Regional study of mode-2 internal solitary waves in the Pacific coast of Central America using marine seismic survey data

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Abstract. In this paper, a regional study of the mode-2 internal solitary waves (ISWs) in the Pacific coast of Central America is carried out by using seismic reflection method. The observed relationship between the dimensionless phase velocity and the dimensionless amplitude (DA) of the mode-2 ISWs was analysed. When DA<1, the dimensionless phase velocity increases with the increasing dimensionless amplitude, divided into two parts with different growth rates. When DA>1, the dimensionless phase velocity increases with the increasing dimensionless amplitude at a relatively small growth rate. We suggest that the influences of seawater depth (submarine topography), pycnocline depth, and pycnocline thickness on the phase velocity of the mode-2 ISWs in the study area, cause the relationship between the dimensionless phase velocity and the dimensionless amplitude diversified. The observed relationship between the dimensionless wavelength and the dimensionless amplitude of the mode-2 ISWs was also analysed. When DA<1 and DA>2, the dimensionless wavelength decreases and increases with the increasing dimensionless amplitude, respectively. Additionally, the seawater depth has a great influence on the wavelength of the mode-2 ISWs in the study area, and overall the wavelength increases with the increasing seawater depth. As for the vertical structure of the amplitude of the mode-2 ISWs in the study area, we find that it is affected by the nonlinearity of the ISWs and the pycnocline deviation (especially the downward pycnocline deviation).

1 Introduction

The amplitude and propagation velocity of the mode-1 ISWs are larger than those in the mode-2 ISWs. The mode-1 ISWs are more common in the ocean. In recent years, with the advancement of observation instruments, the mode-2 ISWs in the ocean have been gradually observed, such as on the New Jersey shelf (Shroyer et al., 2010), in the South China Sea (Liu et al., 2013; Ramp et al., 2015; Yang et al., 2009), at Georges Bank (Bogucki et al., 2005), over Mascarene Ridge in Indian Ocean (Da Silva et al., 2011), and on the Australian North West Shelf (Rayson et al., 2019). Conventional physical oceanography observation and remote sensing observation have spatial resolution limitations. That is, the horizontal resolution of conventional physical oceanography observation methods (such as mooring) is low, and the vertical resolution of remote sensing observations is low. Seismic oceanography (Holbrook et al., 2003; Ruddick et al., 2009), as a new oceanography survey method, has high spatial resolution (the vertical resolution and horizontal resolution can reach about 10m). It can better describe the spatial structure and related characteristics of mesoscale and small scale phenomena in the
At present, the researches on the mode-2 ISWs in the ocean are mainly based on simulation. Through simulation, scholars have found that the pycnocline deviation will affect the stability of the mode-2 ISWs, making the top and bottom structure of the mode-2 ISWs asymmetrical (Carr et al., 2015; Cheng et al., 2018; Olsthoorn et al., 2013). The instability caused by the pycnocline deviation mainly appears at the bottom of the mode-2 ISWs, is manifested in that the amplitude of the mode-2 ISWs peak is smaller than the amplitude of the trough, because the upper sea layer is thinner than the bottom sea layer. The wave tail will appear similar to K-H instability billow and the wave core will appear small-scale flip (Carr et al., 2015; Cheng et al., 2018). For the phase velocity of the mode-2 ISWs, scholars found through simulation experiments that it increases with the increasing amplitude (Maxworthy, 1983; Salloum et al., 2012; Stamp & Jacka, 1995; Terez & Knio, 1998). Brandt et al. (2014) simulated the material transport of mode-2 ISWs with large amplitude in the laboratory. They found that, when $2a/h_2>4$ ($a$ is the amplitude of the mode-2 ISWs and $h_2$ is the pycnocline thickness), the linear relationship between the phase velocity (wavelength) and the amplitude is destroyed. That is, when the amplitude $2a/h_2\geq4$, the phase velocity increases relatively slowly, and the wavelength increases rapidly. They believe that the above results are caused by strong internal circulation related to the very large amplitude and the influence of the top and bottom boundaries. Chen et al. (2014) calculated the KdV phase velocity and the fully nonlinear phase velocity of the ISWs as the function of the pycnocline depth and the pycnocline thickness, respectively. They found the phase velocity of the mode-2 ISWs increases monotonously with the increasing pycnocline depth, and firstly increases and then decreases with the increasing pycnocline thickness. Carr et al. (2015) found by simulations that the pycnocline deviation has little effect on the phase velocity, wavelength, and amplitude of the mode-2 ISWs. Maderich et al. (2015) found that for the mode-2 ISWs, when the dimensionless amplitude $2a/h_2<1$, the deep water weakly nonlinear theory (Benjamin, 1967) can describe the numerical simulation and experimental simulation results well. When $2a/h_2>1$, the wavelength (phase velocity) increases with the amplitude faster than the results predicted by the deep water weakly nonlinear theory. But the solution of Kozlov and Makarov (1990) can well estimate the corresponding wavelength and phase velocity when the amplitude is $1<2a/h_2<5$. Terletskya et al. (2016) found that the phase velocity and amplitude of the mode-2 ISWs will decrease after passing the step. And the closer the mode-2 ISWs is to the step in the vertical direction at the time of incidence, the smaller the phase velocity and amplitude of the mode-2 ISWs after passing the step. Kurkina et al. (2017) used GDEM (Generalized Digital Environmental Model) to find that the seawater depth in the South China Sea is the main controlling factor of the mode-2 ISWs phase velocity, and the phase velocity increases exponentially with the increasing seawater depth. Deepwell et al. (2019) found by simulation that the relationship curve that the mode-2 ISWs phase velocity increases with the increasing
amplitude has a strong quadratic fitting relationship. They speculated that this quadratic fitting relationship comes from the influence of seawater depth (when the seawater depth is smaller, the phase velocity is also smaller).

The simulation can well reveal the kinematics characteristics of the mode-2 ISWs, but the actual ocean conditions are often more complicated, which is manifested by the diversity of controlling factors in the kinematics process. The observations including seismic oceanography method are also required to continually provide basic understanding of the geometry and kinematics characteristics of the mode-2 ISWs. For example, limited by factors such as the lower spatial resolution of the observation methods, previous scholars have less direct observation research on the phase velocity and wavelength of the mode-2 ISWs in the ocean. And there is even less research (including observation research) on the vertical structure of the mode-2 ISWs. The seismic oceanography method has more advantages for carrying out the above-mentioned research due to its higher spatial resolution. The Pacific coast of Central America (western Nicaragua) has relatively continuous submarine topography along the coastline, including continental shelf and continental slope, with the seawater depth of 100-2000m (Fig. 1). At present, there is relatively little research work on internal waves in this area. We reprocessed the historical seismic data in this area and identified a large number of mode-2 ISWs with relatively complete spatial structures in the region. This discovery is very helpful to carry out observation research on the geometry and kinematics characteristics of the mode-2 ISWs. Fan et al. (2021a, 2021b) used the multichannel seismic data of the survey lines L88 and L76 (cruise EW0412, see Fig. 1 for the survey line locations) in the Pacific coast of Central America to respectively report the mode-2 ISWs in this area and study the shoaling features of the mode-2 ISWs in this area. However, a single survey line can only reveal the local characteristics of the mode-2 ISWs in the study area. Deep understanding of the geometry and kinematics characteristics of the mode-2 ISWs in the study area requires a regional systematic study. In this work, we reprocessed the seismic data of the entire study area, and identified numerous mode-2 ISWs on multiple survey lines in the region (the positions of the observed ISWs and the survey lines they located are shown by the black filled circles and the red lines in Fig. 1, respectively). Based on the numerous mode-2 ISWs observed by multiple survey lines in the study area, this paper will conduct a regional study on the characteristic parameters such as the pycnocline deviation degree, phase velocity, and wavelength of the mode-2 ISWs, as well as the vertical structure characteristics of the mode-2 ISWs’ amplitude in the study area.
Figure 1. Distribution of multichannel seismic data. The red lines indicate the positions of the survey lines, and the black filled circles on the red lines indicate the positions of the observed mode-2 ISWs. The blue lines S1, S2 and S3 are part of the seismic sections containing the mode-2 ISWs, which will be displayed in Fig. 3 and Fig. 4.

