Study of Internal Solitary Waves Characteristics Using Synthetic Aperture Radar Imagery and The Korteweg-de Vries Numerical Model in the Southern Andaman Sea

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Abstract Internal solitary waves (ISWs) are energetic nonlinear phenomena that strongly influence ocean mixing and circulation. internal solitary waves (ISWs) generated are by the transformation of internal tides as they interact with complex seafloor topography, leading to intense vertical mixing and influencing subsurface transport processes. This study examines ISWs in the Southern Andaman Sea through the integration of Sentinel-1 Synthetic Aperture Radar (SAR) imagery and the Korteweg-de Vries (KdV) numerical model. SAR analysis on 31 January 2018 identified six soliton packets with alternating bright–dark band patterns, propagating east–southeast from the 500–1000 m bathymetric contours. Surface signatures revealed stronger backscatter in the leading soliton and gradual attenuation downstream. Numerical simulations based on hydrographic data confirmed substantial isopycnal displacement and high energy concentration in the leading soliton, with amplitudes up to ~138 m, stable phase speed of ~2.9 m/s, and kinetic energy dominance (KE/APE ratio > 14). Both approaches consistently indicated energy dissipation, manifested in reduced amplitude, velocity, and soliton strength during propagation. By combining SAR observations with KdV modelling, this study provides spatial and quantitative insights into ISW dynamics. The results establish the Southern Andaman Sea as a hotspot for large ISWs and underline implications for navigation safety, fisheries, and offshore structures.

Keywords: Andaman Sea, Internal Solitary Waves, Korteweg-de Vries, SAR

Introduction

Internal solitary waves are nonlinear gravity waves that propagate along the pycnocline and are able to maintain their shape and speed during propagation (Febriano, 2014). Internal solitary waves are formed through the evolution of internal tides that propagate away from the generation area due to non-hydrostatic dispersion (Jayanti *et al*., 2024; Putra *et al*., 2024). Internal tides are generated when barotropic tidal currents interact with steep topography. This process depends on the combined influence of bathymetry, stratification, and current flow. Their formation mechanism involves water mass interaction, the weakening of lee waves under critical conditions, and nonlinear steepening (Purwandana *et al*., 2023). This phenomenon causes displacement of isopycnal layers and generates strong local currents, thereby enhancing turbulent mixing in the water column. Its impacts include sediment transport, nutrient distribution, and interactions between the surface and deeper layers. In addition, the presence of ISWs needs to be considered in fisheries activities and navigation safety (Huang *et al*., 2024; Putra *et al*., 2024; Purwandana and Cuypers, 2023).

Indonesian waters are one of the hotspots for Internal Solitary Wave generation (Chonnaniyah *et al*., 2021; Purwandana, 2024; Purwandana and Cuypers, 2023; Putra *et al*., 2024; Prasetya *et al*., 2021). The Andaman Sea is one of the regions with the highest ISW generation in the world. The Andaman Sea borders Myanmar, Thailand, Malaysia, and Indonesia (Kiran, 2017). Its distinctive characteristics include steep seafloor topography, a persistent pycnocline, and large-amplitude internal tides (Sun *et al*., 2024; Mohanty *et al*., 2018). The interaction of barotropic currents with seafloor morphology triggers disturbances in density stratification, producing ISWs that propagate along the pycnocline.

Internal solitary waves can be identified using satellite imagery (Karang *et al*., 2019; Huang *et al*., 2024). Bright and dark band patterns in Synthetic Aperture Radar (SAR) imagery are formed due to variations in sea surface roughness (Chonnaniyah *et al*., 2021; Tao *et al*., 2022). However, SAR technology only captures surface information, which is insufficient to describe the vertical dynamics of ISWs. The study by Prasetya *et al*. (2021) demonstrated that visualisation of internal solitary waves is still limited to surface pattern observation using SAR imagery. However, this research focused on surface pattern detection and has not presented quantitative analysis of physical wave parameters such as amplitude, propagation speed, nonlinearity coefficient, and dispersion coefficient.

This study aims to examine the characteristics and dynamics of internal solitary waves in the southern Andaman Sea through the integration of Sentinel-1 SAR imagery analysis and numerical modelling using the Korteweg–de Vries (KdV) equation. The results of this study are expected to provide information on the propagation characteristics of internal solitary waves through SAR imagery analysis and the vertical structure of internal solitary waves in the southern Andaman Sea using the Korteweg–de Vries numerical model.

