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REVIEW ARTICLE

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Interaction between internal solitary waves and the seafloor in the deep sea

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Abstract

Internal solitary wave (ISW), as a typical marine dynamic process in the deep sea, widely exists in oceans and marginal seas worldwide. The interaction between ISW and the seafloor mainly occurs in the bottom boundary layer. For the seabed boundary layer of the deep sea, ISW is the most important dynamic process. This study analyzed the current status, hotspots, and frontiers of research on the interaction between ISW and the seafloor by CiteSpace. Focusing on the action of ISW on the seabed, such as transformation and reaction, a large amount of research work and results were systematically analyzed and summarized. On this basis, this study analyzed the wave–wave interaction and interaction between ISW and the bedform or slope of the seabed, which provided a new perspective for an in-depth understanding of the interaction between ISW and the seafloor. Finally, the latest research results of the bottom boundary layer and marine engineering stability by ISW were introduced, and the unresolved problems in the current research work were summarized. This study provides a valuable reference for further research on the hazards of ISW to marine engineering geology.

KEYWORDS

bottom boundary layer, interaction, internal solitary wave, seafloor, sediment

Highlights

- The latest research results of the interaction between internal solitary waves (ISWs) and the seafloor are introduced, and the unresolved problems in the current research work are summarized.
- ISW generates forces and shear on the seafloor and thus affects sediment suspension in the deep bottom boundary layer.
- This study provides a new perspective for an in-depth understanding of the interaction between ISW and the seafloor.

1 | INTRODUCTION

With the development of ocean engineering into deep water, more offshore oil and gas and offshore wind turbine systems are built on the deep seabed of more than 200 m or even 2000 m. Internal solitary wave (ISW) is a typical marine dynamic process in the deep sea, whose hazards to marine engineering geology should be in no way neglected. ISW, a strong nonlinear, large-amplitude, short-period fluctuation occurring inside the ocean, is widely distributed in the global ocean (Boegman & Stastna, 2019). The South China Sea is a marginal sea with the strongest and most active ISW in the world, and the maximum amplitude of ISW can reach 240 m (Alford et al., 2015; Huang et al., 2016). Surface waves (i.e., waves) disturb sediments in shallow waters with a depth of generally 100–200 m (Cheriton et al., 2014). In deep waters where surface waves cannot reach, ISW can affect seafloor sediments. During the shoreward propagation of the ISW, there will be significant interactions with the seafloor, accompanied by nonlinear evolution, such as reflection, splitting, and polarity switching (Zhang et al., 2018). The interactions result in strong bottom shear flow velocity, which in turn leads to erosion and transport. It transports seafloor sediments and helps to reshape the seafloor (Miramontes et al., 2020; Tian, Jia, Chen, et al., 2021). At the same time, the seafloor also reacts to the ISW, which not only affects the breaking process of ISW but also affects the resuspension of sediments (La Forgia et al., 2018; Wang et al., 2016).

Due to the extremely strong flow velocity and nonlinearity, ISW can effectively affect the seabed geological environment, thus exerting an important impact on marine engineering facilities. It is a catastrophic factor second only to typhoons (Dong et al., 2015), and its important impact on the marine environment has attracted great attention from oceanographers. ISW disturbs seafloor sediments and forms marine nepheloid layers (Geng et al., 2017; Tian, Jia, et al., 2019; Tian, Liu, et al., 2022; Tian, Zhang, et al., 2019). At the same time, ISW transforms the seafloor to form sand waves, which have been extensively observed and studied in marginal seas (Ma et al., 2016). In addition, bedforms (such as sand waves, sediment wave, etc.) are prevalent on the seafloor of the global ocean, and the bedforms and slope will affect the reflection characteristics and break mechanism of ISW (La Forgia et al., 2018; Wang et al., 2020). However, the current research on sediment resuspension mainly focuses on unbroken ISW. By contrast, the understanding of the suspension process of broken ISW is not comprehensive, and the transformation process of ISW on the seafloor is still unclear. At the same time, how the seafloor affects the ISW breaking mechanism and the resuspension also needs to be further studied in detail.

The effect of ISW on the seabed includes many processes. First, ISW produces a force on the seabed, which then induces the resuspension and transportation of seabed sediments. Subsequent ISW induces erosion or siltation of the seafloor, and transformation of the seabed, including screening of surface sediments, transformation of the seabed bottom, and so on. At the same time, the seafloor slope and bedform can also affect the shoaling process of the ISW, which in turn affects the suspended seafloor sediments of the ISW. How does ISW of different break types suspend sediment? What are the characteristics of each ISW? As for these questions, there is still no systematic research and comparative analysis. How the seabed erosion and siltation caused by suspended sediments can transform the bedform of the seabed and the specific process of forming seabed sand waves also needs to be further studied. Although the impact of the seafloor on ISW has been mentioned, the exact extent of the impact is unclear. This review, in no way exhaustive, discusses some important research on this process. Many questions still remain, and much work needs to be done to understand the enormous significance and importance of the interaction of ISW with the seafloor.

2 | BIBLIOMETRICS ANALYSIS

2.1 | Methods and data sources

As a cross-discipline integrating mathematics, statistics, and philology, bibliometrics is an important means of statistical and visual analysis of documents. With the development of social science and technology in recent years, many scholars use Bibliometrics to conduct quantitative analyses in their research fields. In some sense, quantitative analysis of academic research has formed an important trend. By using the software CiteSpace for visual analysis of research literature, one can grasp the development trends, explore hot frontiers in the research field, and also analyze the relationships between knowledge foundations. This study used CiteSpace (version 6.2.R2) to analyze, explore, and visualize literature data on the interaction between ISW and the seabed.

Currently, as an important database for studying international marine geology and geography disciplines, the Web of Science (WOS) database contains a large amount of research data in the field of marine geology and geography. This study searched the WOS core database and recorded any literature that contains words like “internal waves,” “seafloor,” or “seabed” in the title, keyword list, or abstract. The search period was set from 1900 to 2023, and the literature data was updated on April 21, 2023. Finally, a total of 435 valid data records were obtained as data sources for analysis and research. Then the data were exported to make complete records and saved as txt files so as to establish a local database. The time slice was set to 1 year, and the data selection standard was set to be the top 50%. That is, only the top 50% with the most citations or occurrences in each slice were selected for research and analysis.

2.2 | Results and analysis

2.2.1 | Number of papers and journal analysis

In recent years, research articles on the interaction between ISW and the seabed have been increasing year by year, indicating the importance and progress in this research field (Figure 1). Since 2019, the number of annual publications has remained relatively high. Especially in 2021, the number of published papers witnesses a significant increase. Through analysis, it can be known that this research field has been the hot spot and focus of academic studies.

