Transport modelling of sediment re-suspended during submarine cable laying operation

Lele Wang, Jie Shao and Wenwei Yao
Zhejiang Institute of Hydraulics and Estuary, Key Laboratory of Estuary and Coast of Zhejiang Province, Hangzhou 310020, China
Email: lele0926@126.com

Abstract. A two-dimensional depth-averaged hydrodynamics and suspended sediment transport numerical model is presented, which is discretized with finite volume method based on a triangular mesh. It is applied to investigate the diffusion and transport characteristics of sediment re-suspended during a demonstration staged submarine cable laying across the Jintang Channel, Zhejiang Province, China. The model is validated primarily against the observed data during the spring, middle and neap tidal cycles in July 2015. The model results show well agreements between the predicted and observed processes of tidal level, velocity and suspended sediment concentration (SSC). The validated model is then applied to simulate the distribution of the tidal velocity and additional SSC during the cable laying. The results show a close relationship between the additional SSC distribution and tidal hydrodynamics.

1. Introduction
In the case of a water jetting cable burial system (WJCBS) applied in a submarine cable laying, the bed material would be inevitably disturbed to re-suspended and the additional suspended sediment would be diffused and transported driven by tidal hydrodynamics, which may have an impact on water environment. Therefore, it can offer a significance practice and reference to study on diffusion and transport characteristics of sediment re-suspended during the submarine cable laying, which are documented in previous related research literature [1-4].

The Jintang Channel, Zhejiang Province, China is located in the south of the Hangzhou Bay and between the Jintang Island and land area of Ningbo City. It is a typical tidal channel evolved under a long term erosion, and is also a key channel connect the Chuanshan Channel, Luotou Channel and Cezi Channel with the Hangzhou Bay. Plus the complex submarine topography, the characteristics of tidal hydrodynamics is distinct from the Hangzhou Bay and other nearby areas [5]. Previous studies have proved $M_2$ semi-diurnal constituent is dominant in the Jintang Channel, of which the southwest and northeast part is flood current dominated whereas the rest part is ebb current dominated [6]. The suspended sediment concentration (SSC) distribution presents high in the north and low in the south, and also an obvious tidally driven cyclical variation, while the SSC decreases during the flood tidal phase and increases during the ebb tidal phase [7].

In this study, investigation has been conducted on distribution characteristics of the additional SSC during a demonstration staged submarine cable laying with a WJCBS across the Jintang Channel. A two-dimensional depth-integrated numerical model is presented for predicting the hydrodynamics and suspended sediment transport (SST) process in the study domain. The TPXO7.2 global tide model [8] is also employed to provide the tidal level process for open sea boundary in both validation and application simulations. The model is validated against the available observed data of tidal level, tidal
velocity and SSC during the spring, middle and neap tidal cycles in July 2015. The validated model is then applied to simulate the distribution of both the tidal velocity and additional SSC during the cable laying. The results show that the additional SSC distribution is closely related to tidal hydrodynamics, which can offer a reference for related demonstrations on submarine cable construction.

2. Model description

2.1. Hydrodynamics model
In a coastal area where flow is well mixed vertically and the vertical component is neglectable, two-dimensional depth-integrated unsteady flow equations can be applied. They can be written in the following form:

\[
\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0
\]

\[
\frac{\partial hu}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}(huv) = -gh \left(\frac{\partial z_0}{\partial x} + \frac{u\sqrt{u^2 + v^2}}{C_z h}\right) + fhv + \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{xy})
\]

\[
\frac{\partial hv}{\partial t} + \frac{\partial}{\partial x}\left(hv^2 + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}(huv) = -gh \left(\frac{\partial z_0}{\partial y} + \frac{v\sqrt{u^2 + v^2}}{C_z h}\right) + fhu + \frac{\partial}{\partial x}(hT_{yx}) + \frac{\partial}{\partial y}(hT_{yy})
\]

Where \( h \) is the total water depth including the water surface elevation and still water depth; \( u, v \) are the depth-averaged velocities in the \( x \) and \( y \) directions, respectively; \( t \) is time; \( z_0 \) is bed elevation; \( T_{xx}, T_{xy}, T_{yx}, T_{yy} \) are components of the turbulent shear stress; \( f \) is the Coriolis force coefficient due to the earth’s rotation, in which \( f = 2\omega \sin \phi \), \( \omega \) is earth’s angular velocity and \( \phi \) is the latitude of study domain; \( W_{xx}, W_{yy} \) are the surface wind shear stress in the \( x \) and \( y \) directions, respectively; \( g \) is the gravity acceleration; \( C_z \) is the Chezy coefficient. To investigate the SST characteristics and simplify the simulation, the bed elevation change is neglected in the modelling.

