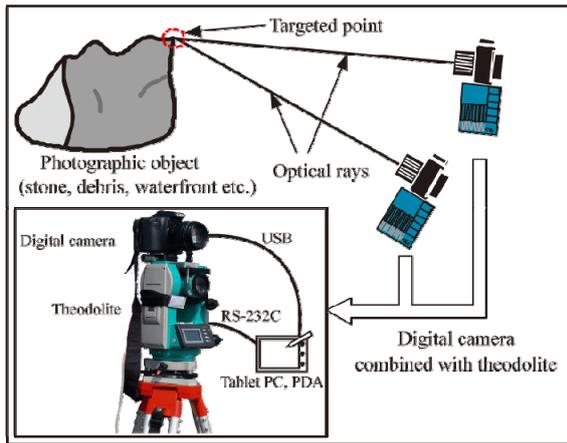


Fig. 4 Illustration of the digital photo-theodolite system used, together with principle of determination of a targeted material point of three-dimensional coordinates

digital camera used (Canon EOS 20D) had 8.2 million pixels ( $3504 \times 2336$ ), allowing a high spatial resolution. The theodolite facilitated the measurement of two angles of orientation on vertical and horizontal planes at every photographing position. The three-dimensional coordinates of a targeted object may be determined based on the method of spatial intersection (Ono and Hattori, 2002; Ono *et al.*, 2004). In essence, a pair of two photographs of the targeted point from two different positions permits its three-dimensional coordinates to be determined (Fig. 4).

### 3.2 Performance of the digital photo-theodolite surveys

#### (1) Survey 1 conducted on January 17, 2006

First topographical measurement of river bank using the digital photo-theodolite survey was carried out over a section approximately 1000m long on January 17, 2006 (Fig.5). This is hereinafter referred to as Survey 1. In Survey 1, we selected 8 pairs (16 positions) of

Table 1 Classification of identified points in Survey 1

Targeted objects	Number of points
Bank topography, Debris	3897
Top edges of outcrop	899
Waterfront	461
Rubbles of revetment	50
Total	5307

photographing on the crown of the right-hand levee. The interval between cameras was set at 20m and the interval of pairs of camera was set at 100m. In the distance to the river bank on which the camera focused, resolution was evaluated from the image corresponded to approximately 1cm per 1 pixel. When the calibration was performed in the analysis process, there was no error larger than 1 pixel. Thus it can be concluded that the measurement accuracy of survey 1 is of the order of millimeter.

In the case of analyzing process, a key for the identification of survey points was to seek objects with sharp corners (Fig.4). For this purpose, the boundary line of sedimentary facies, pebbles, debris and waterfront became a good target. Identified points in Survey 1 are summarized in Table 1 and a total of 5307 points were able to be identified. It follows from what has been discussed thus far that high-resolution and high-accuracy topographical data can be measured by digital-photo theodolite survey, compared with the normal survey.

#### (2) Survey 2 conducted on October 17, 2006

The second topographical measurement (hereinafter referred to as Survey 2) was carried out on October 17, 2006. Survey 2 focused on the 250m-long section of the left bank where erosion was particularly significant. The three camera positions were selected on the gravel bar that extended on the right bank of the main channel (Fig.6).