2 Data and Methods

This paper mainly uses seismic reflection to conduct a regional study on the mode-2 ISWs in the Pacific coast of Central America. The seismic data of the cruise EW0412 used in this study was provided by the MGDS (The Marine Geoscience Data System) (http://www.marine-geo.org/). The cruise EW0412 collected high-resolution multichannel seismic data from the continental shelf to the continental slope in the coastal areas of Sandino Forearc Basin, Costa Rica, Nicaragua, Honduras, and El Salvador (Fulthorpe & McIntosh, 2014). The seismic acquisition parameters of the cruise EW0412 are as follows: the sampling interval is 1 ms, each shot gather has 168 traces, the shot interval is 12.5 m, the trace interval is 12.5 m, and the minimum offset is 16.65 m. The seawater seismic reflection sections used in this study were obtained through the following processing processes: defining geometry, noise attenuation, common midpoint (CMP) sorting, velocity analysis, normal moveout (NMO), stacking, and post-stack denoising.

The mode-2 ISWs in the actual ocean has the multilayer structure, which is different from the three-layer model used in the simulation experiment to describe the convex mode-2 ISWs. As for three-layer model, the upper layer of the convex mode-2 ISWs is the peak and the lower layer is the trough. In order to establish the connection between this observational data research and previous simulation experiments, we calculated the equivalent amplitude, the equivalent pycnocline
thickness, and the equivalent wavelength of the mode-2 ISWs. For the mode-2 ISWs with a multilayer structure, the sum of all ISWs peak amplitudes $a_p$ and the sum of all ISWs trough amplitudes $a_t$ are respectively taken as the equivalent peak and trough amplitude of the mode-2 ISWs with a three-layer model structure. Then the equivalent amplitude of the mode-2 ISWs with a three-layer model structure is the average of $a_p$ and $a_t$, and the equivalent pycnocline thickness is calculated by $h_2 = h - a_p - a_t$, where $h$ is the seawater thickness affected by the mode-2 ISWs with a multilayer structure. The equivalent wavelength of the mode-2 ISWs with a three-layer model structure is the average of all ISWs peak and trough wavelengths in the multilayer structure. The detailed calculation process is described in Fan et al. (2021a). This study uses an improved ISWs apparent phase velocity calculation method to calculate the apparent phase velocity of ISWs. This method firstly does pre-stack migration of the common offset gather sections, and then pick the CMP and shot point pairs corresponding to the ISWs trough or peak from the pre-stack migration sections of different offset with high signal-to-noise ratio. By fitting the CMP-shot point pairs, we can calculate the apparent phase velocity and apparent propagation direction of the ISWs. The ISWs horizontal velocity can be expressed by $v = (cmp2-cmp1)/T = (cmp2-cmp1)/[(s2-s1)*dt]$, where $cmp1$ and $cmp2$ are the peak or trough positions of the ISWs at different time, $s1$ and $s2$ are the shot numbers corresponding to $cmp1$ and $cmp2$, and $dt$ is the time interval of shots. The detailed calculation process is described in Fan et al. (2021a).

The wavelength of the mode-2 ISWs is usually defined as half-width at half-amplitude of the ISWs (Carr et al., 2015; Stamp & Jacka, 1995), as shown by $\lambda$ in Fig. 2. Since the ISWs move in the horizontal direction during the seismic acquisition process, the wavelength of the ISWs observed by the seismic reflection method is the apparent wavelength. The apparent wavelength of the ISWs is controlled by the relative motion direction of the ship and the ISWs, the ship speed, and the propagation speed of the ISWs. The propagation speed of the mode-2 ISWs (about 0.5m/s) is generally lower than the ship speed (about 2.5m/s) during seismic acquisition. When correcting the apparent wavelength of the ISWs to obtain the actual wavelength, it is divided into two situations in which the motion direction of the ISWs and the ship is the same and opposite, as shown in Fig. 2. When the ISWs and the ship move in the same direction, the wavelength (apparent wavelength) estimated from the seismic stacked section is larger. That is, the wavelength (apparent wavelength $\lambda_s$) of the ISWs observed on the seismic stacked section denoted by the blue curve in Fig. 2a is greater than the wavelength $\lambda$ of the actual ISWs at the beginning and end respectively denoted by the black and red curves in Fig. 2a. In order to eliminate the influence of the horizontal movement of the ISWs, when correcting the apparent wavelength $\lambda_s$ to obtain the actual wavelength $\lambda$, it is necessary to subtract the distance $x_w$ moved by the ISWs within the seismic acquisition time corresponding to the apparent wavelength distance of the ISWs. That is:

$$\lambda = \lambda_s - x_w = \lambda_s - \lambda_s/V_{ship} * V_{water}$$ (1)

where $V_{ship}$ is the ship speed, and $V_{water}$ is the propagation speed of the ISWs (Fig. 2a).

When the ISWs and the ship move in the opposite direction, the wavelength (apparent wavelength) estimated from the seismic stacked section is smaller. That is, the wavelength (apparent wavelength $\lambda_s$) of the ISWs observed on the seismic stacked section denoted by the blue curve in Fig. 2b is smaller than the wavelength $\lambda$ of the actual ISWs at the beginning and end respectively denoted by the black and red curves in Fig. 2b. In order to eliminate the influence of the horizontal
movement of the ISWs, when correcting the apparent wavelength $\lambda_s$ to obtain the actual wavelength $\lambda$, it is necessary to add the distance $x_w$ moved by the ISWs within the seismic acquisition time corresponding to the apparent wavelength distance of the ISWs. That is:

$$\lambda = \lambda_s + x_w = \lambda_s + \frac{\lambda_s}{V_{\text{ship}}} \cdot V_{\text{water}}$$  \hspace{1cm} (2)$$

where $V_{\text{ship}}$ is the ship speed, and $V_{\text{water}}$ is the propagation speed of the ISWs (Fig. 2b).

