Continental Shelf Research 160 (2018) 1–9

Contents lists available at ScienceDirect

Continental Shelf Research

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

Forced wave induced by an atmospheric pressure disturbance moving towards shore

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ARTICLE INFO

Keywords:
Forced wave
Proudman resonance
Nonlinear shallow water equations
Meteotsunami
Storm surge
Atmospheric pressure disturbance

ABSTRACT

Atmospheric pressure disturbances moving over a vast expanse of water can induce different wave patterns, which can be determined by the Froude number *Fr*. Generally, $Fr = 1$ is a critical value for the transformation of the wave pattern and the well-known Proudman resonance happens when $Fr = 1$. In this study, the forced wave induced by an atmospheric pressure disturbance moving over a constant slope from deep sea to shore is numerically investigated. The wave pattern evolves from a concentric-circle type into a triangular type with the increase of the Froude number, as the local water depth decreases, which is in accord with the analysis in the unbounded flat-bottom cases. However, a hysteresis effect has been observed, which implies the obvious amplification of the forced wave induced by a pressure disturbance can not be simply predicted by $Fr = 1$. The effects of the characteristic parameters of pressure disturbances and slope gradient have been discussed. The results show that it is not always possible to observe significant peak of the maximum water elevation before the landing of pressure disturbances, and a significant peak can be generated by a pressure disturbance with small spatial scale and fast moving velocity over a milder slope. Besides, an extremely high run-up occurs when the forced wave hits the shore, which is an essential threat to coastal security. The results also show that the maximum run-up is not monotonously varying with the increase of disturbance moving speed and spatial scale. There exists a most dangerous speed and scale which may cause disastrous nearshore surge.

1. Introduction

The response of sea surface to moving atmospheric pressure disturbances is an interesting problem with a broad background in coastal engineering. Meteorological tsunami (also referred as meteotsunami) is one type of significant, even devastating, sea level oscillations at coastal areas with the same frequency band as typical tsunami waves (Monserrat et al., 2006). This phenomenon has attracted more and more attentions in recent years, and is widely believed to be mainly caused by high-speed moving atmospheric pressure disturbances (Šepić et al., 2015). Moreover, the low pressure in a typhoon or hurricane also acts as an essential factor that causes water level rise in a storm surge process, which is the most serious and frequent natural disaster in coastal areas.

It is known that the decline of pressure with 1 hPa can lead to about 1 cm water level rise under static equilibrium condition and the elevation distribution is consistent with the pressure field. However, the situation will change and become complex when a pressure disturbance is moving especially with high speed. The most well-known phenomenon in this topic is the Proudman resonance, which has been found by Proudman (Proudman, 1929). He provided a theoretical solution based on the linear wave theory, which shows that resonance occurs when the moving speed of pressure disturbance is close to the local shallow water wave velocity on a flat bottom. It means that even a small atmospheric pressure disturbance may cause significant sea level oscillation. The sea level oscillation can be further amplified by other effects such as harbor resonance to cause both casualties and property damage in coastal areas. Recently, destructive long wave events due to moving atmospheric pressure disturbances have been investigated by many researchers all over the world. Mercer et al. (2002) and Mecking et al. (2009) studied the meteotsunami occurred along the coast of the Avalon Peninsula of Newfoundland, which has been linked to the rapidly passing of tropical storms. Vilibić et al. (2008) reproduced the destructive meteotsunami (locally known as “rissaga” wave) occurring on 15 June 2006 in Ciutadella harbor by a numerical model forced by a moving atmospheric disturbance. Choi et al. (2014) numerically analyzed the meteotsunami generated by an atmospheric pressure jump moving southeastward over the eastern Yellow Sea in March 2007. Tanaka et al. (2014) studied a severe meteotsunami (known as “abiki” wave in Japan) that occurred in the coast of west Kyushu in February

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https://doi.org/10.1016/j.csr.2018.03.007
Received 7 August 2017; Received in revised form 27 February 2018; Accepted 17 March 2018
Available online 26 March 2018

2009.

Besides those studies on the specific cases happened worldwide, there are also many researches focusing on the mechanism of the wave excited by atmospheric pressure disturbances under idealized conditions. Vilibić (2008) numerically simulated the Proudman resonance phenomena caused by sinusoidal air pressure disturbances. Vennell et al. conducted a series of analytical researches on the trap and refraction of waves as the atmospheric disturbance moves above step bottom and continental shelf (Thiebaut and Vennell, 2011; Vennell, 2007, 2010). In order to study the shape of water surface oscillation under a moving low pressure system with different moving speeds, Niu and Zhou (2015) adopted a nonlinear shallow water model to simulate the wave pattern induced by a moving low pressure with Gaussian distribution in an unbounded flat-bottom water area, and analyzed the effects of speed, central pressure drop and spatial scales on the water elevation. Choi and Seo (2017) numerically investigated the waves induced by a low pressure system moving over a slope towards shore. It is an idealized problem abstracted out from the landing process of a typhoon or a hurricane. In their study, the atmospheric pressure disturbance acts suddenly on the water surface, both free and forced waves are generated and amplified due to the Proudman resonance and shoaling. A complex wave pattern has been observed. In this study, we focus on the forced wave induced by the pressure disturbance moving over a slope to explore if the Proudman resonance occurs when the moving speed of pressure disturbance is close to the local shallow wave velocity.

