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Effect of sinuosity variation on flow characteristics of sand mined sinuous channel using numerical modeling

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Abstract: *Anthropogenic activities within the river corridor can have a long-term influence on river health if not managed effectively. Uncontrolled practices of sand mining, a common but aggressive activity can cause severe river bed degradation and, as a result, river incisions, lateral channel instability, and bed armoring. This can further affect the downstream structure such as the bridge pier as well as the morphology of the river. The purpose of this study is to examine, with the help of a numerical model, the impact of a mining pit on the downstream pier and the main channel hydrodynamics if it is present on the flood plain of a sinuous channel. To carry out the study we have considered a meandering channel with two different sinuousness (1.1, 1.25). Additionally, a rectangular mining pit and a downstream circular bridge pier were considered on the flood plains of the channel. The numerical model used for the study was Flow 3D HYDRO with the renormalized group turbulence solver (RNG). As sinuosity increases, the highest zone of streamwise velocity narrows near the mining pit and widens out just downstream of the bridge pier, according to the findings. Near the sand mining pit, the shear layer zone shifted towards the main channel from the near bank. The secondary current at the outer bank near the mining pit is more concentrated in both cases. The channel having more sinuosity has shown a significant change in turbulence kinetic energy (TKE) as compared to the other channel. Additionally, this study can provide insight into the morphodynamics of meandering rivers under different in-channel disturbance conditions and thus be helpful in the proper planning and management of river health.*

Keywords: *(Sinuous channel, Floodplain, Sand mining pit, Bridge pier, Flow-3D, Flow characteristics).*

1. Introduction

In nature, a sinuous river is a typical type of river that arises naturally and occasionally by human intervention. These human interventions or any type of anthropogenic activities such as indiscriminate sand mining, channel dredging, and bridge construction are the principal drivers of river planform alteration (Pradhan et al. 2021; Nandi et al. 2022). If it is close to the bridge pier, it may harm the bridge pier due to upstream nick point migration (Kondolf et al. 1997) and downstream mining pit migration (Zolghadr et al. 2021). Many experiments and theoretical analyses have been carried out by researchers to investigate flow characteristics around bridge piers and agree that downflow, wakes, and horseshoe vortices comprise the basic flow structure around a bridge pier, which causes failure of the bridge pier (Laird 1971; Dargahi 1989; Ahmed and Rajaratnam 1998; Ansari et al. 2002; Graf and Istiarto 2002). The Talar and Balaroud Bridges in Iran are two examples of bridges that were destroyed due to scouring caused by river material harvesting (Daneshfaraz et al. 2021). Haghnazar et al. (2020) suggested that the mining pit depth should be 70% of the flow depth to ensure the entire pit is refilled.

The cross-sectional variation of flow velocity at the apex bends tends to increase as the sinuousness of the channel increases (D. Xu and Y. Bia 2013). Local impediments such as bridge piers, abutments, and roadway embankments, according to (Johnson et al. 2010) cause the flow to be extremely three-dimensional. Using a one-dimensional numerical model to predict such flow characteristics is insufficient because the key preconditions have been violated. Two-dimensional free surface models have limited utility in the horizontal directions because they do not account for diffusion or turbulent mixing (Erduran et al. 2002). Therefore, Flow 3D was selected because it is an effective hydraulic engineering tool for modeling free surface flow (Johnson and Savage 2006).

A lot of research has been done to evaluate the influence of flow characteristics around a bridge pier caused by sand mining in open channels (Modalavalasa et al. 2022a). However, they are limited to straight channels. The majority of natural channels are meandering, but there has been little research into the effects of sand mining on bridge piers in sinuous channels. Therefore, it is necessary to conduct a thorough investigation of the influence of flow characteristics around a bridge pier caused by upstream floodplain sand mining. This study investigated the effect of sinuousness (sinuosity index 1.1 and 1.25) on flow characteristics around a circular bridge pier in a sand-mined channel using CFD-based numerical modeling software (Flow-3D).