[Literature Review]

Internal solitary waves are subsurface ocean phenomena generated are by density stratification, where variations in temperature and salinity create distinct water layers. A specific non-linear type, the internal solitary wave (ISW) or soliton, is notable for its ability to propagate whilst maintaining its shape and velocity (Chen *et al*., 2019). The Indonesian seas, with their complex topography and strong tidal currents, provide ideal conditions for the powerful generation of internal tides that evolve into ISWs (Purwandana, 2024). These waves represent the principal mechanism for transporting energy away from their generation sites. ISWs form primarily through two processes, namely non-linear steepening or the release of lee waves under supercritical conditions, although they may also form in estuaries from the collision of water masses (Li and Li, 2024). The dominant mechanism is determined by the Froude number, values close to unity indicating a lee wave origin (Purwandana *et al*., 2023). The transformation of internal tides is central to ISW generation when barotropic tidal currents encounter irregular seafloor topography such as ridges, sills, seamounts, and continental slopes. It is further explained by Huang *et al*. (2024) how barotropic tidal flows passing over topographic features transform into internal wave energy that generates large-amplitude internal waves within the stratified water column. These initially sinusoidal waves undergo nonlinear steepening during propagation and evolve into solitary wave forms.

The Indonesian archipelago has emerged as one of the most dynamic regions for ISW activity due to its bathymetry condition and numerous narrow straits that connect major ocean basins (Purwandana, 2024; Purwandana and Cuypers, 2023; Zhao *et al*., 2021). Furthermore, Jayanti *et al*. (2024) identified exceptionally large-amplitude ISWs reaching 60 m in northern Balinese waters particularly within the Southern Kangean and Eastern Madura regions, highlighting the variability of ISW characteristics across Indonesian seas. Moreover, Putra *et al*. (2024) further traced propagation pathways from the Ombai Strait through the Flores Sea toward Bone Bay and showed that these waves can maintain connectivity across entire basins. These studies establish Indonesian waters as hosts to some of the most energetic ISW systems globally with high implications for oceanographic processes.

The Andaman Sea represents one of the most active generation sites for ISWs worldwide (Tao *et al.*, 2022; Kiran, 2017). The Andaman Sea was identified by Sun *et al*. (2024) as a hotspot where bathymetry and strong tidal interactions with submarine ridges foster pronounced spatial and temporal variability in ISW amplitude and wavelength. The southwest monsoon season produces the most energetic activity, while associated mixing redistributes nutrients and enhances productivity in the water column. Additionally, Huang *et al*. (2024) provided complementary insights by analysing 230 MODIS images (2020–2023) together with MIT general circulation model simulations. They identified two distinct ISW types, which are southeastward-propagating waves (type-SE) from the Preparis South Channel sill and southwestward-propagating waves (type-SW) from the eastern shelf break. Occurrence patterns showed strong correlation with semidiurnal tidal phases and were limited to narrow slack tide windows. Numerical simulations confirmed that both wave types resulted from non-linear steepening of internal tidal waves with background currents modulating their generation.

Prasetya *et al*. (2021) examined ISWs in the southern Andaman Sea near Weh and Breueh Islands using Sentinel-1A imagery (January-May 2018) in combination with CROCO numerical modelling. Satellite observations revealed distinct wave packets with alternating surface roughness, documenting up to 31 solitons with wavelengths of 9–163 km and inter-packet distances of 60–80 km. The primary generation mechanism was attributed to the Breueh submarine ridge, where semidiurnal M2 barotropic tidal currents reaching 5 m/s disrupted stratification and induced pycnocline depressions. ISW activity peaked during March–April, coinciding with weakened monsoonal winds, enhanced thermal stratification, and modulation by the Indian Ocean Kelvin wave. Numerical simulations displayed alternating northeastward flood and southwestward ebb flows, with vertical velocity anomalies of –0.5 m/s above the ridge indicating uplifted water masses. Model validation against tidal observations demonstrated a high correlation ($r \approx 0.90$). These findings confirm that ISW formation in the Andaman Sea is driven by the combined effects of tidal forcing, steep topography, and stratification.

Satellite remote sensing provides a complementary perspective by capturing the surface signatures of ISWs (Zhang *et al*., 2023). Synthetic Aperture Radar (SAR) has revolutionized

ISW observation by detecting radar backscatter variations associated with surface roughness modulation (Peng *et al*., 2023). However, Magalhães *et al*. (2021) found that conventional Bragg scattering theories were insufficient to explain strong radar signals, attributing them instead to surface wave breaking which produces an additional non-polarised scattering mechanism. This phenomenon was further confirmed by their analysis of altimeter data, which revealed a sharp increase in significant wave height (SWH) followed by a decrease, signifying energy dissipation. From a practical standpoint, Chonnaniyah *et al*. (2021) employed a synergy of Sentinel-1 SAR and Himawari-8 optical imagery to estimate ISW propagation speed in the Lombok Strait. Their findings showed that wave speed decreased markedly as ISWs travelled from deep to shallower waters. Quantitatively, the speed dropped from approximately 2.69 m/s in the strait to 1.30 m/s in the northern area, a consistent decrease directly linked to the region's bathymetric variations. Collectively, these two studies demonstrate the range of satellite technology applications for ISWs, spanning investigations of imaging physics to practical assessments of wave dynamics.

