MODELING EVOLUTION OF INTERNAL WAVES IN SOUTH CHINA SEA

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Abstract: Internal waves are an important factor in the design of drill operations and production in deep water, because the waves have very large amplitude and may induce large horizontal velocity. How the internal waves occur and propagate over benthal terrain is of great concern for ocean engineers. In the present paper, we have formulated a mathematical model of internal wave propagation in a two-layer deep water, which involves the effects of friction, dissipation and shoaling, and is capable of manifesting the variation of the amplitude and the velocity pattern. After calibration by field data measured at the Continental Slope in the Northern South China Sea, we have applied the model to the South China Sea, investigating the westward propagation of internal waves from the Luzon Strait, where internal waves originate due to the interaction of benthal ridge and tides. We find that the internal wave induced velocity profile is obviously characterized by the opposite flow below and above the pycnocline, which results in a strong shear, threatening safety of ocean structures, such as mooring system of oil platform, risers, etc. When internal waves propagate westwards, the amplitude attenuates due to the effects of friction and dissipation. The preliminary results show that the amplitude is likely to become half of its initial value at Luzon Strait when the internal waves propagate about 400 kilometers westwards.

Key words: Internal wave evolution, South China Sea, velocity profile, pycnocline

1. INTRODUCTION

A number of ocean structure accidents caused by internal waves have been reported (Yuan and Li et al, 2007). Two of the most important threats from internal waves are dramatic vertical displacements of density interfaces in the ocean interior, which are often several tens of meters and even hundreds of meters in some locations, and the shear of the horizontal currents, which can be strong enough to lead to instability and turbulence. Whereas, internal waves seem to be so elusive that when the associated accidents occur the ocean surface looks very calm (Li, 2005). Due to invisibility over the sea surface, internal waves can only be detected by equipment, such as CTD, remote sensing and acoustic equipments, at local sites. South China Sea, an internal wave-prone region, is rich of resources and lots of ocean structures exist there. In order to prevent structures from being destroyed by internal waves, it is indispensable to manifest the amplitude of internal waves, especially the internal solitary ones, and their induced current velocity pattern.

Numerical simulation is an effective way to approach this purpose. First of all, with the aid of field measurements, we have calibrated the mathematical model of internal wave propagation, which involves the effects of friction, dissipation and shoaling. Then, we use the calibrated model to simulate the process of internal solitons originated at Luzon Strait propagating 400 km westwards to the place, where an oil field locates, obtaining variation of the amplitude of an internal soliton and the characteristics of its induced current pattern.

2. EVOLUTION MODEL OF INTERNAL SOLITONS AND CALIBRATION

We consider internal solitons traveling in a two-layer fluid with the pycnocline in between.

The water is assumed incompressible and bounded by sea bottom and the rigid sea surface. The origin is set on the pycnocline, and the coordinates are shown as in Figure 1.

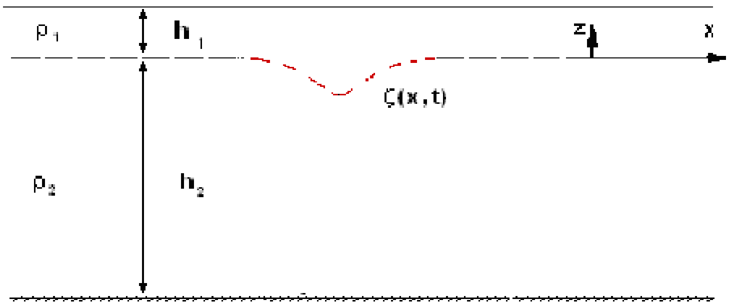

Figure 1 The coordinate of two-layer fluid internal waves, in this figure, the origin of the coordinate is located on the water interface, and the densities of the two layers are ρ_1 and ρ_2 respectively and the depth are h_1 and h_2

In this situation, the wave amplitude $\zeta(x,t)$ is subjected to the KdV equation (Liu et al, 1998),

$$\zeta_t + c_0\zeta_x + c_1\zeta\zeta_x + 3c_5\zeta^2\zeta_x + c_2\zeta_{(3x)} = 0. \tag{1}$$

