# Characterization of solitary internal waves in the northern Bali waters

*Nuning Jayanti*[1*], *Ashari Wicaksono*[1,3], and *Adi Purwandana*[2]

[1]Study Program of Marine Science, Universitas Trunojoyo Madura, Bangkalan, Indonesia
[2]Research Center for Oceanography-National Research and Innovation Agency (RCO-BRIN), Jakarta, Indonesia
[3]Laboratory of Oceanography, Universitas Trunojoyo Madura, Bangkalan, Indonesia

**Abstract.** Internal solitary wave (ISW) is an underwater wave, formed due to the evolution of internal tides. The presence of breaking ISWs in coastal areas can potentially influence coastal ecosystems through cross-shelf exchange mechanisms. The southern waters of the Kangean Island and the eastern waters of the Madura Island, known also as part of the northern Bali waters, have been an active habitat for ISW propagation. This study aims to identify and characterize ISW which potentially breaking onshore the Southern Kangean Waters (SKW) and the Eastern Madura Waters (EMW) using Sentinel 1 SAR (Synthetic Aperture Radar) imagery. ISW characterization was carried out using the Korteweg-de Vries (KdV) model. The ISW amplitudes which propagate to EMW varies from 1 - 28 m with a propagation speed of 1.60 - 1.98 m/s, while the ISW which propagate to the SKW has an amplitude of 1 - 60 m with a propagation speed of 0.83 to 2.17 m/s. The results show that the ISW propagating to the SKW has stronger amplitude, phase velocity, and horizontal-vertical velocities than the ISW propagating to the EMW. The maximum speed of the horizontal current triggered by ISW leading to the EMW is 0.03 - 0.17 m/s and the vertical velocity 0.11 - 4.53 cm/s; the maximum speed of horizontal velocity leading to the SKW is 0.02 - 1.29 m/s and the maximum speed of the vertical velocity 0.04 - 19.03 cm/s.
Keywords: Internal Solitary Wave, Southern Kangean Waters, Eastern Madura Waters

## 1 Introduction

Various phenomena occur in the ocean, one of which is waves. Generally, waves can be observed on the surface of the water, yet under certain conditions, waves can occur below the sea surface. This phenomenon is known as internal solitary waves (ISW) or internal solitons. ISWs are short-time nonlinear waves that are widely distributed in the global ocean[1]. The velocity propagation of these waves is influenced locally by thermocline layer thickness, and may influenced by climate variability [2]. During their propagation, the waves

* Corresponding authors: ashari.wicaksono@trunojoyo.ac.id, adip003@brin.go.id

maintain their shape and speed despite interacting with other solitons[3]. The direction of ISW propagation is influenced by zonal and meridional current velocities[4]. This waves can change shape and amplitude due to radial dispersion and turbulence dissipation[5]. ISW has larger amplitude and crest length than surface wave [6].

ISWs are formed through the evolution of internal tides which propagate away from the generating site due to non-hydrostatic dispersion[7]. The processes also rely on the combined influence of bathymetry, stratification, and background current flow[8]. These waves are formed due to the interaction between barotropic forces and underwater topography, formed when barotropic tidal currents pass through steep topography, experiencing supercritical conditions[9]. Indonesian seas have complex topography with strong tidal currents that contribute to the formation of solitary internal waves[8].

The existence of ISWs cannot be observed by naked eye as they occur below the sea surface[3]. However, these waves maintain a combination of relationships through non-linear hydrodynamic mechanisms that can be observed and seen from the dark and light bands on the sea surface hence can be observed by satellite imagery[2]. SAR (Synthetic Aperature Radar) imagery, also known as radar, is a remote sensing system composed of active sensors that can reflect microwaves to the earth's surface with wide range of up to 250 km[10], [11]. SAR data can be used to characterize ISW parameters including their amplitude, wavelength, number of solitons in the packet, and wave propagationspeed [11], [12] through image processing analysis [13]. One of the SAR acquisition programs is Sentinel 1, a combination of sentinel 1 A and B images launched by ESA (European Space Agency). Sentinel 1 is composed of C-SAR with medium to high resolution[14]. Sentinel 1 is a SAR image with an active sensor that can scan day and night, and is able to penetrate clouds and is not affected by weather changes[15].