The efficacy of Korteweg–de Vries (KdV) modelling for ISW simulation is evidenced in studies that apply the framework to explore ISW dynamics across different seas. The Korteweg–de Vries (KdV) equation provides a theoretical framework for resolving the vertical structure and nonlinear evolution of internal solitary waves (Wang *et al*., 2025; Karang *et al*., 2019; Febriano, 2014). The approach begins with hydrographic observations of temperature and salinity profiles which define the vertical density stratification and the depth of the pycnocline. From these profiles, Jayanti *et al*. (2024) derive the nonlinear coefficient (α) and the dispersion coefficient (β) that quantify the balance between steepening and dispersive spreading in northern Bali waters. Substitution of these coefficients into the KdV formulation yields analytical solutions from which wave parameters can be determined. In the Flores Sea, Putra *et al*. (2024) investigated ISW evolution and shoaling using SAR imagery and hydroacoustic measurements, documenting propagation from Ombai Strait towards Bone Bay with amplitude reduction and breaking consistent with KdV non-linear frameworks under topographic constraints. Furthermore, Vasavi *et al*. (2021) developed a hybrid approach that integrates U-Net deep learning segmentation with KdV solvers for automated ISW detection and modelling. This method extracted wave parameters from SAR imagery and generated velocity–density fields through KdV equations, establishing a robust framework linking satellite observations with non-linear wave theory. Previous work in the Andaman Sea has therefore mostly adopted fragmented approaches, where SAR observations detect surface manifestations, hydrodynamic numerical models explore generation processes, and KdV theories are examined in isolation. To date, no study has explicitly integrated KdV modelling with SAR observations in this region. Research in other Indonesian seas by Purwandana and Cuypers (2023) has, however, demonstrated the advantages of combining satellite remote sensing with numerical modelling to capture ISW dynamics more comprehensively.

Methodology

Study Area

This study was conducted in the southern Andaman Sea, specifically off the northwestern coast of Sumatra, and administratively located around We Island and Breueh Island, Aceh Province, Indonesia, within the geographic coordinates of 5°29'48.0" to 6°19'15.3" N and 94°26'07.8" to 95°16'15.7" E shown in Figure 1. (Prasetya *et al.*, 2021; Mohanty *et al.*, 2018).

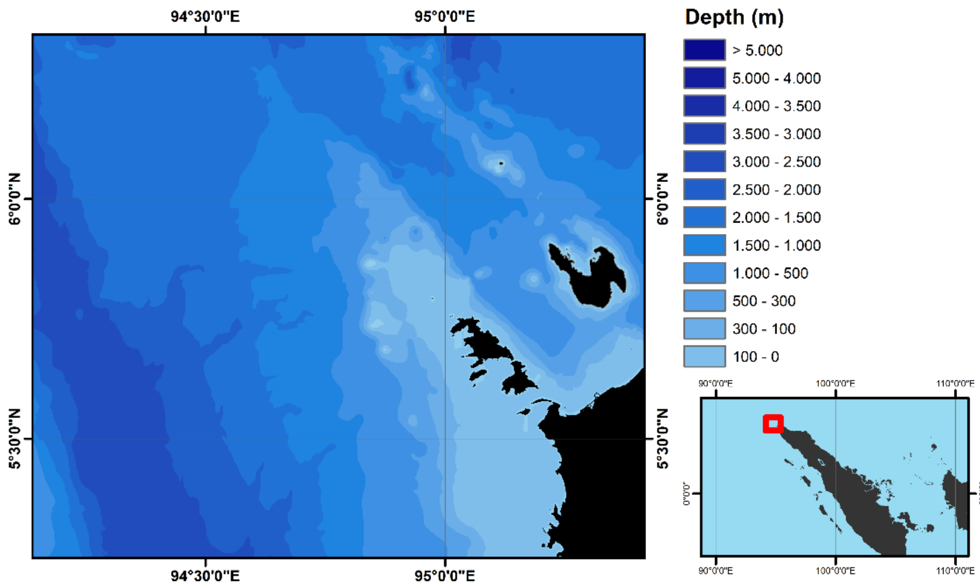


Figure 1: Location map of the Southern Andaman Sea study area, showing the positions of Weh and Breueh Islands off northwestern Sumatra, with bathymetric contours highlighting potential ISW generation zones.

Data

The data used in this research consists of Sentinel-1A Synthetic Aperture Radar (SAR) satellite images from the website *https://search.asf.alaska.edu/#/* (Chonnaniyah *et al.*, 2021; Tao *et al.*, 2022), with Interferometric Wide Swath (IW) mode, Ground Range Detected (GRD) product, and single VV polarization, as well as hydrographic data from the Hybrid Coordinate Ocean Model (HYCOM) downloaded from the website *https://www.hycom.org/* , which includes information on depth, temperature, salinity, eastward water velocity, and northward water velocity (Purwandana and Cuypers, 2023).

