Effect of environmental parameters on the amount of scour in marine structures

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ABSTRACT: Scour is a phenomenon that occurs as a result of natural erosion by ground water flow and transport of seabed material. In this research, scour around the legs of marine structures is simulated using the FLOW3D.V.9.3™ commercial software. The general scour model consists of two components, namely, the lift and thrust forces. The drag force, that is inserted to the structure, is a combination of those two components. As the sediment concentration equals the volume fraction of cohesion, the drag force that determines the rigidity of the sediment model, is activated. Also, as the sediment concentration changes, the viscosity and density of the fluid changes. The numerical model used in this research is similar to the experimental set-up that was performed in a sedimentation tank two meters long, 1.5 m wide and 0.3 m high; while the sandy sediment particle diameter was 0.084 cm. The numerical model implements an RNG turbulence model. After the studies, the time to reach equilibrium in the model was 100 seconds. The relative error between experimental and numerical scour depth is about 10 percent. Scour depth was determined for legs with circular and elliptic as well as for rectangular base shapes with different aspect ratios. Numerical results indicate that the scour depth decreases for the more streamlined elliptic base shapes. Also, the effect of water depth on scour depth, while all other parameters are kept constant, is a linear relationship. Finally, as sediment particle diameter increases, scour depth decreases.

Keywords: Scour; computational fluid dynamics; turbulence model; aspect ratio

INTRODUCTION

Today the beaches and river scour is one of the major problems in coastal and marine engineering. Placement of different structures along with the marine currents, constantly exposes their basis to scour. Typical bridges, jetties, pipelines, vertical breakwater or combination of structures (such as offshore platforms and coastal structures), are structures that are affected by the scour phenomenon in the coasts and rivers. In General, structures in the coastal region alter the flow pattern, which usually increases sedimentation and eventually leads to the creation of the scour phenomenon. To determine the scour depth, also in this respect, is important firstly because, expresses the level of potential development of flow around structures, and secondly influences the design of the structures in the path of the water current. The following are some of the research done in the field of water scour:

Tseng, Yen & Song (2000)
This was a 3D model based on finite volume method using weakly compressible flows to simulate the steady flow around cylindrical legs. Equations were solved by explicit methods for the modified McCormick prediction method (Tseng et al., 2000). Turbulence model of large eddy simulation (LES) for turbulent flow model has been applied in this study. The numerical model was compared with experimental results of (Dargahi, 1989).

Yuhi and Ishida (2000)
Flow pattern by the direct integration of equations of three-dimensional Navier-Stokes is
simulated. The amount of base shear before and after scour was reported (Yuhi et al., 2000).

Using Fluent software simulation of turbulent flow around the leg in clear water conditions was performed. Calculations have been made using different turbulence models. Bed shear stress using turbulence model K-ε were measured. The experimental results show some differences. Reynolds stress turbulence model produces excellent results for the flow pattern and bed shear stress around a cylindrical base for smooth and scour bed conditions (Salaheldin et al., 2004).

Also (Ghiassi, 1995) should be mentioned which presents the three dimensional coastal flow modeling using the finite volume method.

MATERIALS AND METHODS
Four methods of assessing scour can be cited:
1- Physical models;
2- Field study;
3- Mathematical models and then computer models;
4- Analytical and approximate methods and formulas.

The first and the second are experimental methods. The second approach is more accurate and appropriate to solve problems and to strengthen the structure against scour. The most important problem using these methods is that the application of advanced and well equipped facility which can operate underwater in order to monitor the scour might be very costly. The third method is essentially based on theoretical and mathematical relations for bed erosion and the theory presented in conjunction with the marine hydraulic structures and scour. After this stage, and according to a mathematical model prepared a computer model that can adapt to different conditions and situations of these phenomena (scour) is made. Parameters affecting scour are scour depth and range at the base of a marine structure and at a specific time instant. Here we suffice to the headlines:
1- Bottom slope;
2- Type and amount of the translating material;
3- Geometry and direction of the base;
4- Classification, stratification and consolidation of soil and ground materials;
5- Natural or artificial changes in flow regime or sediment;
6- Increase of sediment load;
7- Oblique leg in the direction of the flow which is a significant obstruction.

Governing equations for the flow of water and scour
The main equation governing the water flow is the mass conservation or continuity equation which is defined as:
\[ \vec{V} \cdot \nabla = 0 \quad , \] (1)

where \( \vec{V} \) is the particle velocity vector with three components \( u, v \) and \( w \) in Cartesian coordinates, then
\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad . \] (2)

Another important equation governing the flow is the three-dimensional Navier-Stokes equation:
\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = f_x - \frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{1}{\rho} \left[ \frac{\partial (\tau_{xx})}{\partial y} + \frac{\partial (\tau_{xy})}{\partial z} \right] \] (3)

\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = f_y - \frac{1}{\rho} \frac{\partial P}{\partial y} + \frac{1}{\rho} \left[ \frac{\partial (\tau_{yx})}{\partial x} + \frac{\partial (\tau_{yy})}{\partial z} \right] \] (4)

\[ \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = f_z - \frac{1}{\rho} \frac{\partial P}{\partial z} + \frac{1}{\rho} \left[ \frac{\partial (\tau_{xz})}{\partial x} + \frac{\partial (\tau_{yx})}{\partial y} + \frac{\partial (\tau_{yz})}{\partial z} \right] \] (5)

In equations (3) and (4) terms \( f_x, f_y \) and \( f_z \) are the volumetric forces respectively, along \( x, y \) and \( z \).