In the distribution analysis of published journals, it can be seen that among these papers, *Journal of Geophysical Research Oceans, Marine Geology,* and *Journal of Physical Oceanography* have published 38, 36, and 30 articles, respectively, making them the top three journals in terms of publication volume (Figure 2). Despite a large overall publication volume in this field, the number of journals involved in this field is also great. Accordingly, not a single journal boasts of an excessively

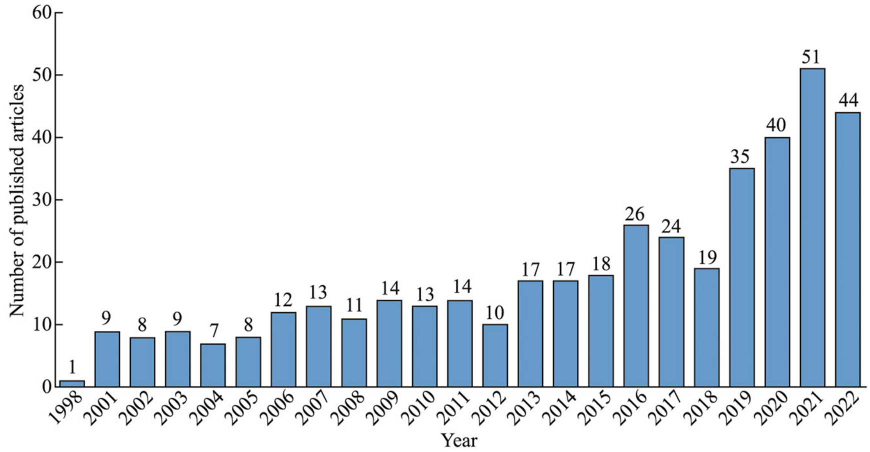

FIGURE 1 Annual distribution of the number of articles on the interaction between internal solitary wave and seabed.

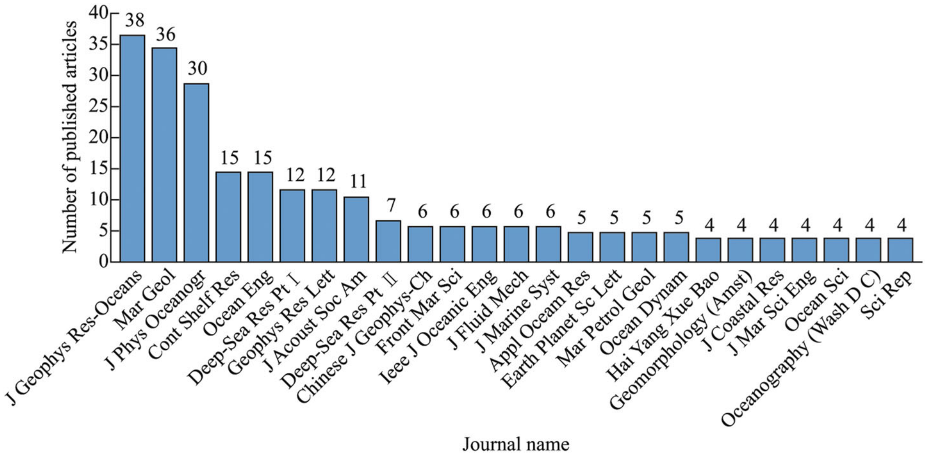

FIGURE 2 Journal distribution of articles on the interaction between solitary waves and the seabed.

high publication volume, which indirectly proves the importance that researchers attach to this research field.

2.2.2 | National and regional concerns and international cooperation

By analyzing the number of articles published by a country and region in a certain field, one can understand the country's development and emphasis on this field. The number of nodes in the figure is 51 and the number of connections is 212 (Figure 3). This indicates that scholars from 51 countries and regions have conducted research on the interaction between sea waves and the seabed, and there is a certain degree of cooperation between these countries and regions (the size of the nodes in the figure is proportional to the number of published articles; the color of the nodes corresponds to the publication time of the articles; and the lines between the nodes represent the cooperation relationship between countries or regions). The largest node among them is the United States, followed by China's mainland, England, and Australia. This means that all of these countries have been actively researching this topic, which may be justified by the fact that they all have a long coastline (Liu et al., 2016). Meanwhile, the abundant marine resources also provide important guarantees for research. At the same time, ISW in these ocean regions are also frequent in the world, and it also has greater advantages to study the interactions between ISW and the seabed.

2.2.3 | Keyword co-occurrence analysis

As highly refined and summarized condensation of the content of academic papers, keywords are indicative of the research hotspots in the research field. Therefore, the research focus and theme in this field can be revealed over time by analyzing keywords. By analyzing the occurrence of keywords, it is possible to predict future research hotspots and trends in this field. In CiteSpace, the co-occurrence of keywords is extracted from the "Title, Abstract, Author Keywords, Keywords+" provided by the WOS database. The visualization analysis of keyword co-occurrence studied in this field since 1998 is shown in Figure 4. Among them, a total of 496 nodes and 2442 connection lines were obtained (only the larger nodes were retained here, and the connection lines were processed), with a total network density of 0.0199 (node size reflects the co-occurrence frequency of keywords; the

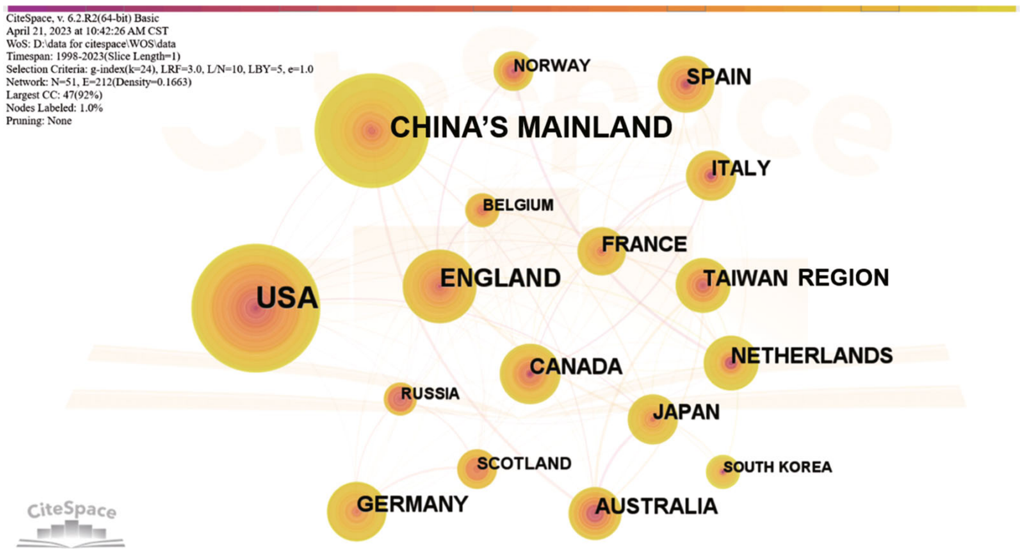

FIGURE 3 National and regional cooperation relationship in the interaction between solitary waves and seabed.