The Sentinel-1 SAR image acquired on 31 January 2018 revealed alternating bright and dark surface roughness bands, which are typical indicators of internal solitary waves. These features, shown in Figure 2, formed the basis for subsequent transect analysis.

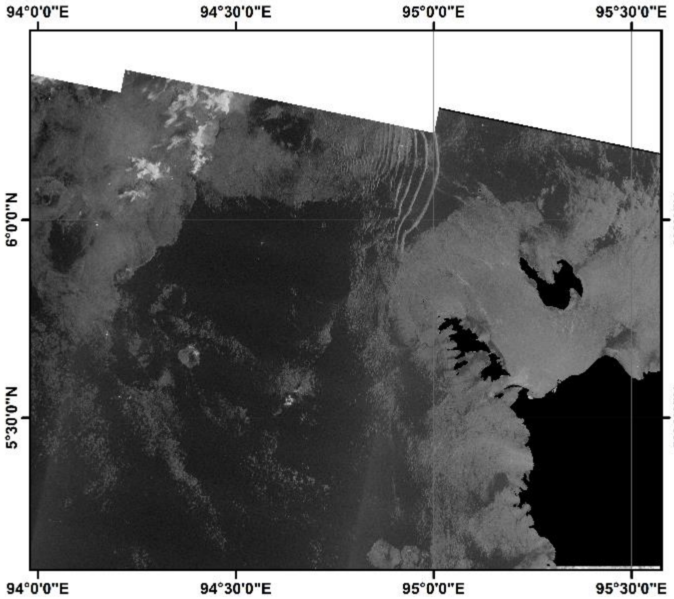


Figure 2: Sentinel-1 SAR imagery acquired on 31 Januari 2018, showing alternating bright and dark patterns indicative of internal solitary waves propagation in the Southern Andaman Sea.

SAR Image Processing

SAR image processing was carried out using the Sentinel Application Platform (SNAP) through the following steps: radiometric calibration to correct backscatter values, speckle filtering using the Lee Sigma algorithm to reduce granular noise, terrain correction via Range-Doppler methodology to eliminate geometric distortions, conversion of backscatter values to decibel (dB) scale, transect analysis to identify wave signatures, and calculation of the D parameter. Parameter D represents the spatial distance between bright and dark bands indicative of ISWs which is expressed as $\Delta^2 = \frac{12}{(\alpha\eta_0)}$ (Peng *et al*., 2023; Magalhães *et al*., 2021).

Numerical Modelling

Numerical wave modelling was conducted using the Korteweg-de Vries (KdV) equation approach, which is employed to describe the dynamics of ISWs propagation (Huang *et al*., 2023; Karang *et al*., 2019):

$$\frac{\partial\eta}{\partial t} + c\frac{\partial\eta}{\partial x} + \alpha\eta\frac{\partial\eta}{\partial x} + \beta\frac{\partial^3\eta}{\partial^3 x} = 0$$

The solution to the KdV equation shows that the profile and stability of solitary waves are determined by the balance of nonlinearity and dispersion in the density stratified medium (Vasavi *et al*., 2021). The classical solution of the KdV equation is as follows:

$$\eta = \eta_0 sech^2\left[\frac{\left(c + \frac{\alpha\eta_0}{3}\right)(t_0 - t)}{\Delta}\right]$$

where η(x,t) is the amplitude of the wave disturbance, c is the mode-1 wave speed. The value η_0 represents the wave amplitude, the phase speed (C_p) or the propagation speed of the wave is expressed as $\left(c + \frac{\alpha\eta_0}{3}\right)$. The width of the wave can be estimated as Δ2=120. The nonlinearity parameter (α), dispersion (β) are calculated based on the ocean density stratification profile (Purwandana *et al*., 2023). It can be expressed as:

$$\alpha = \left(\frac{3}{2}\right)\frac{\int_{-H}^{0}(c-U)^2\left(\frac{d\Phi}{dz}\right)^3 dz}{\int_{-H}^{0}(c-U)\left(\frac{d\Phi}{dz}\right)^2 dz}\ dz$$

$$\beta = \left(\frac{1}{2}\right)\frac{\int_{-H}^{0}(c-U)^2\Phi^3 dz}{\int_{-H}^{0}(c-U)\left(\frac{d\Phi}{dz}\right)^2 dz}\ dz$$

η_0 is determined based on a rough estimate of wave height obtained from the observed image pattern. The vertical mode-1 structure of vertical displacement is denoted as Φ(z), calculated using the ocean density stratification profile expressed as $N^2(z)$ (Li and Li, 2024).The wave amplitude is obtained from image observation results, then analysed using Ocean Data View (ODV) and SOLITON 2.0 software to produce visualisation and estimation of wave parameters such as width, energy, and propagation speed.

