Environmental Earth Sciences (2018) 77:776
https://doi.org/10.1007/s12665-018-7967-4

ORIGINAL ARTICLE

Numerical modeling of sediment scouring phenomenon around the offshore wind turbine pile in marine environment

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Received: 5 May 2018 / Accepted: 17 November 2018 / Published online: 24 November 2018

Abstract
In recent years, with daily progress in technology, application of wind turbines for energy generation has become common all around the world. Installation of these turbines at sea encountered a great deal of challenge. One of the most important challenges is scouring around the piles of these turbines due to sea waves and current interaction. Many studies have been conducted in this respect; however, the results are insufficient, and the phenomenon remains poorly understood in tripod wind turbines. In this work, an attempt is made by combining the waves and currents, and changing the substructure of the turbine and the type of the bed materials, to extend the investigation of this phenomenon. The current research is focused on presenting the trend of changes in the amount of scouring. By changing the conditions (including variation in the wave height, variation of the current velocity, variation of the pile diameter, and variation in the size of bed particles), one can arrive at an appropriate estimate and prediction of the shape and the depth of the scour pit.

Keywords Wind turbine · Sediment scour · Waves · Current

Introduction

After becoming industrialized, humans have utilized new energy sources. Wood, coal, oil, and gas have been among the primary energy sources; however, advancements in the new energies' science, such as nuclear energy, have emerged. All these energy sources are finite; thus, unlimited energies or, in other words, the renewable energies such as the solar energy are welcomed. One of the novel methods is the use of wind energy which has been utilized in many countries of the world including The Netherlands, Denmark, Britain, etc. The method used in this way includes turbines with great heights installed against the wind direction and the wind energy causes rotation of the turbine blades whose rotation provides the needed energy.

Nevertheless, use of this method has some disadvantages. Wind farms need large spaces, and this becomes problematic for small countries like The Netherlands. In addition, rotation of the turbine blades and the nearby power plants produce noise which could create problems for the neighboring inhabitants.

After many discussions and research works, offshore wind turbines became the focus of attention. Installation of turbines at sea does not occupy land, the noise produced is outside of the urban environments, and they would not endanger the lives of the neighboring inhabitants. Perhaps, the most important issue is the wind which is up to 20% stronger in the marine environment and this makes it an ideal place for turbine installation.

Nevertheless, installation of the turbines at sea is not an easy task. Transport of the long piles and gigantic turbine blades needs special operations. Also working in the marine environment doubles the hardship of work. The major problem is to find an appropriate land for installation of the turbine and precise design of the turbine pile according to the regional conditions. In addition, the effects of sea waves and currents on the foundation and the installed turbine pile are another issue associated with working in the marine environment. The waves create vorticity around the turbine's pile and cause scour of the soil around the pile and make it unstable. Scour around the turbines piles is a serious issue in relation to the offshore wind turbines.

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As seen in the diagram of Fig. 1, application of the wind turbines for energy generation has become increasingly widespread.

Currents and waves could greatly affect the soil around the turbine. After finding a proper bed for installation of the turbines at sea, the precise effect of the currents and waves on the turbine pile should be taken into account. Scouring could cause instability of the turbine or even lead to its drowning. Scouring also is dependent on other factors like the bed constituent particles and pipe diameter. In the present work, we investigate the effects of pile diameter and the bed constituent particles in relation to the effect of currents and waves.

Literature review

The scouring phenomenon has been problematic for the engineers a long time. Principally, where the water flows we are faced with some degrees of scouring phenomenon, whether it be the pier of a bridge or the foundation of a building. All research performed in this respect which we could observe the effects of this phenomenon on the structures (Whitehouse 1998). One of the well-known effects of scouring is observed in Oroville Dam (located in California) which occurred on February 12, 2017 due to increase in the water volume of the dam reservoir and a high amount of flow over the spillways. It caused scouring downstream of the dam and displacement of 130,000 of the people living in the cities' downstream of the dam (Goodling et al. 2018). This phenomenon causes scouring of the surface and creation of hole around the structure. The basis for this phenomenon is the vacuum induced at the contact borders of the two media due to change in the fluid velocity. As we know, the fluid at the contact borders with other media is affected by the roughness and the form of the media which is in contact with. In the hydraulic structures, this phenomenon could damage the stability and strength of the hydraulic structure as the water could wash out the soil at the bed and around the piles of the hydraulic structures or erode the walls and banks of the rivers and seas and transport them along the flow direction (Gimbert et al. 2016; Sadeghi Googheri et al. 2017).

By installing the wind turbines at sea, these problems were amplified. After damage to a number of turbines in Denmark due to scouring, research began for investigating this phenomenon on the offshore turbines which are very expensive structures. Nevertheless, investigating this phenomenon on the wind turbines has not a long history and is still at the primitive stages (Petersen 2014).

In continuation, we would deal with the research performed on scouring of the offshore wind turbines piles. Many studies have been performed in the experimental form and attempt is made to examine the effect of wave and current on the monopile foundations. Temporal extension of the scouring and its effect on the structure frequency is among other issues which are examined. In addition, the methods of bed protection against scouring are not overlooked and many studies are conducted in this field. However, protective measures are very hard to execute and are not cost-effective.

While installation of the wind turbines at sea has become widespread in the past decade, there are many cases which need further research and investigation. One of these cases is the scouring of the turbine pile. The turbine piles are in very different conditions with respect to piles of the river bridges and are affected by many factors like waves, tides, currents, etc.

In an article which was first published by Sumer et al. (1992), it was stated that there is a difference between scouring of the bridge piers in the river and the offshore wind

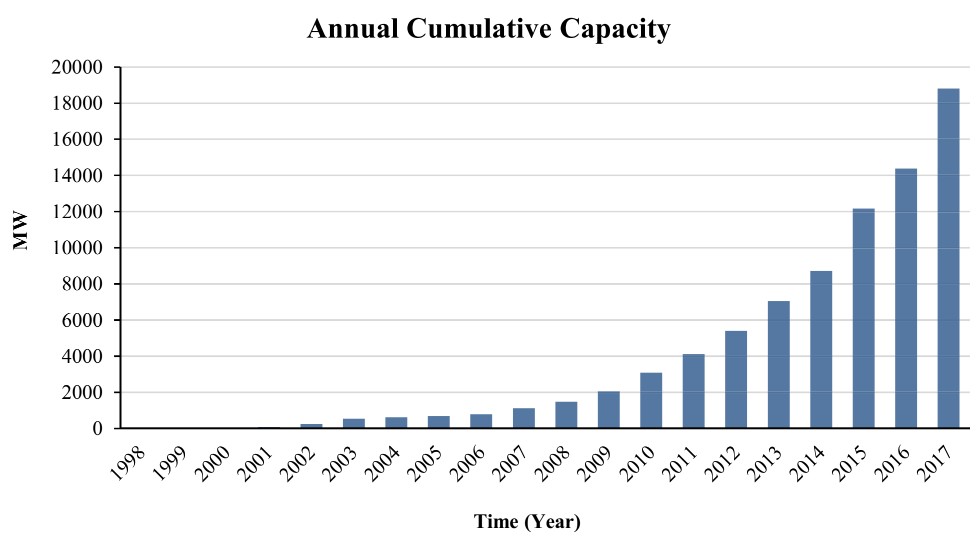


Fig. 1 Electricity generation capacity of the offshore turbines in MW (Global Wind Statistics 2017)

turbine piles. In this article written on the scouring around a vertical pile under the wave force, referring to the Keulegan–Carpenter (KC) equation, it is shown that the formation of scouring due to the waves is completely different from the scouring due to the current only which is the phenomenon observed in the river.

In continuation, the effect of these currents, i.e., currents within the sea, is substantially dependent upon the Keulegan–Carpenter number. This number is the main element in the equation by which the scouring pit depth at the bed could be measured.

The Keulegan–Carpenter number is calculated by the following expression:

$$KC = \frac{U_m T}{D}, \quad (1)$$

where U_m shows the wave velocity and T is the wave period (Sumer et al. 1992; Sadeghi Googheri et al. 2017).