ISW distributes mass and momentum over hundreds of kilometers[16] hence becomes a transport medium for internal tidal energy to the breaking zone, away from the from the generation site. This breaking wave will increase the vertical nutrient flux which later increase the productivity of the pelagic zone[8]. This process also plays a role for local biogeochemical dynamics[7]. It plays a role in transporting sediment, particulate organic matter and contaminants present in the ocean[8], [17], [18]. ISWs jeopardize underwater navigation because they can induce strong currents, and also cause disturbance in seawater sound velocity (related to sonar variability for submarines) and buoyancy structures [19]. The energy of ISW is very large and can blow away the terrain through which it passes[20]. ISWs with a high frequency have a potential to break and affect the biological system around the coastal waters[21], especially in the coastal waters with rich marine biodiversity such as fish, seagrass, and coral reefs.

In the Indonesian seas, ISWs can be observed in several locations [22], one of which in northern Bali waters. The northern Bali waters, i.e. the southern Kangean waters and eastern Madura waters have dense coral reefs ecosystem and can be a potential marine tourism destination[23], [24]. Kangean Waters are a conservation area with 50,000 Ha of existing coral reef cover [25]. The formation of ISW in the northern Bali waters is driven by strong tidal currents and the water stratification the irregular topography over the Nusa Penida Sill[26]. This research aims to identify the characteristics of solitary internal waves through SAR images in the northtern Bali waters. This preliminary study to is particulary intended to characterize physical aspect of ISW which may potentially give benefits or endanger the coastal ecosystems around the the waters.

## 2 Material and Methods

We use satellite images data acquired from the Alaska Satellite Facility (ASF), https://search.asf.alaska.edu/#/[27] .The image used is Sentinel 1 A with dual polarization, which has high resolution. The presence of the ISW was observed for 1 year, i.e. 2022. We inspect two directions of propagation of the wave, i.e., those towards the Southern Kangean Waters (hereinafter ISW-SKW) and those towards the Eastern Madura Waters (hereinafter ISW-EMW) as shown in Figure 1.

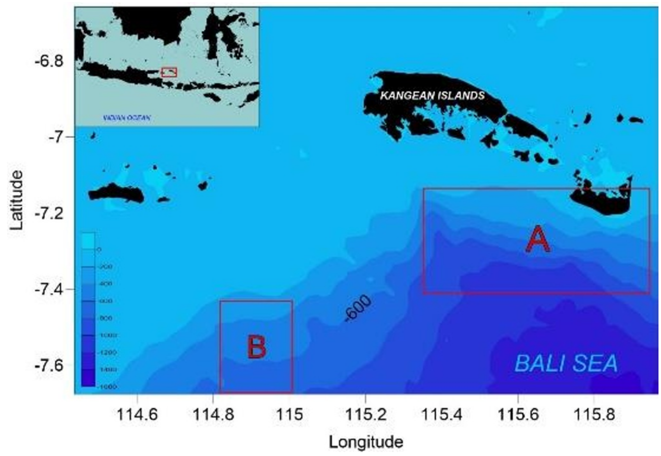


**Figure 1**. Location of ISW occurrence in the northern Bali waters with two directions of propagation of the waves, those towards the Southern Kangean Waters (A, ISW-SKW) and those towards the Eastern Madura Waters (B, ISW-EMW).

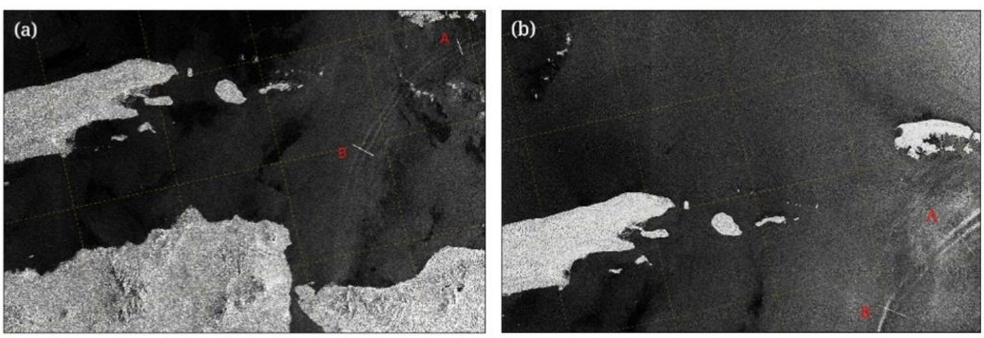


**Figure 2.** The signatures of ISWs events observed in the northern Bali waters on : (a) 3 January 2022 at 22.01 GMT+7 and (b) 30 October 2022 at 22.01 GMT+7. A and B represent the waves analyzed directing towards the Kangean and Madura Islands, respectively.