![Figure 2](https://doi.org/10.5194/npg-2021-31)

**Figure 2.** Schematic diagram of the apparent wavelength correction of the mode-2 ISWs. (a) The ISWs move in the same direction as the ship. (b) The ISWs move in the opposite direction to the ship. S1 denotes the self-excitation and self-reception position of the ship at 1/2 amplitude of the ISWs at the beginning. S2 denotes the self-excitation and self-reception position of the ship at the peak of the amplitude of the ISWs, $V_{\text{ship}}$ is the ship speed, and $V_{\text{water}}$ is the ISWs propagation speed. $\lambda_s$ is the apparent wavelength of the ISWs observed by the seismic stacked section. $\lambda$ is the actual wavelength of the ISWs. $a$ is the amplitude of the ISWs. $x_w$ is the distance moved by the ISWs during the time the ship moves from S1 to S2. The black curve denotes the ISWs at the beginning, the red curve denotes the ISWs moved $x_w$ distance from the starting position, and the blue curve denotes the ISWs observed on the seismic stacked section.

### 3 Results and Interpretations

#### 3.1 Typical Sections Interpretation and Regional Distribution Characteristics of the Mode-2 ISWs

In addition to the survey lines L88 and L76 with mode-2 ISWs observed by Fan et al. (2021a, 2021b), we also found mode-2 ISWs on many other survey lines in the study area. Two typical survey lines are L84 and L74 (see the red lines in Fig. 1 for the locations of these two survey lines). Figure 3 shows the partial seismic stacked section S1 of the survey line L84 (see the blue line in Fig. 1 for the location of this section S1). We have identified 10 mode-2 ISWs from the seismic section S1 (see Fig. 3 for their positions and corresponding numbers. ISW1-ISW4 are located at the shelf break, and ISW5-ISW10 are located on the continental shelf), and calculated the characteristic parameters of these 10 mode-2 ISWs, such as the seafloor depth (seawater depth) $H$, maximum amplitude (in the vertical direction), equivalent amplitude $a$, equivalent pycnocline thickness $h_2$, dimensionless amplitude $2a/h_2$, mid-depths of the pycnocline $hc$, the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth $Op$, equivalent wavelength $\lambda$, dimensionless wavelength $2\lambda/h_2$, and apparent phase velocity $U_c$ (Table 1). The equivalent wavelength and the dimensionless wavelength in Table 1 have been
corrected using Eq. (1) (the ISWs have the same motion direction as the ship, and the ISWs with the large phase velocity estimation error have been corrected using a phase velocity of 0.5 m/s). The maximum amplitudes of the ISWs ISW1-ISW7 on the survey line L84 are all less than 10 m, and the maximum amplitudes of ISW8-ISW10 are larger, around 15 m. The $2a/h_2$ values of these ten mode-2 ISWs on the survey line L84 are all less than 2, and they belong to the mode-2 ISWs with small amplitude (Brandt et al., 2014). The $2a/h_2$ values of ISW8, ISW9, and ISW10 are around 1, and their amplitudes are slightly larger in these small-amplitude mode-2 ISWs. When calculating the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth, it is found that except for the pycnocline centres of ISW8, ISW9, and ISW10 are deeper than 1/2 seafloor depths, the pycnocline centres of the other seven mode-2 ISWs are shallower than 1/2 seafloor depths. For ISW1, ISW2, and ISW3, the degrees to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth are both greater than 20%, which appear as the asymmetry of waveforms (the asymmetry of the front and rear waveform, and the asymmetry of the top and bottom waveform). When the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth is small, the waveform of the mode-2 ISWs is more symmetrical, such as ISW8, ISW9, and ISW10. The waveforms of ISW1, ISW2, and ISW3 at the shelf break are asymmetrical, and their dimensionless wavelength $2\lambda/h_2$ is significantly larger than the $2\lambda/h_2$ of the ISWs on the continental shelf which have the same level of dimensionless amplitudes ($2a/h_2$) (for example, the $2a/h_2$ value of ISW2 is 0.45, and the value of $2\lambda/h_2$ is 9.55; the value of $2a/h_2$ of ISW7 is 0.42, and the value of $2\lambda/h_2$ is 3.49), making the overall relationship between dimensionless wavelength $2\lambda/h_2$ and the dimensionless amplitude $2a/h_2$ not absolute linear correlation (the dimensionless wavelength $2\lambda/h_2$ increases with the increasing dimensionless amplitude). The apparent phase velocities of the 10 mode-2 ISWs on the survey line L84 are about 0.5 m/s, and the apparent propagation directions are all shoreward. For ISWs with small apparent phase velocity calculation errors in shallow water (ISW6, ISW7, and ISW9), the apparent phase velocity does not strictly increase with the increasing dimensionless amplitude $2a/h_2$. For example, the $2a/h_2$ value of ISW6 is 0.4, and the apparent phase velocity is about 0.58 m/s; The $2a/h_2$ value of ISW9 is 1.19, and the apparent phase velocity is about 0.38 m/s.
Figure 3. Seismic stacked section S1, observed mode-2 ISWs part on the survey line L84. Arrows and numbers indicate the ten identified mode-2 ISWs ISW1-ISW10. The location of the S1 seismic stacked section is shown in Fig. 1. The horizontal axis indicates the distance to the starting point of the survey line L84. The survey line L84 acquisition time is from 07:15:14 on 17 December 2004, to 17:26:49 on 17 December 2004.

Table 1. Characteristic Parameters of the 10 Mode-2 Internal Solitary Waves in Survey Line L84.