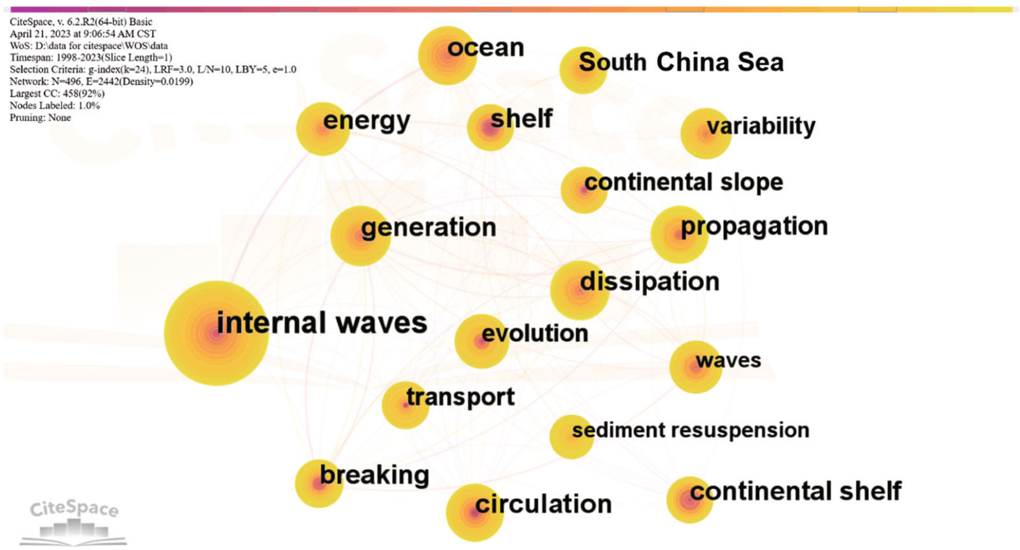

FIGURE 4 Keyword co-occurrence analysis of articles on the interaction between solitary waves and seabed.

connections between nodes indicate that these different keywords appeared in the same paper at the same time; the color of the connections represents the corresponding correlation time). The most frequent occurrences of internal waves, such as "internal waves," "generation," "divergence," "ocean," are consistent with the propagation characteristics of internal waves in our research topic (Table 1). Second, "energy," "propagation," "circulation," "evolution," and other factors reflect the effects of ISW on the seabed and various interactions, and also represent important research focuses of this topic, providing us with research directions.

CiteSpace also provides an analysis of the emergence of research keywords, which helps to grasp future research hotspots and priorities. By analyzing the keyword emergence graph, the period of research hotspots represented by each keyword can be accurately grasped (Figure 5). For example, the keyword "sedimentation waves" was a popular research topic in 2017, but after 2020, the number of studies represented by this keyword has decreased significantly. At the same time, the analysis of the keyword emergence map also presents a preliminary understanding of the future research hotspots in the field of marine geography, such as "slope," "submarine canyon," and "turbulent mixing," which can guide us to expand toward the research direction of submarine slope, submarine canyon, and so on. This is highly consistent with the interaction between solitary waves and the seabed in this study and also proves that the research and discussion in this study are innovative. Moreover, it can also reflect the foresight of this research field.

2.3 | Limitations

Due to the limitations of the CiteSpace software itself, detailed information in the literature has not been fully presented and analyzed. Therefore, further research is

TABLE 1 High-frequency keywords of articles on the interaction between internal solitary wave and seabed.

Number	Keywords	Frequency	Number	Keywords	Frequency
1	Internal waves	119	9	Waves	31
2	Generation	44	10	Variability	28
3	Dissipation	44	11	Transport	27
4	Ocean	42	12	Continental slope	27
5	Energy	39	13	Breaking	26
6	Propagation	34	14	Shelf	26
7	Circulation	34	15	Continental shelf	26
8	Evolution	32	16	South China Sea	23

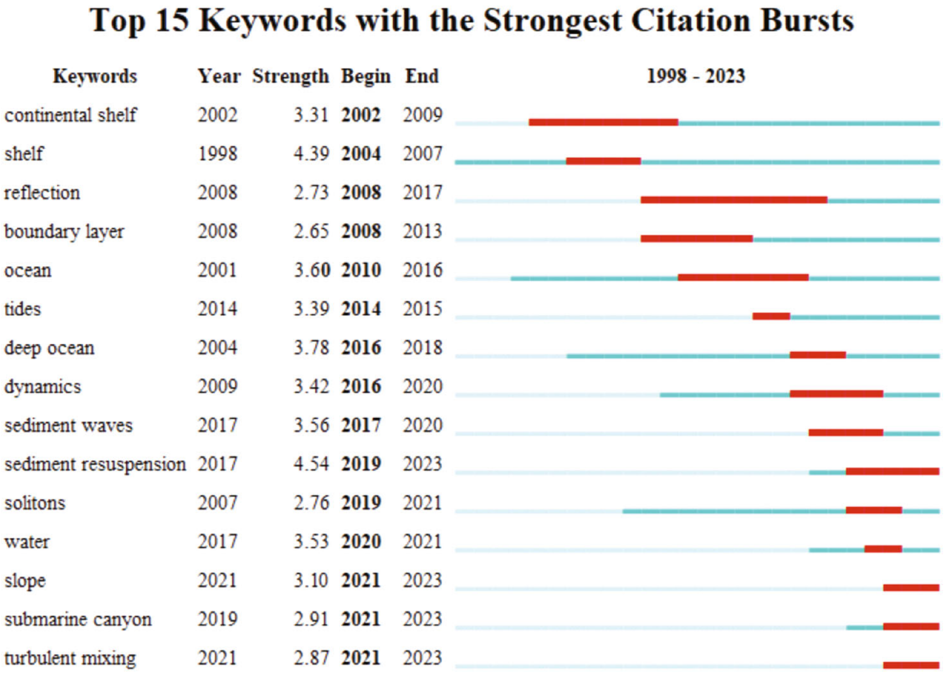

FIGURE 5 Analysis of keyword emergence in articles on the interaction between internal solitary wave and seabed.

needed to analyze the differences between different types of literature. At the same time, this study only covered the core database of WOS for analysis, but excluded other databases that study the interaction between ISW and the seabed, such as PubMed, Scopus, and Springer.

3 | ACTION OF ISW ON THE SEAFLOOR

The influence of ISW on the seabed mainly exists in the bottom boundary layer. In the field of marine geology, the bottom boundary layer refers to the area where the bottom seawater interacts with the shallow sediments on both sides of the seabed interface. Within this range, seawater and sediments undergo strong material and energy exchanges (Gibbs & Ronald, 1974; Lueck et al., 2019). From the perspective of material transport, the specific scope of the seabed boundary layer includes both the overlying fluid within 1–2 m above the seabed interface and the shallow sediment layer on the seabed (McKee et al., 2004). Affected by currents in the bottom boundary layer, the sediments in the bottom boundary layer undergo erosion, resuspension, transport, and transport of seafloor chemicals at all times (Hir et al., 2000), so they are of great research value (Trowbridge & Lentz, 2018; Wenegrat et al., 2018). For the deep-sea bottom boundary layer, the effect of surface waves is almost negligible, but ISW can cause sudden large-amplitude vertical flow of seawater (Tian, Jia, Chen, et al., 2021). Observational studies have demonstrated that it can act on the seafloor at a depth of 1500 m, causing the resuspension of seafloor sediments (Jia et al., 2019; Tian, Jia, Chen, et al., 2021).