Based on the previous study (Mercer et al., 2002; Niu and Zhou, 2015), a moving low pressure can cause different wave patterns in conditions of different water depths. It is expected that the sea level change caused by a low pressure moving towards shore should also evolve with the decrease of water depth. This study aims to get better understanding on where and when the high wave level occurs, and to investigate the influences of factors on the maximum nearshore run-up. A two-dimensional numerical model based on the nonlinear shallow water equations is used to study the forced wave caused by the moving pressure disturbance towards shore over a uniform slope. In Section 2, we describe and illustrate the basic assumptions and our numerical tool. Section 3 presents the evolution of the forced wave propagating along the slope towards shore and discusses its similarities and differences comparing to the results under unbounded flat-bottom condition. In Section 4, the influences of disturbance spatial scale, central pressure drop, moving speed and slope gradient are discussed. Finally, the main results are summarized in Section 5.

2. Numerical model

The shallow water equations are widely accepted for simulating meteotsunamis and storm surges. Here, a two-dimensional nonlinear shallow water model is adopted (Niu et al., 2009), in which the effects of Coriolis force, wind surface stress and wave radiation stress are ignored. The governing equations expressed in the Cartesian coordinates are shown as follows.

$$\frac{\partial \eta}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial hu}{\partial t} + \frac{\partial (huu)}{\partial x} + \frac{\partial (huv)}{\partial y} + gh\frac{\partial \eta}{\partial x} + \frac{h}{\rho}\frac{\partial P_a}{\partial x} + \frac{gu\sqrt{u^2+v^2}}{C^2} - h\left[\frac{\partial}{\partial x}\left(\nu_e\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_e\frac{\partial u}{\partial y}\right)\right] = 0 \tag{2}$$

$$\frac{\partial hv}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hvv)}{\partial y} + gh\frac{\partial \eta}{\partial y} + \frac{h}{\rho}\frac{\partial P_a}{\partial y} + \frac{gv\sqrt{u^2+v^2}}{C^2} - h\left[\frac{\partial}{\partial x}\left(\nu_e\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_e\frac{\partial v}{\partial y}\right)\right] = 0 \tag{3}$$

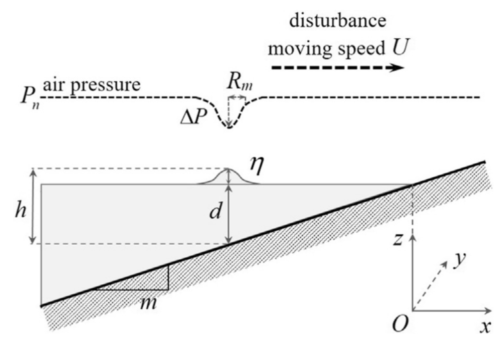

Fig. 1. Illustration of the idealized physical problem.

where t is time; u and v are vertically averaged velocities in the x and y directions; η is the surface elevation; h is the total water depth, $h = d + \eta$, here d is the still water depth; g is the acceleration of gravity; ρ is the sea water density; P_a is the atmospheric pressure at sea level; C is the Chezy friction coefficient of sea bottom; ν_e is the eddy viscosity. The fifth terms in Eqs. (2) and (3) are the force exerted by the atmospheric pressure.

An idealized atmospheric pressure disturbance moving with a constant velocity U from deep sea to shore is considered, while the topography is simplified as a constant slope. The illustration of the idealized physical problem is shown as Fig. 1. The y coordinate is along the shoreline, and the x coordinate is perpendicular to the shoreline. The spatial distribution of atmospheric pressure disturbance is assumed as:

$$P_a = P_n - \Delta P\left[1 - \exp\left(-\frac{R_m}{\sqrt{(x-Ut)^2 + y^2}}\right)\right] \tag{4}$$

where P_n is the neutral pressure, ΔP is the maximum central pressure drop, which is the difference between the neutral pressure and the pressure located in the center of the low pressure system, R_m is defined as the radius of pressure disturbance.

The governing equations are discretized on a set of orthogonal grid, and solved by the alternating direction implicit difference scheme (ADI scheme). Open boundaries are applied at the sea boundaries, and in order to reduce the unwanted influence of the boundary, a sponge layer is applied at both sides of the boundaries parallel to the direction of the pressure movement. The treatment of the sponge layer follows Chapman (1985). In consideration of the calculation domain change at the shoreline boundary caused by water level oscillations, a wet-dry variable boundary is applied at the shoreline boundary. The water surface elevation under a stationary low pressure in hydrostatic equilibrium is set to be the initial condition. Grid sensitivity test has been carried out, which shows that the influence of grid size can be ignored when the grid size is not more than $1/20R_m$. In the following numerical cases, the grid size is set to be less than $1/20R_m$ if not specified.

3. Variation of the forced wave from deep sea to shore

According to previous study (e.g., Vilibić, 2008; Niu and Zhou, 2015), it has already known that the Froude number Fr, defined as the ratio of the moving speed of pressure disturbance to the shallow water wave velocity, $Fr = U/\sqrt{gh}$, is the main factor that controls the wave pattern. Here, h is the local water depth corresponding to the location of waves induced by a pressure disturbance. As a pressure disturbance moves toward shore, we speculate that the wave pattern would gradually change with the decrease of water depth or the increase of Fr, and the instantaneous wave pattern should be similar to that in the flat-bottom case with corresponding Fr. To test the hypothesis, a numerical experiment is conducted to investigate the forced wave induced by a moving pressure disturbance as shown in Fig. 1.

Here, the slope is 1/500. The shoreline is located at $x = 0$. The