<table>
<thead>
<tr>
<th>ISW#</th>
<th>$H$  (m)</th>
<th>$A$  (m)</th>
<th>$a$  (m)</th>
<th>$h_2$  (m)</th>
<th>$2a/h_2$</th>
<th>$hc$  (m)</th>
<th>$Op$ (%)</th>
<th>$\lambda$  (m)</th>
<th>$2\lambda/h_2$  (m)</th>
<th>$U_c$  (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISW1</td>
<td>145.5</td>
<td>3</td>
<td>2.22</td>
<td>29.23</td>
<td>0.15</td>
<td>54.88</td>
<td>24.6</td>
<td>103.6</td>
<td>7.09</td>
<td>0.85±0.6</td>
</tr>
<tr>
<td>ISW2</td>
<td>138.8</td>
<td>4.7</td>
<td>5.84</td>
<td>25.93</td>
<td>0.45</td>
<td>51.31</td>
<td>26.1</td>
<td>123.8</td>
<td>9.55</td>
<td>0.69±0.19</td>
</tr>
<tr>
<td>ISW3</td>
<td>130.5</td>
<td>4.1</td>
<td>4.45</td>
<td>27.6</td>
<td>0.32</td>
<td>49.05</td>
<td>24.8</td>
<td>84.6</td>
<td>6.13</td>
<td>0.52±0.12</td>
</tr>
<tr>
<td>ISW4</td>
<td>121.5</td>
<td>5.2</td>
<td>6.04</td>
<td>34.72</td>
<td>0.35</td>
<td>59.4</td>
<td>2.2</td>
<td>55.18</td>
<td>3.18</td>
<td>0.19±0.11</td>
</tr>
<tr>
<td>ISW5</td>
<td>111</td>
<td>6.79</td>
<td>12.67</td>
<td>40.84</td>
<td>0.62</td>
<td>51.31</td>
<td>7.6</td>
<td>95.38</td>
<td>4.67</td>
<td>0.32±0.16</td>
</tr>
<tr>
<td>ISW6</td>
<td>108</td>
<td>4.6</td>
<td>7.5</td>
<td>37.19</td>
<td>0.4</td>
<td>48.48</td>
<td>10.2</td>
<td>50.61</td>
<td>2.72</td>
<td>0.58±0.16</td>
</tr>
<tr>
<td>ISW7</td>
<td>104.3</td>
<td>6.4</td>
<td>7.34</td>
<td>34.83</td>
<td>0.42</td>
<td>48.11</td>
<td>7.8</td>
<td>60.86</td>
<td>3.49</td>
<td>0.64±0.28</td>
</tr>
<tr>
<td>ISW8</td>
<td>103.5</td>
<td>13.2</td>
<td>15.82</td>
<td>32.94</td>
<td>0.96</td>
<td>53.38</td>
<td>-3.2</td>
<td>72.97</td>
<td>4.43</td>
<td>0.46±0.24</td>
</tr>
<tr>
<td>ISW9</td>
<td>103.5</td>
<td>15.9</td>
<td>13.56</td>
<td>22.79</td>
<td>1.19</td>
<td>52.81</td>
<td>-2.1</td>
<td>88.47</td>
<td>7.76</td>
<td>0.38±0.17</td>
</tr>
<tr>
<td>ISW10</td>
<td>102.8</td>
<td>13.6</td>
<td>15.87</td>
<td>20.62</td>
<td>1.54</td>
<td>52.62</td>
<td>-2.4</td>
<td>94.1</td>
<td>9.13</td>
<td>0.55±0.34</td>
</tr>
</tbody>
</table>

Note. $H$, seafloor depths. $A$, maximum amplitudes. $a$, equivalent ISWs amplitudes. $h_2$, equivalent pycnocline thicknesses. $hc$, the mid-depths of the pycnocline. $Op$, the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth. $\lambda$, equivalent wavelengths. $U_c$, apparent phase velocities obtained from seismic observation.
The survey line L74 is located in the southeast direction of the survey line L84 (see Fig. 1 for the specific location). Figure 4 shows the partial seismic stacked sections (S2 and S3) of the survey line L74. We have identified seven mode-2 ISWs from the seismic sections S2 and S3. Their positions and corresponding numbers are shown in Fig. 4, and the statistical characteristic parameters are shown in Table 2. The equivalent wavelength and the dimensionless wavelength in Table 2 have been corrected using Eq. (1) (the ISWs have the same motion direction as the ship, and the ISWs with the large phase velocity estimation error have been corrected using a phase velocity of 0.5 m/s). The maximum amplitudes of the ISWs ISW12-ISW17 on the survey line L74 are all less than 10 m, and the maximum amplitude of ISW11 is larger, 13.6 m. The $2a/h_2$ values of these seven mode-2 ISWs are all less than 2. They are the mode-2 ISWs with small amplitude, and the amplitude of ISW11 is slightly larger among them. When calculating the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth, it is found that the pycnocline centres of the mode-2 ISWs ISW11-ISW17 are all deeper than 1/2 of the seafloor depths. Except for ISW11 (the bottom reflection event is broken), as for the other six mode-2 ISWs ISW12-ISW17, the degrees to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth are both greater than 15%. The asymmetry of ISW12 and ISW13 is manifested in that the connection between the top peaks of the ISWs and the bottom troughs of the ISWs is not vertical. The pycnocline centre of ISW14 deviates from 1/2 of the seafloor depth the most, which is 51.5%. Its asymmetry is manifested in the large difference between the top and bottom waveforms near the pycnocline centre. ISW15, ISW16, and ISW17 are located on the continental shelf, and their pycnocline deviations are larger, but the waveforms are more symmetrical than other ISWs. When the downward pycnocline deviation is large, the influence of pycnocline deviation on the stability of the mode-2 ISWs is more complicated than when the pycnocline deviates upwards, and it may be controlled by factors such as wavelength. There is no absolute linear correlation relationship between the dimensionless wavelength $2\lambda/h_2$ and the dimensionless amplitude $2a/h_2$ of the seven mode-2 ISWs on the survey line L74 (the dimensionless wavelength $2\lambda/h_2$ increases with the increasing dimensionless amplitude $2a/h_2$). For example, the $2a/h_2$ values of ISW12 and ISW14 are greater than that of ISW16, but the dimensionless wavelength of ISW16 is greater than the dimensionless wavelengths of ISW12 and ISW14. The apparent phase velocities of the seven mode-2 ISWs on the survey line L74 are about 0.5 m/s, and their propagation directions are all shoreward. For the ISWs in shallow water where the apparent phase velocity calculation errors are small (ISW12, ISW14, ISW16, and ISW17), the apparent phase velocity generally increases with the increasing dimensionless amplitude $2a/h_2$. 
Figure 4. (a) and (b) are respectively the seismic stacked sections S2 and S3, observed mode-2 ISWs parts on the survey line L74. The arrows and the numbers indicate the seven identified mode-2 ISWs ISW11-17. The locations of the seismic stack section S2 and S3 are shown in Fig. 1, and the horizontal axis indicates the distance to the starting point of the survey line L74. The survey line 74 acquisition time is from 06:31:03 on 3 December 2004 to 02:30:01 on 4 December 2004.

Table 2. Characteristic Parameters of the Seven Mode-2 Internal Solitary Waves in Survey Line L74.

