Numerical simulation of Holmboe waves in intrusive gravity current using LES method

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ABSTRACT

Gravitational currents are important currents in atmospheric and oceanic studies. Gravity current is caused when a fluid with different density moves into another fluid. If the fluid of a given density enters the stratified ambient, such that its density is lower than the underneath layers and higher than the upper layers, the gravity current is of the intrusive type. The Kelvin-Helmholtz and the Holmboe instabilities are seen in the interface. The decisive parameters in the type of instability are the Richardson number local and the ratio of shear layer thickness to the density layer. In this study, two-dimensional numerical simulation of Holmboe waves with the Eulerian-Eulerian approach on intrusive gravitational flow is investigated. OpenFOAM code was used to perform this simulation, and due to the turbulence of the flow, the LES method was used to model the turbulence. The obtained results show that with increasing the intrusive current density, the value of Richardson number decreases and the R parameter increases. Also, as the density increases, the frequency of the Holmboe waves first increases, then decreases. An increase in the wavelength of Holmboe waves is observed with increasing the intrusive current density. The phase velocity of Holmboe waves also does not have a specific trend with density changes.

KEYWORDS

Intrusive gravity current, Richardson number, shear layer thickness, density layer thickness, Holmboe instability

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1. Introduction

Most geophysical currents that occur on the Earth's surface inevitably have density stratification. Gravity currents are created by the flow of two fluids with different densities. Density differences can be due to temperature differences, concentration differences, the presence of suspended particles or other factors [1]. Now, a more complex situation occurs when a density current is propagated in a non-uniform (stratified) ambient fluid. In this case, the existing current is called the intrusive gravity current. It has been observed that instabilities occur at the interface of fluid flows (the interface of two layers with different densities) [2]. Among these instabilities, there are Holmboe waves, which are much less common than the Kelvin-Helmholtz waves due to the many constraints they have. However, they are an influential phenomenon in the field of geophysical flows and can be seen in photographs and radar observations of the atmosphere.

Investigation of Holmboe instability in intrusive gravity current in a stratified environment and on flat beds, similar to the geometry conditions of the present work, has not been investigated so far; Therefore, the motivation of the present work is to study the Holmboe instability with the Eulerian-Eulerian viewpoint in the intrusive gravity current inside the channel by Large Eddy Simulation (LES) method, to better understand this phenomenon and to investigate the effect of various factors on it. The results of the present study will be compared with the results obtained by Khodkar et al. [3], Which has been done by direct numerical simulation method.

2. Methodology

In the present study, numerical simulation of interstitial intrusive gravity current by Lock-Exchange method in a two-dimensional channel with length of 6 m and height of 10 cm has been performed. The upper and lower boundaries are assumed to be wall. Also, due to the lack of inlet and outlet boundaries in this type of problems, the left and right boundaries of the channel have been selected as wall.

In the left of the channel, there is a fluid with a density of ρ_c, which is an average density of ambient fluids ρ_u and ρ_l. In this simulation, which is Eulerian-Eulerian, the Boussinesq approximation is established and the fluid is of Newtonian type and flow is two-dimensional and incompressible.

The final equations governing this flow, are the equations of continuity, momentum and concentration in the filtered form, which are introduced as follows [4]:

$$\frac{\partial u_j}{\partial x_j} = 0 \qquad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \nu_w \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(2\upsilon_{SGS} S_{ij}\right) - \frac{1}{\rho_w}\frac{\partial p}{\partial x_i} - g'\left(C + C_2\right)\delta_{2i} \qquad (2)$$

$$\frac{\partial C}{\partial t} + u_j \frac{\partial C}{\partial x_j} = \xi \frac{\partial^2 C}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(\xi_{SGS}\frac{\partial C}{\partial x_j}\right) \qquad (3)$$

$$\frac{\partial C_2}{\partial t} + u_j \frac{\partial C_2}{\partial x_j} = \xi \frac{\partial^2 C_2}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(\xi_{SGS}\frac{\partial C_2}{\partial x_j}\right) \qquad (4)$$

It should be noted that for simplicity of the equations, the bar mark on the filtered quantities has been removed and all available quantities are of the filtered type. In these equations, u represent velocity, t time, p pressure, ρ_w and ν_w density and viscosity of the ambient fluid (water), C and C_2 are equal to the concentration of the density current and the concentration of the surrounding environment respectively, δ_{2i} the Kronecker delta, ξ and ξ_{SGS} respectively are the molecular diffusion coefficient and subgrid-scale diffusion coefficient, and S_{ij} is the strain rate tensor. Also, the direction of gravity is opposite to the direction of y or i = 2. The density difference between the two fluids is the main reason for the motion of gravity current. The initial reduced gravity g' is to describe this difference, which is equal to $g' = g\beta$ at which the $\beta = \left(\rho_{max} - \rho_w\right)/\rho_w$, $C = \left(\rho - \rho_w\right)/\left(\rho_{\max} - \rho_w\right)$ and also ρ is current density.