For large scale waves in the ocean where the bottom topography changes rapidly, the effects of friction, dissipation and shoaling should be taken into account. Hence, the KdV equation is extended as follows (Liu et al, 1998, Holloway et al, 1997):

$$\zeta_t + c_0\zeta_x + c_1\zeta\zeta_x + 3c_5\zeta^2\zeta_x + c_2\zeta_{(3x)} + \frac{k}{c_2}\zeta\left|\zeta\right| - \frac{1}{2}\varepsilon\zeta_{(2x)} + \gamma\zeta = 0. \tag{2}$$

The coefficients c_0, c_1, c_5, c_2 are functions of water depth and density of the two-layer system, and read respectively (Liu et al, 1998),

$$c_0 = \sqrt{\frac{gh_1h_2(1-\sigma)}{h_1+h_2\sigma}},\quad c_1 = \frac{3c_0}{2}\frac{h_1^2-h_2^2\sigma}{h_1h_2(h_1+h_2\sigma)},$$

$$c_5 = -\frac{c_0}{8}\frac{h_1^4+8h_1^3h_2\sigma+14h_1^2h_2^2\sigma+8h_2^3h_1\sigma+h_2^4\sigma^2}{h_1^2h_1^2(h_1+h_2\sigma)^2},\quad c_2 = \frac{c_0}{6}\frac{h_1h_2(h_2+h_1\sigma)}{h_1+h_2\sigma}.$$

γ is shoaling coefficient and described by $\gamma = \frac{1}{4}c_0\frac{\partial h_2}{\partial x}\frac{h_1}{h_2(h_1+h_2)}$ (Small, 2001). k and ε are friction and dissipation coefficients respectively, and have been calibrated by field data measured at the Continental Slope in the Northern South China Sea (Duda et al, 2004). Calibration tests show that, in the circumstance of South China Sea, the friction coefficient drops in the range from 7.3×10^{-4} to 9.2×10^{-4}, and the dissipation coefficient in the range from 0.02 to 0.1. Moreover, the amplitudes of internal waves are more sensitive to friction than dissipation.

3. NUMERICAL SIMULATION

We now applied the above-calibrated model to simulate the evolution of an internal soliton in South China Sea. One of the numerical simulation example was performed by solving Equation (2), with the initial condition described by $\zeta(x,0) = -A_0\,\mathrm{sec}\,h^2\left(x/l\right)$, where A_0=70m, and $l = 2h_1h_2\left[3A_0\left(h_2-h_1\right)\right]^{-\frac{1}{2}}$. From initial point (20.4^0 N, 119^0 E), the internal soliton travels 400 km westwards along the topography shown in Figure 2.

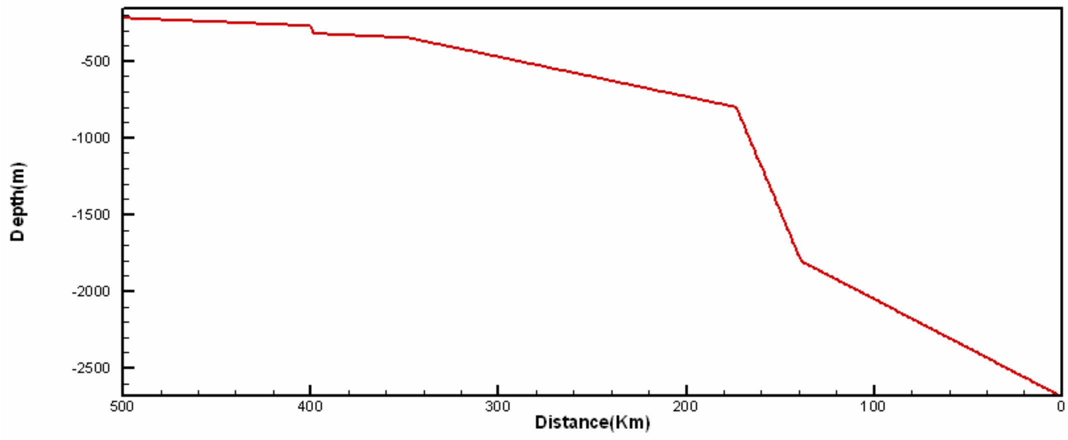

Figure 2 Topography used in numerical simulation

The numerical results show that the internal soliton undergoes significant changes as it propagates westwards. Its amplitude reduces more than a half and its shape becomes flatter and flatter. The faster the water depth becomes shallow, the more the soliton's amplitude decays. After propagating 400 kilometers, the soliton has divided into several solitons, which make up a packet of several solitary waves. (Figure 3)