The appearance of ISW-SKW was clearly observed on January 3, 2022 at 22.01 GMT+7; May 15, 2022 at 22.01 GMT+7; May 19, 2022 at 10.42 GMT+7; October 25, 2022 at 21.53 GMT+7; October 30, 2022 at 22.01 GMT+7; and ISW-EMW were clearly observed on January 3, 2022 at 22.01 GMT+7; May 15, 2022 at 22.01 GMT+7; September 12, 2022 at 22.01 GMT+7; October 30, 2022 at 22:01 GMT+7. The SAR datasets analyzed in this study are shown in Table 1.

**Table 1.** Six SAR images analyzed in this study.

| No | Day/ Month/ Year | Number of waves in the packet | Propagation direction |
|---|---|---|---|
| 1 | 3 January 2022 | 2 | to Madura |
| | | 2 | to Kangean |
| 2 | 15 May 2022 | 1 | to Madura |
| | | 2 | to Kangean |
| 3 | 19 May 2022 | 4 | to Kangean |
| 4 | 12 September 2022 | 2 | to Madura |
| 5 | 25 October 2022 | 2 | to Kangean |
| 6 | 30 October 2022 | 1 | to Madura |
| | | 2 | to Kangean |

Considering the direction of ISWs observed from SAR images as shown in Figure 1, we assume that the observed waves were formed through the evolution of internal tides generated in the Lombok Strait, i.e. above the Nusa Penida Sill.

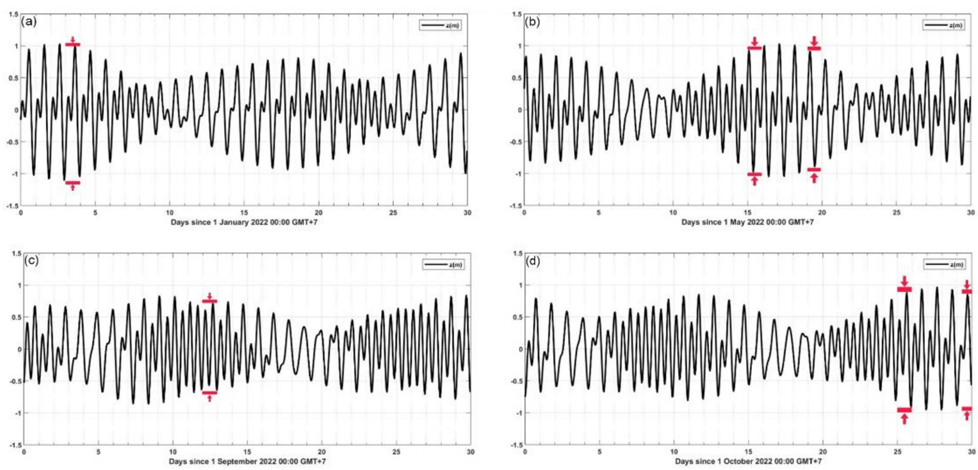


**Figure 3.** Tidal height prediction in the Lombok Strait above the Nusa Penida Sill (8.5484 ºS; 115.8024 ºE) derived from Oregon State University Tidal model in : (a) January 2022 (b) May 2022 (c) September 2022 (d) October 2022. Red marks indicate the timing of ISW appearances in six SAR images analyzed in this study.

The ISW characterization needs an information regarding the hydrography conditions during the passage. The hydrography (temperature and salinity) profile is obtained from Hybrid Coordinate Ocean Model (HYCOM), downloaded at https://ncss.hycom.org/thredds/catalog.html[28]. The HYCOM datasets have spatial resolution of 1/12º (~9 km).

We employ the Korteweg-de Vries (KdV) equation to characterize the wave as it is known as the soliton solution[22]. The ISW is composed following the classical *sech* solution of the KdV equation where the nonlinear and dispersive terms define the waveform. The KdV equation according[12] is defined as,

$$\frac{\partial \eta}{\partial t} + Co\frac{\partial \eta}{\partial x} + \alpha\eta\frac{\partial \eta}{\partial x} + \beta\frac{\partial^3 \eta}{\partial^3 x} = 0 \quad (1)$$

$\eta$ (x,t) is the maximum isopycnal displacement vertically, *x* = distance and *t* = time.