3. Results and Discussion

In this section, first, by examining the two parameters *R* and Richardson number, the chance of the presence of Holmboe waves with increase of the density of intrusive current is investigated. In addition, the effect of increasing the intrusive current density on the characteristics of Holmboe waves such as wavelength, wave number, phase velocity and frequency of the waves is investigated.

Study of R and J:

By calculating the mean values of R and J, in the cases where $0.1 < C < 0.9$ and $h^* = 0.3$, Figure 1 is drawn, and there are important points in the figure that are expressed below. As can be seen, with increase of the intrusive current density (decreasing the density difference), the value of Richardson number decreases and the R parameter increases.

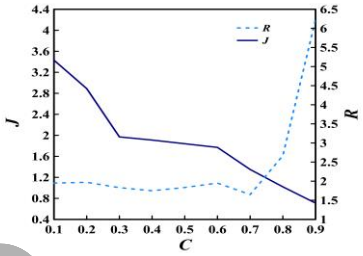

Figure 1. Mean values of J and R at different intrusive current densities

Study of Holmboe waves frequency:

In this section, Figure 2 is drawn by obtaining the average frequency of the Holmboe waves over a period of 38 seconds at different densities of intrusive gravity current at different sections of the channel. As the density increases from $C = 0.1$ to $C = 0.9$, the frequency of the waves changes from 0.118 Hz to 0.046 Hz. One of the points in Figure 2 is that as the intrusive current density increases, the frequency of the waves first increases, then decreases.

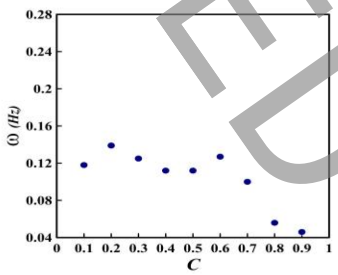

Figure 2. The average value of the frequency of Holmboe waves at different densities of intrusive gravity current

Study of Holmboe waves wavelength:

Figure 3 shows the interface between the intrusive gravity current and the reverse current in the bottom wall at different intrusive current densities, which shows the average wavelength of Holmboe waves. The average wavelength of Holmboe waves in the simulations is 6.5 cm. As mentioned in last sections, the value of Richardson number decreases as the density difference decreases; And according to Figure 3, except for case $C = 0.2$, it can be concluded that reducing the Richardson number increases the wavelength of Holmboe waves.

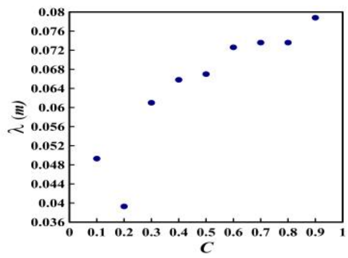

Figure 3. The average value of the wave length of Holmboe waves at different densities of intrusive gravity current

Study of Holmboe phase velocity:

In this section, the average phase velocity of Holmboe waves is presented by Figure 4 at different intrusive gravity current densities. In examining the general trend of the graph, it is also observed that with increasing Richardson number, first the phase velocity of the waves increases and then decreases and there is no specific trend. This result has been reported in experimental work of Khavasi and Firoozabadi [5] and Zhou, Lawerence [6]; but the results of the linear stability theory [7] show that the phase velocity of the Holmboe wave with Richardson number is always increasing.

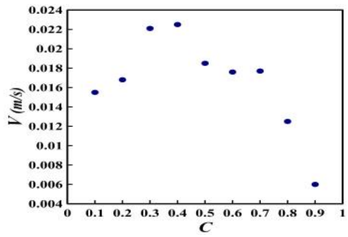

Figure 4. The average value of the phase velocity of Holmboe waves at different densities of intrusive gravity current

4. Conclusions

The effect of changing the density of intrusive gravity current on the characteristics of Holmboe waves was investigated and it was observed that with increasing the density of intrusive current, the value of Richardson number decreases and the *R* parameter increases.

Following the study of the characteristics of Holmboe waves with changes in the density of intrusive gravity current, it was observed that with increasing density from $C = 0.1$ to $C = 0.9$, the frequency of the waves changes from 0.118 Hz to 0.046 Hz. In addition, the greatest increase in frequency occurs when the density of intrusive current is $C = 0.2$. Also, an increase in the wavelength of Holmboe waves was observed with increasing the density of intrusive current. The phase velocity of Holmboe waves did not have a specific trend with density changes, and this result was consistent with the experimental results, but different from the viewpoint of linear stability theory.

5. References

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