Harris et al. (2010) published an article in which they presented a model for predicting the development and growth of scouring over time for an offshore pile. They focused on the factors such as the current, wave, and their combination. By presenting this model, they were successful in explaining the development of scouring in the time scales and found that, in deep waters, it is the current which mostly affects the pit form, even in the stormy conditions, whereas this conclusion is deeply influenced by the current form and velocity. Some other literature has been reviewed in this area (Ghodsi et al. 2018; Khosravi et al. 2018; Mortezaei and Karimpour Fard 2017).

Sørensen and Ibsen (2011) presented an article entitled practical experiments for investigating the scouring pit. At the beginning of their article, referred to the costs of protecting the turbine piles and recommended that, by proper prediction of the scouring pit, the pile is designed accordingly, and the penetration depth is increased. In addition, Sørensen and Ibsen (2011), performing an experiment, showed that the pile could penetrate up to 25% of its length into the soil due to the scouring.

Qi and Gao (2014) performed a number of experiments at Peking University of Science. They passed waves with variable heights together with a constant current over a monopile cylinder and published their results.

De Vos et al. (2012), in an experimental work, were successful in modeling the adopted methods for sediment scour protection and represented the damage that these protective measures might endure. They also divided the damages to the protective methods into four levels.

In the De Vos et al. (2012) studies, it was observed that the executed protective methods could be damaged due to the turbulent marine environment, powerful waves and currents, and with the passage of time. One of the recommended methods is an application of filters with fine grains. When the wave and/or the current impacts the turbine, the fine grains around the turbine are spread and scouring occurs. However, applying a filter method similar to the method used in the earthen dams, this event could be prevented.

Prendergast et al. (2015) proved that the scouring phenomenon could even affect the structure's natural frequency.

In China, use of the gravity base foundations is almost common. In a research done by Yu et al. (2016) at Tianjin University, the performance of these foundations against scouring was investigated. They modeled scouring around these piles in the laboratory and measured it.

It should be noted that the gravity base foundations have numerous problems. Their heavy weight causes problems in their transport; in addition, they could not be installed at large depths. Their manufacturing cost is high. Use of this type of foundations exhibits a low technology except for the special conditions.

Research methodology

Numerical modeling of the flow field has a great importance in examining the scouring field in the vicinity of the wind turbines piles and presenting design solutions for these structures. Experience of the researchers with respect to this type of simulations has shown that, among the available software packages, the Flow-3D software has a better capability in the modeling of these hydraulic structures. In this study, FLOW-3D (ver.10.01) software has been used for numerical investigation of the scouring field around the wind turbine tripod structure under the current and wave impacts. The structure simulated in this research corresponds to the experimental model in a scale of 1:40 which has been studied by Stahlmann (2013). This model was related to the "Gigawind alpha ventus-sub project 5" project which was investigated by the Environment Ministry of Federal Republic of Germany.

Physical modeling was set up into Laboratory flume with the width of 2.2 m, the depth of 2 m, and the length of 100 m. The turbine tripod is laid on the fine sandy bed with an average diameter of 0.2–0.25 mm, length of 4.6 m, and thickness of 0.25 m. Here, using a wave maker device available at the laboratory, waves with a height of 0.35 m are generated which encounter the pile. The main column diameter of the tripod is 15 cm and the diameter of the pile sleeves is 7 cm install upon a disk with 77 cm diameter (Stahlmann 2013).

Stages of flow simulation over the stepped spillways

The boundaries of meshing should be determined with respect to the model geometry using the mesh blocks, where all the sizes of the intended structure and the free space within it are defined (Razavi Alavi et al. 2018; Razavi and

Ahmadi 2017; Movahedi et al. 2017; Ekeleme and Agunwamba 2018; Gamil et al. 2017).

In Fig. 2 the built solid geometry is added to the FLOW-3D numerical model. Then, using the mesh block, the computational space for the stepped spillways in the FLOW-3D numerical model is created.

Considering the bed conditions in the experimental model, the erodible bed with a height equal to 25 cm taken from the flume bottom is added to the flume.

Validation of the numerical model results using the laboratory data

For calibration and validation of the numerical model, the laboratory studies performed by Stahlmann (2013) are utilized. As stated in the previous sections, referring to the studies of Stahlmann, by utilizing a wave flume and producing the regular and irregular waves with Jonswap spectrum,

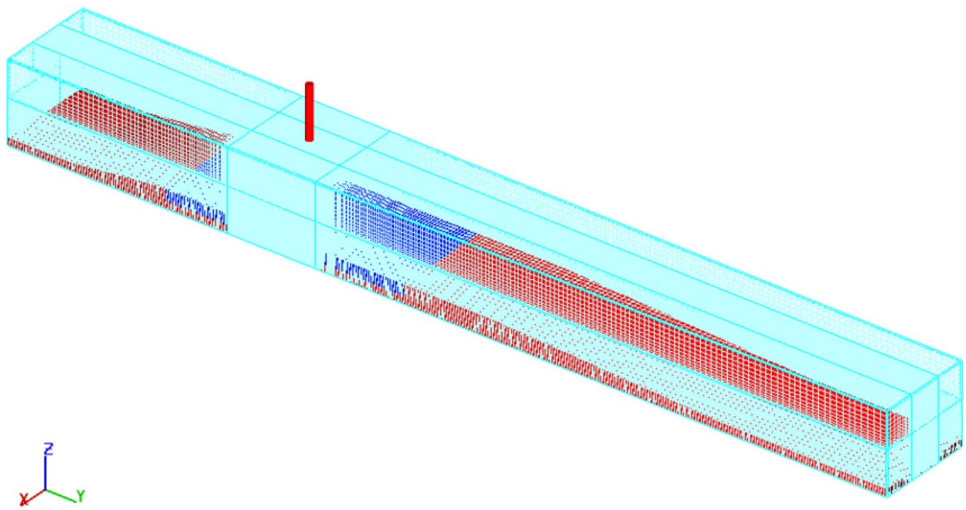


Fig. 2 Meshing conditions: meshing block and computational cells

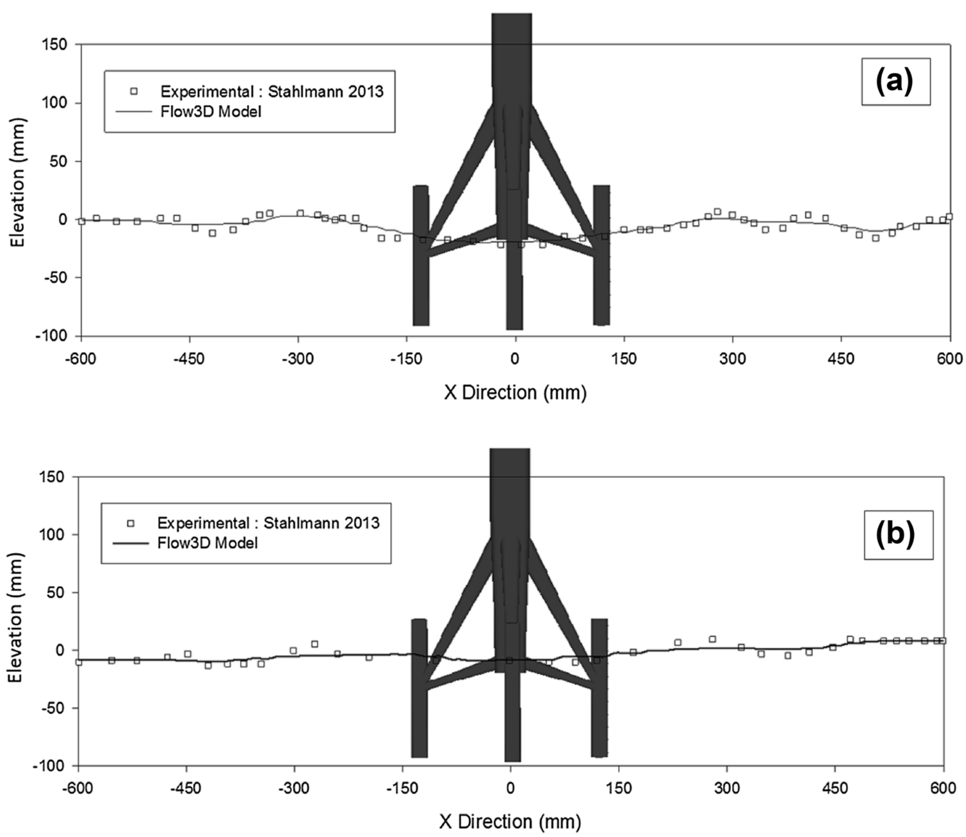


Fig. 3 Comparison between the numerical and experimental results of the bed scour profile for **a** irregular waves; **b** regular waves