<table>
<thead>
<tr>
<th>ISW#</th>
<th>H</th>
<th>A</th>
<th>a</th>
<th>h^2</th>
<th>2a/h^2</th>
<th>hc</th>
<th>Op (%H)</th>
<th>λ</th>
<th>2λ/h^2</th>
<th>Uc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISW11</td>
<td>138.8</td>
<td>13.6</td>
<td>24.19</td>
<td>26.98</td>
<td>1.79</td>
<td>73.38</td>
<td>-5.7</td>
<td>83.05</td>
<td>6.16</td>
<td>0.19±0.1</td>
</tr>
<tr>
<td>ISW12</td>
<td>103.5</td>
<td>7.31</td>
<td>9.95</td>
<td>32.82</td>
<td>0.61</td>
<td>60.34</td>
<td>-16.6</td>
<td>68.11</td>
<td>4.15</td>
<td>0.63±0.08</td>
</tr>
</tbody>
</table>
In addition to the survey lines L74 and L84, the mode-2 ISWs also have sporadic distribution on other survey lines in the area (see the black filled circles in Fig. 1). We have identified 70 mode-2 ISWs in the study area. They appeared from 2 December 2004 to 18 December 2004. On 17 December 2004 and 18 December 2004, there were more mode-2 ISWs (Fig. 5a), 21 (10 for survey line L84, 6 for survey line L88, and 5 for survey line L76) and 9 (1 for survey line L72, 5 for survey line L76, and 3 for survey line L103) respectively. Observe the distribution of the appearance time of mode-2 ISWs observed in the study area in Fig. 5a (in days). It can be found that the mode-2 ISWs frequently appeared on the northwest side of the study area in December 2004, and appeared in early and late December. In addition, the spatial distribution range of the mode-2 ISWs is large, ranging from the continental slope to the continental shelf (see Figures 1, 3, and 4). Figure 5b shows the time when the mode-2 ISWs observed in the study area appeared in hours. Combined with Fig. 5a, it can be found that from 2 December 2004 to 8 December 2004, the ISWs appeared at around 12:00 and 00:00 (or 24:00) in a day; From 10 December 2004 to 13 December 2004, the ISWs appeared at around 12:00 and 24:00 in a day, and relatively more appeared around 12:00; From 14 December 2004 to 18 December 2004, the ISWs appeared at around 12:00 and 00:00 (or 24:00) in a day, and relatively more appeared around 00:00 (or 24:00). The survey lines L103, L105, and L107 are perpendicular to the propagation direction of the mode-2 ISWs in the study area (Fig. 1). Therefore, these three survey lines are not included in the subsequent statistical analysis of the mode-2 ISWs characteristic parameters. We have counted the characteristic parameters of 53 mode-2 ISWs in the study area. In these 53 mode-2 ISWs, there are 51 small-amplitude ISWs ($2a/h_2<2$), and there are 40 ISWs with smaller amplitude ($2a/h_2<1$) among these 51 small-amplitude ISWs (Fig. 6a). The mode-2 ISWs in the study area are dominated by smaller amplitudes (Fig. 6a). The maximum amplitude (in the vertical direction) of the mode-2 ISWs mainly changes in the range of 3-13 m (Fig. 6d), and the equivalent wavelengths of most of the mode-2 ISWs are on the order of about 100 m (Fig. 6c, the equivalent wavelength in the figure has been corrected according to Eq. (1) and Eq. (2)). When calculating the phase velocity of the mode-2 ISWs, due to the low signal-to-noise ratio of some survey lines, the calculation errors of some ISWs phase velocities are relatively large. Therefore, when analysing the apparent phase velocity of the mode-2 ISWs of the study area, we only used 26 ISWs with relatively small errors (the error is less than half

<table>
<thead>
<tr>
<th>ISW</th>
<th>$H_1$</th>
<th>$A$</th>
<th>$\alpha$</th>
<th>$h_2$</th>
<th>$\lambda_a$</th>
<th>$U_c$</th>
</tr>
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<tr>
<td>ISW13</td>
<td>90.75</td>
<td>5.68</td>
<td>6.08</td>
<td>36.22</td>
<td>-22.6</td>
<td>94.41</td>
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<tr>
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<td>92.25</td>
<td>6.86</td>
<td>11.17</td>
<td>35.04</td>
<td>-51.5</td>
<td>50.69</td>
</tr>
<tr>
<td>ISW15</td>
<td>90</td>
<td>5.46</td>
<td>8.91</td>
<td>38.94</td>
<td>-15.8</td>
<td>112.7</td>
</tr>
<tr>
<td>ISW16</td>
<td>91.5</td>
<td>5.74</td>
<td>8.67</td>
<td>39.53</td>
<td>-26.7</td>
<td>100.7</td>
</tr>
<tr>
<td>ISW17</td>
<td>91.5</td>
<td>6.4</td>
<td>12.71</td>
<td>32.56</td>
<td>-25.9</td>
<td>69.56</td>
</tr>
</tbody>
</table>

Note. $H$, seafloor depths. $A$, maximum amplitudes. $\alpha$, equivalent ISWs amplitudes. $h_2$, equivalent pycnocline thicknesses. $\lambda_a$, the mid-depths of the pycnocline. $O_p$, the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth. $\lambda$, equivalent wavelengths. $U_c$, apparent phase velocities obtained from seismic observation.
of the calculated value). The apparent phase velocities of the mode-2 ISWs in the study area are on the order of 0.5 m/s (Fig. 6b), and most of the mode-2 ISWs propagate in the shoreward direction. We have traced back the time when each ISWs in the study area (mainly the ISWs located on the continental shelf) appeared at the continental shelf break using the ISWs phase velocity of 0.5 m/s, as shown in Fig. 5c, in hours. Combined with Fig. 5a, it is found that from 2 December 2004 to 8 December 2004, the ISWs traced back to the continental shelf break appeared at around 12:00 and 00:00 (or 24:00) in a day, and relatively more appeared around 12:00; From 10 December 2004 to 13 December 2004, most of the ISWs traced back to the continental shelf break appeared at around 24:00 (or 0:00) in a day; From 14 December 2004 to 18 December 2004, the ISWs traced back to the continental shelf break appeared at around 12:00 and 24:00 (or 0:00) in a day. The mode-2 ISWs observed in the study area may be generated by the interaction between the internal tide and the continental shelf break.

Figure 5. (a) The time when the mode-2 ISWs observed in the study area appeared in days. (b) The time when the mode-2 ISWs observed in the study area appeared in hours. (c) Tracing back the time (in hours) when internal solitary waves appeared at the continental shelf break in the study area.
Figure 6. (a) The histogram of the dimensionless amplitude of the mode-2 ISWs in the study area. (b) The histogram of the phase velocity of the mode-2 ISWs in the study area. (c) The histogram of the wavelength of the mode-2 ISWs in the study area, the dark blue and red color bars denote the ISWs on the survey lines in SW-NE direction and in NE-SW direction, respectively. (d) The histogram of the maximum amplitude of the mode-2 ISWs in the study area.

