Study of erosion and sedimentation in urban areas for river with meander pattern

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Abstract. Most of the river in Indonesia has a meander pattern particularly located in urban area. Since the river plains and delta consist of alluvial soils, thus, Meander River in urban area usually encourage sediment transport problem for instance river cliff erosion or bank erosion in outer meander bend and sedimentation in the inside of the meander bend that affect migration of the channel. However, to solve problems in the area of meanders is not easy, because the factors that affect the movement of the river flow and channel migration are very complex. Therefore, simulation of channel migration is increasingly required to assess the risk especially from erosion and sedimentation along meander bend. To simulate the process be approached with built a physical modeling of curved channel at hydraulics indoor laboratory with two different soil classification and composition. This model constructed on mobile bed table apparatus, whereas, the table covered by clayey silt material and sandy silt material with 80 mm thickness. Laboratory findings concluded soil composition with high percentage of silt would be change rapidly compare than soil composition with low percentage of silt. The result of the experiment its qualitative approach without quantifying of sedimentation in the inner bend and erodible sand in the outer bank.

1. Introduction
Indonesia has 127 river basins and most of them are facing an increasing number of environmental problems because of economic development and population growth. Human activities induced the natural ecological environment and subsequently generate unfavourable condition, for instance, the increase of soil erosion and sedimentation that give impact i.e. decay of carrying capacity of river basin for holding and storing water, reduction of lake area and weakness of natural balance on the water surface. As a general rule, river consist of three zone, upper, middle and downstream and there is a continuum of river patterns between straight, meandering and braiding depend on the geomorphological condition and bed roughness. Since the meander river flow pass through urban area, therefore, serious problem related with erosion and sedimentation may occur.

This problem such as widening of the river, evolution of floodplain area, migration of the channel and variations in sediment transport problem may disturb many human activities along the riverside. Primary flow effects are dominant at high discharges because the main flow follows a straighter path, but secondary currents are relatively strong at intermediate discharges [1]. As consequences, the minimum energy dissipation act on the inside of the bend thus some of the sediment loads are deposited.

These two major processes, erosion on the outside of the meander and deposition on the inside,
cause meandering loops to migrate laterally (figure 1).

![Figure 1. Flow path at the meander bend.](image)

Part of the Meander Rivers that channelized in the past causing environmental problem, change the ecological of the river and need heavy maintenance. Therefore, simulation of the relation between flow and curve channel migration as part of meander pattern is increasingly.

![Figure 2. Meander bend at Kalibata, South Jakarta (Ciliwung River, downstream zone).](image)

To simulate the process be approached with built a physical modeling of curved channel at hydraulics indoor laboratory. This model constructed on mobile bed table apparatus, whereas, the table covered by clayey silt material and sandy silt material with 80 mm thickness.

2. Problem identification
Urban area usually located at downstream zone (figure 2), since the Meander belt has a curvilinear shape which is reflects the problems inherent in monitoring spatially distributed patterns of flow depth, velocity and turbulence characteristics on the outer bend, thus, erosion of river cliff or bank erosion is the one of seriously problem at the meander belt. Another problem there is also landslide that sometimes occurs as a response to the natural or man-made disturbance of the fluvial system [2].

Many years ago, the solution to the problems in meander bend associated with flood control and bank erosion is the normalization of the river, which result straight flow and river cutoff. However, this infrastructure to control the flow direction such as the embankment, retaining wall, kribs and groyn needs the heavy maintenance and subsequently cannot avoid environmental problem due to an imbalance within the ecosystem.

For example, Bengawan Solo River located at Java Islands has developed and part of the development along 24.2 km from Tawangsari to Karanganyar has normalized since 1994. As a result,
channel geometry was changed and longitudinal slope became higher, consequently the sedimentation at the downstream growth rapidly causes seriously environmental damage such as flood disaster, habitat loss, structural damage and pollution.

At the end of year 2007 up to early year 2008, Bojonegoro which is located at the downstream of the Bengawan Solo River become flood and 80 villages in 14 districts was submerge. This situation is probably the impact of the Tawangsari – Karanganyar normalization that is resulting imbalance of the whole river thus increasing the burden of flooding in downstream zone.

![Figure 3. Problem associate with meander belt.](image)

A problem that exists in downstream zone associated with the meander bend, banks are most susceptible to erosion following heavy rain when banks are saturated and surface water level has fallen. Channelized river also prone to the sedimentation at the inner bank and scour at the outer bank, therefore, a gradual shift of bank line occurs over time, possible could break the revetment at the river bank and loss of useful land might be need a millions for replacement of the structure (figure 3).

