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Empirical model for Darrieus-type tidal current turbine induced seabed scour

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ABSTRACT

Tidal current turbine has attracted many attentions, but the impact of Darrieus-type tidal current turbine on the seabed scour process still remains unclear. This work aims to propose an empirical model, which can be used to predict the maximum scour depth against different tip clearance and rotor radius. The study also presents the scour profiles along centreline of turbine by using the proposed empirical equations. A series of three-dimensional printed turbine models were placed in a circulating water flume to investigate the scour profiles. The results suggest that the scour depth increases with the decrease of tip clearance. When the turbine is installed very close to seabed, the scour process is live bed scour with the collapse of the slant bed. Under this kind of condition, the maximum scour depth will not further increase with the continuous decrease of tip clearance. The current experimental results propose that the maximum scour depth is about 80% deeper than scour depth around single pile. The maximum scour depth increases firstly and then decreases with the increase of rotor radius. Based on experimental results, an empirical model of Darrieus-type tidal current turbine induced seabed scour is proposed to predict the maximum scour depth and scour profiles along centreline of turbine.

1. Introduction

The development of marine renewable energy has huge potential to reduce environmental pollution and ease energy shortages [1]. As a clean and pollution-free renewable energy, tidal current energy has advantages of rich resource reveres, wide distribution and high predictability compared to other energy sources [2]. Interest in the use of tidal current energy has been growing over the past years.

Tidal current turbines can be categorized as either vertical-axis, or horizontal-axis turbines with different relative orientation between flow and rotation axis [3]. The development of Darrieus-type tidal current turbine has gained more and more interest due to its ability to capture the energy from various directions without adjusting the turbine position. The original concept of the Darrieus-type turbine was patented by French engineer George Darrieus in 1931 [4]. Since that time many applications and improvements have been devised to extract tidal current energy.

The impact of tidal current turbine to seabed is an essential issue when carries on the engineering design and installation of tidal current turbine. For Darrieus-type tidal current turbine with monopile foundation, the formation of horse vortex can happen in front of the monopile structure, whereas the formation of wake vortices can happen behind the monopile structure [5]. The turbine rotor changes the boundary layer profile, and consequently alters the formation of horseshoe vortex. The action of flow contraction accelerates the flow between turbine and seabed. Hence the scour depth increases compared to scour at piles.

Seabed scour around a pier or pile has been widely studied in the past years. The characters of fluid, bed material, flow, and geometry of offshore foundation may influence the scour phenomenon. In 1973,

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Nomenclature

List of symbols

R	rotor radius
H	height of turbine rotor
c	chord length of turbine rotor
C	turbine tip clearance
D	diameter of supporting pile
ω	rotational speed of turbine
h	flow depth
Q_w	flow discharge
b	channel width
d_{50}	mean sediment grain diameter
F_r	Froude number of incoming flow
U_c	depth-averaged current speed
U_{cr}	threshold depth-averaged current speed
x	longitudinal (streamwise) direction
y	lateral direction
z	vertical direction
S	scour depth at different locations
S_t	maximum scour depth
l_t	horizontal distance of downstream end of scour hole from supporting pile
T	turbine torque
A	The swept area of rotor
t	time
ρ	density of fluid
C_P	dimensionless coefficients for power
g	acceleration due to gravity
ρ_s	density of sediment
K_t	correction factor for Darrieus-type tidal current turbine
K_r	correction factor for rotor radius
K_c	correction factor for tip clearance
K_s	correction factor for pier shape
K_b	correction factor for bed condition
K_d	correction factor for size of bed material
K_θ	correction factor for flow angle of attack
K_w	correction factor for pier width or pile diameter
K_{yw}	depth size
K_I	flow intensity
K_D	sediment size
K_G	channel geometry
S_0	scour depth at C/H = 0.5, R/D = 5.63
$S_{\max}$	maximum scour depth against different rotor radius at C/H = 0.5
$S_{\min}$	minimum scour depth against different rotor radius at C/H = 0.5
u	coefficient
σ	coefficient
a_{0-3}	coefficients
b_{0-3}	coefficients
c_{0-3}	coefficients
$\hat{x}$	dimensionless horizontal distance from centre of foundation
$\hat{y}$	dimensionless vertical distance from initial flat surface