2. Material and method

2.1 Flow-3D

FLOW-3D is a general-purpose computational fluid dynamics (CFD) software. It employs specially developed numerical techniques (Volume of Fluid method) to solve the equations of motion for fluids to obtain transient, three-dimensional solutions to multi-scale, multi-physics flow problems. Typically, a numerical model starts with a computational mesh or grid. It consists of several interconnected elements or cells. These cells subdivide the physical space into small volumes with several nodes associated with each such volume. The FLOW-3D approach is to subdivide the flow domain into a grid of rectangular cells. Researchers find it more usable because of the advantages such as reduced time, costs, and no limitation in scale constraints.

2.2 Governing equations

The governing equations of the flow include continuity and conservation of momentum. The continuity equation is expressed as follows for the Cartesian coordinate and incompressible flow:

$$\frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z) = \frac{R_{SOR}}{\rho} \tag{1}$$

where, ρ is the fluid density, and R_{SOR} is a mass source. The velocity components (u, v, w) are in the coordinate directions (x, y, z). A_x is the fractional area open to flow in the x-direction, A_y and A_z are similar area fractions for flow in the y and z directions, respectively.

The equations of motion for the fluid velocity components (u, v, w) in the three coordinate directions are the Navier-Stokes equations with some additional terms

$$\frac{\partial u_i}{\partial t} + \frac{1}{V_F}\left(u_j A_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_i} + g_i + f_i \tag{2}$$

where,

- V_F is the fractional volume open to flow,
- g_i is body accelerations,
- f_i is viscous accelerations,

2.3 Numerical setup

The channel geometry, built-in Solid works CAD software, is based on the dimension of the flume setup of the IIT Guwahati Fluvial hydro-ecological laboratory with a dimension of 18 m long, 1 m wide, and 0.3 m deep.

Table 1. Detail of Numerical setup with all the dimension of model setup and flow conditions

Sinuosity index (SI)	Flood plain height (m)	Mining pit size (m^3)	Bridge pier diameter (m)	Flow discharge(m^3/sec)	Depth of water (m)	Bed roughness(m)
1.1	0.08	0.4*0.2*0.06	0.04	0.01536	0.14	0.0016
1.25	0.08	0.4*0.2*0.06	0.04	0.01536	0.14	0.0016

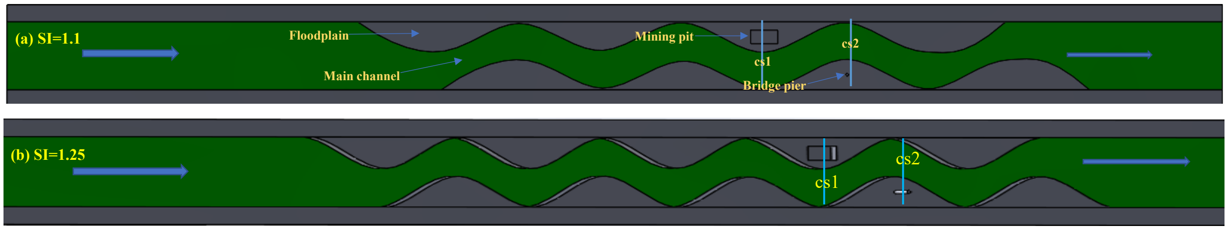

Figure 1. CAD Modelling of numerical setup for two different sinuousness of 1.1 and 1.25 with a sand mining pit on the upstream flood plain and a bridge pier on its downstream flood plain

3. Numerical modeling

The user can simulate multi-physical scenarios using Flow 3D software. In this study, the required physical models are: (1) Gravity and Non-inertial, (2) Turbulence and viscosity

3.1 Gravity and non-inertial

This model takes into account both constant body forces (such as gravity) and non-constant, non-uniform body forces caused by an accelerating reference frame. There is no accelerating reference frame in this investigation. The numerical setup's slope (1:1000) can be used by introducing gravity components in the direction of the slope (x,y,z).