The classical solution of the KdV equation is,

$$\eta = \eta_o sech^2 \left[ \frac{\left(Co+\frac{\alpha\eta_o}{3}\right)(t_o-t)}{\Delta} \right] \tag{2}$$

$Co + \frac{\alpha\eta_o}{3}$ is the phase velocity of the solitary wave or symbolized as *Cp*; $C_o$ is the linear mode-1 phase velocity which is a function of the density gradient and the thickness of the top-bottom layer separated by the pynocline layer[22]; $\eta_o$ is the ISW amplitude, defined as the bright-dark signature observed in the SAR image [22], [29],

$$\eta_o = \frac{12\beta}{\alpha\Delta^2} = 1.32^2 \frac{12\beta}{\alpha D^2} \tag{3}$$

*D* is the distance between the dark and light peaks in the SAR image; Δ is half-width of the wave; $1.32^2$ is the balance constant derived empirically from previous study. The *D* parameter is inferred from pixel analysis from the SAR image as shown in Figure 4. For example, SKW-ISW on May 19, 2022 generated 4 wave packets with distances *D1*, *D2*, *D3* and *D4* of 866 m, 672 m, 631 m and 682 m respectively. Meanwhile, the EMW-ISW on January 3, 2022 produced 2 wave packets with a distance of D1 of 1.910 m and D2 of 1.163 m.

The parameter $\alpha$ as the nonlinear coefficient and $\beta$ as the dispersion coefficient are defined as,

$$\alpha = \left(\frac{3}{2}\right) \frac{\int_{-H}^{o}(C_1-U)^2(d\emptyset/dz)^3dz}{\int_{-H}^{o}(C_1-U)(d\emptyset/dz)^2dz} dz \tag{4}$$

$$\beta = \left(\frac{1}{2}\right) \frac{\int_{-H}^{o}(C_1-U)^2\emptyset^2dz}{\int_{-H}^{o}(C_1-U)(d\emptyset/dz)^2dz} dz \tag{5}$$

*U* is the background current, and has been ignored in this study as the current dataset is not available at HYCOM. ISW drives both vertical and horizontal currents. The zonal current (*U*) and meridional current (*w*) are defined as [22], [30] :

$$U = Cp \frac{d\emptyset}{dz} sech^2 \left[ \frac{\left(C_1+\frac{\alpha\eta_o}{3}\right)(t_o-t)}{\Delta} \right] \tag{6}$$