3.1 | Seafloor pressure change induced by ISW

Surface waves mainly generate cyclic loads on the seabed in shallow water areas, causing changes in pore water pressure in seabed sediments, liquefaction and instability of the seabed, and even seafloor landslides (Cheriton et al., 2014; Zhang et al., 2017). In the deep sea, where surface waves exert no impact, ISW within the ocean can interact with the seafloor. ISW propagating from the deep water area to the shore will fission during the climbing process of the continental slope and continental shelf slope break area to generate high-frequency internal waves (Bai et al., 2013; Lien et al., 2005) and dissipate most of the energy, causing the seafloor velocity to multiply, and exert a strong force on the seafloor.

Moum and Smyth (2006) found that internal waves could cause changes in seafloor pressure, which was verified by field observations (Moum & Nash, 2008). Alford et al. (2015) observed that ISW caused a downward displacement of the thermocline above 150 m within 5 min (Alford et al., 2015). Field observations in Massachusetts Bay revealed that ISW caused large changes in seafloor pressure in a short period of time (Thomas et al., 2016). Through further research, Thomas et al. (2016) found that the changes in seafloor pressure caused by ISW are closely related to kinetic energy. Tian, Jia, Du et al. (2021) studied the shear effect of shoaling ISW on the seafloor based on laboratory experiments and field observations, and directly measured the shear stress in the laboratory for the first time. At present, some scholars have theoretically analyzed the total pressure of internal waves on rigid horizontal planes and the calculation method of internal wave loads (Kistovich & Chashechkin, 2001), as well as the force of internal waves on floating bodies. The influence of the fluid density ratio and the depth of the thermocline on the internal wave force is also discussed (Kashiwagi, 2005). However, there is a lack of accurate understanding of the force of ISW on the seafloor, and existing studies are confined to the display of observational results. More theoretical models need to be established to accurately predict the intensity of the action of ISW on the seafloor.

Early research on the influence of ISW on seabed stability mainly combined with the two-dimensional Biot consolidation theory to analyze how internal waves cause excessive pore water pressure on the seabed, and discussed the effects of different seabed and internal wave parameters on dynamic response (Williams & Jeng, 2007a, 2007b). Rivera Rosario et al. (2017) found in their study on the permeability horizontal seabed model that the range of seabed damage is 2% of the depth of the low permeability seabed, and the gas-bearing muddy seabed may experience instability within typical depths of the continental shelf. However, these studies are limited to quasi-static Biot theory elastic models, thus failing to reflect accurately the accumulation of excess pore pressure caused by dynamic loads. Zhao et al. (2016) conducted a preliminary study on the cumulative liquefaction mechanism and parameter effects of slope seabed induced by surface solitary waves through numerical simulation and found that the cumulative response of excess pore pressure caused by the breaking process of surface solitary waves is much greater than that caused by horizontal propagation. Tian, Chen, Guo, et al. (2019) found through indoor flume experiments and numerical simulations that the excessive pore water pressure on the horizontal and uniform seabed caused by ISW greatly affects the surface layer of the seabed, and the dynamic response depth of the seabed is approximately one order of magnitude smaller than the half wave characteristic width of the ISW. Meanwhile, these studies indicate that ISW can induce seabed instability, especially during the process of shallow and broken ISW, which have a stronger impact on the seabed. Tian, Jia, Xiang et al. (2023) simulated the breaking of ISW by large Eddy simulation (LES) and analyzed the pressure induced by ISW. They found that ISW-induced pressure changed the polarity when it propagated over the slope, and the two different parts of the seabed faced different failure risks (Tian, Jia, Xiang, et al., 2023).

3.2 | Parameterization of suspended seabed sediments by ISW

The research on the resuspension of sediments by ISW began in the 1970s. Southard and Cacchione (1972) first analyzed and studied the ability of ISW to suspend sediments through laboratory experiments. Numerous studies have clarified the process of suspending sediments in both broken and unbroken conditions by ISW. The resuspension of sediments by ISW has been theoretically clarified in the case of unbroken horizontal seafloor, mainly through locally strong currents shearing and local vortices suspending sediments (Aghsaee & Boegman, 2015; Masunaga et al., 2015). Shoaling ISW climbs slopes and suspends sediments in the form of vortices. The horizontal velocity of the vortex front increases and produces vertical jets of water. The strong bottom current suspends the sediments into the vortex (Bourgault et al., 2014; Deepwell et al., 2020). There are also many studies focusing on the role of bottom shear stress, Reynolds stress, and vertical flow velocity. Some scholars maintained that bottom shear stress combines vertical flow velocity with vortex, and then suspends sediments (Aghsaee et al., 2010; Boegman & Ivey, 2009). Some scholars held that when the vertical flow velocity reaches the maximum, the sediment in the adverse pressure gradient area will be resuspended, and the resuspension has little relationship with the bottom shear stress (Aghsaee & Boegman, 2015). Based on the vertical flow velocity, Aghsaee and Boegman (2015) proposed the resuspension standard of the internal wave-suspended sediment, and defined it as the type of Shields parameter.

$$\theta_{\mathrm{ISW}} = \frac{\tau_{\mathrm{ISW}}}{(\rho_s - \rho_2) g d_{50}} = \frac{\rho_2 c_0^2 [0.09 \ln(Re_{\mathrm{ISW}}) - 0.44]^2}{(\rho_s - \rho_2) g d_{50}}, \tag{1}$$

where τ_{ISW} is the critical starting shear stress; d_{50} is the sediment median particle size; ρ_s is the sediment particle density; ρ_2 is the water density of lower layer; g is the acceleration of gravity; c_0 is the wave velocity; and Re_{ISW} is the Reynolds number.

Considering seepage flow, the parameterization of critical starting shear stress of coarse-grained sediments is developed (Tian, Liu, Ren, et al., 2022). Tian, Liu, Ren et al. (2022) defined it based on flume experiments.

$$\tau_s = \frac{4d\left[(\rho_s - \rho)g - \dfrac{\partial u}{\partial L}\right]\tan\varphi}{3(C_D\cos\alpha + C_L\tan\varphi)}, \tag{2}$$

where τ_s is the critical starting shear stress; d is the sediment particle size (usually taken as the median particle size d_{50}); ρ is the water density; ∂L is the depth difference between two points inside the seabed; ∂u is the excess pore water pressure difference between the two points; α is the angle of gentle slope; the drag coefficient $C_D = 0.4$; the lifting force coefficient $C_L = 0.1$; and φ denotes the static internal friction angle of the saturated soil.