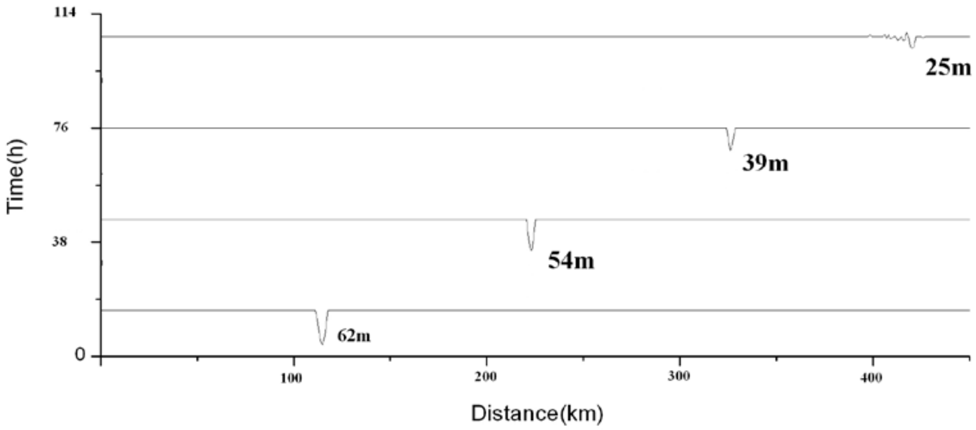

Figure 3 Numerically simulated space-time evolution of internal waveform as it propagates in the Northern South China Sea

The horizontal velocity of the flow field induced by internal waves is always of opposite signs below and above the pycnocline, whereas the vertical velocity can be negligible as compared with the horizontal component. The velocity decreases from the interface upwards and downwards. Consequently, strong shear takes place at the pycnocline, threatening structures across the pycnocline. This remarkable character of the currents induced by internal waves could be the most important effect of the internal waves on the underwater system of ocean platforms, to which engineers should pay enough attention.

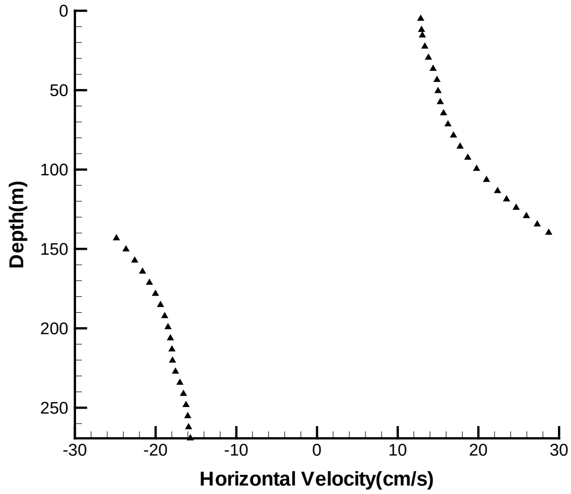

Figure 4 horizontal velocity profile in the final point of the simulation (20.4^0 N, 115^0 E)

4. CONCLUSIONS

In order to manifest spatial and temporal characteristics of internal solitons in South China Sea, we have formulated and calibrated the mathematical model of internal wave evolution in a two-layer water system, which involves the effects of friction, dissipation and shoaling. Calibration tests show that, in the circumstance of South China Sea, the friction coefficient drops in the range from 7.3×10^{-4} to 9.2×10^{-4}, and the dissipation coefficient in the range from 0.02 to 0.1. Moreover, the amplitudes of internal waves are more sensitive to friction than dissipation. Applying the calibrated model to South China Sea, we have found that solitons' amplitudes decay with decreasing water depth as they propagate toward coast, and that the horizontal velocity induced by internal waves are always of opposite signs below and above the pycnocline, suggesting a strong shear at the density interface.

ACKNOWLEDGEMENT

This research is financially supported by the National High Technology Research and Development Program of China (863 Program, Grand No. 2006AA09A103).

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