Internal solitary waves (ISWs) generate both vertical and horizontal flows (Jayanti *et al*., 2024). The zonal current (*U*) and meridional current (*w*) are expressed following:

$$U = Cp\frac{d\Phi}{dz}sech^2\left[\frac{\left(c + \frac{\alpha\eta_0}{3}\right)(t_0 - t)}{\Delta}\right]$$

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

Energetics of Internal Solitary Waves

The wave's energetic characteristics were determined from the density disturbances generated by the ISW and the current fields. The total energy of an ISW consists of both available potential energy (APE) and kinetic energy (KE). The APE per unit length was calculated by integrating across the vertical and horizontal range of the ISW as:

$$APE = \int_{-L}^{L}\int_{-H}^{0}\int_{0}^{\eta(z)}\rho(z)N^2(z')z'dz'dzdx$$

$$KE = \frac{1}{2}\int_{H}^{0}\int_{-L}^{L}\rho(u^2 + w^2)dxdz$$

Hydrographic data from HYCOM were processed by extracting temperature, salinity, eastward water velocity, and northward water velocity profiles corresponding to the SAR acquisition time and location. From these profiles, seawater density was calculated, and the pycnocline layer was identified (Wang *et al*., 2025). Stratification analysis and Richardson Number calculations were conducted to assess water column stability. These results were then used as input parameters for the KdV model (Putra *et al*., 2024).

The research integrates SAR-derived observations with hydrographic modelling to validate the characteristics of internal solitary waves (Chonnaniyah *et al*., 2021). Validation was achieved by comparing spatial parameters extracted from SAR imagery (Parameter D) with numerical outputs (amplitude, speed, and energy), providing a comprehensive understanding of ISW dynamics in the study region (Peng *et al*., 2023).

Results and Discussion

ISW Detection from SAR Imagery in the Southern Andaman Sea

The detection of internal solitary waves in this study was carried out using Synthetic Aperture Radar (SAR) on 31 January 2018 with a pixel-based analysis approach (Prasetya *et al*., 2021; Chonnaniyah *et al*., 2021). The parameter analysed was the backscatter coefficient (σ0, in dB) along the wave track. The extracted values of σ0 are presented in Figure 3.

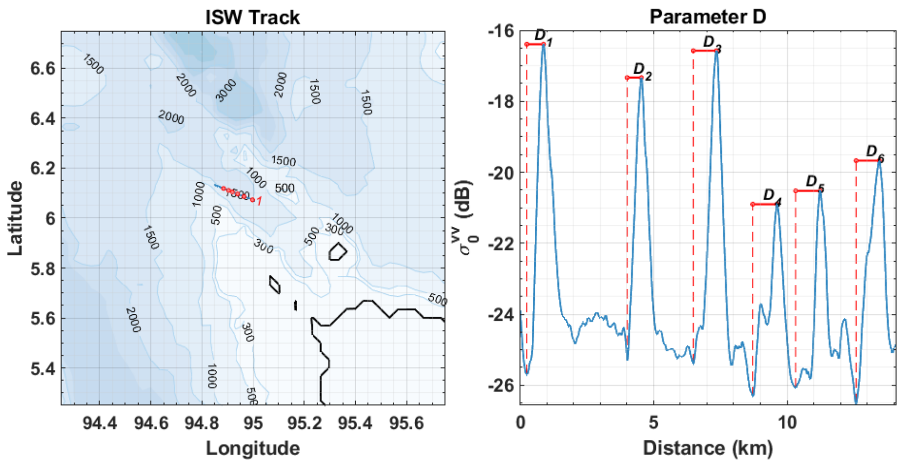


Figure 3: (a) Propagation track of internal solitary waves (ISW-1 to ISW-6) detected in the Southern Andaman Sea, and (b) transect analysis showing variations in backscatter coefficient (σ0) used to calculate Parameter D between bright-dark bands.

Based on the graph, six peaks (ISW-1 to ISW-6) can be observed, indicating the presence of internal solitary waves. These peaks demonstrate significant differences in backscatter values as detected by the image sensor in terms of surface roughness, ranging from approximately -16 dB in the first soliton to about -22 dB in the last soliton (Magalhães *et al*., 2021; Peng *et al*., 2023; Chonnaniyah *et al*., 2024). This phenomenon represents a train of solitons, namely a sequence of internal waves generated by the propagation of the primary wave from the slope region towards deeper waters. The ISW track map in Figure 3 illustrates the propagation direction of the waves from around the 500–1000 m bathymetric contour towards the east–southeast. This is consistent with the theory that ISWs generally form in slope/steep topographic regions (shelf break) due to the interaction between tidal waves, bathymetry, and subsequently propagate away from the generation area.