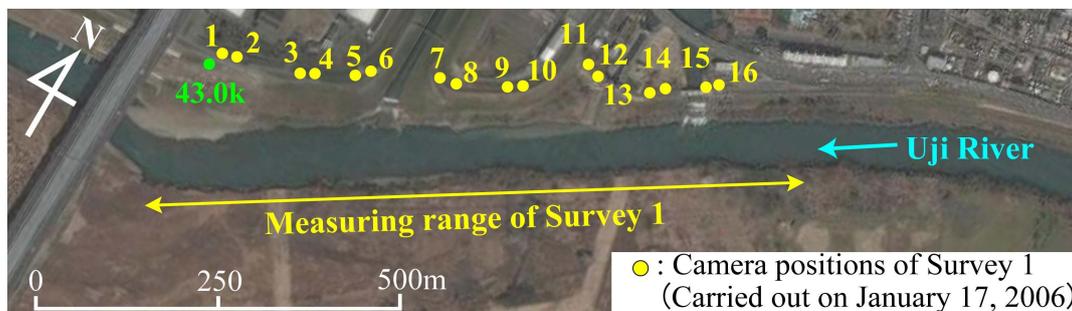
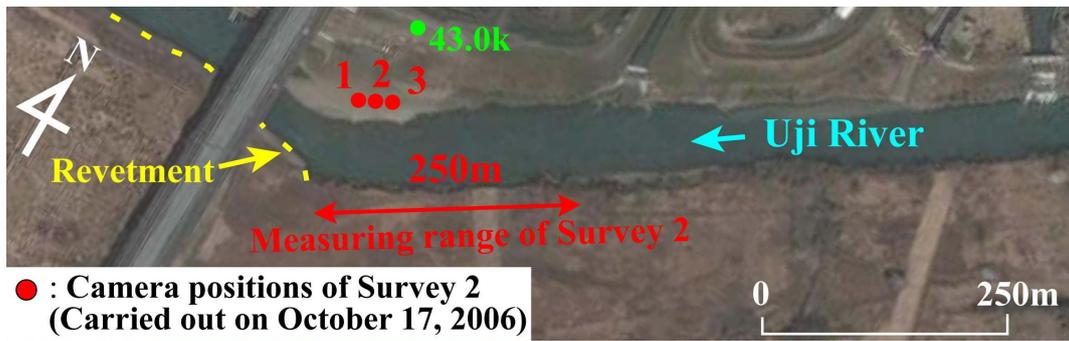


Fig.5 Camera positions and measurement range of Survey 1 performed on January 17, 2006



● : Camera positions of Survey 2  
(Carried out on October 17, 2006)

Fig.6 Camera positions and measurement range of Survey 2 performed on October 17, 2006

The appearance of the face of the left bank is typified in Photo 2. One can notice caves standing just above the waterfront. They were an evidence of scouring due to stream power, leading to instability of the overlying soil mass. This interesting aspect of erosion will be discussed later in this paper in more detail. It would suffice at this point to mention that such caves were formed in a clayey soil layer and stood over a prolonged period of weeks or so.

Survey 2 enabled identification of a total of 5092 points for which three-dimensional coordinates were determined with high-resolution. Namely, the precision of the coordinate determination is 0.65mm per pixel.

### 3.3 Evaluation of topographical changes and extent of bank erosion

#### (1) TIN representations of 3-D topographical data

The 6th plane rectangular coordinate system of Japanese Geodetic Datum 2000 was referred when analyzing the datasets of Surveys 1 and 2 in terms of Geophysical Information System (GIS; ArcGIS software (ESRI)). The three-dimensional topographical data with TIN (Triangulated Irregular Network) representations are

Table 2 Classification of identified points in Survey 2

Targeted objects	Number of points
Bank topography, Debris	4034
Top edges of outcrop	282
Waterfront	332
Rubbles of revetment	444
Total	5092

shown in Fig. 7 in terms of contour maps.

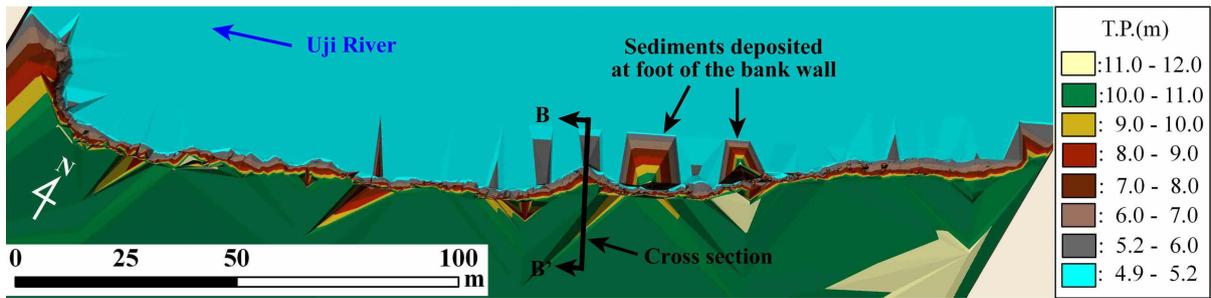
Comparison of Figs. 7(A) and (B) presents of bank erosion that occurred in the 9-month period between surveys 1 and 2. For instance, one may note that the sediment taluses at the foot of the river bank were gone by erosion. Also, one may note significant changes that occurred to cross-sectional profiles B-B' (Fig. 8). The retreat of the bank amounted to approximately 6m.