2.2. Suspended sediment transport model
In the case of low SSCs in a coast area, SST equation can be usually written as:

\[
\frac{\partial S}{\partial t} + \frac{\partial (uS)}{\partial x} + \frac{\partial (vS)}{\partial y} = D_s \frac{\partial^2 S}{\partial x^2} + D_s \frac{\partial^2 S}{\partial y^2} + \frac{F_s}{h}
\]

Where \( S \) is the depth-averaged SSC; \( D_s, D_s \) are the sediment diffusion coefficient in the \( x \) and \( y \) directions, respectively, which is usually equivalent to the value of flow turbulent viscosity in the case of low SSCs; \( F_s \) is suspended sediment source terms (SSST), in which \( F_s = F_s^t + F_s^r \), \( F_s^t = -\alpha \omega S \), \( \alpha \) is deposition probability and \( \omega \) is sediment settling velocity. In this study, \( F_s^r \) denotes the source of additional sediment suspended during the submarine cable laying operation.

2.3. Numerical Solution
Based on an unstructured triangular mesh, a finite volume method (FVM) to solve the above governing equations is adopted in this model, while a cell-centered method has been also applied. Hence, the calculation of the flow fluxes between two neighbor cells can be treated as a local one-dimensional problem in the direction normal to the interface, and the convection fluxes can be evaluated by an approximate Riemann solver, which can be calculated by several schemes formulated in the literature, such as the TVD scheme [9], BGK scheme [10], etc., among which the Roe scheme [11] is applied in the solution. In addition, an explicit scheme is used for the terms such as the Coriolis force and surface wind shear stress.
2.4. Treatment of key problems
In this model, both the normal velocity and water level gradient to the wall boundary are assumed to be zero. The tidal level processes in the north and south boundary are provided by the observed data from Zhapu (ZP) in the Qiantang River Estuary, Luchaogang (LCG) in the Yangtze River Estuary (YRE) and Damutu (DMT), respectively. As the open sea boundary, a tidal level process along the open sea is specified from the prediction provided by the TPXO7.2, in which the main tidal components of M2, S2, K1, O1, N2, P1, K1, Q1 and long-term tidal components of Mf and Ms can be predicted properly. Hence, a tidal level process can be structured in the following expression:

\[ \zeta_0(x) = \zeta_p(x) + \sum_{i=1}^{10} A_i(x) \cdot \sin[\omega_i t + \alpha_i(x)] \]  

(5)

Where \( \zeta_0 \) is tidal level relative to a specified datum; \( \zeta_p \) is the mean tidal level; \( i \) is an integer ranged from 1 to 10, which represents the different tidal components; \( A_i, \alpha_i \) are the amplitude and phase lag of a certain \( i \) tidal component, respectively; \( \omega_i \) is the angular frequency of a certain \( i \) tidal component.

A suspended sediment boundary condition in the SST model can be given as:

\[ S(x, y, t) = 0 \quad \text{(for flux outflow the domain)} \]  

(6)

\[ \frac{\partial S}{\partial t} + \frac{\partial (uS)}{\partial x} + \frac{\partial (vS)}{\partial y} = -\alpha S \quad \text{(for flux inflow the domain)} \]  

(7)

Besides, to solve the moving boundary problem, a cell interface blocking approach is adopted in this model, based on a criteria that if the total water depth at a cell is below a set threshold value, then flow fluxes through the interface is prevented.

Figure 1. Sketch of the bathymetry and locations of observation points in the study domain

3. Model validation
The study domain covers a plane water surface with the lateral width of 325 km and vertical length of 306 km, where is south to DMT, north to the Xuliujing (XLJ) in the YRE, west to the Fuchunjiang Hydropower Station (FCJHS) in the Qiantang River and offshore within the depth contour of -60 m. And it is divided into a set of computational mesh with 98153 nodes and 52280 cells. The bathymetry, locations of observation points and local mesh are shown in Figure 1. To obtain a better simulation accuracy, the grid is refined locally to give a higher resolution around the cable routing. Eventually, the space step ranges from approximately 1900 m to 9200 m in the open sea, and its maximum value is limited to 160 m around the routing area.