3.2 Phase Velocity and Wavelength Characteristics of the Mode-2 ISWs in Study Area

Inspired by the work of Maderich et al. (2015) and Chen et al. (2014), we respectively calculated the relationships between the dimensionless phase velocity and the dimensionless amplitude, the dimensionless wavelength and the dimensionless amplitude, the phase velocity (apparent phase velocity) and the maximum amplitude, the wavelength (equivalent wavelength) and the maximum amplitude, the phase velocity (apparent phase velocity) and the pycnocline depth, the phase velocity (apparent phase velocity) and the pycnocline thickness. Figure 7 shows the relationship between the dimensionless phase velocity $U_c/C$ and the dimensionless amplitude $2a/h_2$ of the observed 26 mode-2 ISWs (with relatively small errors) in the study area. When $2a/h_2<1$, the relationship between the dimensionless phase velocity and the dimensionless amplitude of the observed mode-2 ISWs in the study area has the trends respectively given by Kozlov and
Makarov (1990), as well as Salloum et al. (2012). That is, the dimensionless phase velocity of the mode-2 ISWs increases with the increasing dimensionless amplitude, but with different growth rates. When $2a/h_2 > 1$, the relationship between the dimensionless phase velocity and the dimensionless amplitude of the observed mode-2 ISWs in the study area is closer to the result predicted by the deep water weakly nonlinear theory (Benjamin, 1967). That is, The dimensionless phase velocity of the mode-2 ISWs increases with the increasing dimensionless amplitude at a relatively small growth rate. Figure 8 shows the relationship between the dimensionless wavelength $2\lambda/h_2$ and the dimensionless amplitude $2a/h_2$ of the observed 32 mode-2 ISWs (there are 13 ISWs on the survey lines in SW-NE direction, and 19 ISWs on the survey lines in NE-SW direction, see Fig. 6c) in the study area, where the black and red crosses denote the ISWs on the survey lines in SW-NE direction and in NE-SW direction, respectively. The survey line in SW-NE direction is consistent with the movement direction of the ISWs. Use Eq. (1) to correct the apparent wavelength to obtain the actual wavelength. The survey line in NE-SW direction is opposite to the movement direction of the ISWs. Use Eq. (2) to correct the apparent wavelength to obtain the actual wavelength. Figure 8 shows the result after correcting the apparent wavelength of the ISWs. When using Eq. (1) and Eq. (2) to correct the apparent wavelength, the phase velocity of the ISWs estimated in Fig. 7 needs to be used. The dimensionless wavelengths of the ISWs with the large error in the estimation of the phase velocity are not shown in Fig. 8. Observing Fig. 8, it can be found that when $2a/h_2 < 1$, the relationship between the dimensionless wavelength and the dimensionless amplitude of the observed mode-2 ISWs in the study area is closer to the result predicted by the deep water weakly nonlinear theory (Benjamin, 1967). That is, the dimensionless wavelength of the mode-2 ISWs decreases with the increasing dimensionless amplitude. When $2a/h_2 > 2$, the relationship between the dimensionless wavelength and the dimensionless amplitude of the observed mode-2 ISWs in the study area is closer to the solution of Salloum et al. (2012). That is, the dimensionless wavelength of the mode-2 ISWs increases with the increasing dimensionless amplitude. When $1 < 2a/h_2 < 2$, the dimensionless wavelength of the observed mode-2 ISWs in the study area is higher than that predicted by the deep water weakly nonlinear theory (Benjamin, 1967) and Salloum et al. (2012).
Figure 7. The relationship between the dimensionless phase velocity and the dimensionless amplitude of the mode-2 ISWs observed in the study area. The black crosses denote the seismic observation results of the mode-2 ISWs.

Figure 8. The relationship between the dimensionless wavelength and the dimensionless amplitude of the mode-2 ISWs observed in the study area. The black and red crosses denote the ISWs on the survey lines in SW-NE direction and in NE-SW direction, respectively.

The relationship between the phase velocity and the maximum amplitude of the mode-2 ISWs observed in the study area, and the relationship between the wavelength and the maximum amplitude are shown in Figs. 9a and 9b, respectively. It can be found that the phase velocity and wavelength of the mode-2 ISWs in the study area are less affected by the maximum...
amplitude. There is no obvious linear correlation between phase velocity and maximum amplitude, as well as between wavelength and maximum amplitude (Figs. 9a and 9b). When the maximum amplitudes are between 6 m and 11 m, the variety range of phase velocity is relatively large, and there is a significant increase in phase velocity (Fig. 9a). When the maximum amplitudes are between 7 m and 13 m, there is a significant increase in wavelength (Fig. 9b). The relationships between the phase velocity and the pycnocline depth, as well as the phase velocity and the pycnocline thickness of the observed mode-2 ISWs in the study area are shown in Figs. 10a and 10b, respectively. As for the observed mode-2 ISWs in the study area, their pycnocline depths are mainly concentrated in the range of 40-70 m, and their pycnocline thicknesses (equivalent pycnocline thickness) are mainly concentrated in the range of 10-60 m. As with the numerical simulation results of Chen et al. (2014), the phase velocity of the observed mode-2 ISWs in the study area has the trends to increase slowly with the increasing pycnocline depth and pycnocline thickness, respectively. The trend mentioned above is not completely monotonous in Fig. 10, which is manifested as the large variation range of the phase velocity on the vertical axis. We analyse it is caused by the fact that other factors (such as seawater depth), other than the pycnocline depth and the pycnocline thickness, also affect the phase velocity.

Figure 9. (a) The relationship between the phase velocity and the maximum amplitude of the mode-2 ISWs observed in the study area. (b) The relationship between the wavelength and the maximum amplitude of the mode-2 ISWs observed in the study area, where the black and red crosses denote the ISWs on the survey lines in SW-NE direction and in NE-SW direction, respectively.
3.3 Vertical Structure Characteristics of the Mode-2 ISWs’ Amplitude in Study Area

Observing the vertical structure of the mode-2 ISWs’ amplitude in the study area, it is found that they follow the following characteristics as a whole. The amplitude of ISWs in the upper half of the pycnocline decreases with the increasing seawater depth. The amplitude of ISWs in the lower half of the pycnocline firstly increases and then decreases with the increasing seawater depth (see Figs. 11 and 12 in this paper, Fig. 5 of Fan et al., 2021a, and Fig. 6 of Fan et al., 2021b). Due to the influence of the pycnocline centre deviation on the development of the vertical structure of the ISWs’ amplitude, the vertical structure of the mode-2 ISWs’ amplitude in the study area generally only exhibits part of the characteristics given by the vertical mode function (the amplitude of the ISWs in the upper and lower half of the pycnocline firstly increases and then decreases with the increasing seawater depth, respectively, as shown by the blue and red curves in Figs. 11 and 12). Since the pycnocline centre of most of the mode-2 ISWs observed in the study area deviates upwards, the ISWs structure at the top is not as well developed as the ISWs structure at the bottom. Therefore, the amplitude of ISWs in the upper half of the pycnocline usually decreases with the increasing seawater depth. Figure 11 shows the vertical structure of the amplitude of the 10 mode-2 ISWs ISW1-ISW10 in the survey line L84. The pycnocline centres corresponding to ISW1-ISW7 all deviate upwards (see the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth in Table 1, the positive sign indicates that the pycnocline deviates upward, and the negative sign indicates that the pycnocline deviates downward). Among them, ISW1-ISW4 (Fig. 11a-d) and ISW7 (Fig. 11g) were only picked up one reflection event in upper half of the pycnocline. From ISW6 (Fig. 11f), it can be seen that the amplitude of ISWs in the upper half of the pycnocline decreases with the increasing seawater depth. From ISW2 (Fig. 11b), ISW4 (Fig. 11d), ISW5 (Fig. 11e), and ISW7 (Fig. 11g), it can be clearly seen that the amplitude of ISWs in the lower half of the pycnocline firstly increases and then decreases with the

Figure 10. (a) The relationship between the phase velocity and the pycnocline depth of the mode-2 ISWs observed in the study area, (b) The relationship between the phase velocity and the pycnocline thickness of the mode-2 ISWs observed in the study area, the colour filled the circle indicates the dimensionless amplitude.
increasing seawater depth. The pycnocline centres corresponding to ISW8-ISW10 all slightly deviate downwards (see the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth in Table 1, the positive sign indicates that the pycnocline deviates upward, and the negative sign indicates that the pycnocline deviates downward). From ISW8 (Fig. 11h) and ISW10 (Fig. 11j), it can be seen that the amplitude of ISWs in the upper half of the pycnocline decreases with the increasing seawater depth. Figure 12 shows the vertical structure of the amplitude of the four mode-2 ISWs (ISW11, ISW12, ISW16, and ISW17) in the survey line L74. The pycnocline centres corresponding to ISW11, ISW12, ISW16, and ISW17 significantly deviate downwards (see the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth in Table 2, the positive sign indicates that the pycnocline deviates upward, and the negative sign indicates that the pycnocline deviates downward), which makes the ISWs structure at the top more developed. From ISW11, ISW12, and ISW17 (Fig. 12a, b, d), it can be seen that the amplitude of the ISWs in the upper half of the pycnocline firstly increases and then decreases with the increasing seawater depth.