#### (2) Retreat of bank crown in entire segment surveyed

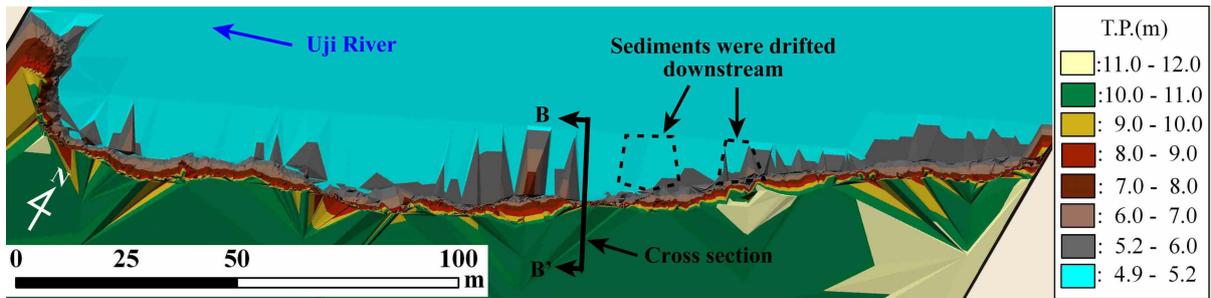
In order to make apparent the recession distance, the edge lines of bank crown in Surveys 1 and 2 are plotted on to a horizontal plane with elevation of T.P. +10.78m as indicated in Fig. 9. Clearly, the bank underwent erosion at the most significant rates in the middle of the surveyed segment.



Photo 2 Topographical features of the left bank face as of October 17, 2006



(A) Survey 1 on January 17, 2006



(B) Survey 2 on October 17, 2006

Fig. 7 Contour maps showing the three-dimensional topographical data based on TIN representation

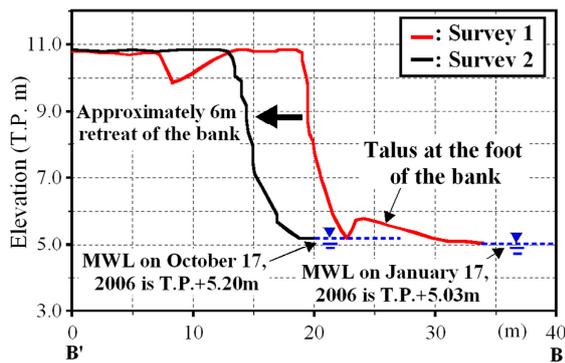


Table 3 Results of volume analysis

	Volume evaluated (m <sup>3</sup> )
Survey 1 (Jan. 17, 2006)	100,000
Survey 2 (Oct. 17, 2006)	97,000
Erosional volume	3,000

Fig. 8 Cross section profiles B-B' through the bank

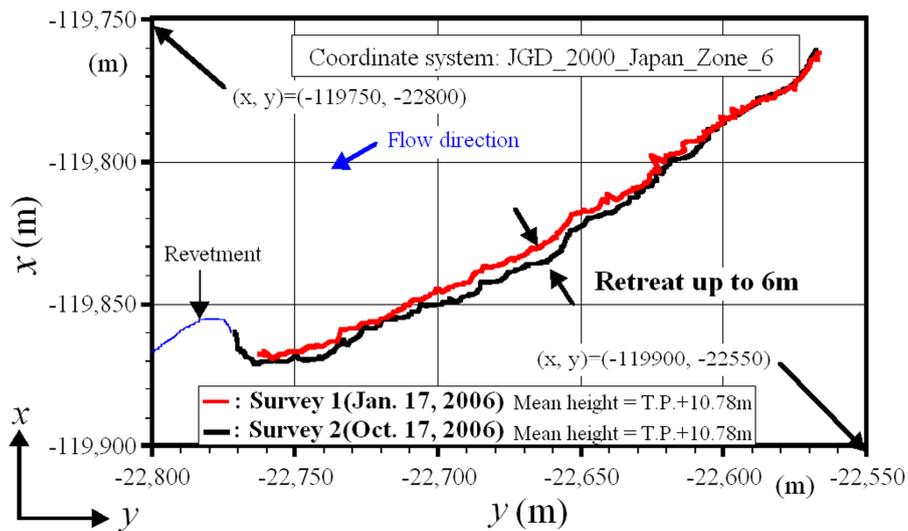


Fig. 9 Lines of bank crown plotted on the  $x$ - $y$  coordinate system indicated