In the validation, the observed data during the spring, middle and neap tidal cycles in July 2015 is collected to validate the processes of tidal level, tidal velocity and SSC, and the time step is set not
greater than 1.0 s after validation. Figure 2 shows the detailed validation comparisons between the calculated and observed tidal level process at Xinhongkou (XHK) and Dapengshan (DPS) observation points during the spring, middle and neap tidal cycle, respectively. It can be seen that the predicted tidal level hydrographs and observed values agree well, with most calculation error less than 0.1 m. Figure 3 shows the comparisons between the calculated and observed tidal velocity process at V2 and V6 during the spring, middle and neap tidal cycle, respectively. The predicted and observed tidal velocity are in well agreement with the relative error within ±10%. Figure 4 shows the comparisons between the calculated and observed SSC process at V3 and V5 during the spring, middle and neap tidal cycle, respectively. The predicted and observed SSC are generally in well agreement on both magnitude and trend, except separately relative calculation deviations not greater than ±40% around the peak times.

Therefore, with the practicable and reliable predictions on processes of tidal level, tidal velocity and SSC, the model can be applied in research on the hydrodynamics and SST characteristics in a coast area.
4. Model application

4.1. SSST Determination

According to the cable laying technique with a WJCBS, the burial depth $h_l$ and width $d_l$ can be given
values equal to 3.5 m and 0.3 m, respectively. The sediment excavated area during one single cable laying can be estimated as \( A_l = 1.2 h d = 1.26 \) m\(^2\), in which the extra area is considered. With laying speed generally ranged from 3 ~ 10 m/min, \( v_l \) is set to 7 m/min in this study. Based on the measurement on sediment obtained on site, the density of bed material is given as \( \rho_s = 898 \) kg/m\(^3\). It is assumed that the re-suspended sediment would be no more than 20% of the excavated volume. Hence, the source strength of sediment re-suspended during one single cable laying can be written as \( \nu_s = 0.2 v_l \rho_s A_l = 26.4 \) kg/s, and the corresponding SSST can be determined as \( F_s' = \frac{\nu_s}{A_l} = 20.95 \) kg/(m\(^2\)•s).

In this study, seven cables with the same length of 16.5 km are all laid simultaneously sharing the mutual launching and receiving points to complete the circuit. For the plane layout of the cable routings, separations between cables are generally around 50 m in the middle of routing and total width reaches nearly 300 m, while separations are set to 60 ~ 70 m in the area around DPS and total width ranges from 300 ~ 400 m. To simplify the simulation, the one single cable is equally divided into 34 sections with the same length of 485 m and then the source of sediment re-suspended during the cable laying can be generalized to 34 point. Hence, one source point would release suspended sediment for 70 mins in the certain estimated strength sequencely forward to the laying direction.

4.2. Calculation condition
According to the statistical analysis on tidal level data obtained from ZH station within the study domain, the 90% and 10% cumulative frequency tidal range are 3.26 m and 1.15 m, respectively. A certain period during July 2015 is selected to obtain a relatively more representative observed data, including processes of tidal level, tidal velocity and SSC. The validated two-dimensional model is applied in the investigation on the predictions of tidal hydrodynamics and SST process in the study domain. After the ten simulation days, a plane distribution layout of additional suspended sediment can be derived from modelling on diffusion and transport of the sediment re-suspended from the generalized 34 source points.

4.3. Results analysis
4.3.1. Tidal velocity field
The tidal processes in the study domain are calculated in the application. Figure 5 presents the distribution of tidal velocity field at the very moment of flood peak and ebb peak, respectively. It can be seen that the hydrodynamic process is influenced obviously by the boundary. Plus the complex incoming flow, the tidal current is strong in the middle main stream of the narrow channel with the mean tidal velocity up to 2.10 m/s. The current directions in the field shows that the flood currents flow radially whereas ebb currents flow convergently. And both the flood and ebb currents are basically alternating current parallel to the bathymetric contour. The tidal current is relatively weak in the shallow water area near XHK with the mean tidal velocity around 1.20 m/s, while the mean tidal velocity reaches 1.6 m/s near DPS.
Figure 5. Calculated tidal velocity field locally around the cable routing