Scour process can be simulated using the sediment continuity equation. Sediment continuity equation is as follows:
\[ \frac{\partial \xi}{\partial x} + \frac{\partial \eta}{\partial y} + (1 - \lambda) \frac{\partial Z_b}{\partial t} = 0 \quad , \] (6)

where \( \xi \) and \( \eta \) are the sediment transport rates along \( x \) and \( y \) respectively, \( \lambda \) is the porosity of the sediment particles and \( Z_b \) is the bottom level. (Chew, 1992)
RESULTS AND DISCUSSION
Modeling requires the use of the effective parameters on scour depth such as particle size, water depth and flow velocity. In this study, the experimental results conducted on a sediment basin (Fig. 1) 1.5 m long, 2 m wide and 0.3 m high is used for the verification of simulation results. Sediment particle size 0.84 mm, depth 380 mm, flow speed is 0.6 meters per second. Experimental results for flow depth and velocity for circular cylinders of ten different diameters are shown in Table 1. The test duration is three hours (Babu et al., 2003). Results in line (C-9) of Table 1 are used for the verification.

Numerical simulation of physical models
Numerical methods for modeling erosion in different flow conditions are used for various applications. Studies have shown that these programs are not able to accurately describe sediment transport. In this study, the FLOW-3D software that has had success in terms of numerical coding is used. Flow-3d™ software that is powerful in the field of fluid mechanics was developed to study one, two and three-dimensional fluid dynamics in a wide range of applications, including shallow water, viscosity, cavitation, agitation, tension, environmental engineering, aerospace and marine sciences. Flow-3d™ software uses finite volume method with regular rectangular meshing (Flow-3d Manual, 2015). Figs. (2) and (3) respectively show a simulation model of the software and its boundary conditions. The numerical simulation in fact uses a 3D model but as can be noted the sediment transport and scour takes place in the 2D plane of xz. Therefore we only need two of the equations from momentum Navier-Stokes equations (3) to (5).

Table 1: Experimental data from (Babu et al., 2003) used for validation of simulation results

<table>
<thead>
<tr>
<th>Run no</th>
<th>Diameter of obstruction D (mm)</th>
<th>Water depth d (mm)</th>
<th>Current velocity U (m/s)</th>
<th>Scour depth (at the end of the experiment) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-1</td>
<td>50</td>
<td>380</td>
<td>0.6</td>
<td>14.40</td>
</tr>
<tr>
<td>c-2</td>
<td>50</td>
<td>450</td>
<td>0.328</td>
<td>11.10</td>
</tr>
<tr>
<td>c-3</td>
<td>50</td>
<td>500</td>
<td>0.258</td>
<td>9.20</td>
</tr>
<tr>
<td>c-4</td>
<td>50</td>
<td>600</td>
<td>0.199</td>
<td>7.30</td>
</tr>
<tr>
<td>c-5</td>
<td>90</td>
<td>380</td>
<td>0.6</td>
<td>31.20</td>
</tr>
<tr>
<td>c-6</td>
<td>90</td>
<td>450</td>
<td>0.328</td>
<td>22.10</td>
</tr>
<tr>
<td>c-7</td>
<td>90</td>
<td>500</td>
<td>0.258</td>
<td>17.30</td>
</tr>
<tr>
<td>c-8</td>
<td>90</td>
<td>600</td>
<td>0.199</td>
<td>13.70</td>
</tr>
<tr>
<td>c-9</td>
<td>110</td>
<td>380</td>
<td>0.6</td>
<td>48.60</td>
</tr>
<tr>
<td>c-10</td>
<td>110</td>
<td>450</td>
<td>0.28</td>
<td>30.10</td>
</tr>
</tbody>
</table>

Fig. 1: The experimental set-up in (Babu et al., 2003)
**Boundary conditions**
According to the experimental set-up, the inlet velocity boundary condition (Specified Velocity) and the outlet flow velocity (Outflow) are selected so that flow obstruction does not occur. The y-left, y-right rigid wall conditions are selected and in the Z-down direction rigid wall (Wall) was applied, since there is no flow at the border. In the direction of Z-up Specified Pressure boundary condition is considered.

