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AN IDEALIZED MEANDERING RIVER MODEL FOR TIDAL BACKWATER STUDY

Irma Noorazurah Mohamad[1] and Wei-Koon Lee[2]
[1]Faculty of Civil Engineering, Universiti Teknologi Mara, Shah Alam, Selangor, Malaysia
[2]Flood Control Research Centre, Universiti Teknologi Mara, Shah Alam, Selangor, Malaysia
E-Mail: irma1095@salam.uitm.edu.my

ABSTRACT

This paper discussed on the design of an idealized meandering river model. Idealized river meander geometry is constructed using the improved sine-generated curve. This method simplifies the river meander planform by constructing the meander path as combinations of line and arc with direct reference to practical dimensions. Meander and channel geometries are selected based on the Lower Klang River which is tide-dominated area. Complete computational domain is constructed by joining the river model with semi-circular open sea domain. Topography and bathymetry of river model are also presented. The idealized model will greatly facilitate related researches to better understand the physics and behaviours of tidal rivers with meandering effects.

Keywords: idealized meandering river, improved sine-generated curve, tidal river, arc-line pattern, computational domain.

INTRODUCTION

Idealized river models are frequently used to investigate the behaviour of river hydrodynamics [1-4]. This approach allows the effects of external forcing on river flow and water surface fluctuations to be explored and assessed in isolated condition [1]. Previous researches had reported investigations on sediments behaviour [1], numerical and analytical studies on tide-river flow [2-7] and flood behaviour in meandering rivers [8-10].

It is well known that tidal backwater is commonly found at the downstream of river reach. Effects of tidal backwater depend on astronomical, meteorological and surface gradient of flow pattern in the estuary. Combinations of tidal backwater and river discharge may produce water level variations [11]. For example, the prolonged flood of nearly two weeks which hit Kota Tinggi, Johor from December 2006 through January 2007 was cited to be due to the coupled effect of tides and heavy rainfall [12]. The major flood in the east coast states of the Peninsular Malaysia namely Kemaman, Terengganu and Kuantan, Pahang in December 2013 also were quoted to be the results of high rainfall intensities combined with the effects of spring tides [13]. Hence, failure to consider the compound effects of tidal backwater and river discharge can potential lead to disastrous outcome.

Literature search shows that most idealized river studies adopt a simple straight river configuration. This approach inherently neglected the meandering on flow behaviour, especially in the downriver section where lateral effect is important. Lateral mixing by secondary flows in meandering river will cause the outside bend eroded, while inside bend deposited with sediments. This secondary circulation can be resolved through two-dimensional (2D) and three-dimensional (3D), and totally neglected in one-dimensional (1D) computational domain. Thus, a realistic 2D river model is sufficient to discover the structure and character of secondary flows which are related to tidal backwater and river discharges in meandering river.

There are a number of studies related to river meander geometry [14-18]. Meander geometry such as amplitude, wave length, arc length and arc angle has been commonly used to transform meander path into simple planimetric layout using appropriate mathematical model [19-21]. The sine-generated curve (SGC) was introduced by [19] show that the down-valley direction of meander changes as a sinusoidal function of distance. Subsequently, a simpler method known as the improved sine-generated curve (ISGC) was developed by [22]. The ISGC method defines completely the geometrical dimensions of river meander based on meander geometrical dimensions such as arc and line pattern, and is useful for simplifying the river meander channel pattern.

In the present study, a meandering river planform in a tide-dominated area is considered. The ISGC method is adopted to develop an idealized, but realistic meandering planform using the Lower Klang River (LKR) in Selangor as a reference case. A typical cross section comprising a rectangular main channel and a flood plain is proposed, where its size reduces uniformly upriver with gentle bed slope. This idealized model is expected to allow systematic assessment of tidal backwater effect in meandering tidal river.

DESIGN OF AN IDEALIZED MEANDERING RIVER

In this section, the idealized meandering river formulation using the ISGC method is presented. Next, a computational algorithm is proposed to design an evolving meander profile.

River meander based on ISGC method

The ISGC method uses the geometrical dimensions of river meander, namely the meander wavelength L_m, stream length per meander M, sinuosity K, and amplitude A_m to approximate the river meander pattern. Simplified pattern of river meander which can be illustrated as combinations of arc and line pattern is shown in Figure-1.

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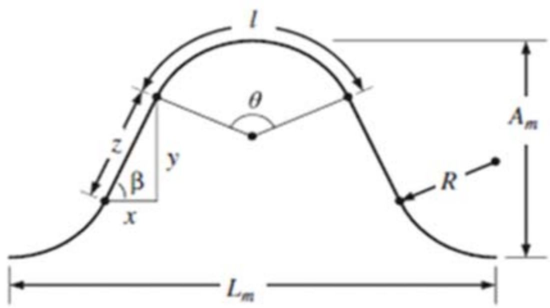

Figure-1. Arc-line pattern properties of river meander [22].