$$w = \frac{d\eta}{dt} \tag{7}$$

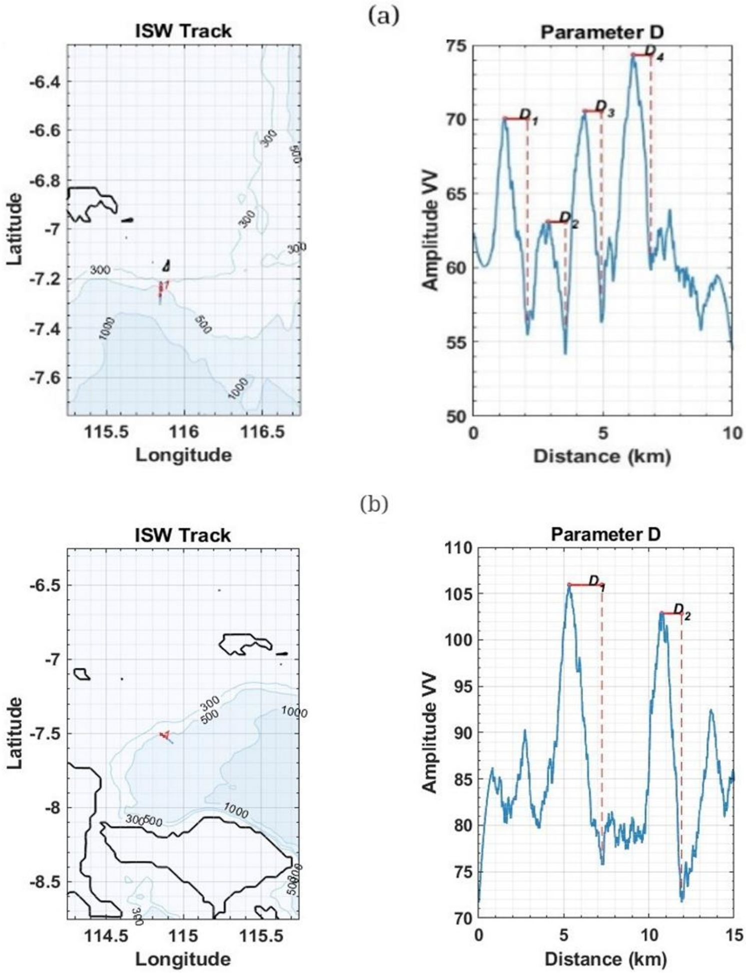


**Figure 4.** The ISWs track and *D* parameter: (a) directing towards the Southern Kangean Waters (SKW) on May 19, 2022 and (b) Eastern Madura Waters (EMW) on January 3, 2022.

## 3 Result and Discussion

The ISWs in the northern Bali waters analyzed in this study are categorized based on the direction of their propagation, as shown Table 2. The waves were suggested to break onshore of the southern Kangean waters (SKW) and eastern Madura waters (EMW).

**Table 2.** Characteristics of ISWS heading to the southern Kangean waters and eastern Madura waters.

| *Category* | *Date* | *Wave Order* | $\alpha$ *(s)* | $\beta$ *(m/s)* | *D* (m) | $\eta_o$ *(m)* | *Cp* *(m/s)* | $\Delta$ *(m)* | $U_{max}$ *(m/s)* | $w_{max}$ *(cm/s)* |
|---|---|---|---|---|---|---|---|---|---|---|
| *Heading to Madura Island* | 3/1/2022 | *D1* | $8.48\times10^{-3}$ | $1.19\times10^{4}$ | 1910 | 8.0 | 1.61 | 1447 | 0.13 | 0.69 |
| | | *D2* | $1.05\times10^{-2}$ | $1.91\times10^{4}$ | 1163 | 28.2 | 1.84 | 881 | 0.48 | 4.53 |
| | 15/5/2022 | *D1* | $1.31\times10^{-2}$ | $9.21\times10^{3}$ | 2800 | 1.9 | 1.68 | 2121 | 0.04 | 0.11 |
| | 12/9/2022 | *D1* | $1.36\times10^{-2}$ | $1.78\times10^{4}$ | 3074 | 2.9 | 1.75 | 2329 | 0.05 | 0.17 |
| | | *D2* | $1.47\times10^{-2}$ | $2.53\times10^{4}$ | 2844 | 4.4 | 1.86 | 2155 | 0.08 | 0.29 |
| | 30/10/2022 | *D1* | $1.38\times10^{-2}$ | $3.62\times10^{4}$ | 2295 | 10.4 | 1.98 | 1739 | 0.17 | 0.91 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 3/1/2022 | *D1* | 2.03×10⁻³ | 9.11×10² | 470 | 42.4 | 0.83 | 356 | 0.70 | 7.63 |
| | | *D2* | 5.90×10⁻³ | 3.73×10³ | 1145 | 10.1 | 1.23 | 867 | 0.17 | 1.10 |
| | 15/5/2022 | *D1* | 8.62×10⁻³ | 4.07×10³ | 3051 | 1.1 | 1.36 | 2311 | 0.02 | 0.05 |
| | | *D2* | 1.34×10⁻² | 1.20×10⁴ | 2820 | 2.4 | 1.71 | 2137 | 0.05 | 0.15 |
| *Heading to Kangean Island* | 19/5/2022 | *D1* | 1.20×10⁻² | 8.18×10³ | 866 | 19.0 | 1.56 | 656 | 0.37 | 3.49 |
| | | *D2* | 1.20×10⁻² | 8.18×10³ | 672 | 31.6 | 1.61 | 509 | 0.63 | 7.69 |
| | | *D3* | 1.20×10⁻² | 8.18×10³ | 631 | 35.8 | 1.63 | 478 | 0.72 | 9.37 |
| | | *D4* | 1.42×10⁻² | 1.91×10⁴ | 682 | 60.6 | 2.11 | 517 | 1.30 | 19.04 |
| | 25/10/2022 | *D1* | 1.05×10⁻² | 1.17×10⁴ | 2571 | 3.5 | 1.61 | 1948 | 0.06 | 0.22 |
| | | *D2* | 1.41×10⁻² | 3.60×10⁴ | 1551 | 22.2 | 2.05 | 1175 | 0.38 | 2.97 |
| | 30/10/2022 | *D1* | 1.49×10⁻² | 4.72×10⁴ | 2457 | 11.0 | 2.10 | 1861 | 0.18 | 0.95 |
| | | *D2* | 1.54×10⁻² | 5.86×10⁴ | 2528 | 12.4 | 2.18 | 1915 | 0.21 | 1.09 |