3.2 Turbulence and viscosity model

By including the viscosity and turbulence model, the computation of viscous stresses and turbulence quantities is also included in the solution. Turbulence occurs whenever there are insufficient stabilizing viscous forces that prevent fluids from flowing in an organized, predictable manner. The natural instabilities that exist within a flow at high Reynolds numbers do not get dampened, and this leads to the formation of eddies of various sizes. The striations visible on the free surface of a faucet or a fast-moving stream are a good example of this behaviour.
In an ideal world, we'd be able to replicate the entire spectrum of turbulent fluctuations using mass and momentum conservation equations. For solving the nonlinear term of the Navier-Stokes equation and the Reynolds Averaged Navier Stokes equation turbulence model is required. In Flow-3D there are six turbulence models are given (Prandtl mixing length, turbulence energy model, $K - \omega$, $K - \varepsilon$, RNG $k - \varepsilon$, and LES). In this study RNG $k - \varepsilon$ model is used because of its best agreement with the experiment (Karami et al. 2014).

3.3 Boundary conditions and initial conditions

There are four different boundary conditions are defined at mesh faces in this study:

- Specified pressure: Specify the pressure at the boundary. If the fluid elevation is specified, the pressure at the boundary will follow a hydrostatic distribution (applied at outlet and free surface of flow along with fluid elevation and fluid fraction).
- Symmetry: Applies a zero-gradient condition at the boundary as well as a zero-velocity condition normal to the boundary (applied at smooth side walls)
- Volume flow rate: Applies the specified flow rate at the boundary (Discharge at inlet = 0.01536 m^3/s).
- Wall: Applies the no-slip condition at the boundary as well as a zero-velocity condition normal to the boundary (applied at bed of the setup).

4. Results and discussions

4.1 Flow characteristics near the sand mining pit (cross-section 1)

Figure 2 represents the comparison of the flow characteristics (streamwise velocity, secondary velocity, secondary current, and turbulence kinetic energy) at cross-section (1) of two different sinuous (SI = 1.1 and 1.25) channels. The flow characteristics is measured after the simulation equilibrium (at 180 s). The streamwise velocity distribution along the inner bank shows a high velocity (at cross-section1). After passing by the apex, the main flow velocity moves to near the opposite side (at cross-section 2), see figure 2 and 3. This is a common aspect of a sinuous or meandering river's flow (D. Xu and Y. Bia 2013; Blanckaert 2011; Abad and Garcia 2009; Whiting and Dietrich 1993). Cross-sectional velocity redistribution, which forms a point bar in the low velocity area and a pool on the opposite side, has been widely proven and considered vital to the formation and maintenance of river meanders in fluvial environments (Federici and Seminara 2003; Braudrick et al. 2009). As sinuosity increases, the greatest streamwise velocity zone at cross-section 1 narrows see figure 2. As a result, the shear layer zone in the main stream is slightly more sifted, which may result in aquatic life being shifted in the main stream as well as sedimentation in the main stream. As sinuosity rises, secondary velocity and secondary current become highly concentrated near the outer bank. Turbulence kinetic energy is more concentrated in the sand mining pit in the sinuosity 1.1 case (it indicates the high velocity fluctuation into the mining pit), but it is more concentrated in the inner bank in the sinuosity 1.25 case (as a result, there may be more chance of erosion).