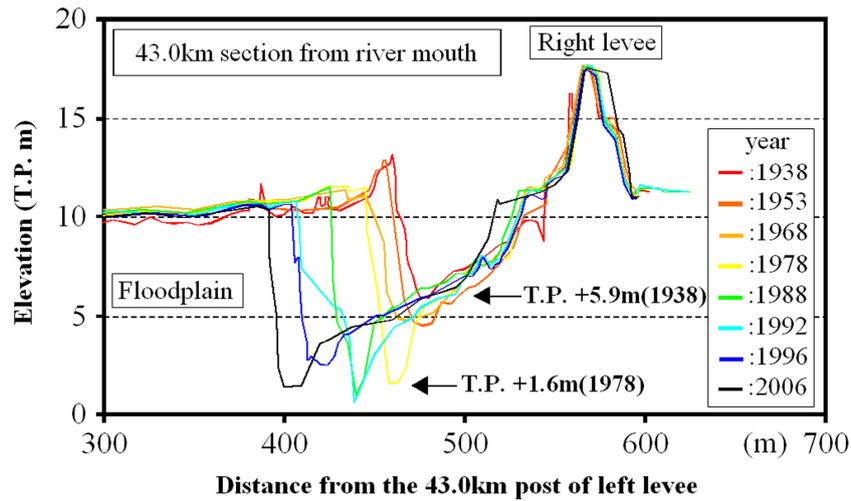


Fig. 10 Evolution of cross-section profiles of channel bottom (43.0km post, adapted from survey results of Yodogawa River office, MLIT)

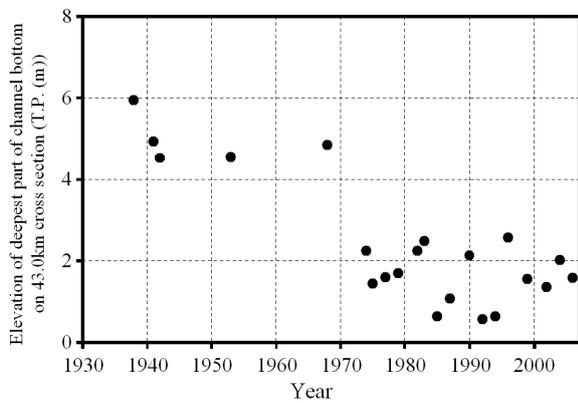


Fig. 11 Evolution of channel bottom degradation

was 150m long ( $x = -119,900$  to  $-119,750$ m), 250m wide ( $y = -22,800$  to  $-22,550$ m) and had elevations equal to and higher than T.P. +5.30m. The height of this horizontal plane was selected in view of the highest point of water surface in both surveys. The subaerial sediment volumes evaluated are listed in Table 3. Thus, subaerial sediment volume lost due to bank erosion proved to be equal to  $3000\text{m}^3$ . Since the survey segment of river bank was approximately 250m-long and 5m-high above the river water stage, averaged recession of the river bank was equal to 2.4m over the 9-month period.

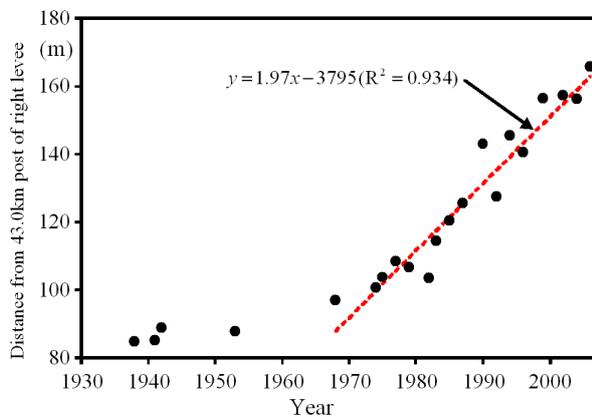
### (3) Volume of sediment released by bank erosion

