Ocean Engineering 142 (2017) 625–638

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical investigation of local scour around three adjacent piles with different arrangements under current

Qi Zhang[a,b], Xiang-Lian Zhou[a,b,*], Jian-Hua Wang[c]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai 200240, PR China
[c] Centre for Marine Geotechnical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Keywords:
Three adjacent piles
Local scour
Sediment transport
Current
Numerical modeling

ABSTRACT

A set of three-dimensional numerical models is established to investigate the mechanisms of local scour around three adjacent piles with different arrangements under steady currents. The RANS equations, closed with a $RNGk-\varepsilon$ turbulence model, are established for simulating the flow field around pile groups. A sediment scour model is adopted to estimate the motion of the sediment by predicting the erosion, advection, and deposition of the sediment. The simulation results of the bed elevation contours and the time evolution of scour depth around a single pile model are verified with the previous experimental results and show good agreement. Then, the effects of pile spacing for three adjacent piles with different arrangements on the flow field, bed elevation contours, and scour depth are discussed in detail. The results reveal that the dimensionless pile spacing has a significant effect on the flow field and local scour around the three adjacent piles. The scour hole patterns and scour depth around each pile with different arrangements are totally different.

1. Introduction

Pile foundations are one of the most commonly used foundation concepts in offshore platforms, bridges, offshore wind turbines etc. The existence of the pile foundation will change the flow pattern and enhance the turbulence around the pile foundation, which leads to the horseshoe vortex in front of the pile, the lee-wake vortex behind the pile, and the contraction of streamlines at the side edges of the pile. These factors lead to an increase in the local sediment transport capacity, and the development of local scour around the pile foundation under waves or currents in marine environment. The insertion depth of the pile decreases as the scour depth around the pile increases, which is closely related to the stability of pile foundation. Once the depth of local scour around the pile is deep enough, the pile foundation may become unstable or even collapse. Therefore, it is commonly accepted that local scour is one of the main causes of pile foundation failure in marine environments.

Scour around pile foundation has been extensively studied through experimental and numerical methods in the last few decades. Due to the limitation of computational capacity, researchers studied the local scour around pile foundation (cylinder) by experimental method in the early years, during which several scour formulas were proposed for estimating the maximum scour depth around a pile or cylinder (Breusers et al., 1977; Melville and Sutherland, 1988; Yanmaz and Altinbilek, 1991; Dey, 1999; Melville and Chiew, 1999). Researchers studied the mechanisms of local scour around the pile mainly divided into three situations: local scour under waves, currents, and combined waves and currents. (1) *Local scour under waves*. The mechanism of wave-induced local scour around a vertical cylinder was discussed in detail in some previous researches. Sumer and Fredsøe (2001) investigated the scour progress around a large vertical cylinder that was exposed to a progressive wave by experimental method, in which two kinds of experiments were made in their research, including the rigid bed and the actual scour. Their results showed that the waves stirred up the sediment and brought it in suspension which leaded to the local scour around the cylinder. The scour was found to depend on the Keulegan-Carpenter number and the diffraction parameter. Zhou and Chen (2004) conducted a series of physical models to study the local scour around a circular cylinder under the action of irregular waves, in which the effects of some wave and sediment parameters (such as wave period, wave height, water depth, sediment grain size etc.) were taken into account in their research. Dey et al. (2011) studied the mechanisms of local scour at circular piles embedded in clay and sand-clay mixed beds under wave loadings. Different proportions of sand-clay mixtures were involved in their experiments. (2) *Local scour under currents*. Baglio et al. (2001) investigated the local scour around a pile in an oscillating flow by experimental method, in which some morphological parameters of the scour such as the maximum scour depth, the extension of the eroded area, and the position of the

* Corresponding author at: State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China.
E-mail addresses: zhouxl99@hotmail.com, zhouxl@sjtu.edu.cn (X.-L. Zhou).

http://dx.doi.org/10.1016/j.oceaneng.2017.07.045
Received 20 December 2016; Received in revised form 22 May 2017; Accepted 13 July 2017
Available online 21 July 2017
0029-8018/

maximum scour toe were measured in their research. Graf and Istiarto (2002) studied the flow pattern in the established scour hole in the front and rear of a cylinder on a mobile channel bed by experimental method. The vorticity of the flow was calculated, and the horseshoe vortex and wake vortex were established in their research. The effects of d_{50} on the scaling of scour depth around bridge piers was studied by employing both laboratory and field measurements (Lee and Sturm, 2009). Dey and Raikar (2007) investigated the flow and turbulence characteristics of the horseshoe vortex around a circular pier, which were changed with the development of the scour hole. The differences of the scour depths and scour holes between submerged and unsubmerged cylinders under steady flow were investigated in detail (Dey et al., 2008). Debnath and Chaudhuri (2010) carried out a series of laboratory experiments in investigating the mechanism of the scouring process around cylinders embedded in clay-mixed beds. The effects of the clay-content, water content, bed shear strength, and pier Froude number on the maximum scour depth, equilibrium scour hole geometry, scouring process, and time variation of scour were investigated in their research. A further investigation was proposed by them to study the effects of suspended sediment concentration on local scour (Debnath and Chaudhuri, 2011). A laboratory experiment was performed by McGovern and Ilic (2014) to investigate the development of scour around an offshore turbine monopile in tidal currents, in which the effects on scour hole development of simultaneous changes in flow depth and speed through the tidal cycle was investigated in detail. (3) *Local scour under combined waves and currents*. Among that, Around et al. (2001) investigated the scour around a pile subject to combined waves and currents through a series of flume and basin experiments, in which the measured scour depth was plotted as a function of the undisturbed current velocity and the maximum velocity at the sea bottom for various KC numbers. An experimental study on the control of scour at vertical piles under waves and current was carried out by Dey et al. (2006), in which the main purpose of their research was to determine the effectiveness of the splitter plate attached to the pile and the threaded pile for controlling scour. Liang et al. (2013) investigated the scour around single piles and two adjacent piles subject to oscillatory flows by setting up a series of laboratory experiments, in which the effects of the pile height and the twin-pile layout on the local scour had been studied in detail. An experimental study had been conducted by Liang et al. (2015b) to investigate the differences in scour depth for four countermeasures that included the sacrificial piles, a downstream bed sill, sleeve, and slot in the pile. Also, the differences of scour under currents only and under coexisting waves and currents were investigated in their research.