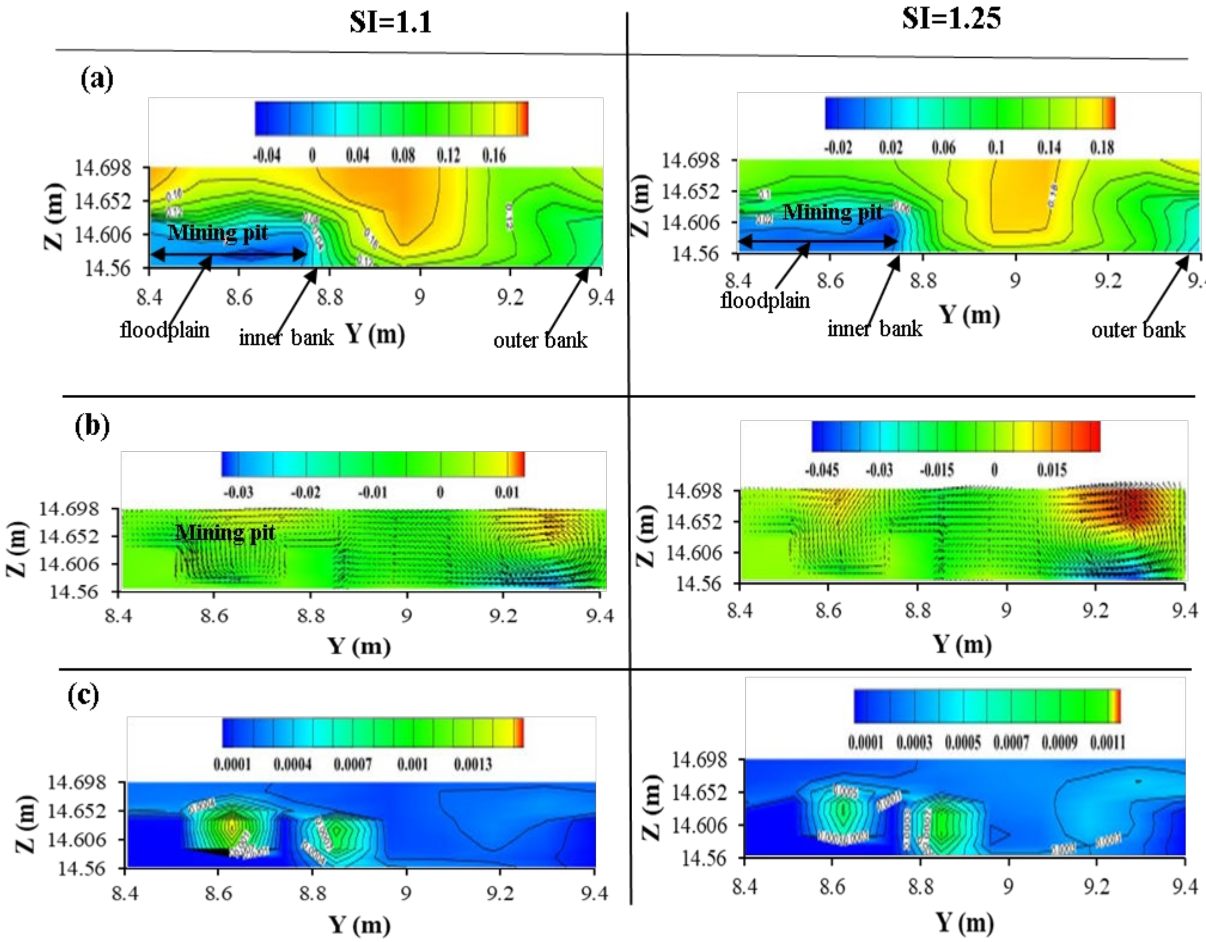

Figure 2. Contour plots at CS2, (a) Streamwise velocity (m/s), (b) Secondary velocity (m/s) and secondary current, (c) Turbulence kinetic energy (J/kg)

4.2 Flow structure just downstream of bridge pier (cross-section 2)

Figure 3. represents the comparison of the flow characteristics (streamwise velocity, secondary velocity, secondary current, and turbulence kinetic energy) at cross-section (1) of two different sinuous (SI = 1.1 and 1.25) channels. The flow characteristics is measured after the simulation equilibrium (at 180 s. The plots clearly show that just downstream of the bridge pier, as increasing the sinuosity, the maximum streamwise velocity zone sifts towards the flood plain, and in the vicinity of the bridge pier, a low streamwise velocity zone and vortex are created (Modalavalasa et al. 2022b). And at the outer bank, a highly low velocity zone is created in the case of sinuosity 1.25, which indicates the increase in the siltation phenomenon at the outer bank. At the location of bridge pier flow is diverted and secondary current in the main stream almost happens in the same pattern, but near the inner zone of

sinuosity 1.25, a negative secondary current (anticlockwise) zone is generated (which may cause a highly low-pressure zone). Turbulence kinetic energy is more concentrated near the inner bank in the case of sinuosity 1.1 and on the flood plain in the case of sinuosity 1.25 (which may cause high turbulence generated by increasing the sinuosity near the downstream of the bridge pier). It is little bit increases in the main channel as sinuosity increased see figure 3.