Table 1 Comparison of the validation and calibration results of the numerical model for the pressure parameters in the FLOW-3D numerical model

X direction (m)	Elv. (mm) exp. Run 1	Elv. (mm) num.	Error %	Elv. (mm) exp. Run 2	Elv. (mm) num.	Error %
−600	−2.35	−2.65	12.77	−11.3	−10.8	4.42
−450	−4.03	−4.23	4.96	−3.09	−3.11	0.65
−300	2.01	1.85	7.91	−2.87	−2.77	3.48
−150	−11.10	−10.87	2.09	−8.94	−8.14	8.95
0	−10.87	−10.12	6.94	−8.75	−7.98	8.80
150	−11.21	−10.89	2.88	−8.71	−8.54	1.95
300	−4.30	−4.23	1.70	−3.2	−3.42	6.87
450	−3.35	−3.47	3.46	−2.53	−2.63	3.95
600	−4.11	−4.21	2.48	−3.14	−3.18	1.27
		Ave. er.	4.48		Ave. er.	5.02

the scouring due to encounter of waves and currents at the bed and in vicinity of the turbine piles is measured by installing the proper gauges.

In Stahlmann's laboratory studies, the installed wind turbine pile for the sea wave condition is built with a 1:40 scale and is subjected to waves and currents with different conditions. The diameter of the main pile in this offshore turbine is 7.5 cm and the depth of water is 1 m. Regular waves with a significant wave height of 15 cm and period of 2.3 s encounter the structure. The irregular waves are generated from the Jonswap spectrum with a maximum significant wave height of 20.8 cm and period of 3 s which encounter the wind turbine structure. It should be noted that, in this study, the current velocity is taken equal to 0.206 m/s. Based on the laboratory study, the bed materials with uniform grading and an average diameter of $D_{50} = 0.148$ mm and density of 2650 kg/m^3 are utilized.

In the laboratory studies, by installing the recording gauges, changes in the bed scour depth due to the waves which encounter with the turbine pile have been measured. In the numerical model also, using the geometric coordinates, we could extract changes in the bed depth on various points of the pile. After a series of modeling according to different conditions, finally, the results of the numerical model have been compared and assessed based on the best modeling conditions. Calibration and validation of the numerical modeling results are divided into two parts. The first part of calibration and validation of the numerical model would be done for the hydrodynamic parameters including the period, wave height, and maximum values of the energy spectrum (there is no energy spectrum for the regular waves) and comparison is made with the laboratory values for precise determination of the numerical model error in the simulation of the hydrodynamic parameters. The second part also would be performed based on the scour depth parameter in the vicinity of the pile due to the forces produced by a combined wave and current action along the longitudinal and transverse directions.

Table 2 Wave height characteristics for different cases of the FLOW-3D numerical model

Run	Percentage of wave height changes (%)	Wave height Hs (cm)	Wave period Ts (s)	Current velocity *u* (cm/s)
C	+50	31.2	3	20.6
B	0	20.8	3	20.6
A	−50	10.4	3	20.6

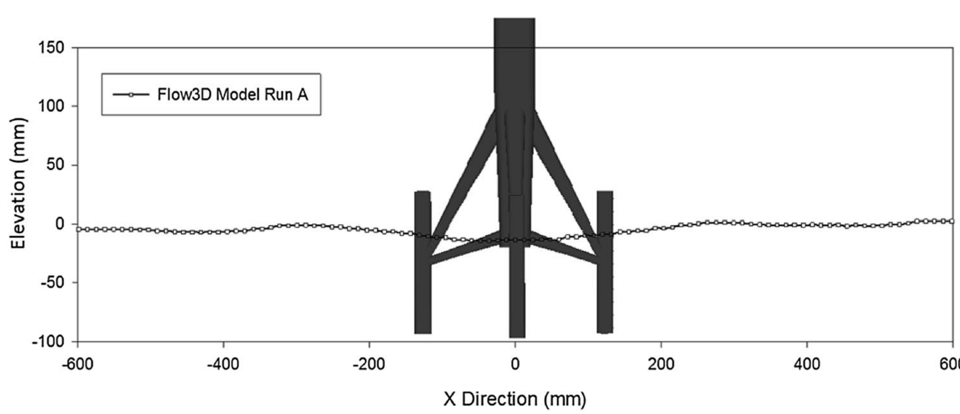


Fig. 4 Comparison of the numerical and experimental results of the bed scour profile for irregular waves and the current condition of Run A

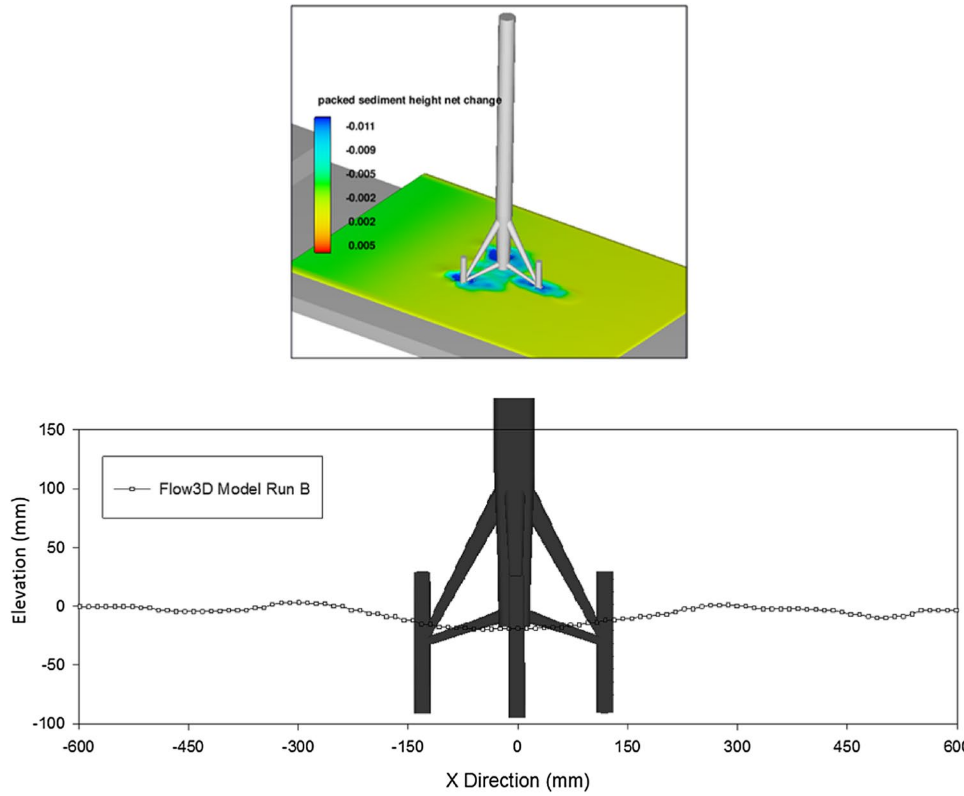


Fig. 5 Comparison of the numerical and experimental results of the bed scour profile for irregular waves and the current condition of Run B