Characteristics of Internal Solitary Waves in the Southern Andaman Sea

Numerical modelling using the Korteweg–de Vries (KdV) equation was carried out with input from hydrographic data at three observation points due to data limitations. The simulation results are presented in Figure 4. The density perturbation between ISW-1 and ISW-6 indicate that the energy of internal solitary waves tends to be attenuation during propagation (Sun *et al*., 2024). Similar attenuation processes have also been observed in the Flores Sea by Putra *et al*. (2024), where wave packets experience energy loss while propagating across complex bathymetry. This shows that the weakening trend found in the Southern Andaman Sea is consistent with patterns reported in other Indonesian waters.

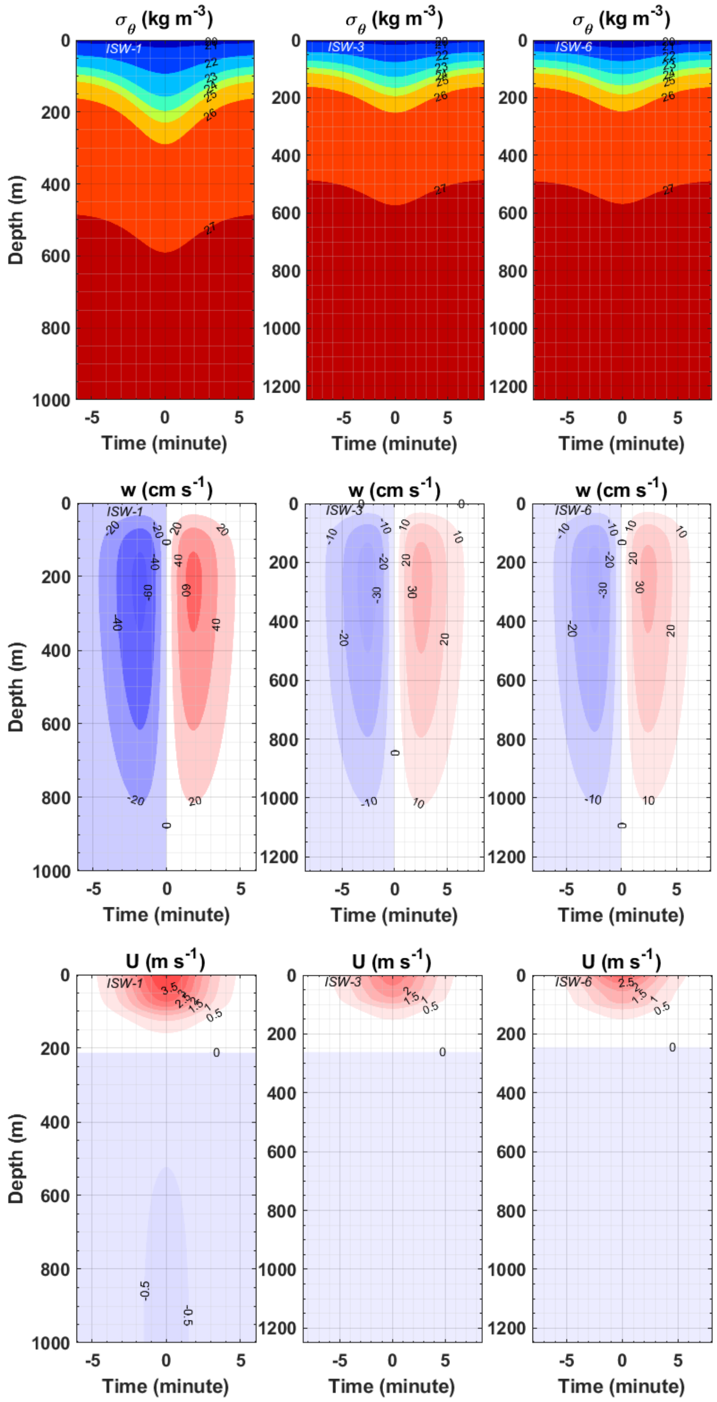
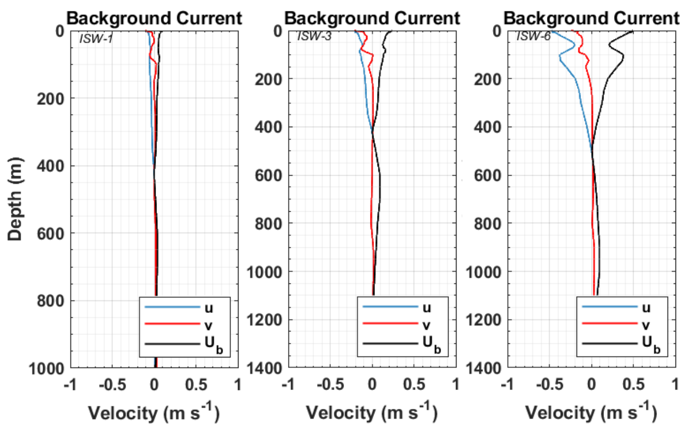