3. Methodology

3.1. Simulation of river cliff erosion on single curve channel

River channel has become much wider and deeper as the channel has eroded and many tributaries upstream have fed the river. Consequently, despite the gentler gradient, the velocity of flow may be as fast as in the uplands. One of the most distinctive features of the river in the lower reach is its increased sinuosity or channel migration. Unlike the relatively straight channel of the upper reach, in the middle and lower reach there are many meanders bends in the river (figure 4).

![Figure 4. Parameters defining meander geometry [3.](image)
The basic process of bank erosion in meander area is the abrasion by suspended solid transport. However, the state of bed load transport (equilibrium or non-equilibrium) is essentially a key issue in the modeling of local sediment deposition and riverbed erosion. Meandering phenomena have been attracted many researches to simulate its dynamics [4-7] which are very complex phenomenon and large scale system, therefore finding analytical solutions is very difficult.

Generally, River Cliff or Bank erosion consists of two interactive physical processes: basal erosion and bank failure [8,9]. Basal erosion refers to the fluvial entrainment of bank material by flow-induced forces that act on the bank surface, for instance drag force, resistance force, and lift force, however river cliff or bank failure occurs due to alluvial processes or geotechnical instability such as planar failure, rotational failure, sapping or piping. The process does not guarantee the retreat of bank line because the eroded bank material may be deposited close to the banks.

Figure 5 shows the cross profile along the curve channel in the various positions and orientations, in the large scale strata geometries of channel belts.

![Figure 5. Simplified plan forms, cross profiles in various positions and orientations, and large-scale stratal geometries of channel belts [9].](image)

Since the fundamental elements of meandering are the curvature of the channel axis and the erodibility of the bed and banks, therefore, the laboratory experiments to illustrate the behaviour of flow in curve channel should be done and the result of propagation shear stress (τ) reflects the possibility of channel migration [10,11].

The Friction Force is represented by Manning's Formula:

\[
X_i = \frac{C_f u_i}{h^{1/3} |u_i|} = \frac{g n^2 u_i}{h^{4/3} |u_i|} 
\]

\[
\tau = \rho g RS 
\]
For wide channel $R \approx S$:

$$S = \frac{n^2}{h^{4/3}} \bar{u}U$$  \hspace{1cm} (3)

Thus, the friction shear stress at the $x$ and $y$ direction as state below in which $\bar{u}$ is velocity in $x$ direction and $\bar{v}$ velocity in $y$ direction and $U$ is depth-averaged total velocity and $n$ is Manning’s roughness coefficient:

$$\tau_{bx} = \frac{n^2 g}{h^{1/3}} \bar{u}U; \quad \tau_{by} = \frac{n^2 g}{h^{1/3}} \bar{v}U$$  \hspace{1cm} (4)

It is very difficult to measure vertical velocity in this physical model, therefore in this paper the computation of friction shear stress is only done in the $x$ direction:

$$\tau_{bx} = \frac{n^2 g}{h^{1/3}} U^2$$  \hspace{1cm} (5)

The result of the experiment its qualitative approach without quantifying of sedimentation in the inner bend and erodible sand in the outer bank.

4. Result and discussion

4.1. Laboratory testing

The experiments were conducted in Laboratory Hydraulics and Hydrology University of Indonesia by using mobile bed and visualization table equipment, which is 200 cm long, 60 cm width and 12 cm deep (figure 6). Channel bed had a non-erodible rigid acrylic material while the banks consist of non-cohesive material as shown in Grain Size Distribution for each material classification and composition (figure 7). Flow Discharge is specified as a constant at the inlet, however, water surface elevation decreases gradually along the channel.

In the first experiment, a curve channel with bend angle ($\phi$) 60$^\circ$ molded from the relatively uniform sand with a mean size diameter of 0.425 mm. The cross-section was rectangular with channel width of 50 mm, the depth of the channel of 80 mm and the elevation of surface water level was 50 mm from the channel bed. A constant discharge of 0.34 l/s was introduced at the inlet and initial velocity was 10 cm/s. There were five control points in this model and the observation was made every 30 minutes. After 3 minutes, channel cliff erosion began in particular at the curvilinear area. Widening channel occurred after 13 minutes, meander formation after 24 minutes and straight channel changed to Meander after 2 hours and 4 minute (figure 8).