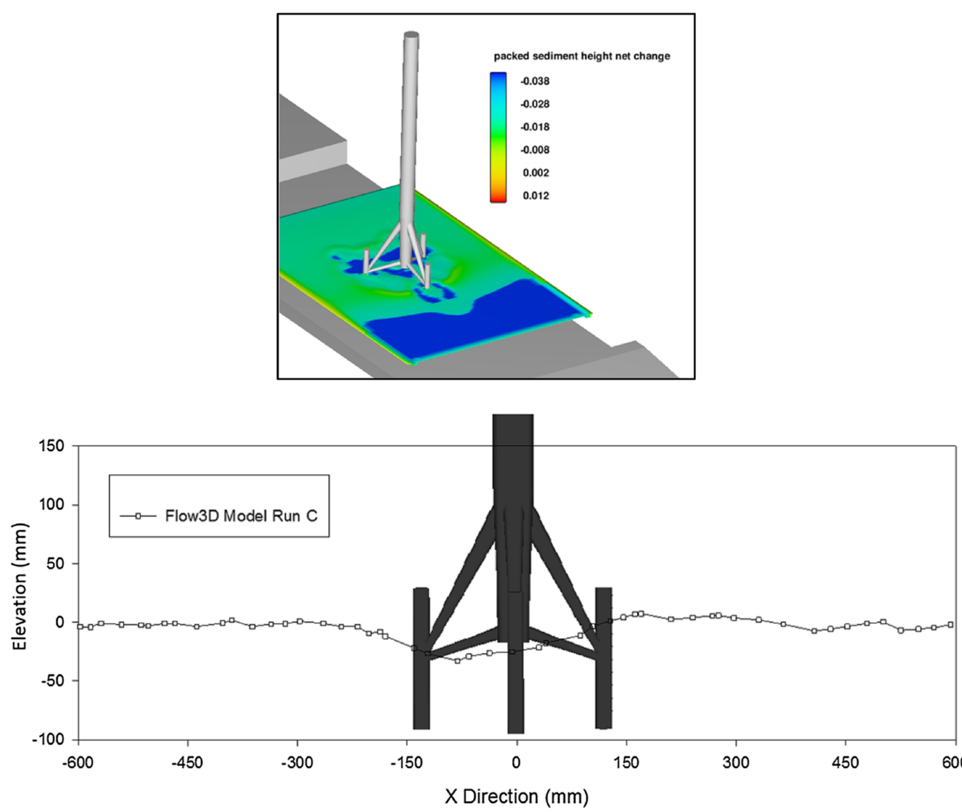


Fig. 6 Comparison of the numerical and experimental results of the bed scour profile for irregular waves and the current condition of Run C

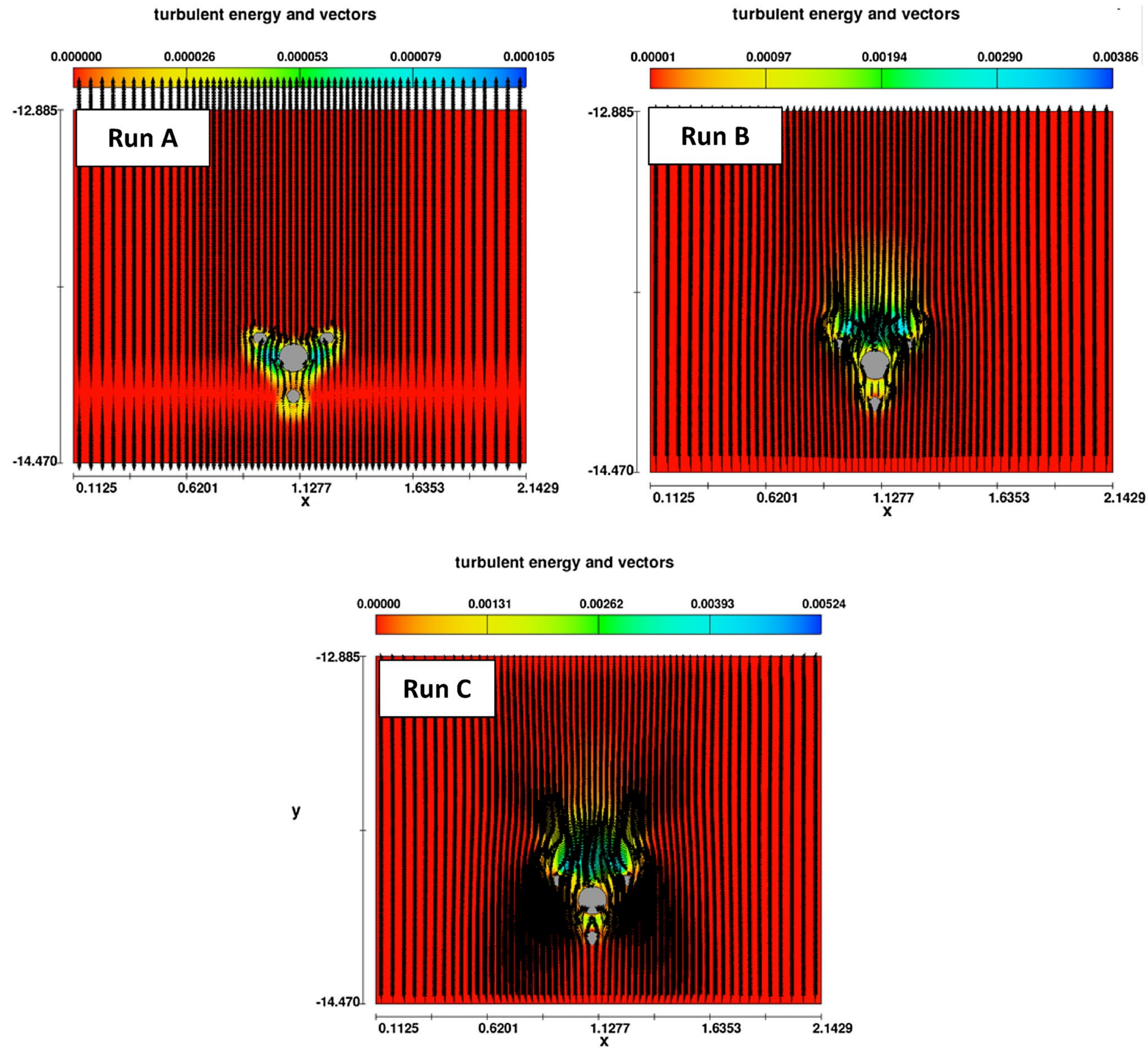


Fig. 7 Velocity vectors during encountering the offshore platform together with turbulence energy intensity values

According to the numerical modeling results, the maximum relative error for the parameters of wave height and period in the regular case is 1.73 and 4.34%, respectively. In the irregular case, these error values for the parameters of the wave height and period are 5.31 and 2%, respectively. In addition, the maximum simulation error value of the wave peak spectral density with respect to the laboratory results is equal to 4.36%. Comparison of the hydrodynamic parameter value results and their corresponding relative error shows that the present numerical model has an acceptable relative error, and the present numerical model is a calibrated and validated one in terms of the hydrodynamic parameters.

Table 3 Characteristics of the current velocity for different cases of the FLOW-3D numerical model

Run	Wave height	Wave period	Current velocity	u (cm/s)
	Percentage of current velocity changes (%)	Hs (cm)	Ts (s)	
G	+ 50	20.8	3	30.9
F	0	20.8	3	20.6
E	− 50	20.8	3	10.3

For calibration and validation purpose, the scour depth values and changes in the bed profile are also extracted from the numerical model and compared with the experimental results. The bed scour profile along the flume central axis and longitudinal direction is determined, as shown in the Fig. 3a, b. It should be noted that the results of the below diagrams are extracted for the central axis and the combined regular wave and current in the first case, and the irregular wave and current in the second case.

In Table 1, the relative error values between the experimental and FLOW-3D numerical model results for similar conditions are extracted and calculated. Comparison of the scour depth parameter values in the vicinity of the turbine pile per two types of irregular wave height and period (Run 1) and the regular wave height and period (Run 2) together with a current velocity equal to 0.206 m/s is performed. It should be noted that various tests with different boundary conditions, initial conditions, and meshing conditions have been conducted in the numerical model, and the best results are presented in this section.