### 3.1 Underwater characteristics of the ISW

#### *3.1.1 ISW propagating towards the Southern Kangean Waters (SKW)*

The highest amplitude of SKW-ISW was observed on May 19, 2022, i.e. the 4th wave order. It has an amplitude of 60.6 m, and the 3rd wave order has an amplitude height of 35.8 m (Figure 5). As shown in Figure 4a, the SAR image on May 19, 2022 contained amount four solitary waves in the packet, propagating towards the southern waters of the Kangean Island.

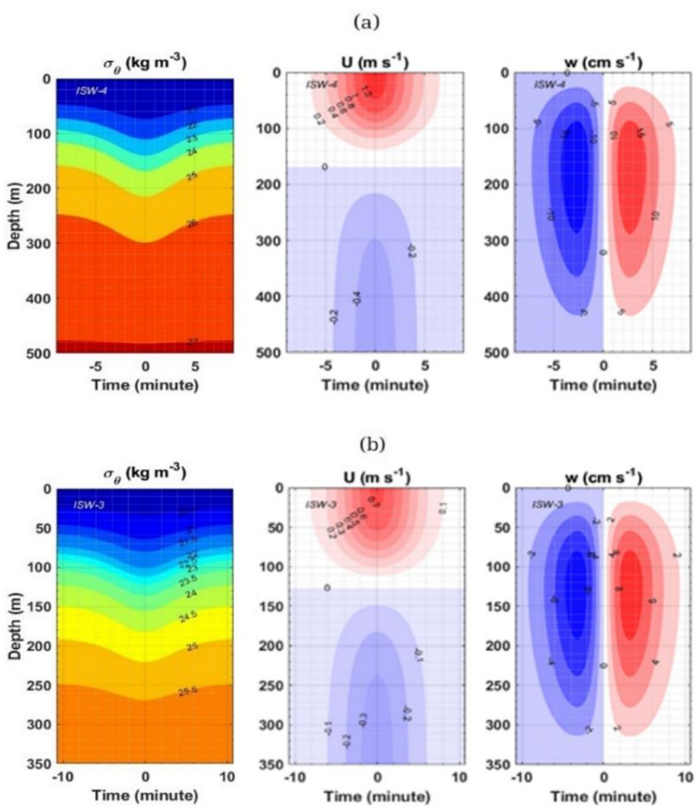

**Figure 5.** SKW-ISW with highest amplitude on May 19 2022: (a) 4th wave order, and (b) 3rd wave order. $\sigma$ is the density perturbation during the passage of the wave, $U$ is the horizontal velocity, and $w$ is the vertical velocity.

On May 19, 2022, the 4th order of the waves of the SKW-ISW has an amplitude of 60.6 m with the phase velocities of 2.11 m/s and half-width of 517 m. The horizontal current extension reached 140 m depth, with the core velocity was located at 50 m depth, and maximum velocity ($U_{max}$) reaching 1.30 m/s (Figure 5a, the middle panel). The vertical current reaches a depth of 430 m, with a maximum vertical velocity ($w_{max}$) of 19.04 cm/s (Figure 5a, the rightmost panel).

The 3rd order of the waves has an amplitude of 35.8 m with the phase velocities of 1.63 m/s and half-widths of 478 m. The horizontal current extension reached a depth of 110 m, with the core velocity located at 25 m depth, with maximum horizontal velocity ($U_{max}$) of 0.72 m/s (Figure 5b, the middle panel). The vertical current reaches a depth of 315 m, with a maximum vertical velocity ($w_{max}$) of 9.37 cm/s (Figure 5b, the rightmost panel). The decreasing amplitude (the 4th order of the waves is higher than the 3rd order) is related to shallowing topography issue towards onshore region. As shown in Figure 3, such high amplitude is likely related also to the spring tide period above the Nusa Penida Sill. The spring tide period encouraged the generation of strong internal tides that triggered the formation of high amplitude ISW.