Neill [6] proposed a simple equation supposing that scour depth divided by diameter of the structure is a constant (K_s), where K_s is the correction factor of pier shape. Breusers et al. [7] improved an empirical equation to predict the scour depth with consideration of bed conditions, size of bed sediment, current velocity, and water depth based on series of experiments in 1977. Richardson and Davis [8] adopted Froude number in their expression. Sumer et al. [9] carried out the experimental investigation on scour around piles exposed to waves. Recently, Simons et al. [10] indicated that seabed scour is reduced in two-direction flow compared to unidirectional flow. Whitehouse [11] proposed a scour time evolution predictor (STEP) to predict the development of scour evolution of offshore structures. These researches can be foundation to study the Darrieus-type tidal current turbine induced seabed scour.

The existence of turbine rotor makes the seabed scour phenomenon more complex. The investigation of flow field around tidal current turbine is an initial input to study Darrieus-type tidal current turbine induced seabed scour. For horizontal-axis tidal current turbine, Sun et al. [12] used the actuator disk model to estimate the near wake of horizontal-axis tidal current turbine. Harrison et al. [13] conducted CFD (computational fluid dynamics) simulation to research the wake behaviour of tidal current turbine and compared to the experimental results. Lam and Chen [14] proposed two equations to predict the wake characteristics based on the fundamental works of ship propeller jet. Tahani et al. [15] used the multi objective optimization of the horizontal-axis tidal current turbine to achieve its optimum performance. Lam and Chen [16] also used CFD simulation to investigate the slipstream between marine current turbine and seabed. Their results indicated the flow acceleration phenomenon occurred below the tidal current turbine. For Darrieus-type turbine, Ghasemian et al. [17] review the computational fluid dynamic simulation techniques for Darrieus-type wind turbines. Wang et al. [18] proposed a potential flow 2D vortex panel model to calculate unsteady hydrodynamics of Darrieus-type tidal current turbine for tidal streams energy conversion. Dai and Lam [19] used CFD simulation to predict the rotor performance and hydrodynamic loads of Darrieus-type tidal current turbine for structural design calculations. In addition, the double multiple streamtube (DMS) model, which was originally developed by Strickland [20] based on the momentum models, can also be used to investigate the hydrodynamic performance of turbine. However, there is few researches focus on the flow field around Darrieus-type tidal current turbine.

To date, the researches of scour characteristics around tidal current turbine are still limited. Chen and Lam [21] reviewed the numerical equations to predict the seabed scour around piles. Hill et al. [22] performed laboratory experiments to study the effect of an axial-flow hydrokinetic turbine model on an erodible channel. The results indicated that the presence of turbine rotor increased the local shear stress and accelerated the scour development. Jisheng Zhang [23] developed a mathematical model to numerically investigate the fluid-structure interaction and its induced sediment scour around a horizontal-axis tidal current turbine. Giles et al. [24] presented a preliminary experimental study investigating the potential benefits of foundation-based flow acceleration structures for tidal current turbine and its function of scour protection. However, all above researches were focused on horizontal-axis tidal current turbine, the scour profiles of Darrieus-type tidal current turbine induced seabed scour is still unavailable.

In the current research, experimental work has been performed in Marine Renewable Energy Laboratory at Tianjin University. Vertical and horizontal extents of scour hole are studied at various tip clearance and radius of turbines. After series of experimental tests, an empirical model for Darrieus-type tidal current turbine induced seabed scour was proposed. The outcomes of the study provide a fundamental understanding on the scour nature of Darrieus-type tidal current turbine.

2. Comparison of three types of seabed scour

Seabed scour around tidal current turbine has been well recognized as an engineering issue for its possibility to cause structural instability. The dominant feature is the horseshoe-vortex system like scour around