With the development of computer science, the numerical method has a wide range of applications in many fields such as hydromechanics and local scour, as it boasts such advantages as low expense, high precision, and free from the modeling scale. Among that, Olsen and Kjellesvig (1998) developed a three-dimensional numerical model to estimate the maximum local scour depth around a circular cylinder placed vertically in a flume under steady flow, in which the Navier-Stokes equations with the $k-\varepsilon$ turbulence model were solved in the model, and the bed concentrations were used to solve the convection-diffusion equation for the sediments. Nagata et al. (2005) established a three-dimensional numerical model to simulate flow and bed deformation around river hydraulic structures, including a bridge pier. The Reynolds-averaged Navier-Stokes equation closed with the nonlinear $k-\varepsilon$ turbulence model was employed to calculate the flow field. A moving grid system was adopted to conform numerical grids to both bed and water surfaces in the numerical model. Liu and García (2008) developed a numerical model to study the local scour around a pile under wave loading, in which the volume of fluid (VOF) method was adopted to track the water free surface. The behavior of the water-sediment interface was captured with the moving-mesh method in the research. Laboratory experiments and numerical simulations were carried out by Zhao et al. (2010) to investigate the mechanism of local scour around a submerged vertical circular cylinder in steady currents. The RANS equations were coupled with the bed morphological model to simulate the scour process. The suspended load and bed load were included in the numerical model. Khosronejad et al. (2012) investigated clear-water scour around bridge piers by experimental and numerical methods. Time evolution of the bed topography for several cross-sectional shapes of the bridge pier including cylindrical, square, and diamond was investigated in the research. Kim et al. (2014) investigated the local scour around two adjacent cylinders, in which the Large-eddy simulation (LES) was employed to simulate the instantaneous turbulent flow around the two adjacent cylinders. The effects of the longitudinal and transverse cylinders spacing on the flow structure, scour evolution, bed topography, and maximum scour depth were investigated in detail in the study. In the recent decade, artificial intelligence (AI) approaches, such as artificial neural networks (ANNs), adaptive neuro-fuzzy inference system (ANFIS), support vector machine (SVM), model tree (MT), and group method of data handling (GMDH), have been applied to predict local scour depth around pile groups under waves and currents (Bateni and Jeng, 2007; Etemad-Shahidi and Ghaemi, 2011; Ghazanfari-Hashemi et al., 2011; Najafzadeh, 2015; Zounemat-Kermani et al., 2009). The GMDH approach, which was known as the self-organized approach that solved various problems in non-linear systems, produced relatively more accurate prediction than those yielded using conventional regression-based equations and other soft computing tools (Najafzadeh and Azamathulla, 2013). Moreover, the neuro-fuzzy based group method of data handling (NF-GMDH), which had higher flexibility and lower complexity compared to the GMDH approach, was utilized to predict the scour depth around pile groups recently (Najafzadeh and Azamathulla, 2015; Najafzadeh, 2015). These artificial intelligence approaches indicated that predictive methods could present good validations with low error for measured datasets compared with empirical equations.

To date, most previous investigations had been mainly concerned with local scour around single pile by experimental method, few researchers studied the mechanisms of local scour around single pile by numerical method in recent years. Whereas, the mechanisms of the local scour around pile foundation, especially the pile groups, had not been fully understood. Only a few researchers attempted to consider local scour around two adjacent piles under currents (Kim et al., 2014; Liang et al., 2013) and wave scour around pile groups (Sumer and Fredsøe, 1998), in which the differences of the local scour results between each single pile in a pile group had not been studied in detail. It is known that the maximum scour depth, equilibrium scour hole geometry, scouring process, and time variation of scour for each pile among the pile group are different due to effects of the number of piles, pile spacing, pile group layout, flow direction, and some other affecting factors. Therefore, it is necessary to give a systematic and comprehensive analysis in the mechanisms of local scour around pile groups, which could provide the theoretical references for pile foundation designing. A comparison of the sediment scour model between the present model and the previous experimental results is presented, which indicates that the numerical model is accurate and capable to investigate the local scour in complex conditions. The computed velocity vectors, streamlines around a single pile, development of scour depth, morphological changes, and deposition patterns are firstly investigated to understand the mechanisms of local scour around a single pile. Then, the mechanisms of local scour around three adjacent piles with different arrangements under steady currents are numerical investigated. The effects of pile spacing G/D and different kinds of pile group arrangements on the development of scour depth, changes of scour hole geometry, and scouring process are studied in detail.

2. Numerical method

Flow3D is used to investigate the local scour around three adjacent piles with different arrangements under current. The volume of fluid (VOF) method (Hirt and Nichols, 1981) is adopted to track the free water surface. The model utilizes the Fractional Area/Volume Obstacle Representation (FAVOR) method (Hirt and Sicilian, 1985) to model complex geometric regions (such as the packed sediment) in fixed rectangular meshes by means of area fractions A_i and volume fractions