### *3.1.2 ISW propagating towards the Eastern Madura Waters (EMW)*

The highest amplitude of EMW-ISW was observed on January 3, 2022 in the 2nd order of the wave with an amplitude of 28.2 meters. The wave packet contains two solitary waves (Figure 4b). The 2nd order of the wave has an amplitude of 28.2 m with phase velocity of 1.84 m/s and the half-widths of 881 m. The horizontal current extended to 150 m depth, with the core velocity located at 60 m depth with the maximum horizontal current velocity ($U_{max}$) of 0.48 m/s (Figure 6b). The vertical velocity reached 440 m depth, with the maximum velocity ($w_{max}$) of 4.53 cm/s (Figure 6c).

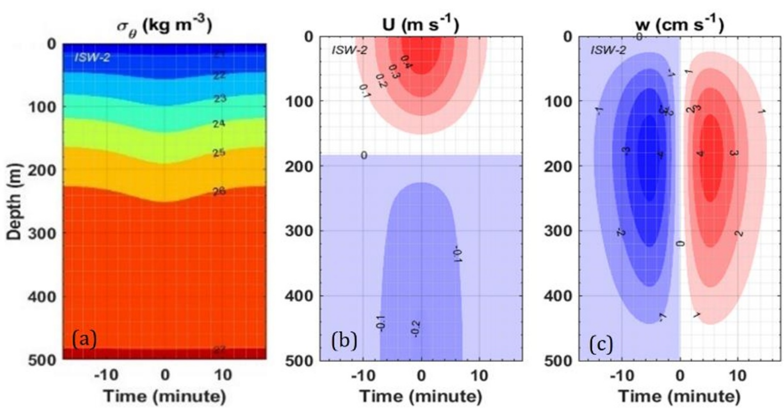


**Figure 6.** EMW-ISW with the highest amplitude on January 3 2022 for the 2nd wave order: (a) $\sigma$ is the density perturbation during the passage of the wave, $U$ is the horizontal velocity, and $w$ is the vertical velocity.

As shown in Figure 3a, the waves observed on January 3, 2022 was observed during the spring tide period. Therefore, the high amplitude ISW observed was the typical highest amplitude in this region. We also identify a typical decreasing amplitude of the EMW-ISW from 28.2 m to 8.0 m. We suggest that it is related to the decreasing stage of the wave propagation. This might be due to the decreasing topographic depth and possibly the influence background current, and energy dissipation which reduce the wave amplitude (~energy).

### 3.2 Discussion

The waves observed in this study is strongly suggested to be the waves formed by the internal tides generated above the Nusa Penida Sill of the Lombok Strait. This can be indicated from circular patterns of the wave's signatures shown in the SAR images. In general, the ISWs observed in this study were formed during the spring tide period, with typical highest amplitudes were found during the peak period of the spring tide.

The low amplitude of the ISWs can be caused due to the waves were entering the decreasing stages of the propagation, possibly related to the shallowing topography, the influence of the background current, and also the energy dissipations (loss) during the propagation. The wave observed on May 15, 2022 for example, produced only a low amplitude of 1.9 m. The similar case was also observed on September 12, 2022, the ISW amplitude was less than 5 m; the SKW-ISW on May 15, 2022 which produced an amplitude of <3 m; on October 25, 2022 which also produced the 1$^{st}$ wave amplitude of 3.5 m.

The highest amplitude for SKW-ISW observed on May 19, 2022 of 60.6 and 35.8 m with phase speed of 2.11 m/s and 1.63 m/s; and the SKW-ISW observed on January 3, 2022 of 42.4 m with a phase speed of 0.83 m/s are comparable or slightly higher than the research conducted previously by Purwandana et al., 2023 [19] which obtained amplitudes of 45, 35, 30, and 25 m and average phase speed of 1.8 m/s in the same waters. This underwater characteristic study highlights that ISW events can have a significant dynamic impact, not only in the upper layers but also in the deeper layers.

## 4 Conclusions

Based on the analysis conducted using sentinel 1 A images and the KdV equation, significant internal wave amplitudes were found in the southern Kangean waters, occurred mainly during the spring tide period. This value is greater than the ISW found in the Eastern Madura Waters area. The ISWs observed is mostly generated by the Lombok Strait internal tides. Unfortunately, we neglected the influence of background currents and also possibly the impact of winds variability which may contribute to noisy features in the SAR image hence lowering the accuracy of the *D* parameter. We left this for further investigation in the future.

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