Coastal Engineering 138 (2018) 9–21

Contents lists available at ScienceDirect

Coastal Engineering

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

Experimental study of tsunami-induced scour around a monopile foundation

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ARTICLE INFO

Keywords:
Tsunamis
Boundary layers
Scour
Morphology
Monopiles
Computational fluid dynamics

ABSTRACT

This paper presents an experimental study of the tsunami-induced scour process around a monopile foundation, representative of those commonly used for offshore wind farms. The scour process is studied by subjecting the monopile to a time varying current, which enables a properly down-scaled experiment from the boundary layer and scour perspective. It is shown how the scaled experiments corresponds to real life idealized tsunami cases with periods ranging from 10 to 40 min. It is then shown that the boundary layers of the model tsunami are well described by recently developed empirical relations for tsunami boundary layers. By subjecting the monopile to several successive tsunami waves the scour process is shown to occur in a stepwise cumulative fashion, with the final equilibrium scour depth tending to the depth limited steady current limit. It is shown that the entire scour development can reasonably be predicted by a recently developed simple engineering model. Finally, the experimental results are compared to a fully coupled hydrodynamic and morphologic CFD model and a good correspondence is obtained.

1. Introduction

Tsunamis are long waves, typically having periods the order of minutes to hours, that are commonly caused by sudden motions of the bed e.g. due to landslides or earthquakes. Tsunami research has been carried out using many different approaches. Tsunami deposits have been gathered to get an idea of prehistoric tsunamis, see. e.g. Dawson and Shi (2000) for an overview. Tsunamis have also been studied by conducting surveys and actual field measurements, see Lacy et al. (2012), Bricker et al. (2012), Kuriyama et al. (2014), Fu et al. (2013), Udo et al. (2016) and Jayaratne et al. (2016). A few analytical studies exists e.g. Madsen et al. (2008) and Yeh and Mason (2014). Numerically, most tsunami research has focused on solving the non-linear shallow water equations or simulating the tsunami with a Boussinesq model see e.g. Madsen and Fuhrman (2008), Fuhrman and Madsen (2009), Apotsos et al. (2011a), Apotsos et al. (2011c), Apotsos et al. (2011b), Cheng and Weiss (2013), Sugawara et al. (2014a), Sugawara et al. (2014b). Recently, more computationally heavy numerical studies have been performed by solving the Reynolds-Averaged-Navier-Stokes (RANS) equations by Douglas and Nistor (2015) and Jiang et al. (2015), or with the Smoothed Particle Hydrodynamics Method (SPH) by Wei et al. (2016). Experimentally, tsunamis have often been attempted to be studied using solitary waves. However, when scaled up, these waves resemble more wind wave than tsunami scales, as their flow durations are far too short, and their relevance to real-world-geophysical tsunamis is questionable (see Madsen et al. (2008) and Chan and Liu (2012)). Schimmels et al. (2016) have succeed in producing properly-scaled tsunamis and the same experimental facility was used to study tsunami propagation by Sriram et al. (2016), where the feasibility of studying tsunami run-up was also discussed. Onshore tsunamis have also been studied as bores see. e.g. Lavictoire (2015) or Douglas and Nistor (2015). However, as noted by Sriram et al. (2016), the undular or breaking bores are just two realizations of tsunami run-up, and one cannot generalize a particular tsunami case, as even the same tsunami event can have very different manifestations at different locations. Also, when studying tsunamis as bores, scaling considerations are still important, as the duration of the experimental bore should be sufficiently long. As discussed by Schimmels et al. (2016), a typical full scale tsunami event with a duration of 1000 s, corresponds to 100 s at model scale using a scaling factor of 100 using a standard Froude scaling approach. This is a much longer duration than most model-scale tsunami experiments.