This study emphasizes on the method to more generalized conditions based on different angle of moving direction β. For known meander wavelength L_m and stream length per meander M, the initial river sinuosity can be calculated:

$$K = \frac{M}{L_m} . \tag{1}$$

Then, the maximum turning angle ω and amplitude of meander A_m are estimated as follows:

$$\omega = 2\sqrt{2}\sqrt{1-1}/\sqrt{K} , \tag{2}$$

$$A_m = \frac{M}{\pi}\left(\omega - \frac{\omega^3}{9} + \frac{\omega^5}{225} - \frac{\omega^7}{11025}\right). \tag{3}$$

The radius of curvature R of arc-line pattern is calculated as:

$$R = \frac{L_m K^{1.27}}{16.34\left(K^{0.5}-1\right)^{0.5}} . \tag{4}$$

The angle of direction β and arc angle θ, where both in radians unit are given as:

$$\beta = \cos^{-1}\left(\frac{16R^2 - 8A_m R + L_m\sqrt{4A_m^2 - 16RA_m + L_m^2}}{4A_m^2 - 16RA_m + L_m^2 + 16R^2}\right) \tag{5}$$

$$\theta = 2\beta . \tag{6}$$

Thus, the arc length of river meander path can be estimated as:

$$l = 2\beta R . \tag{7}$$

While, the component of x and y are calculated based on geometrical considerations. This part shows that determination of y precedes x in the case where $\beta > \pi/2$:

$$y = \begin{cases} A_m - 2R + 2R\cos(\beta) & , \beta < \frac{\pi}{2} , \\ A_m - 2R - 2R\cos(\beta) & , \beta > \frac{\pi}{2} \end{cases} \tag{8}$$

$$x = \begin{cases} \frac{L_m}{2} - 2R\sin(\beta) & , \beta < \frac{\pi}{2} \\ \frac{y}{\tan(\beta)} & , \beta > \frac{\pi}{2} \end{cases} . \tag{9}$$

Therefore, the line path length of meander path z is found as:

$$z = \sqrt{x^2 + y^2} . \tag{10}$$

Lastly, the idealized river sinuosity K_i is determined by:

$$K_i = \frac{4\beta R + 2z}{L_m} , \tag{11}$$

where this idealized river sinuosity K_i is need to be checked with the initial river sinuosity K for precision factor.

Algorithm for an evolving meander

For a realistic representation of river meander, the meander geometry is expected to change gradually from the downriver to the upriver section. More specifically, the river sinuosity K and the meander wavelength L_m increases in the down-valley direction.

In the design of an idealized river meander in the present case, the geometry of the first idealized meander adjacent to the estuary is prescribed based on a suitable reference case. The stream length per meander M and the meander wavelength L_m are set such that the river sinuosity K can be calculated from Equation. (1). For subsequent meander in the upriver direction, the values of K and L_m are reduced uniformly at 10% reduction. This is performed until the sinuosity approaches unity at the upstream limit of the river model.

The arc-line pattern for each meander is then calculated using the ISGC method as described in the preceding section. The geometry of meander thus obtained represents the centreline of the idealized meandering river. The practicality of ISGC had been tested on several tide-dominated rivers in Malaysia [23]. The computational algorithm is summarized in the flow chart in Figure-2.

MODEL DEVELOPMENT

In order to develop an idealized yet realistic meandering river with tidal effects, the Lower Klang River (LKR) was selected to derive suitable values for the river depth, floodplain and channel. The river model is then combined with an idealized adjoining semi-circular open sea with horizontal bed to produce the complete computational domain.

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Reference case: Lower Klang River

Lower Klang River (LKR) is used in the present study as a reference case. LKR stretches from Port Klang estuary up to Taman Sri Muda, Shah Alam (Figure-3). LKR is situated at downstream path of Klang River in the state of Selangor, Malaysia. Klang River has an estimated total length of 120 km, originating from Ulu Gombak Forest Reserved area and fed by 13 major tributaries. The last major tributary is the Damansara River. Klang River exits on the west coast at Port Klang, where the tide is semi-diurnal and the estuary is well-mixed. LKR is located in a flat and low lying plain. The river bed slope is mild at the Klang-Damansara confluence point (~1/2300) and is near flat (1/7000) when the river meets the sea. Meanwhile, the river width increases from 50 m at Klang-Damansara confluence point to 300 m at Port Klang estuary [24].