The process of the meander groove was affected by the degree of erosion in the outer bend and sedimentation in the inner bend. It could be observed that the process of forming meanders when the curve began to erode and the straight channel at the downstream of the curve began to change to the meander form triggered by curvilinear shape at the beginning of the groove.
Figure 6. Plan form of physical model (first experiment).

Figure 7. Grain size distribution uniform material (Dm = 0.425 mm).
Figure 8. Laboratory experiment (uniform material; $D_m = 0.425 \text{ mm}$).

The second experiment, a curve channel with bend angle ($\varphi$) 90° (figure 9) and 4 (four) different material classification and composition (Table 1) were carried out, and each experiment was stopped when equilibrium conditions were obtained, that reflected its no material migration along the channel. The duration of the experiment have time range for 30 minutes to 245 minutes, depends on the equilibrium conditions its achieved by each material classification.

Table 1. Material classification and composition.

| NO | Duration of the Experiment (minute) | Material Classification | Material Composition | Result |
|----|-----------------------------------|-------------------------|----------------------|--------|
| 1  | 190                               | Clayey Silt             | Sand 2 %; Silt 67 %; Clay 31 %
D$_{50}$=0.014 mm
U$_{avg}$=0.1721 m/det | Curvature Changes |
| 2  | 245                               | Sandy Silt Mix Design 1 Sand : 2 Silt | Sand 65 %; Silt 27%; Clay 8 %
D$_{50}$=0.25 mm
U$_{avg}$=0.1764 m/det | Erosion occurs at the end of the curve corner and downstream gradually eroded |
| 3  | 180                               | Clayey Silt             | Sand 2 %; Silt 67 %; Clay 31 %
D$_{50}$=0.014 mm
U$_{avg}$=0.1977 m/det | Cliff Erosion at the Inner Curve |
| 4  | 30                                | Sandy Silt Mix Design 1 Sand : 3 Silt | Sand 76 %; Silt 18,5%; Clay 5,5 %
D$_{50}$=0.24 mm
U$_{avg}$=0.1811 m/det | Erosion occurs and Channel Rapidly Changed |
Experiment with Clayey Silt material and material composition as Sand 2%; Silt 67%; Clay 31%; show that around 30 minutes after starting the laboratory testing, the initial of channel cliff erosion was begun in particular at the curvilinear area as shown in figure 10. Grain size distribution is shown in figure 11 and the longitudinal profile shear stress is shown in figure 12.
However, for Sandy Silt material and material composition as Sand 65%; Silt 27%; Clay 8%; show that around 90 minutes channel erosion was begun at the end of the curve corner and after 180 minutes running, section at the downstream of the curve gradually eroded (figure 13). Grain size distribution is shown in figure 14 and the longitudinal profile shear stress is shown in figure 15.

![Start](image1.png) ![After 90 minutes](image2.png) ![After 180 minutes](image3.png) ![Dry Condition](image4.png)

**Figure 13.** Laboratory experiment; material composition sand 65%; silt 27%; clay 8% (sandy silt).

![Graph](image5.png)

**Figure 14.** Grain size distribution (sand 65%; silt 27%; clay 8%).
Analytical solution shown in figures 12 and 15, illustrate the longitudinal shear stress along the channel for the material classification Clayey Silt and Sandy Silt respectively. The result of these experiments shows that stability of Sandy Silt material more solid than Clayey Silt material.

5. Conclusion

- The result of physical model studies can be concluded that the fundamental elements of meandering are the curvature of the channel axis and the erodibility of the bed and banks. Therefore, channel migration is strongly influenced by geometry of initial curvature, soil classification and composition.
- The first experiment when material of the model is uniform sand, the occurrence of the channel migration is too fast, because for sand material the strain of the grain is too small.
- However, in the second experiment when soil composition with high percentage of silt (Clayey Silt), therefore the magnitude of longitudinal profile shear stress would be change rapidly compare than soil composition with low percentage of silt (Sandy Silt). The result of the second experiment are consistent with the concept of CHILD model [12] in which derives from the experiment that secondary flow transfer of momentum and shear stress towards the channel cliff and propagate to the downstream causing erosion and channel migration.
- The behavior of erosion and sedimentation caused by the interaction between the shear force due to flow velocity and river cliff material triggered by the angle of the curve channel and the watershed geomorphology condition.
- Regarding to the research finding, river managers are therefore increasingly seeking to preserve cliff or bank erosion within a defined erodible corridor [13] to realize natural stream processes for erosion and sedimentation along the channel. Hence, simulation of bank erosion should be done before determine stream corridor reservation especially along meandering river in urban area.

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