3.3 | Suspended sediments by wave–wave interaction

Wave–wave interaction, be it between surface waves or internal waves, is a common phenomenon in the ocean, especially on the continental margin or over a submarine obstacle (Hsu et al., 2013). The interaction among surface waves has often been reported. However, ISW has received less attention. When two or more trains of ISWs meet and interact, their amplitude, wave speed, and phase change would be affected (Wang et al., 2016; Yuan et al., 2018). If the angle, amplitude, and propagation directions of two trains of ISW are limited to a specific range, a new train of ISW emerges. This phenomenon is called the wave–wave interaction of ISW in the ocean (Wang & Pawlowicz, 2012). The wave–wave interactions significantly impact marine environmental characteristics, such as temperature and salt field distribution, thus greatly enhancing the destructive power upon marine engineering structures and threatening the safety of underwater vehicles. Wave–wave interaction has become a frontier topic of nonlinear science, ship and ocean engineering, and marine environment in recent years.

The amplitude and waveform of two trains of ISWs remain unchanged after nonlinear interaction, and the propagation of each ISW exhibits the basic characteristic of soliton propagation. However, the wave–wave interactions in the ocean significantly increase the amplitude and propagation speed of newly generated ISW. Actual ocean observations show that the amplitude of ISW could reach four times that of the preaction wave at the site of wave–wave interactions (Wang & Pawlowicz, 2012). Wang and Pawlowicz (2012) also classified ISW interactions into seven categories through systematic research and tested the related nonlinear theoretical models by observation of ISW interactions in the Georgia Strait. Wang et al. (2016) found that the wave–wave interactions of two trains could significantly increase the wave amplitude and propagation speed. Yuan et al. (2018) investigated the topographic effect on the interactions between two oblique ISWs.

Quite a few efforts have been made to explore the influence of wave–wave interactions on the sediment resuspension caused by ISW. The interaction of ISW was a fundamental problem in fluid dynamics and nonlinear sciences more broadly. Early theoretical consideration of this problem for acute, collisional angles of incidence dates back to the 1970s. Miles (1977) first identified that strong interactions were intrinsically nonlinear and associated with resonant interactions. When the amplitudes of ISW were small, the dynamics were "linear" and the waves interacted weakly, if not at all, without changing their amplitude, wavelength, or propagation direction. When amplitudes were large, their speed could depend to some extent on the wave amplitude, with larger waves moving faster (Wang & Pawlowicz, 2012). Wang and Pawlowicz (2012) classified ISW interactions into seven categories: overtaking, obliquely overtaking, nonsteady Mach interaction, regular interaction, noninteracting, obliquely colliding, and head-on colliding; and the head-on colliding belonged to "linear" with weak interactions. Jo and Choi (2008) conducted numerical modeling of the head-on collision of two ISWs and concluded that the two interacting ISWs would merge into a single peak, with the resulting height being slightly higher than a linear sum of the two initial wave heights before the collision. Hsu et al. (2013) found that the waveform might retain the initial value for depression-type ISW, but show light broadening with ISW of elevation after the process of head-on collision of two ISWs. Moreover, a single peak formed by the merging of two incident ISWs was observed when the crests or troughs of two ISWs collided, and the merged maximum amplitude was similar to the sum of two incident amplitudes (Hsu et al., 2013). As for strong interactions, the observations showed that the amplitude of ISW could reach four times that of the preaction wave (Wang & Pawlowicz, 2012). Larger displacement implied larger currents. In some cases, larger displacement could lead to breaking and hence enhanced mixing. However, the current research focuses on the suspension of colliding internal waves without any knowledge of the bottom boundary layer process in the wave–wave interaction process. It is unclear how the wave–wave interaction promotes resuspension. Tian, Liu, and Jia (2023) found that ISW in the wave–wave interaction zone enhanced sediment mixing and resuspension by profile investigation in the northern South China Sea. ISW in the wave–wave interaction zone near Dongsha can induce twice the concentration of the bottom nepheloid layer than those in other areas (Tian, Liu, & Jia, 2023). However, the detailed process of wave–wave interactions on the sediment resuspension caused by ISW still remains unknown.

4 | TRANSFORMATION OF THE BEDFORMS BY ISW

Unlike the water flow caused by surface waves, which is a vibratory flow, solitary waves have the ability to transfer energy (mass and heat) during propagation (La Forgia et al., 2018; Shroyer et al., 2010). ISW interacts with the continental slope and shelf during its propagation, and the wave energy is redistributed in the water body and dissipated when the wave group velocity decreases and the wavelength increases (Reeder et al., 2011). After reaching the continental shelf, the ISW of depression energy dissipates further and becomes an ISW of elevation in shallow water. Field observations show that ISW dissipate almost all energy on continental slopes and shelves (Alford et al., 2015), especially on continental slopes (Reeder et al., 2011). ISW reflecting on continental slopes can generate sufficiently high bottom shear velocities to inhibit the deposition of fine-grained sediments and possibly erode the surface sediment (Cacchione et al., 2002; Puig et al., 2004). These extremely high near-bottom velocities (and the associated high bottom-shear stress) may result in relatively low sediment deposition rates and large surface sediment particle sizes, which contribute to the remodeling of continental slopes (Ma et al., 2016; Ribó et al., 2016). Jia et al. (2019) estimated through field observations that the suspended volume of ISW in the northern South China Sea could reach 787×10^6 ton/year, which was 2.7 times that of all river-inlet sediments in the northern South China Sea (Jia et al., 2019). Yin et al. (2019) synthesized multiyear multibeam observation data and pointed out that the linear erosion-dominated area on the northern shelf of the South China Sea may be attributed to the erosive turbidity current caused by ISW. It is well known that the continental slope is the steepest part of the continental margin, and the average slope of the continental slope is 2–4 degrees, which is an order of magnitude lower than the internal natural angle of repose of marine sediments (Puig et al., 2004). This indicates that the continental slope has been severely eroded and transformed over geological time. The bottom shear stress caused by ISW can erode the upper continental slope. In this sense, ISW is considered to play an important role in reforming the entire continental slope (Cacchione et al., 2002; Klymak et al., 2011; Puig et al., 2004).