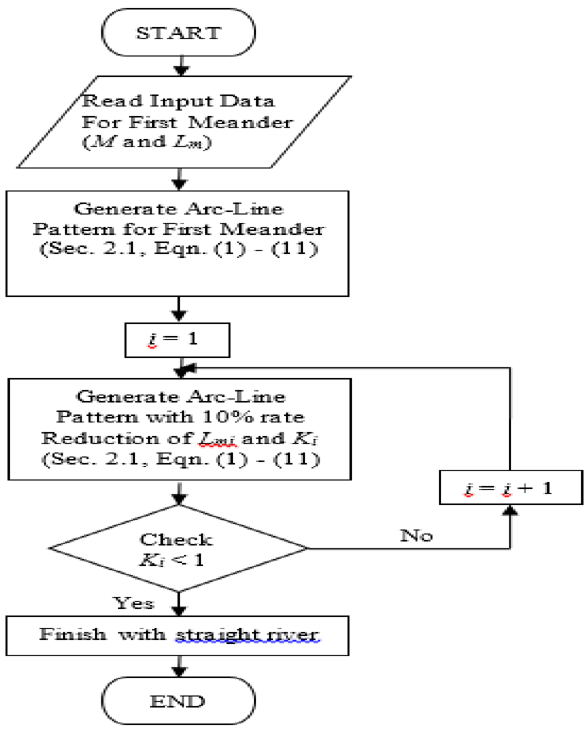

Figure-2. Computational algorithm of an evolving river meander based on ISGC method.

Figure-3. Lower Klang River (Source: Google Earth).

Arc-line pattern of an idealized model

Based on LKR, the first meander is taken to have a stream length per meander M of 8.5 km and meander length L_m of 2.5 km. It is known that the tidal reach limit is 20 km, reaching Taman Sri Muda in Shah Alam and thus this distance is adopted for the river model. The subsequent meanders are generated by introducing 10% uniform reductions of K and L_m from downstream to upstream. The stream length M is calculated from Equation. (1), the meander amplitude A_m from Equation. (3) and the angle of direction β from Equation. (5) as detailed in Table-1. The arc-line pattern generated for the idealized meandering river is presented in Figure-4.

Referring to Figure-4, there are a total of 12 meanders in the idealized river model over the up-valley distance of 20 km. The origin of the coordinate system is used as the starting point of the arc-line pattern which presents the thalweg of the river. The reference horizontal axis is located at half the meander amplitude Am of the first meander. For all subsequent meanders, the arc-line pattern is maintained symmetrical about this horizontal axis such that eventually the model tapers off with a straight reach at y = 1678 m. As shown in Table-1, the angle of direction β reduces with subsequent meander in the up-valley direction. Meander 1 to meander 4 having the angle of direction $\beta>\pi/2$. Meanwhile, the rest of meanders have angle of direction $\beta<\pi/2$. It can be observed that the downriver section (meander 1) has a horseshoe shape (inset (i)), whereas at the upriver section (meander 8), meander shape changes to wavy pattern (inset (ii)).

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Table-1. Arc-line pattern for idealized meandering river.

Meander number	L_m (m)	K	M (m)	A_m (m)	β (rad)
1	**2500**	**3.40**	**8500**	**3356**	**1.77**
2	2250	3.06	6885	2709	1.72
3	2025	2.75	5577	2180	1.66
4	1823	2.48	4517	1747	1.60
5	1640	2.23	3659	1393	1.52
6	1476	2.01	2964	1103	1.44
7	1329	1.81	2401	864	1.35
8	1196	1.63	1945	668	1.24
9	1076	1.46	1575	504	1.12
10	969	1.32	1276	367	0.96
11	872	1.19	1033	247	0.77
12	785	1.07	837	131	0.48
13	706	1.00	706	0	0

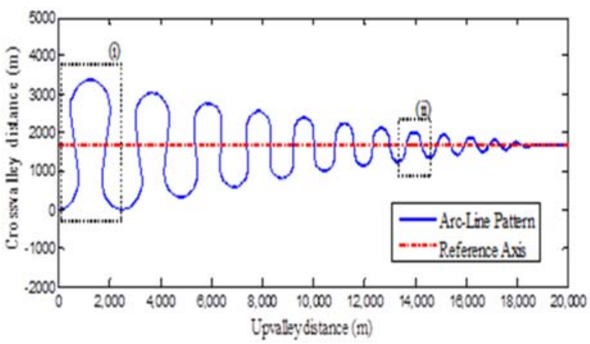

Figure-4. Arc-line pattern of idealized meandering river model.

COMPUTATIONAL DOMAIN

The model domain of idealized meandering river is attached to semi-circular open sea as shown in Figure-5. The estuary has a coastline of 10 km and a semi-circular open sea domain with radius R_s = 10 km and elevation at z = 0 m. The idealized meandering river main channel is designed to be rectangular with a width of 300 m at the river mouth, and then decreases steadily to 50 m at the upstream limit. The floodplain is considered to be symmetrical about the river centre line and the widths on both sides are designed to be the same as the channel width.