As shown in Table 1, the average error of the numerical model for the scour depth values due to the wave and current encounter with the offshore turbine pile under various irregular wave heights and periods is equal to 4.48%. Also based on the numerical analysis performed for the condition of irregular waves, the average error value for the scour depth is 5.02% in the model. Performing various tests and examining the available parameters, it is concluded that the present numerical model is a calibrated and validated model for the regular and irregular waves. Thus, it could be utilized in similar conditions for simulation of the wave action with different wave heights, pile geometries, and bed particles.

Results and discussion

Investigation of the numerical modelling results of the wave and current action on the wind turbine pile under the effect of variation in the wave height

One of the main parameters affecting the scour profile due to the wave and current encounter with the wind turbines piles is the height of waves. By increasing in the wave height around the turbine pile, the turbulence in the vicinity of the pile increases. By increasing the turbulence in the vicinity of the pile, changes of the velocity near the bottom and bed increase, and consequently, the scour profile also changes in the vicinity of the pile. Accordingly, in the present study, by

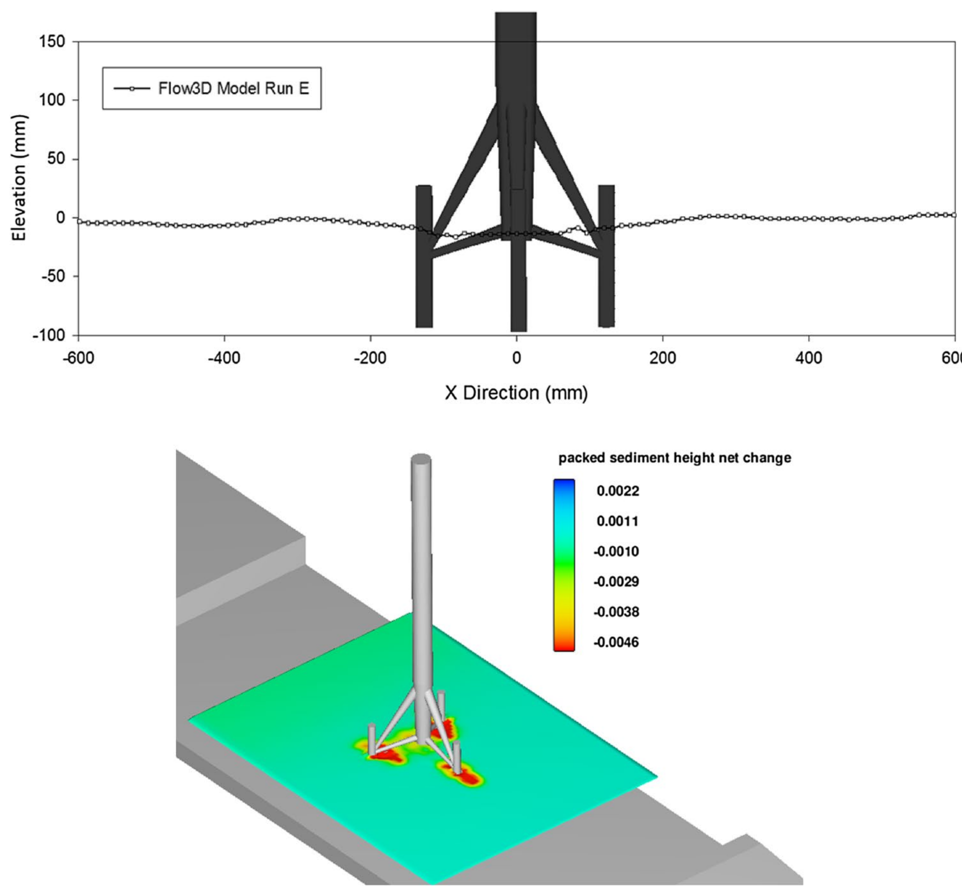


Fig. 8 Numerical results of the bed scour profile for irregular waves and Run E conditions

increasing and decreasing the wave height value with a constant period, attempt is made to examine the effect of wave height on the scour depth and the bed profile. In the first case, modeling is done by 50% increase in the wave height together with the current and the second case modeling is performed by 50% decrease in the wave height together with current. In Table 2, the precise wave characteristics in the performed modeling are observed. It should be noted that, in this case, also the waves are selected as irregular waves with Jonswap spectrum.

Using numerical modeling in accordance with the above table conditions (Table 2), the bed scour profile is extracted from the numerical model for different cases of the wave heights which is shown in the following diagrams (Figs. 4, 5, 6).

Based on the numerical modeling results, by increasing in the height of waves encountering the installed wind turbines piles in the sea under the effect of combined irregular waves and current, the depth of sediment scour pit increases, so that, by 50% increase in the wave height with a constant period, the maximum depth of scouring increases from 11 to 38 mm which is 3.45 times. In addition, by 50% decrease in the wave height, the maximum depth of scouring decreases from 11 to 5 mm. The reason for the impact of wave height on the scouring amount lies in the amount of flow turbulence. In the following figures, the energy values corresponding to the flow turbulence for the three cases of wave heights have been compared. As seen in these figures (Fig. 7), the turbulence intensity of the wave and current is greater in the waves with higher heights.

Investigation of the numerical modelling results of the waves and current encounter with the wind turbines piles, under the impact of variation in the current velocity

In this section of the present study, we investigated the effect of variation in the current velocity in combination with the waves on the scouring and bed profile in the vicinity of the marine platforms. Increase and/or decrease in the combination of the current and waves could cause change in the bed scour pattern, so that, by increasing in the current velocity, the backflow zone formed around the pile becomes stronger and, consequently, causes increase in the sediment scour depth. Accordingly, in this study, by increasing and decreasing of the current velocity and with constant wave height and period, attempt is made to investigate the effect of current velocity on the scour depth and

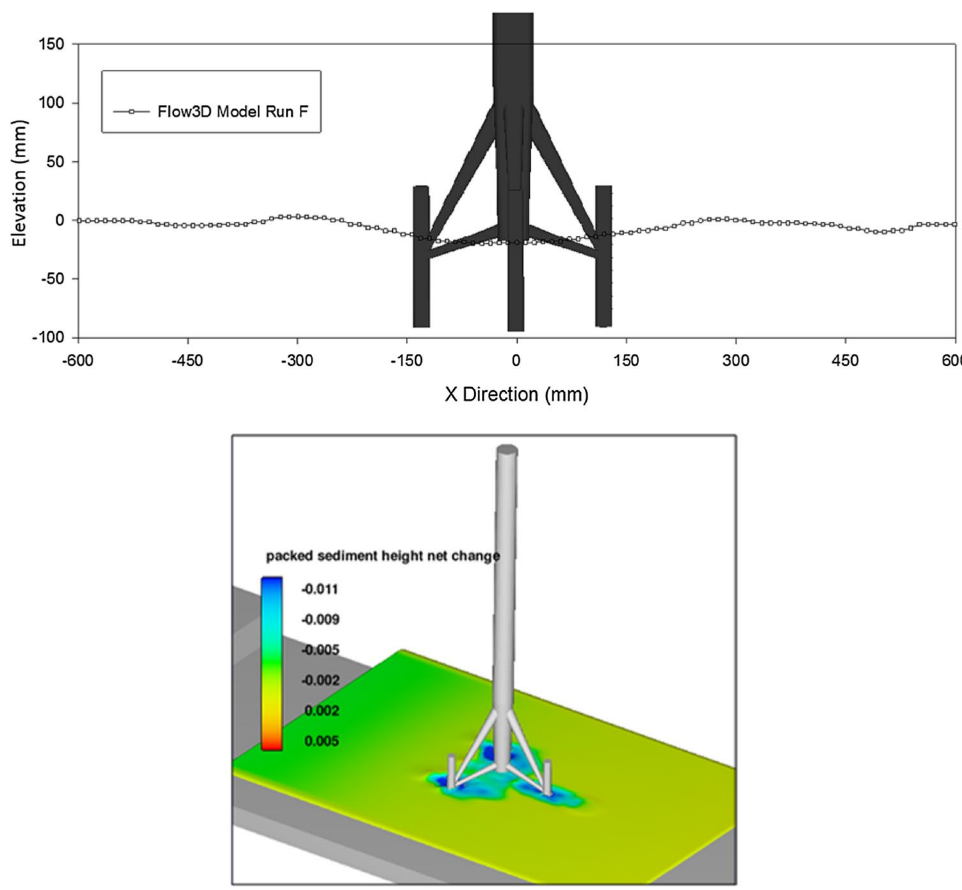


Fig. 9 Numerical results of the bed scour profile for irregular waves and Run F conditions

the bed profile. Modeling is performed for the two cases of 50% increase in the current velocity together with the waves and the case of 50% decrease in the current velocity together with the waves. In Table 3 the precise wave and current characteristics for the performed modeling are presented. It is noted that, in this case, the irregular waves with Jonswap spectrum are selected.