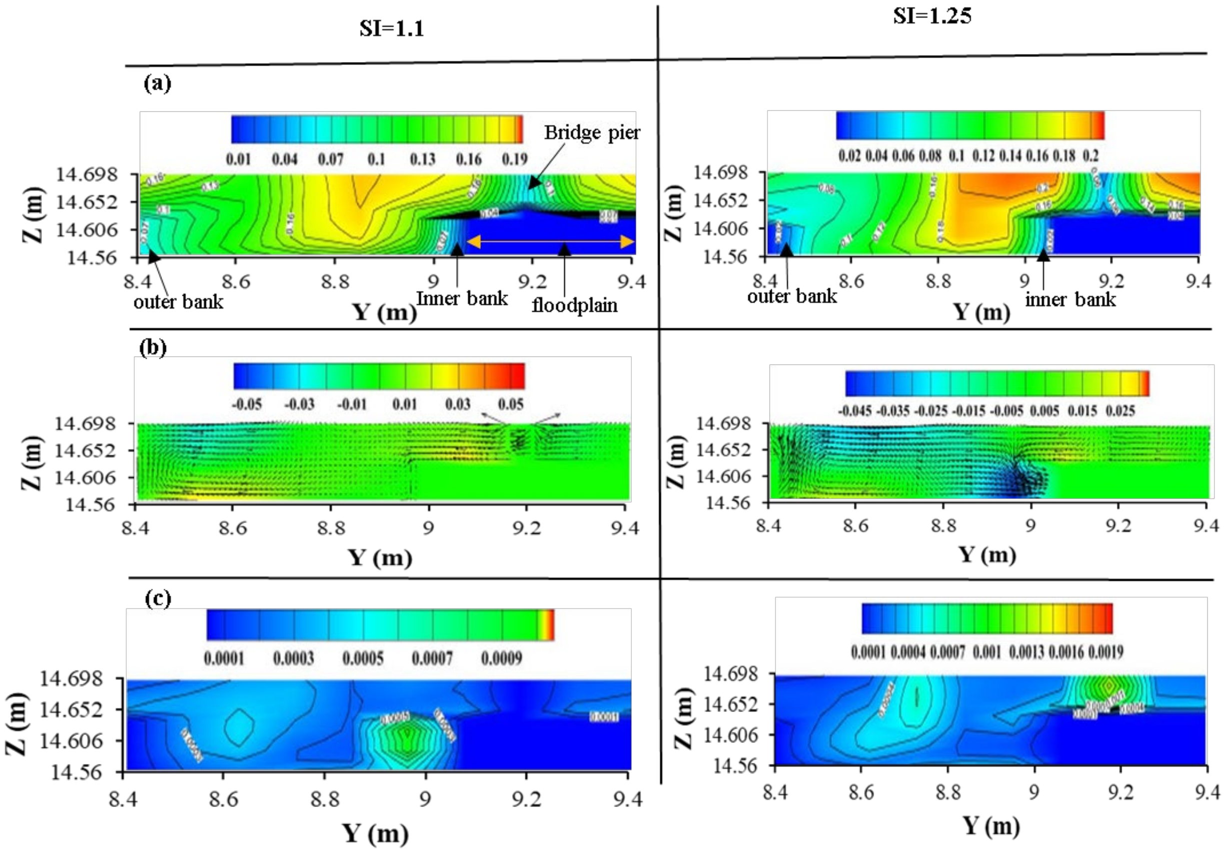

Figure 3. Contour plots at CS2, (a) Streamwise velocity (m/s), (b) Secondary velocity (m/s) and secondary current, (c) Turbulence kinetic energy (J/kg)

5. Conclusion

The impact of sinuosity variation (SI = 1.1 and 1.25) on the flow parameters of a sinuous channel with a flood plain sand mining pit and bridge pier was explored in this study. Flow-3D software was used to conduct a numerical study for this aim.

- As sinuosity increased, the shear layer zone shifted from the inner bank to the main stream, and the maximum zone of streamwise velocity narrowed near the mining pit (at cross-section 1), but the maximum zone of streamwise velocity shifted a little bit towards the flood plain just downstream of the bridge pier.
- The secondary current pattern is almost the same near the mining pit, but downstream of the bridge pier, an anticlockwise secondary current is generated near the inner bank of the main stream in the case of sinuosity 1.25.
- Turbulence kinetic energy is concentrated near the inner bank and into the mining pit in both cases at cross-section 1, but just downstream of the bridge pier, turbulence kinetic energy is concentrated on the flood plain in the case of sinuosity 1.25.

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