The idealized meandering river is laid on bed slopes between 1/2300 at the upstream limit and 1/7000 at the river mouth respectively. This longitudinal bed slope is similarly applied to the floodplain. Figure-6 shows the gradual changes of the longitudinal channel profile of the river bed, river channel and river floodplain. This channel profile was plotted to the reference of total stream length. The river main channel water depths are set to be 5 m and 2.5 m at the river mouth and upstream limit respectively. Considering the lateral floodplain slope of 1/100, the elevations of the floodplain boundary are thus 3 m at the river mouth and 0.5 m at the upstream limit.

Meanwhile, Figure-7 shows the domain topography and bathymetry of the idealized meandering river interpolated at regular interval. The grid iteration number of the model domain was set to N = 125 in the cross-valley direction and M = 500 in the up-valley direction respectively. The completed model domain is ready for the hydrodynamic simulation model that investigates combined effect of tidal level and rainfall, which are not discussed in the current study.

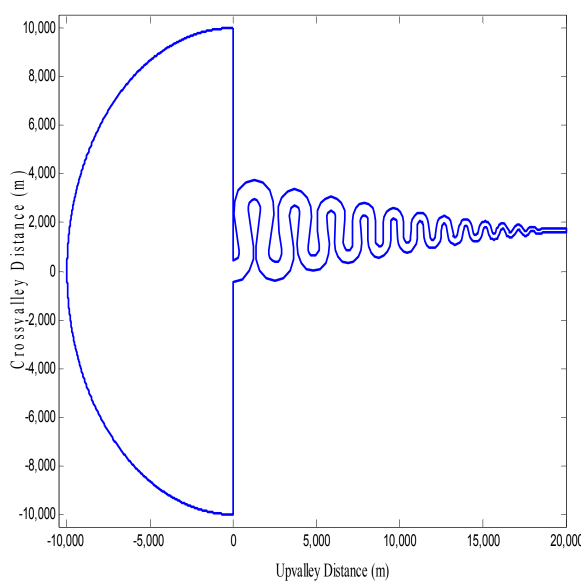

Figure-5. Model domain of an idealized meandering river with open sea.

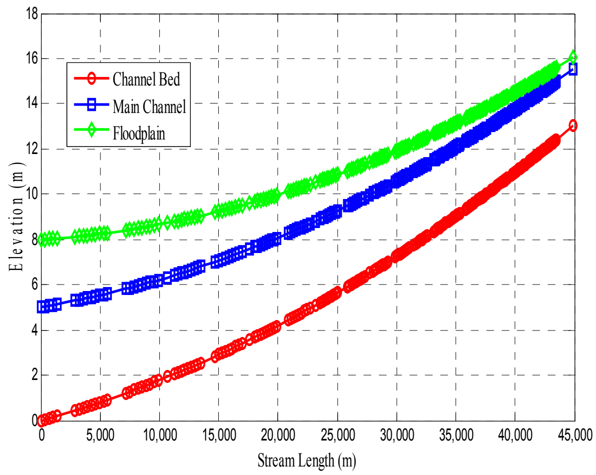

Figure-6. Longitudinal profile of the idealized meandering river model.

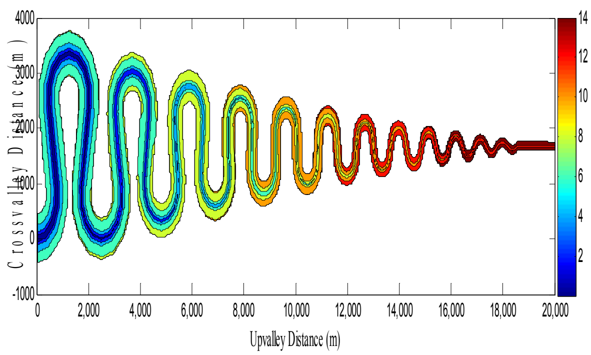

Figure-7. Interpolated elevation of the idealized meandering river model domain.

CONCLUSIONS

This paper presented the design of the idealized meandering river model. The river meander planform is developed using the improved sine-generated curve (ISGC) method. ISGC method is selected due to its simplification to define completely the geometrical dimensions of river meander. The idealized parameters are set to mimic the Lower Klang River (LKR). The idealized river model is comprised with 12 meanders over the up-valley distance of 20 km. Besides that, the idealized meandering river model has a rectangular main channel and a floodplain, where its size reduces uniformly upriver with gentle bed slope. Finally, the idealized but realistic river-estuary model is presented in 2D computational domain. This idealized model will be adopted for the combined effect study of tidal level and rainfall of lower river flood inundation.

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