Using the numerical modeling according to Table 3, the bed scour profile for different cases of current velocity is derived from the numerical model as shown in the following diagrams (Figs. 8, 9, 10):

As is seen from the numerical modeling results, by increasing in the current velocity, the scouring zone is extended and the scour depth also increases. By increasing in the current velocity, the scour pit is extended and continued toward the flow direction. The results of numerical model show that, by 50% increase in the current velocity, the maximum scour depth increases from 11 to 26 mm. In addition, by 50% decrease in the current velocity, the maximum scour depth decreases from 11 to 4.6 mm which is nearly 60% reduction. The main reason for the effect of wave height on the bed scour value is the amount of current turbulence. As shown in Fig. 11, the strength of current turbulence energy has been increased with increase in the current velocity and these changes in the turbulence energy have been spread over a wide area.

Investigation of the numerical modelling results of the waves and current encounter with the wind turbine piles under the impact of variation in the pile diameter

In this part of the study, in the first step, the effect of turbine piles diameter, and, in the second step, the effect of bed particles size on the bed scour are investigated. For this purpose, investigation of the effect of wind turbine pile diameter on the bed scour due to the irregular waves and current is assessed in four cases for the present model.

In each case, the pile diameter is increased by 25, 50, and 100% with respect to the initial case in the numerical model. The main and secondary piles' diameters' characteristics installed at the bed are given in Table 4. It is noted that, in this case, the irregular wave height is 20.8 cm and the period is 3 s with a current velocity equal to 20.6 cm/s.

In Figs. 12 and 13, changes in the erodible bed due to the waves and current encounter to the wind turbines pile for the case of Run 04 are shown. As seen in the figure, main scouring has occurred around the pile due to encounter of the waves and formation of the rotational flow with intense

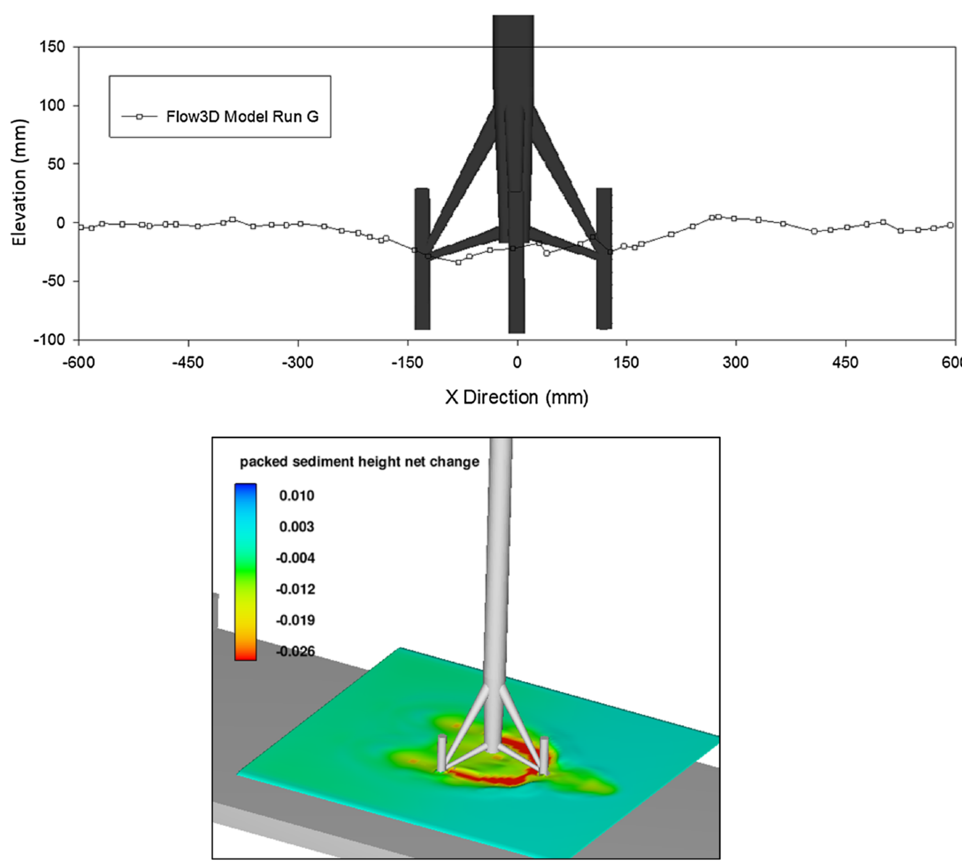


Fig. 10 Numerical results of the bed scour profile for irregular waves and Run G conditions