Recent studies have found that interactions between ISW and the seafloor can form sand waves or dunes on the shallow seabed (Figure 6; Miramontes et al., 2020; Reeder et al., 2011). Occasional ISW-induced resuspension is thought to be sufficient in intensity to reshape the seafloor topography (Pan et al., 2012; Pomar et al., 2012) and to influence seafloor depositional processes (Droghei et al., 2016; Puig et al., 2004). Field observations suggest that ISW can control sand wave migration

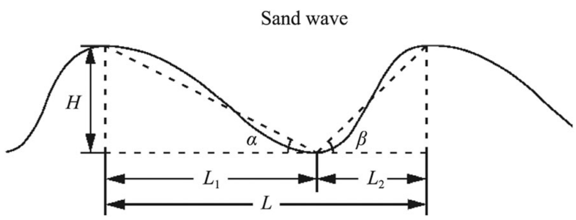

FIGURE 6 Profile chart of submarine sand waves (Lin et al., 2017). H denotes wave height; β is the angle of steep slope; L is wavelength or ridge spacing; L_1 is gentle slope projection length; and L_2 is steep slope projection length.

through local particle resuspension and redeposition (Ma et al., 2016; Miramontes et al., 2020). La Forgia et al. (2020) first studied the formation of sand waves by surface solitary waves on the horizontal seabed through indoor flume experiments and found the process of sand waves formed by bottom-flow suspended sediments. It has been agreed that sand waves are seabed bottoms formed by internal waves (Droghei et al., 2016; Puig et al., 2007; Ribó et al., 2016). Very large underwater dunes have been found on the continental slope and are thought to be the result of ISW-induced bottom current resuspension and transport sediment formation (Reeder et al., 2011). The profile shape of seabed sand waves is wavy, and their morphological characteristics are controlled by factors, such as flow velocity, sediment particle size, and water depth (Ashley, 1990; Barrie et al., 2009). Droghei et al. (2016) proposed that ISW can generate effective unidirectional boundary "water flow," forming asymmetric sand waves. ISWs formed at the interface between intermediate and surface waters are refracted by topography, and the deflected pattern of the sand-wave field is due to the refraction of such ISW (Droghei et al., 2016). This study helps determine the cause of seabed sand waves. However, further research needs to be done to determine the symmetry index of sand waves formed by internal waves.

In addition, ISWs are likely to interact with sand waves to induce local resuspension, which in turn induces sand wave migration (Ma et al., 2016). Field observations have found that internal tides and ISWs in the northern South China Sea cause seafloor sand waves to slightly tilt and migrate uphill or downhill (Ma et al., 2016; Zhang et al., 2019). Miramontes et al. (2020) analyzed multibeam and seismic profile data and found that ISW can strongly erode the upper continental slope of Mozambique and cause seafloor sand waves to migrate upward. Yu et al. (2017) found through indoor flume experiments and field investigations that suspended coarse-grained sediments quickly redeposit to form sand waves, and screen seafloor surface sediments to coarsen the seabed in the suspended area (Tian, Jia, Chen, et al., 2021; Yu et al., 2017). Tian, Jia, Chen et al. (2021) found that ISW screens surface sediments and controls seafloor sediment migration.

At the same time, a large number of observational studies have shown that ISW can form deep-sea sediment waves in the continental slope area, which has been confirmed in field observations, such as the Aquitaine slope in the Bay of Biscay in the North Atlantic (Faugères et al., 2002), the northern part of the Browse Basin in the northwest Australia (Belde et al., 2015) and the slopes of the Gulf of Valencia (Ribó et al., 2016). For the widely developed sediment waves in the continental slope and deep water area of the South China Sea, some studies also prove that it is the effect of ISW (Geng et al., 2017; Li, 2012). Therefore, ISW can suspend a large amount of seabed sediments on both the continental slope and the continental shelf and transform bedforms, forming sand waves, sediment waves, and so on. Accordingly, it is crucial to study the transformative effects of ISW on the shallow and deep seabeds.

A lot of studies have been conducted on the transformation of the bedforms by ISW. Bedforms can

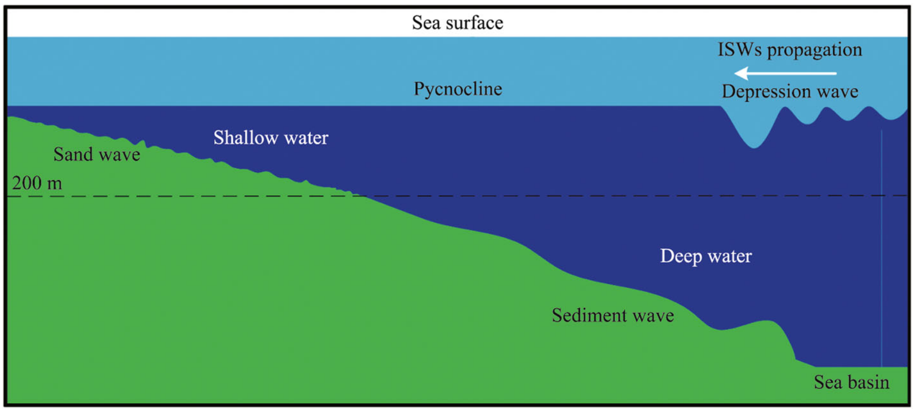

FIGURE 7 Schematic diagram of bedform by shoaling internal solitary wave on the slope (Tian, Huang, et al., 2023).

be formed in the shallow seabed, and sediment waves can be formed in the deep water area (Figure 7; Ma et al., 2016; Miramontes et al., 2020; Tian, Huang, et al., 2023). There is no doubt about the transformation effect of ISW on the seabed, but most of the experimental studies are based on the horizontal seabed. The field investigation mainly analyzes this phenomenon by means of multibeam, earthquake, and other means, combining multiple survey data (Ma et al., 2016; Miramontes et al., 2020; Reeder et al., 2011). However, further research needs to be conducted on the formation process of sand waves and sediment waves by ISW, and no detailed research on the inclined seabed has been published yet. Besides, there is also no research to quantitatively analyze the influence of different types of ISW on various bedforms.

5 | INFLUENCE OF SEAFLOOR ON ISW

The seafloor is not only affected by but also reacts to ISW. Bedforms are common in the global ocean. When ISW undergoes dramatic changes in the seafloor during its propagation, it will cause changes in the thickness of the fluid, which in turn affects the evolution of ISW (Mashayek et al., 2017; Wang et al., 2020; Wei et al., 2012). Seafloor slope also affects energy dissipation in ISW, which in turn affects resuspension (Shimizu, 2019). The influence of bedforms and slopes on internal wave propagation has always been a research hotspot (Tian et al., 2024). Since the 1980s, some theories and experiments have been successively conducted on the propagation of ISW through various bedforms and slopes (Du et al., 2019; Mashayek et al., 2017; Wang et al., 2016).