Figure 11. (a)-(j) respectively demonstrate the vertical structure characteristics of the amplitude of the 10 mode-2 ISWs ISW1-ISW10 in the survey line L84 as well as the vertical mode function fitting results. The black circles denote the observed ISWs’ amplitudes at different depths. The blue curves are the linear vertical mode function (nonlinear correction is not considered), and the red curves are the first-order nonlinear vertical mode function (nonlinear correction is considered).
In order to study the vertical structure of the mode-2 ISWs’ amplitude in more detailed for the study area, we respectively compare the observation result with the linear vertical mode function (nonlinear correction is not considered, the blue curves in Figs. 11 and 12) and the first-order nonlinear vertical mode function (considering nonlinear correction, the red curves in Figs. 11 and 12). The linear vertical mode function can be obtained by solving the eigenvalue equation that satisfies the Taylor-Goldstein problem (Holloway et al., 1999): \( \frac{d^2 \varphi(z)}{dz^2} + \left[ N^2(z) - \omega^2 \right] \frac{1}{C^2} \varphi(z) = 0, \varphi(0) = \varphi(-H) = 0. \) Where \( \varphi(z) \) represents the linear vertical mode function, \( C \) is the linear phase velocity, \( N(z) \) is the Brunt-Väisälä frequency, and \( \omega \) is the wave frequency. The first-order nonlinear vertical mode function is obtained by adding a nonlinear correction term to the linear vertical mode function (Lamb and Yan, 1996), and it can be expressed by \( \varphi_m(z) = \varphi(z) + \eta_0 T(z). \) Where \( \eta_0 \) is the ISWs maximum amplitude in the vertical direction, and \( T(z) \) is the first-order nonlinear correction term. The detailed calculation process is described in Gong et al. (2021). Observing Fig. 11, it can be found that the overall nonlinearity of the ISWs ISW5 (Fig. 11e) and ISW8 (Fig. 11h) on the survey line L84 is relatively strong, and the first-order nonlinear vertical mode function considering nonlinear correction can be used to better fit the vertical structure of the amplitude (the red curves in Fig. 11e, h). The nonlinearity is relatively strong at the bottom of ISW2 (the seawater depth range is 60-80 m in Fig. 11b), the top of ISW7 (the seawater depth range is 40-60 m in Fig. 11g), and the top of ISW10 (the seawater depth is about 40 m...
in Fig. 11j). And the first-order nonlinear vertical mode function considering nonlinear correction can be used to better fit the vertical structure of the amplitude (the red curves in Fig. 11b, g, j). The overall nonlinearity of ISW1 (Fig. 11a), ISW3 (Fig. 11c), ISW6 (Fig. 11f), and ISW9 (Fig. 11i) is relatively weak, and the linear vertical mode function can be used to better fit the vertical structure of the amplitude. The nonlinearity is relatively weak at the top of ISW2 (the seawater depth range is 40-60 m in Fig. 11b), the bottom of ISW7 (the seawater depth range is 60-90 m in Fig. 11g), and the bottom of ISW10 (the seawater depth is below 40 m in Fig. 11j). The linear vertical mode function can be used to better fit the vertical structure of the amplitude (the blue curves in Fig. 11b, g, j). The above analysis reflects that the vertical structure of the mode-2 ISWs’ amplitude in the study area is affected by the nonlinearity degree of the ISWs. Observing Fig. 12, it can be found that neither the linear vertical mode function (without considering nonlinear correction) nor the first-order nonlinear vertical mode function (with consideration of nonlinear correction) can be used to well fit the vertical structure of the amplitude of the ISWs ISW11, ISW12, ISW16, and ISW17 on L74 (especially the position of the upper half of the pycnocline). The ISWs ISW11, ISW12, ISW16, and ISW17 on the survey line L74 have the large downward deviation of the pycnocline centre (see the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth in Table 2, the positive sign indicates that the pycnocline deviates upward, and the negative sign indicates that the pycnocline deviates downward). We observed the fitting result of the vertical amplitude of the ISWs with the large downward pycnocline deviation on other lines of the study area (not shown in this article), and found that the fitting result of the vertical amplitude is usually poorer than that of the ISWs corresponding to the upward deviation of the pycnocline (especially the position of the upper half of the pycnocline). We believe that when the pycnocline centre has the large downward deviation, the vertical mode function (including the linear vertical mode function without considering nonlinear correction and the first-order nonlinear vertical mode function considering nonlinear correction) cannot be used to well fit the vertical structure of the mode-2 ISWs’ amplitude in the study area. The above analysis once again reflects that the pycnocline deviation (especially the downward deviation of the pycnocline) affects the vertical structure of the mode-2 ISWs’ amplitude in the study area.

4 Discussion

As for the relationship between the dimensionless phase velocity and the dimensionless amplitude of the mode-2 ISWs in the study area, as well as the relationship between the dimensionless wavelength and the dimensionless amplitude, both of them are not strictly monotonous in the case of smaller amplitude ($2a/h_2<1$) and show the characteristics of multi-parameter controlling. For this reason, we analysed the influence of seawater depth on the dimensionless phase velocity and dimensionless wavelength of the mode-2 ISWs in the study area. The results are shown in Fig. 13a and b, respectively. Observing Fig. 13a, it can be found that in the shallow seawater (the seafloor depth is less than 120 m) the dimensionless phase velocity variation range is small, and there are both the large-amplitude mode-2 ISWs ($2a/h_2>2$) and the small-amplitude mode-2 ISWs ($2a/h_2<2$). In the deep seawater (or at the shelf break, the seafloor depth is greater than 120 m), the smaller-amplitude mode-2 ISWs ($2a/h_2<1$, dark blue filled circles in Fig. 13a) have a large dimensionless phase velocity...
The maximum dimensionless phase velocity can reach 2.45, and the minimum can reach 0.5. In particular, the smaller dimensionless phase velocities are mainly concentrated in the deep seawater, so that in Fig. 7 when $2a/h_2<1$ the relationship between the dimensionless phase velocity and the dimensionless amplitude of the mode-2 ISWs has the trend given by Kozlov and Makarov (1990). The sharp decrease in the dimensionless phase velocities of the mode-2 ISWs with smaller amplitudes in the deep seawater may be caused by the collision of the ISWs with the seafloor topography (including the step) at the shelf break. In addition, from Fig. 10a and b, it can be found that on the whole, the pycnocline depth and the pycnocline thickness of the larger-amplitude mode-2 ISWs ($2a/h_2>1$) are respectively smaller than the pycnocline depth and the pycnocline thickness of the smaller-amplitude mode-2 ISWs ($2a/h_2<1$). Therefore, the phase velocities of the larger-amplitude mode-2 ISWs ($2a/h_2>1$) are generally smaller than the phase velocities of the smaller-amplitude mode-2 ISWs ($2a/h_2<1$). In Fig. 7 when $2a/h_2>1$, this makes the relationship between the dimensionless phase velocity and the dimensionless amplitude of the mode-2 ISWs is closer to the result predicted by the deep water weakly nonlinear theory (Benjamin, 1967). The above-analysed influences of the seawater depth (seafloor topography), the pycnocline depth and the pycnocline thickness on the mode-2 ISWs phase velocity of the study area have caused the diversity of the relationship between dimensionless phase velocity and dimensionless amplitude. That is, when $2a/h_2<1$, the relationship between the dimensionless phase velocity and the dimensionless amplitude of the observed mode-2 ISWs in the study area has the trends respectively given by Kozlov and Makarov (1990), as well as Salloum et al. (2012). when $2a/h_2>1$, the relationship between the dimensionless phase velocity and the dimensionless amplitude of the observed mode-2 ISWs in the study area is closer to the result predicted by the deep water weakly nonlinear theory (Benjamin, 1967).