**Mesh analysis**
Considering that the mesh structure is of prime importance for the numerical solution and is necessary to achieve the desired results, mesh analysis is performed. Therefore, in order to analyze the effect of several mesh sizes on the results, variations in speed along the x axis was assessed. The results with the mesh size 5.4 x 5.8 x 1.7, 2.22 x 2.31 x 0.67, 1.92 x 2.08x 0.6, and 1.72 x 1.88 x 0.55(cm) on the model and comparison with four speed profiles is shown.

As can be seen in Figs. (4-b to 4-d) by refining mesh size velocities are unchanged, therefore, at this resolution the mesh size do not affect the results.

**Comparison of numerical results with test data**
Given that the depth of the scour is obtained from the laboratory 4.86 cm and depth of scour of numerical simulation 5.41 cm the relative error is about 10 percent which demonstrates good compatibility between numerical and experimental result.

**Steady-state time**
As was stated in the introduction of models balance time of scour is three hours. This time is equivalent to 10800 seconds for performing numerical model on software which is a very long time. In order to speed up the implementation of the program simulation time should be reduced. For this purpose, different time durations were chosen for the simulation and results are seen in Fig. 5. According to the
simulation result for the scour depth, time to balance is about 100 seconds.

**Effect of geometry on scour depth**

In this section, simulation is first performed on a leg with cross-sectional shape of a circle of diameter 15.24 cm, and then for ellipses with different strain (ratio of length in x direction to length in y direction). Finally, scour around legs of same cross-sectional area but in shape of a square and two rectangles with different ratios of strain were modeled. In this simulation water depth is constant 38 cm. It is sought which
cross-sectional shape creates the highest obstacle
in front of the current and which one creates the
least effect on the flow field. In order to measure
the scour depth “macroscopic density” mode of
the software was used (see Figs. 6-a to h).

Effect of water depth on scour depth
In this section, with a change in water depth, the
change in scour depth for the geometry of a
circle of diameter 15.24 cm is discussed. In
addition, the diameter of the particle
sedimentation 0.084cm according to the
experimental case is considered. Simulation for
the depth of 48, 58, 78 and 88 cm were
performed (Figs. 8-a to d). Fig. 9 shows the
effect of water depth on the scour depth.

vertical cylinder mounted on a bed. Costal
Structures, 99: 783-792.

Fig. 5: The equilibrium scour time

Fig. 6-a: changes in sediment density around the cylindrical shape leg ratio=1, \(d_{scour}=13.35\text{cm}\)
Fig. 6-b: changes in sediment density around the elliptical shape leg ratio=0.349, $d_{scour}=24.52$ cm

Fig. 6-c: changes in sediment density around the elliptical shape leg ratio=0.717, $d_{scour}=15.76$ cm

Fig. 6-d: changes in sediment density around the elliptical shape leg ratio=0.717, $d_{scour}=15.76$ cm
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Fig. 6-e: changes in sediment density around the elliptical shape leg ratio=2.867, $d_{scour}=10.82$ cm

Fig. 6-f: changes in sediment density around the square shape leg ratio=1, $d_{scour}=15.26$ cm

Fig. 6-h: changes in sediment density around the rectangular shape leg ratio=0.292, $d_{scour}=23.76$ cm
Fig. 6-h: changes in sediment density around the rectangular shape leg ratio=3.492, $d_{scour}=10.32$ cm

Fig. 8-a: changes in sediment density around the cylindrical shape leg; water depth=48 cm, $d_{scour}=9.44$ cm

Fig. 7: effect of leg geometry on the scour depth
Effect of sediment size on scour depth

Simulation result for scour depth was 13.35 cm for a circular shape of diameter 15.24 and particle size 0.084 cm. Next simulations for particle size 0.14 cm with the same Shield’s parameter as for the 0.084 cm particle, scour
depth was 6.27 cm. This dramatic effect of particle size is seen in Fig. 9; also, the data are presented in Table 2.

Table 2: Effect of sediment size on scour depth

<table>
<thead>
<tr>
<th>Sediment size (cm)</th>
<th>Scour depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.014</td>
<td>23.63</td>
</tr>
<tr>
<td>0.02</td>
<td>21.81</td>
</tr>
<tr>
<td>0.084</td>
<td>13.35</td>
</tr>
<tr>
<td>0.14</td>
<td>6.27</td>
</tr>
<tr>
<td>0.2</td>
<td>5.16</td>
</tr>
</tbody>
</table>

CONCLUSION
In this study, using the Flow-3d™ and RNG turbulence model for scour around a leg was simulated. With regard to the compliance achieved between the simulation and the results of laboratory tests, it can be stated that this software in the analysis of the various issues related to the scour problem, is highly capable.

- As was observed, the aspect ratio for elliptical leg has significant effect on scour depth. Also, for the placement of the base flow is very important to note that it can have effects on the rate of scour.
- The effect of changing the scour depth was observed around leg as with increasing water depth, scour depth also increases. But when the water depth is increased 2.8 times the scour depth stays nearly constant. According to this jacket installation depth should be done in a way that least scour occurs.

REFERENCES
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