Figure 4: (a) Density Perturbation during the passage of an ISWs, (b) Horizontal velocity, and (c) Vertical Velocity

The model outputs show a displacement of density layers caused by soliton propagation. At ISW-1, the isopycnal displacement is clearly visible with a large amplitude reaching several hundred metres, indicating that the soliton in the upstream region formed with maximum energy. At ISW-3, the displacement amplitude begins to decrease, while at ISW-6 the isopycnal displacement appears weaker and shallower. This pattern demonstrates that the soliton undergoes attenuation along the propagation path, consistent with the pixel-based analysis results. The distribution of vertical velocity exhibits an upwelling–downwelling pattern (Chen *et al*., 2019). At ISW-1, the value of *w* reaches its maximum with significant intensity, while at ISW-3 it decreases, and at ISW-6 it is relatively weak. This indicates that the vertical kinetic energy of the wave diminishes during propagation. Comparable findings were reported by Sun *et al*., (2024), who observed that ISWs in the central Andaman Sea also lost vertical energy as they travelled further offshore, suggesting that dissipation mechanisms are robust across different Andaman subregions.

Horizontal velocity shows a strong current pattern in the upper to mid layers at ISW-1, with a clear velocity gradient. However, at ISW-6 the horizontal current pattern nearly disappears. This suggests that the horizontal momentum of the wave cannot be sustained far from the generation area. This also indicates energy dissipation due to nonlinear mechanisms, frictional effects, and is related to the increasingly shallow topography towards the coastal region (Jayanti *et al*., 2024). Also observed by Prasetya *et al*., (2021), further reinforcing the conclusion that bathymetric constraints strongly modulate ISW propagation.

The analysis of buoyancy frequency (N^2) in Figure 5 indicates that the strongly stratified layer occurs at depths of 100–300 m, which constitutes the main region for soliton formation. The highest N^2 values are observed at ISW-1 and decrease towards ISW-6, reflecting the reduction in soliton amplitude. This finding is consistent with Table 1, which also shows a decline in soliton amplitude. In addition, the background current profile reveals a larger current gradient at ISW-1. This factor contributes to the interaction with ocean currents, thereby influencing propagation and energy attenuation.



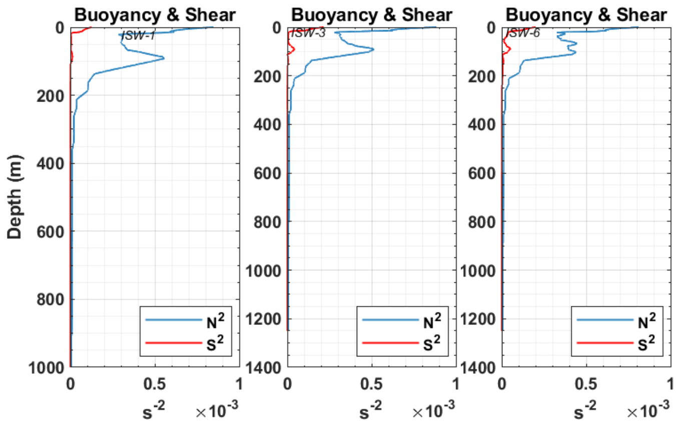


Figure 5: Vertical profiles of buoyancy frequency (N^2) and background current distributions, illustrating stratification intensity

Internal tides are generated when barotropic tidal currents interact with shoaling topographic features such as sills, inducing isopycnal oscillations that transform barotropic energy into baroclinic internal tides. When these internal tides are sufficiently large, non-linear and non-hydrostatic processes may cause them to disintegrate into a train of ISWs, through either a steepening mechanism or a lee-wave mechanism (Purwandana and Cuypers, 2023).

These stratification profiles provide essential inputs for interpreting the spatial variability of ISW energetics discussed in the following section.

The calculation of internal solitary wave parameters in the southern Andaman Sea was conducted using the KdV equation (Vasavi *et al.*, 2021). The results are presented in Table 1.