Observing Fig. 13b, it can be found that the mode-2 ISWs with the smaller amplitudes ($2a/h_2<1$, the dark blue filled circles in Fig. 13b) have a relatively large variation range of the dimensionless wavelength in the deep seawater (the seafloor depth is greater than 120m). The largest dimensionless wavelength can reach up to 9.55 (corresponding to ISW2 on the survey line L84, whose pycnocline deviation is large and waveform is asymmetric), and the smallest dimensionless wavelength can reach 2.44, so that the dimensionless wavelength of the vertical axis in Fig. 8 can be reduced to 2.44 when $2a/h_2<1$. The sharp decrease in the dimensionless wavelengths of the mode-2 ISWs with the smaller amplitudes ($2a/h_2<1$) in deep seawater may be caused by the collision of the ISWs with the seafloor topography at the shelf break. The sharp increase in dimensionless wavelengths of the mode-2 ISWs with the smaller amplitudes in deep seawater may be related to the waveform asymmetry caused by the pycnocline deviation.
Figure 13. (a) the relationship between the dimensionless phase velocity and the seawater depth of the mode-2 ISWs observed in the study area, the colour of the filled circle indicates the dimensionless amplitude. (b) The relationship between the dimensionless wavelength and the seawater depth of the mode-2 ISWs observed in the study area, the colour of the filled circle indicates the dimensionless amplitude. (c) The relationship between the phase velocity and the seawater depth of the mode-2 ISWs observed in the study area, the colour of the filled circle indicates the maximum amplitude. (d) The relationship between the wavelength and the seawater depth of the mode-2 ISWs observed in the study area, the colour of the filled circle indicates the maximum amplitude.

Fig. 13c and d respectively show the relationship between the phase velocity and the seawater depth, and the relationship between the wavelength and the seawater depth of the mode-2 ISWs in the study area. The colour of the filled circles in the figures represents the maximum amplitude. Observing Fig. 13c, it can be found that the seawater depth in the study area has the great influence on the phase velocity of the mode-2 ISWs. In the shallow seawater area (the seawater depth is less than 120 m), the phase velocity variety range is small. In the deep seawater area (the seawater depth is larger than 120 m) the phase velocity has the large variety range. The maximum phase velocity is 1.52 m/s and the minimum phase velocity is 0.21 m/s. In Fig. 9a, when the maximum amplitude is between 6 m and 11 m, the phase velocity has the larger variety range, and there is the significant increase in the phase velocity. The above phenomenon is controlled by the seawater depth. That is, in the deep seawater area (seawater depth greater than 120 m), for the ISWs with the maximum amplitude of 6-11 m, the phase velocity varies widely, and the maximum phase velocity of 1.52 m/s appears (Fig. 13c). Observing Fig.
13d, it can be found that the seawater depth in the study area has the great influence on the wavelength of the mode-2 ISWs. On the whole, the wavelength of the ISWs increases with the increasing seawater depth. For the ISWs with the maximum amplitude of 7-13 m, a considerable part of them are distributed in the deep seawater area (the seawater depth is larger than 120 m), making their wavelengths increase significantly. As a result, when the maximum amplitude is between 7 m and 13 m in Fig. 9b, there is the significant increase in the wavelength.

5 Conclusions

A regional study of the mode-2 ISWs in the Pacific coast of Central America was carried out by using seismic reflection. Through the analysis of the typical seismic sections L84 and L74, it is found that when the degree of downward pycnocline deviation is large, the influence of pycnocline deviation on the stability of the mode-2 ISWs is more complicated than when the pycnocline deviates upwards. There are mode-2 ISWs with the large degree of downward pycnocline deviation but with the relatively symmetrical waveform.

The observed relationship between the dimensionless phase velocity $U_c/C$ and the dimensionless amplitude $2a/h_2$ of the mode-2 ISWs in the study area was analysed. When $2a/h_2<1$, $U_c/C$ increases with the increasing $2a/h_2$, divided into two parts with different growth rates. When $2a/h_2>1$, $U_c/C$ increases with the increasing $2a/h_2$ at a relatively small growth rate. The observed relationship between the dimensionless wavelength $2\lambda/h_2$ and the dimensionless amplitude $2a/h_2$ of the mode-2 ISWs in the study area was also analysed. When $2a/h_2<1$, $2\lambda/h_2$ decreases with the increasing $2a/h_2$. When $2a/h_2>2$, $2\lambda/h_2$ increases with the increasing $2a/h_2$. As for the relationships between $U_c/C$ and $2a/h_2$, as well as $2\lambda/h_2$ and $2a/h_2$ of the mode-2 ISWs in the study area, both of them show the characteristics of multi-parameter controlling. The influences of the seawater depth (seafloor topography), the pycnocline depth, and the pycnocline thickness on the mode-2 ISWs phase velocity of the study area have caused the diversity of the relationship between $U_c/C$ and $2a/h_2$.

The vertical structure of the mode-2 ISWs’ amplitude in the study area is affected by the nonlinearity degree of the ISWs. Part of the mode-2 ISWs with the strong nonlinearity (or the part with strong nonlinearity of the ISWs in the vertical direction) can use the first-order nonlinear vertical mode function (nonlinear correction is considered) to better fit the vertical structure of the amplitude. The pycnocline deviation (especially the downward deviation of the pycnocline) affects the vertical structure of the mode-2 ISWs’ amplitude in the study area. When the pycnocline centre has the large downward deviation, the vertical mode function cannot be used to well fit the vertical structure of the mode-2 ISWs’ amplitude in the study area.

Author contribution. The concept of this study was developed by Haibin Song and extended upon by all involved. Wenhao Fan implemented the study and performed the analysis with guidance from Haibin Song. Yi Gong, Shun Yang and Kun Zhang collaborated in discussing the results and composing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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