4.3.2. Characteristics of suspended sediment distribution

The sediment re-suspended during the cable laying would be diffused and transported driven by the tidal current. Therefore, the SST shares the general direction with the tidal current. During the cable laying operation, the bed material would be re-suspended to diffuse into nearby area, and then the nature background SSC recovers along with the additional SSC disperses gradually. Figure 6 shows the distributions of the additional SSC during the spring, neap and whole tidal cycles, respectively. Two main features of the suspended sediment distribution can be drawn: (A) Driven by the strong tidal hydrodynamics during the spring tidal circle, the diffusion and transport process of suspended sediment is obvious. The additional suspended sediment mass would be diluted causing both the peak value and diffusion area of the additional SSC less than they are during the neap tidal circle. (B) During the neap tidal circle, the suspended sediment would diffuse less in the shallow water area near the west side of the routing with relatively weak tidal hydrodynamics. Thus, the additional SSC would be maintained at higher levels, and the suspended sediment mass with high SSC would diffuse about 6 km towards the north of XHK. In the meantime, the additional SSC would disperses gradually normal outwards from the laying axis.

The statistical analysis on diffusion area of additional suspended sediment below certain SSCs can be seen in Table 1. The results present that the diffusion area reaches about $79.36 \text{ km}^2$ with the additional SSC more than $10 \times 10^{-3} \text{ kg/m}^3$, the diffusion area reaches about $34.64 \text{ km}^2$ with the additional SSC more than $20 \times 10^{-3} \text{ kg/m}^3$, the diffusion area reaches about $12.95 \text{ km}^2$ with the additional SSC more than $50 \times 10^{-3} \text{ kg/m}^3$, the diffusion area reaches only $1.39 \text{ km}^2$ with the additional SSC more than $100 \times 10^{-3} \text{ kg/m}^3$, and the diffusion area reaches only $0.95 \text{ km}^2$ with the additional SSC more than $150 \times 10^{-3} \text{ kg/m}^3$. 
Figure 6. Calculated distribution of the additional SSC locally around the cable routing

Table 1. Diffusion area statistics of the additional suspended sediment below certain SSCs

| Diffusion area (km²) | Additional suspended sediment concentration |
|---------------------|---------------------------------------------|
|                     | > 10×10⁻³ kg/m³ | > 20×10⁻³ kg/m³ | > 50×10⁻³ kg/m³ | > 100×10⁻³ kg/m³ | > 150×10⁻³ kg/m³ |
| spring              | 42.18           | 17.06           | 1.26            | 1.26             | 0.00             |
| neap                | 79.34           | 33.94           | 12.95           | 1.32             | 0.95             |
| whole               | 79.36           | 34.64           | 12.95           | 1.39             | 0.95             |
Figure 7 shows the distribution of the additional SSC during one single source releasing suspended sediment on the middle routing at the very moment of flood peak, flood slack, ebb peak and ebb slack, respectively. It can be seen that the distribution is closely related to the tidal hydrodynamics. Around the flood peak moment when the flood tidal velocities are relatively high, the additional SSC is relatively low to no greater than $10 \times 10^{-3}$ kg/m$^3$, and the suspended sediment would diffuse towards the northwest with an approximate area of 1.5 km$x$0.6 km. Around the flood slack moment when the tidal level is still maintained around the high peak and the ebb tidal current coming, the additional SSC would be maintained up to $20 \times 10^{-3}$ kg/m$^3$, and less suspended sediment would diffuse towards the south with an area of 1.4 km$x$0.9 km under relatively low turbulence mixing. Around the ebb peak moment when the ebb tidal velocities are relatively high, the additional SSC is no greater than $10 \times 10^{-3}$ kg/m$^3$, and the suspended sediment would diffuse further towards southeast with an area of 2.4 km$x$0.5 km. Around the ebb slack moment when the tidal level is still maintained around the low peak and the flood tidal current coming, the additional SSC would be up to $20 \times 10^{-3}$ kg/m$^3$, and less suspended sediment would diffuse towards northwest with an area of 0.6 km$x$0.7 km.

5. Conclusions
The study presents a two-dimensional depth-averaged hydrodynamics and SST numerical model, which employs a FVM based on a triangular mesh. It is applied to investigate distribution characteristics of the additional SSC during a demonstration staged submarine cable laying across the Jintang Channel. The
model is validated against the available observed data of tidal level, tidal velocity and SSC during the spring, middle and neap tidal cycles in July 2015. The validated model is then applied to predict the tidal velocity field and characteristics of suspended sediment distribution during the cable laying. The results show a close relationship between the additional SSC distribution and tidal hydrodynamics.

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