5.1 | Influence of seafloor slope on ISW

There are three types of break at different seafloor slopes during ISW shoaling (Figure 8): Plunging breakers, Collapsing breakers, and Surging breakers (La Forgia et al., 2018). Compared to the case of surface waves, there is no Spilling breaker. Nakayama et al. (2021) further pointed out that the ISW break type also includes a fourth type: Fission breaker, which mainly occurs under the conditions of high Reynolds number and reflection coefficient (Nakayama et al., 2021). The break type of ISW depends on the proportional relationship between the wave group velocity vector angle and the seafloor slope (La Forgia et al., 2018; Nakayama et al., 2021), which can be represented by the Internal Iribarren number (I_r) (Aghsaee et al., 2010; Sutherland et al., 2013). Current research considers that the break type of ISW is Plunging breakers under low I_r conditions, and Surging breakers under high I_r conditions (La Forgia et al., 2020; Sutherland et al., 2013). Under low I_r conditions ($I_r < 0.8$), ISW break induces intense mixing (Boegman et al., 2005; Masunaga et al., 2017), dissipating more than half of the energy (Boegman et al., 2005). Meanwhile, the intensity of mixing and energy dissipation induced by ISW gradually decreases with increasing I_r (Arthur & Fringer, 2016). In addition, I_r can be used to quantify ISW reflection (Aghsaee et al., 2010), mixing efficiency (Boegman et al., 2005), and particle transport (Arthur & Fringer, 2016). Due to the different types of ISW break, this will inevitably lead to differences in energy dissipation, mixing efficiency, and so on, which in turn lead to differences in suspension modes. Therefore, it is very important to study the suspension characteristics of ISW from the perspective of break type.

Although great achievements have been made in the research on suspended sediments with ISW and a lot of knowledge has been gained, the process of suspending sediments by breaking ISW is still controversial. And there is no unified understanding of the specific model (Aghsaee & Boegman, 2015; Deepwell et al., 2020). Currently, the studies on the suspension process only consider the horizontal and inclined seabed, and the broken and unbroken states of ISW. The propagation of ISW along the seabed with different slopes will cause four types of break. However, there is no detailed analysis of the impact of the ISW breaking mechanism, and no analysis of the different suspension processes from the perspective of the ISW breaking type. Therefore, the specific modes and detailed processes of suspended sediments in the case of ISW breakup are still controversial and require systematic research.

The seafloor slope affects the energy dissipation pattern of ISW, which in turn affects the process of suspending the

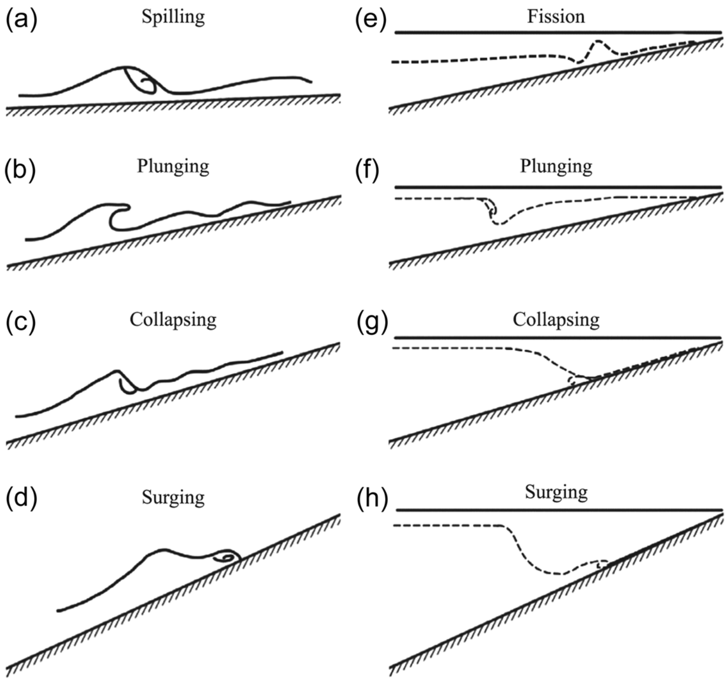

FIGURE 8 Schematization of the different surface (a–d) and internal (e–h) wave breaker types (La Forgia et al., 2018; Nakayama et al., 2021). The scheme considers a single wave interacting with an increasingly inclined sloping boundary. The dashed lines define the pycnocline position and the solid lines over the sloping boundaries indicate the free surfaces.

sediments by ISW. According to the theory of internal wave reflection, the ISW shallowing action zone is determined by the ratio of the wave group velocity vector angle (a) to the seafloor slope (γ), and can be divided into three categories: propagation region (subcritical), critical region (critical), and reflective region (supercritical) (Cacchione & Wunsch, 1974; Puig et al., 2004). In the propagation region ($\gamma/a < 1$), the energy carried by ISW propagates to the shore, and the energy mainly exists between the seafloor and the thermocline. In the critical region ($\gamma/a \sim 1$), the energy carried by ISW is completely dissipated at one location, which can enhance the bottom shear flow velocity, inhibit the redeposition of fine-grained suspended sediments, and erode the bottom surface sediments. In the reflection region ($\gamma/a > 1$), most of the energy carried by ISW is re-reflected into the ocean interior (Cacchione et al., 2002; Puig et al., 2004). Cacchione et al. (2002) first conceptually proposed an important link between internal wave behavior (current and turbulence) near the seafloor and sediment resuspension. Internal waves are thought to cause sediment resuspension, affect particle redeposition, and correlate with the distribution of bottom and middle nepheloid layers and seafloor slopes (Cacchione et al., 2002). Shimizu (2019) studied the dynamics of internal waves theoretically and found that the flat seabed is suitable for the existing internal wave theory, and the seafloor slope exceeding the critical area will increase the error. The different energy propagation modes caused by ISW passing through different seabed slopes will inevitably affect the process of suspending seabed sediments. Although some preliminary studies have found that the seafloor slope affects the suspended sediments of ISW, much still needs to be done; particularly the specific impact degree needs to be analyzed quantitatively.

5.2 | Influence of bedforms on ISW

Bedforms are commonly found in the seabeds around the world. During the propagation of ISW, the bedforms change drastically, which causes the thickness of the fluid to change, affecting the evolution of ISW and the resuspension and redeposition patterns of the seabed sediments (Du et al., 2019; Mashayek et al., 2017; Wei et al., 2012). The influence of bedforms on internal wave propagation has always been a research hotspot. Since the 1980s, some theoretical and experimental studies have been successively conducted on the propagation of ISW through various bedforms (Helfrich et al., 1984; Small, 2003).