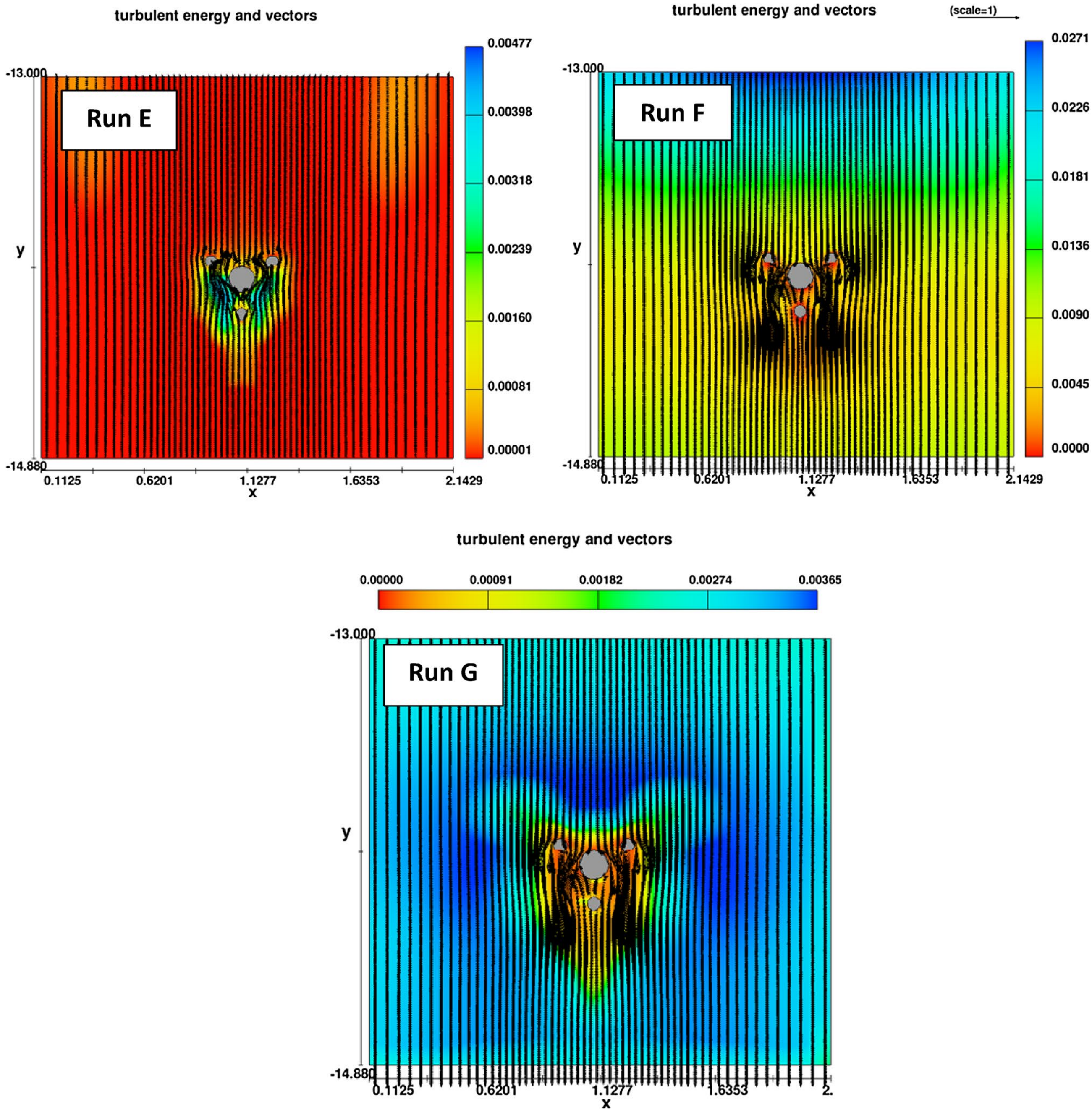


Fig. 11 Velocity vectors during waves encounter with the marine platform together with the turbulence energy intensity values

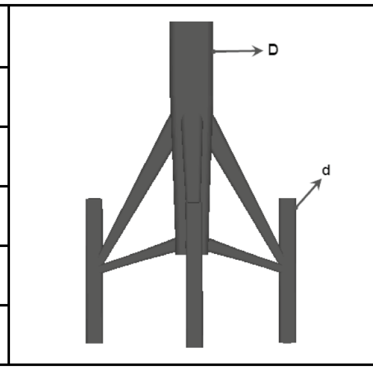
turbulence. Changes in the bed deposition profile are shown at the right and changes in the turbulence energy are shown at the left of Fig. 12. In the diagram of the following figure (Fig. 12), the turbulence energy values show that the main changes in the turbulence energy occur in the vicinity of the pile, where the velocity vectors also change in direction in this zone.

Using the numerical model results for each of the above cases with different pile diameters, the scour depth values due to encounter of irregular waves with 20.8 cm height and period of 3 s and the current velocity equal to 20.6 cm/s were extracted from the numerical model and analyzed. It should be noted that the scour profile is presented along the flume longitudinal direction and in millimeter.

According to the results of numerical modeling, by increase in the pile diameter of installed wind turbines at the sea under the combined effect of irregular waves and current, the depth of scour pit increases (Fig. 13), so that, by

Table 4 Pile diameters' characteristics for different cases of the FLOW-3D numerical model

Run	Percentage of increment	Main column diameter	Rear piles diameter
		D (cm)	d (cm)
01	0	15	5.9
02	25	18.75	7.4
03	50	22.5	8.85
04	100	30	11.8



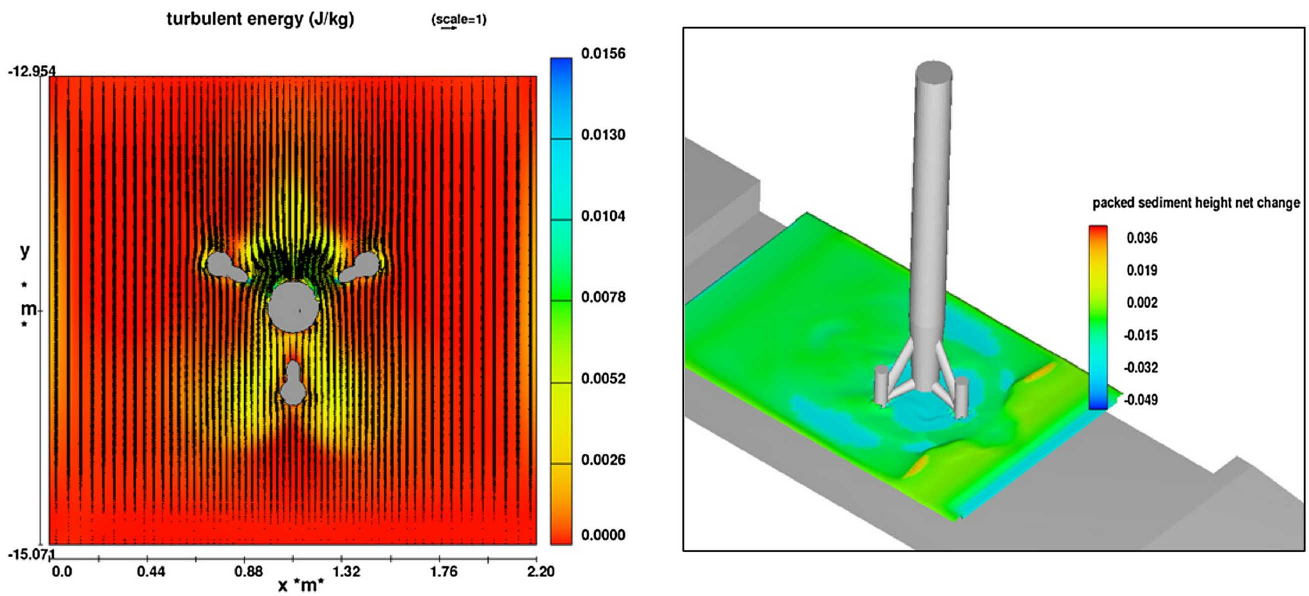


Fig. 12 Changes in the bed scour in the condition of irregular waves of Run 04 and changes in the turbulence energy in the FLOW-3D numerical model

25% increase in the pile diameter, the maximum scour depth increases from 11 to 23 mm. By 50% increase in the wind turbine pile diameter, the maximum scour depth increases from 11 to 37 mm which is an increase of 3.36 times. Also examining the numerical model results, it is revealed that by 100% increase in the wind turbine pile diameter, the maximum scour depth in the numerical model increases from 11 to 49 mm.

Investigation of the numerical modelling results of the waves and current encounter with the wind turbine piles under the impact of variation in the particle size

In this part of the study, we have investigated the changes of the bed profile under the effect of variation in the particle size. In this part, it is necessary to perform numerical analysis once for the case of 50% increase in the particle size and once for the case of 50% decrease in the particle size (Table 5).

In each of the numerical modeling performed in Run 05–07, the values of different particles' diameter are defined in the numerical model and the effect of changes in the particle diameter on the bed scour profile are derived according to these conditions.

In the diagrams of Fig. 14, for each of the defined cases, the changes in the bed profile are illustrated in the longitudinal direction. It should be mentioned that the irregular wave height is 20.8 cm; its period is 3 s with a combined current velocity of 0.206 m/s.

According to the numerical modeling results, by increase in particle diameter, the maximum scour depth due to encounter of the waves with the wind turbines pile decreases, so that, by 50% in the bed particles diameter, the maximum depth value due to the encounter of similar waves decreases from 11 to 6.5 mm which indicates a 41%