In order to evaluate the released sediment volume by bank erosion, we compared the sediment volumes of floodplain in Surveys 1 and 2. The domain of calculation

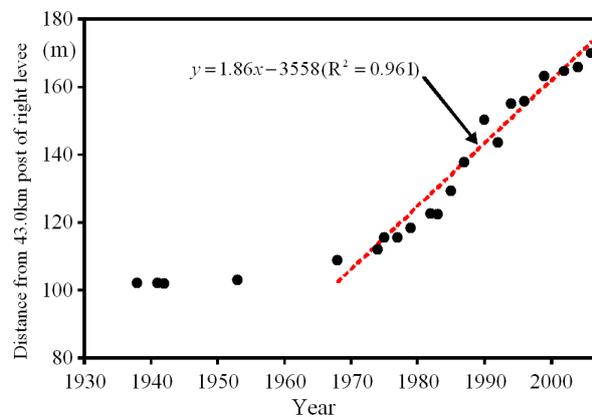
## 4. Discussion of bank erosion processes

### 4.1 Long-term evolution of bank erosion

In order to provide a concrete idea about the secular change of the bottom profile in the main channel, we



(A) Sideway movement of deepest location of channel bottom



(B) Sideway movement of left-hand waterfront of main channel

Fig. 12 Time-series data showing evolution of bank erosion

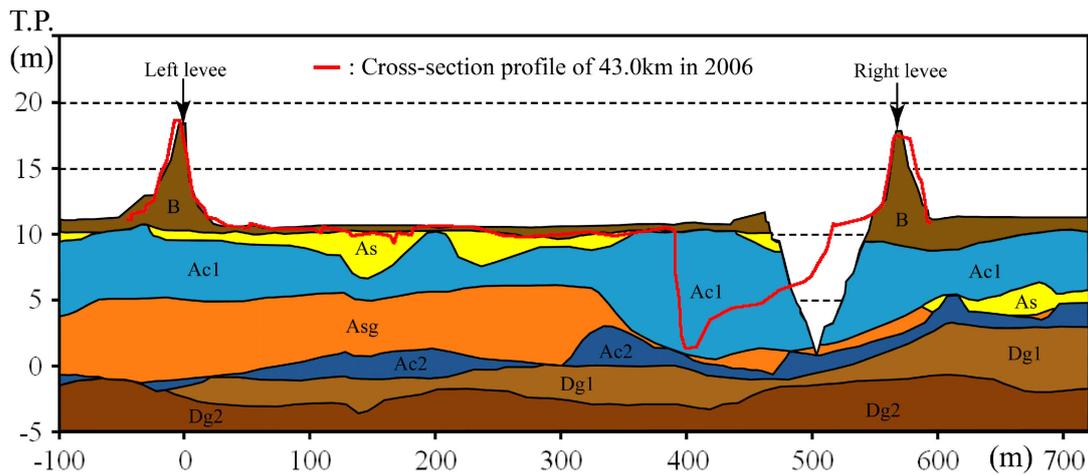


Fig. 13 Cross-section profiles through 43.0km post line is overlain onto a geological profile along Route No.1 bypass (adapted from Kyoto office, MLIT, 1991)

took up the 43.0km section and compiled the survey results available from 1938 to 2006, as shown in Fig. 10. Those survey results were provided by Yodogawa River Office as paper-based data. In addition, the deepest point of channel bottom is presented in Fig. 11 in order to examine the evolution of channel bottom degradation. It is noted in Fig. 11 that the channel bottom in 1938 was relatively high with an elevation of T.P. +5.9m. Significant river bed degradation took place in the period between the late 1960s and early 1970s. After that the river bed elevation on the 43.0km section stayed at the averaged elevation of T.P. +1.6m. However, this observation does not mean the cease of erosion at the particular river section. Degradation stopped since 1978, instead, the bank retreat to the lateral direction has started and is progressing still now.

In order to investigate evolution of the river bank retreat, we referred both the deepest location of the channel bottom and left-hand waterfront of the main channel to the 43.0km post on right-hand levee. The results are shown in Figs. 12 (A) and (B). It is evident from these two figures that the bank erosion became significant in the late 1960s and thereafter has progressed at an approximately constant rate, i.e. nearly 2m recession annually.