During the propagation process of ISW, it undergoes shoaling deformation or even breaks when it propagates through the area where the bedforms change drastically. When ISW of depression propagates along the seabed where the water depth continues to become shallower, the back of the wave becomes steeper, the horizontal velocity exceeds the wave speed, and the dense water is drawn into the upper layer and overturns, causing convective instability and break (Legg & Adcroft, 2003; Vlasenko & Hutter, 2002). Shoaling and break processes enhance near-bottom flow velocity and bottom shear stress, which in turn affects depositional patterns and bedforms (Cacchione et al., 2002; Puig et al., 2004). Recent studies have shown that the breaking of ISW induces stronger mixing near the steep seafloor than previously thought (Masunaga et al., 2015; Mashayek et al., 2017). The flume experiment found that the existence of the concave bedform will make the amplitude of ISW of depression first decrease and then increase (Du et al., 2019). The abrupt bedforms can lead to a significant increase in the amplitude of ISW and steepening and polarity switching of ISW (Qu et al., 2015). At the same time, some experiments have found that the bedforms have a dramatic effect on the velocity and vorticity of ISW (Li, 2019). ISW passing through the bedforms usually enhances bottom flow velocity, which in turn promotes the resuspension of seafloor sediments (Wei et al., 2012). Tian, Liu, et al. (2023) found that submarine trenches have a significant impact on sediment resuspension by ISW by profile investigation in the northern South China Sea. The concentration of the suspended particulate matter inside submarine trenches is significantly higher than that outside them. The concentration of the suspended particulate matter near the bottoms of trenches could be double that outside them and form a vast bottom nepheloid layer. Trenches could increase the concentration of the suspended particulate matter in the entire water column, and a water column with a high concentration of the suspended particulate matter would be formed above the trench (Tian, Liu, et al., 2023). The bedforms have a great influence on the suspended sediments of ISW. In this sense, it is very important to study the specific process and degree of suspension of the suspended sediments of ISW. However, the current studies on the reaction of bedforms are all qualitative, and the specific impact degree needs to be explored quantitatively.

6 | MARINE ENGINEERING GEOLOGICAL HAZARDS INDUCED BY ISW

6.1 | Seabed landslides caused by ISW

Seabed landslide is one of the important types of deep-sea geological hazards. The tremendous impact could damage submarine structures, leading to the destabilization of marine oil drilling platforms, fracture of drill strings, and even triggering catastrophic events (Fan et al., 2023; Yang et al., 2011). In the deep-sea benthic boundary layer, although the influence of surface waves is almost negligible, there still exists a series of active dynamic processes, such as internal waves and mesoscale eddies, among which ISWs exhibit strong nonlinear characteristics and enormous amplitudes (Helfrich & Melvillew, 2006). They not only demonstrate significant convergence and divergence effects in the horizontal propagation direction but also cause sudden increases in vertical currents in seawater. Thereby, they alter the vertical distribution of nutrients in the seawater (Jan & Chen, 2009), transport warmer upper-layer seawater to deeper layers and even the seabed (Huang et al., 2016), and reduce the pressure on the seafloor surface (Thomas et al., 2016). This process leads to the resuspension of seafloor sediments (Jia et al., 2019), accumulation of pore pressure (Chen & Hsu, 2005), and decrease in effective stress on the seabed, ultimately triggering seabed landslides (Sun et al., 2021).

6.2 | Impact of ISW on marine engineering stability

The escalating effects of global warming and rising sea levels have led to an increase in the frequency and magnitude of catastrophic events. These events, such as typhoons, tropical storms, ISW, and complex ocean currents, have a significant impact on the construction and operation of deep-sea projects (Rui, Zhang, et al., 2023, Rui, Zhou, et al., 2023). One notable example is the explosion incident that occurred on April 20, 2010, at the "Deepwater Horizon" drilling platform in the Gulf of Mexico. This incident is closely associated with the activity of internal waves, which further enhances our understanding of the risks involved in the development of deep-sea oil and gas resources. It has also emphasized the importance of comprehending the mechanisms behind geological disasters (Liu et al., 2022). ISW possesses immense energy and thus poses a severe threat to oil drilling platforms and buried pipelines.

The erosion caused by ISW poses a significant challenge to pile foundations and buried pipelines in marine environments. Prolonged erosion resulting from ocean currents, marine bio-corrosion, marine disasters, and human activities could lead to deformation, cracks, and leakage in subsea pipelines (Jiang & Ju, 2008; Tian, Jia, Zhu, et al., 2023). These issues not only directly contribute to marine pollution and the depletion of oil resources but also indirectly impact national economic development. Therefore, it is crucial to efficiently and accurately monitor the condition of subsea pipelines to ensure the sustainable development of offshore oil and gas resources (Luo, 2021). The substantial energy and nondissipative nature of ISW enable it to transmit energy to the seabed depths, causing erosion, resuspension, and transport of contaminated sediments (Tian, Jia, Zhu, et al., 2023). This process could affect sediment deposition and erosion in coastal areas, including the resuspension of sediments on continental slopes, thereby influencing marine productivity (Zhang, 2015).

The impact of ISW on the erosion process could have detrimental effects on pile foundations, resulting in a decrease in the load-bearing capacity and an increased likelihood of structural damage. Buried pipelines are also susceptible to sediment transport caused by erosion, which could lead to pipeline exposure, corrosion, and an elevated risk of rupture (Chen, 2013). Additionally, erosion could induce variations in the burial depth of pipelines, thereby compromising their safety and stability. In the North Sea region of the United Kingdom, the intensified erosion caused by ISW has exacerbated the corrosion of pile foundations, leading to significant infrastructure damage in offshore wind farms. These erosive forces directly expose seabed-embedded pipelines to external conditions, accelerating pipeline corrosion and heightening the potential for leaks. Oceanic phenomena, such as ISW, could induce erosion and sediment accumulation on the seafloor, resulting in alterations in environmental factors, such as boundary layer temperature, pressure, and flow field. These changes directly influence the occurrence of catastrophic events and could trigger the simultaneous onset of multiple disasters, setting off a chain reaction (Tian, Jia, Zhu, et al., 2023).

7 | SUMMARY AND OUTLOOK

The interaction between ISW and the seafloor mainly occurs in the bottom boundary layer. For the deep bottom boundary layer, ISW is the most important dynamic process. ISW generates forces and shear on the seafloor and marine engineering and thus affects sediment suspension. Much research has been done on the process of ISW suspending sediments, mainly related to bottom shear stress, vertical flow velocity, and eddy. However, the detailed suspension processes of different breaking processes need to be further studied; the existing suspension parameterization criteria need to be further improved; and the influence of wave–wave interaction on the bottom boundary layer is still unclear. ISW can form sand waves in shallow water and sediment waves in deep water. There have been many studies on this process, but no quantitative analysis is available yet. ISW impacts marine engineering stability, including seabed landslides, pile foundations, buried pipelines, and so on. At the same time, the bedforms and slopes of the seafloor also affect the break and suspension of ISW, thereby affecting the interaction between the two. While this reaction has received widespread attention, a number of questions remain to be answered.

The current research on the interaction between ISW and the seafloor mainly focuses on laboratory experiments and numerical simulations. However, there is a huge dearth of field monitoring data. Accordingly, a more comprehensive and detailed study is urgently needed. At the same time, many theories are devoid of the support of field observation data. In this case, more research is highly needed to explore the interaction process of ISW and the seafloor. Due to the limitations of CiteSpace software itself and the authors' knowledge, much detailed information in the literature might not be fully presented and analyzed.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All the data are available from the corresponding author.

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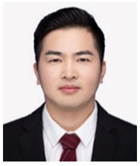
AUTHOR BIOGRAPHY



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