Table 1: Characteristics of the internal solitary waves in Southern Andaman Sea

Wave Order	Amplitude (m)	α (s)	β (m^3/s)	Cp (m/s)	Δ (m)	Umax (m/s)	wmax (cm/s)	APE (MJ/m)	KE (MJ/m)	KE/APE
D1	138.4	-1.99×10^{-2}	5.21×10^4	2.89	476.42	4.07	64.53	37.15	547.53	14.74
D3	101.19	-2.11×10^{-2}	7.71×10^4	2.84	657.91	2.88	33.6	33.38	339.42	10.17
D6	92.64	-2.34×10^{-2}	7.84×10^4	2.99	657.91	3.15	32.44	27.93	321.35	11.51

At ISW-1, the soliton amplitude reached 138.4 m, with a maximum horizontal velocity of 4.07 m/s and a maximum vertical velocity of 64.53 cm/s. These values represent very high energy in the leading wave. The kinetic energy (KE) amounted to 547.53 MJ/m, which is substantially greater than the available potential energy (APE) of 37.15 MJ/m, yielding a KE/APE ratio of 14.74. This indicates that the wave at the initial track is dominated by kinetic energy in the form of strong currents. At ISW-3, the amplitude decreased to 101.19 m, with Umax of 2.88

m/s and wmax of 33.6 cm/s. The kinetic energy also decreased to 339.42 MJ/m, while the potential energy remained relatively stable at 33.38 MJ/m. At ISW-6, the amplitude further weakened to 92.64 m, with a maximum horizontal current of 3.15 m/s and a maximum vertical current of 32.44 cm/s. The kinetic energy declined significantly to 321.35 MJ/m, whereas the potential energy was 27.93 MJ/m. The KE/APE ratio also decreased to 11.51, indicating a shift in energy contribution, from kinetic dominance at the beginning towards a balance with potential energy downstream.

Overall, these results demonstrate that internal solitary waves undergo energy attenuation along their propagation, as reflected in the reduction of amplitude, current velocity, and kinetic energy. Although the phase speed (Cp) remains relatively stable (~2.9 m/s), dispersive effects become more dominant downstream (with increasing β values), resulting in wave broadening. This is consistent with the pixel analysis of SAR imagery, which revealed a weakening of wave intensity. The agreement between the numerical model and the image analysis indicates that combining pixel-based analysis with a mathematical approach is effective in identifying and understanding the dynamics of ISWs. The numerical model plays a role in quantifying the physical parameters of the waves, while SAR imagery provides spatial and temporal validation of the phenomenon (Purwandana *et al*., 2023; Chen *et al*., 2019). Similar methodological synergies were demonstrated by Chonnaniyah *et al*. (2021) in the Maluku Sea, where SAR observations were successfully linked with hydrographic data to estimate wave speed. Hence, the integration performed in this study aligns with global trends in ISW research and fills the existing gap noted in previous works that often treated SAR and KdV separately.

From a broader perspective, the observed amplitudes of up to 138 m in the Southern Andaman Sea are comparable to extreme events documented in Indonesian waters such as northern Bali (Jayanti *et al*., 2024). This suggests that the region is indeed among the global hotspots for large ISWs. Furthermore, the strong KE dominance in leading solitons highlights the potential risk to offshore structures and navigation, echoing concerns raised by Putra *et al*. (2024) about ISWs' impact on marine operations. Therefore, the findings of this study not only confirm theoretical predictions but also provide practical implications for risk management in areas with intense internal wave activity.

Conclusion and Recommendation

Conclusion

This study successfully integrated Sentinel-1 SAR imagery analysis with numerical modelling using the Korteweg–de Vries (KdV) equation to examine the characteristics of internal solitary waves in the southern Andaman Sea. SAR image detection on 31 January 2018 revealed six internal solitary wave packets (ISW-1 to ISW-6) forming a train of solitons pattern. Stronger backscatter intensity in the leading waves indicated energy dominance near the generation area, while the weakening of backscatter values in the subsequent waves suggested energy attenuation along the propagation path.

Numerical modelling with the KdV equation reinforced the SAR image results by calculating physical parameters such as amplitude, propagation speed, nonlinearity coefficient, and dispersion coefficient. The initial soliton amplitude ranged approximately between 92.64 - 138.4 m, with a relatively stable phase speed (Cp) of around ~2.9 m/s, and kinetic energy that was far more dominant than potential energy. However, the amplitude, current velocity, and wave energy values gradually decreased up to ISW-6, confirming energy dissipation as propagation moved towards shallower waters. The consistency between SAR image processing results and numerical modelling demonstrates that integrating these two methods is effective in representing the dynamics of internal solitary waves.

Thus, this integrated method is able to provide both spatial and quantitative insights into the characteristics of ISWs in the southern Andaman Sea. These findings are expected to serve as an important basis for risk mitigation efforts concerning navigation safety, fishing activities, and offshore structure planning in regions with high internal wave intensity.

Recommendations

Future research should incorporate in-situ oceanographic measurements (moorings, CTD, ADCP) to validate model outputs and strengthen reliability. Extending SAR image analysis to multi-seasonal and multi-year datasets would allow better assessment of temporal variability in ISW generation and propagation. In addition, it can complement KdV to capture generation mechanisms more comprehensively. Applied studies should focus on quantifying potential impacts of large-amplitude ISWs on shipping routes, offshore platforms, and fisheries in the Southern Andaman Sea.

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