The question now arises as to what factors controlled the erosion progressing laterally while the river bed elevation stayed nearly constant. We consider that a sort of rock control may be an important factor. In order to make this statement more specific, let us look at Fig.13 in which the cross-sectional profile through 43.0km post

in 2006 and the geological profile along Route No.1 bypass (adapted from Kyoto office, MLIT, 1991) are superimposed. From Fig. 13, the following observations can be made, namely; 1) The Uji River incised the clay layer (Ac1). 2) After arriving at the lower end of the clay layer (Ac1), no further degradation occurred. Then, evolution has developed sideways.

#### 4.2 Dynamical nature of bank erosion in response to runoff characteristics

A set of snapshots showing temporal development of bank erosion are presented in photo 3. The corresponding time series data of the water level of Uji River observed by the Mukaijima observatory (44.8km + 66.8m) is shown in Fig. 14.

The following observations may be made from Photo 3, with reference to Fig. 14 as well. First, vegetation on the bank face visible in Photo 3(A) was gone in Photo 3(B). It is inferred that the flood lasting for four days from April 11, 2006 was responsible for the erosion of the vegetation. However, it should be noted that no discernible topographical changes took place by the April 2006 flooding event.

Second, sediment lumps were visible in Photo 3(C), at the foot of the bank wall. The photograph was taken 15 days after 18 July flooding, the annual maximum flood.

Third, in Photo 3 (D), the fallen sediment lumps were gone, and caves stood immediately above the waterline. Note herein that such significant bank erosion took place under relatively mild stream conditions that lasted for a