Studies investigating tsunami-induced scour around coastal and offshore structures (the focus of the present work) are rather limited. From surveys, Wilson et al. (2012) studied the sediment scour and deposition within harbours in California as a result of the 2011 Tohoku tsunami. Experimentally, Chen et al. (2013) studied the tsunami-induced

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https://doi.org/10.1016/j.coastaleng.2018.04.007
Received 21 September 2017; Received in revised form 19 March 2018; Accepted 5 April 2018

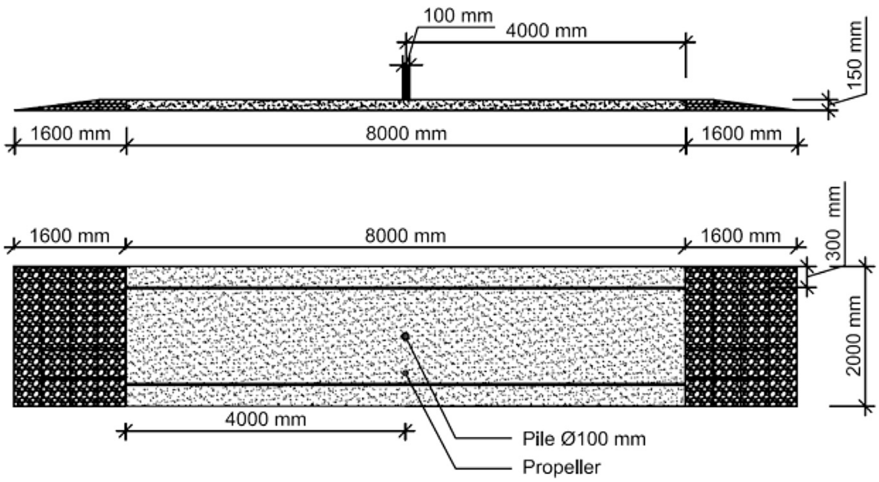

Fig. 1. Schematic view of the test set-up. A pile with a outer diameter of 0.1 m is placed in the middle of a 8 m long, 2 m wide and 0.15 m deep sand bed. A 1:8 slope is placed at both ends of the sand bed.

scour at coastal roadways. Also, Bricker et al. (2012) conducted a field study of scour depths measured on the landward side of seawalls and floodwalls, as well as beside a building foundation footing, from the 2011 Tohoku tsunami. Experimental investigations on the tsunami-induced scour specifically around monopiles are seemingly limited to those of Tonkin et al. (2003), who studied the scour promoted by incident solitary waves around a cylinder on a sloping beach, where the cylinder was mounted near the shoreline, Nakamura et al. (2008) who studied scour around a square pile induced by solitary and long waves, as well as by Shafiei et al. (2015) and Lavictoire (2015) who studied the bore-induced local scour around a circular structure. It is again emphasized that the temporal duration using solitary waves are far less than would be typical of model scale geophysical tsunamis.

While the behaviour and evolution of tsunami waves is indeed difficult to reproduce experimentally due to the long durations, the offshore near-bed processes can be studied by viewing the tsunami as a time varying current, which is justifiable provided that the Froude number is sufficiently small. This has been done by Williams and Fuhrman (2016), who simulated a series of tsunami-scale boundary layers, emphasizing that they are both current like and wave like. The boundary layers resemble steady currents due to their long duration. They also resemble waves, as they are unsteady and the boundary layer may not span the entire water depth. This assertion is likewise consistent with field measurements of Lacy et al. (2012). Larsen et al. (2017) simulated the tsunami-induced scour at model scale by also approximating the tsunami-induced flow as a time varying current within a CFD approach. They developed a procedure for properly scaling tsunami-induced scour and came up with a practical engineering model for predicting the scour development beneath successive tsunami waves.

The two afore mentioned studies approximating tsunami-induced boundary layers and scour are both numerical in nature. However, representing a tsunami via a time varying current is also experimentally attractive, as it enables the study of offshore tsunami-induced boundary layers and scour to be performed using a pump-driven flow, rather than more traditional wave paddles. It can be noted that the scour process beneath a time varying current has also been studied previously by Link et al. (2017), though with the intent to study flood wave-induced scour around bridge piers. The present paper aims to extend knowledge on tsunami-induced scour around off-shore monopile foundations by studying the scour process induced by the pump-driven flow that would be expected beneath long properly-scaled tsunami waves. This approach also means that the effect of variation in pore pressure gradients on the scour process as described by Tonkin et al. (2003) and Nakamura et al. (2008) are not accounted for the current setup. This is reasonable if the monopile is standing off-shore and the Froude number is small. The paper also aims to strengthen the link to the practical engineering models developed in the purely numerical studies by Williams and Fuhrman (2016) and Larsen et al. (2017). The numerical models employed in these studies have therefore also been used in the present study to simulate the boundary layers and scour process of selected cases.

Fig. 2. An image of the set-up in the flume. The carriage used when recording the bed topology is in this image over the upstream end of the sand bed.