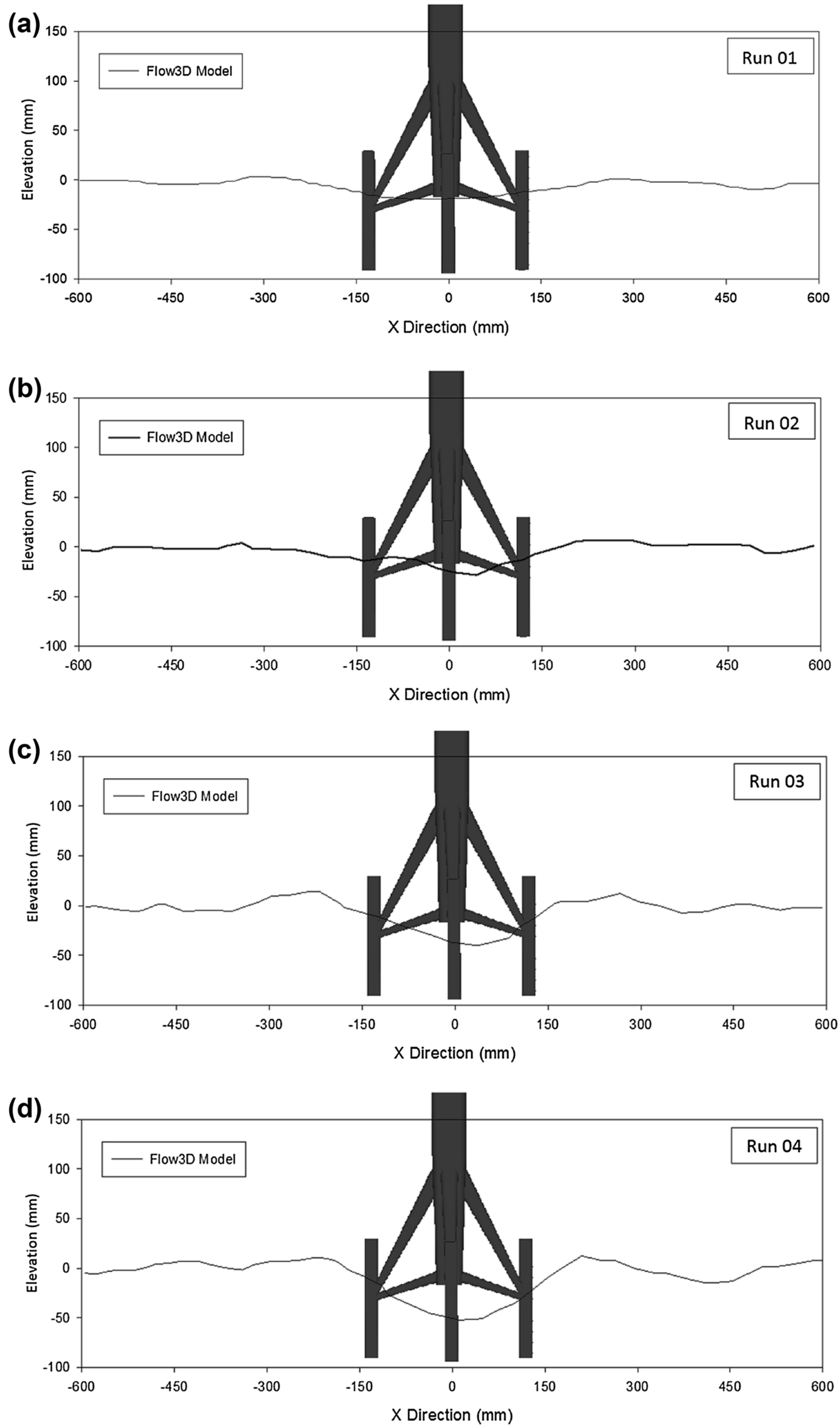


Fig. 13 Numerical results of the scour profile for the irregular waves and current. **a** Run 01; **b** Run 02; **c** Run 03; **d** Run 04

Table 5 Diameters of the deposited particles in the FLOW-3D numerical modeling

Run	Percentage of increment (%)	Grain size Ds (mm)
05	−50	0.074
06	0	0.148
07	+50	0.222

reduction in the maximum scour depth value. In addition, according to the numerical modeling results where the particle diameter decreases by 50%, the maximum bed scour depth value increases, so that, by 50% decrease in the particle diameter, the maximum scour depth value increases from 11 to 24 mm which indicates an increase equal to 2.2 times.

Conclusion

The numerical modeling results show that, by increasing the incident wave height at the wind turbine pile, and under combined action of the irregular waves and current, the scour depth values will be increased. In addition, by 50% increase in the current velocity, the maximum scour depth will be increased nearly 2.36 times. According to the results of the numerical modeling, by increasing the pile diameter of the installed wind

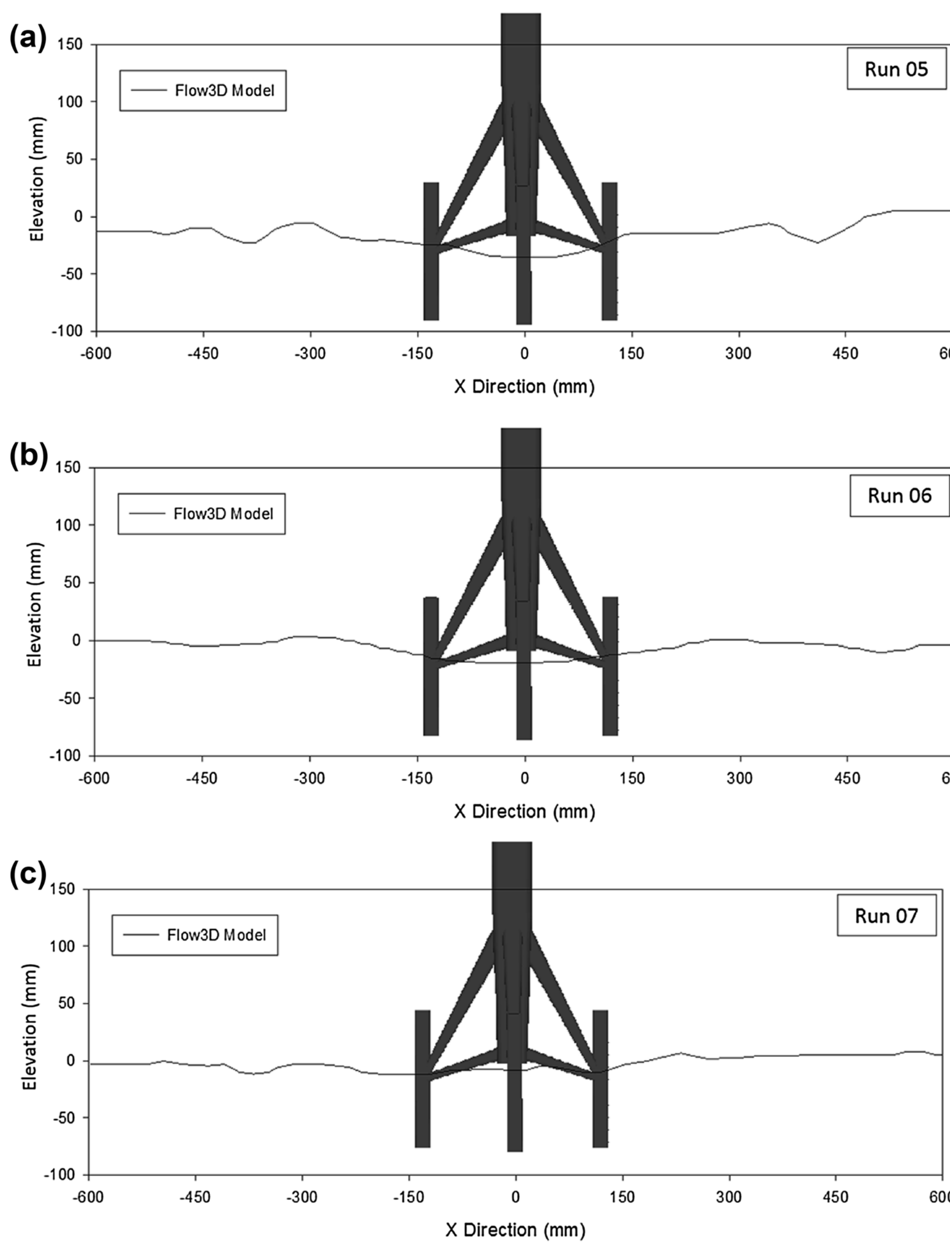


Fig. 14 Numerical results of the scour profile for the irregular waves of **a** Run 05; **b** Run 06; **c** Run 07

turbines at the sea under the effect of irregular waves, the scour depth values increase. Changes in geometric parameters in the pile structure of wind turbines show that, by 100% increase in the pile diameter of the wind turbines, the maximum scour depth will be increased to 4.45 times. Effect of 50% increase in bed particle diameter led to a reduction of about 41% in the maximum scour depth value. Using the results of this study, by applying geometric, hydraulic, and grain size parameters, it can be well estimated and determined by erosion conditions in the vicinity of these structures.

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