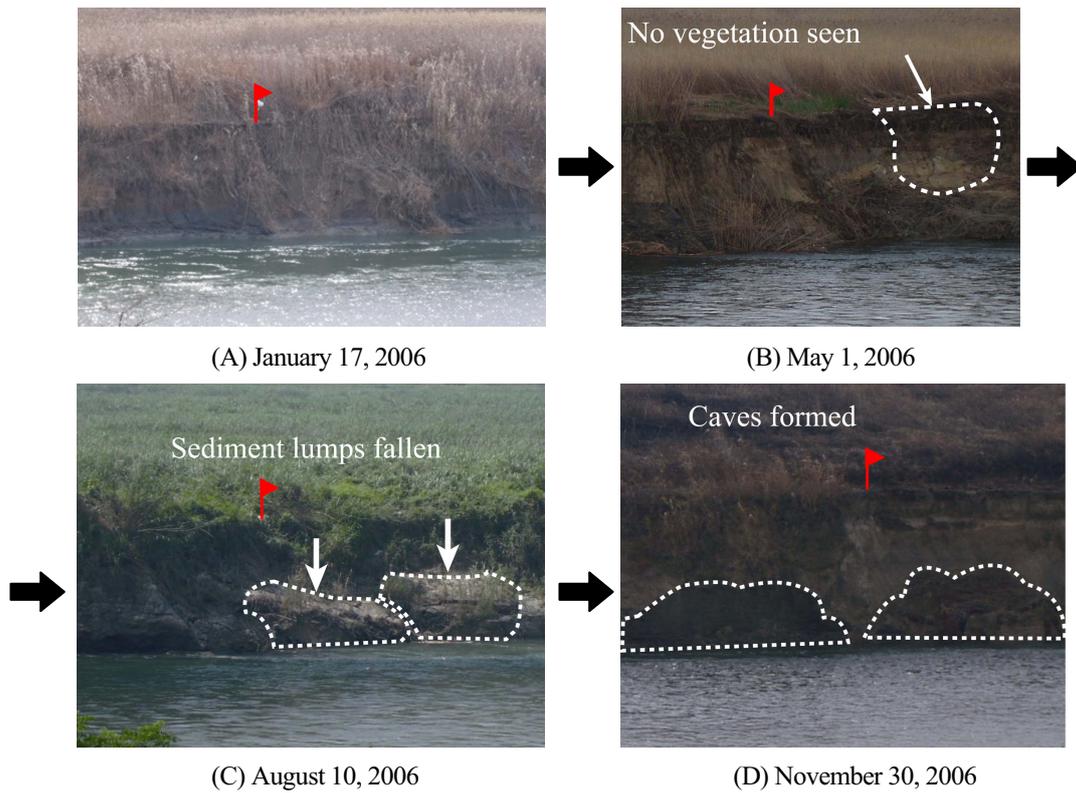


Photo 3 Snapshots showing development of a bank erosion process

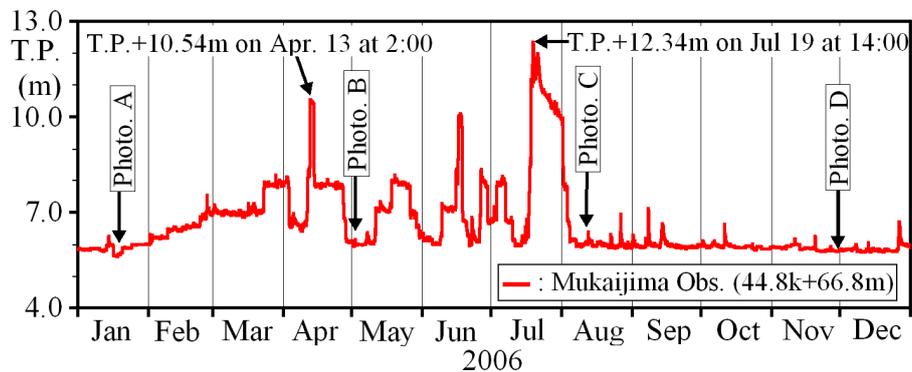


Fig. 14 Time series data of the Uji River water level in the Mukaijima observatory (adapted from the database of hydrology and water quality, MLIT; <http://www1.river.go.jp/>).

period from August 10, 2006 to November 30, 2006.

The bank erosion process based on our field observations may be summarized as follows: 1) A granular soil layer is scoured by stream flows, forming caves; 2) The overlying clayey sediment then collapses in blocks; 3) The fallen clay blocks stay for some time as a kind of talus at the foot of the bank wall; 4) Stream flows may drift such natural protections downstream over a period of time. Then process 1) resumes, allowing the river bank to retreat by an amount.

## 5. Conclusions

The topographical changes induced by bank erosion have been discussed based on the digital photo-theodolite surveys. The topographical datasets obtained were processed and analyzed using GIS. The relations of bank erosion process with runoff characteristics and sedimentary environments were investigated based on observation data and information adapted from Yodogawa River office and Kyoto office, MLIT. The principal conclusions drawn are as follows:

- 1) The digital photo-theodolite survey proved to be a cost-effective and hands-on methodology for obtaining high-resolution topographical data on a river segment scale.
- 2) The 250m-long river segment underwent a bank recession of 6m at maximum during only 9 months; the averaged bank retreat in this duration was 2.4m. The sediment volume released by bank erosion amounted to 3000m<sup>3</sup>, i.e. 12m<sup>3</sup>/m along the river segment.
- 3) Although, bank erosion is commonly believed to occur at the flood stage, this field study showed that bank erosion progressed significantly even if the flow conditions were relatively mild.
- 4) In order to evaluate the erosional velocity, information of sedimentary environments in the floodplain becomes important because layer-scale sedimentary conditions such as the presence of intercalated granular soils in otherwise uniform clayey soil may control the rate and sequence of the bank erosion.

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## 河岸侵食の高分解能地形計測と氾濫原堆積環境に関する考察

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### 要旨

地球規模で温暖化が加速している昨今、異常気象の極値の増大および発生頻度の増加にともない、氾濫原での都市化が進行しているわが国では水災害リスクが確実に増大している。氾濫原の治水安全度を評価する際には、河岸や堤体の侵食速度の評価が非常に重要となる。そこで本研究では、デジタル写真測量解析により、宇治川43.0km地点における低水路河岸侵食の高分解能地形計測を行い、侵食土砂量を評価した。また、過去70年にわたる河床横断地形データおよび地質断面図をもとに、河岸侵食による河床形態の長期変化特性について考察した。さらに、河岸の侵食プロセスと出水特性との関係についても考察を加えた。

**キーワード:** 河岸侵食, 高分解能地形計測, 堆積環境