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Numerical Simulation of Lateral Sediment Transport on Haizhou Bay Beach Based on the XBeach Model

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Abstract: Shoreline sand wave movement is one of the hot issues in coastal dynamics research. The nonlinear nearshore waves constitute the core driving force for shoreline sediment transport, significantly enhancing the lateral sediment transport intensity and exerting an important influence on shoreline sand wave movement. By using the XBeach model, the evolution process of the profile of a typical sandy beach in Haizhou Bay under the action of nonlinear waves was simulated, and the comprehensive influence of wave nonlinearity on the lateral sediment transport and sand wave movement of the beach was analyzed. The results show that the nonlinearity of waves has a relatively significant impact on the sediment transport along the shoreline of Haizhou Bay. The sediment transport in the breakwave zone 500 meters offshore is frequent. The peak line of the sand wave moves towards the shore year by year, and the peak elevation increases year by year. Within the calculation range of the model, the net sediment transport to the sea shows a slightly eroded feature in the intertidal zone of the nearshore tidal flat of Haizhou Bay. The research results have important reference significance for grasping the erosion and topographic evolution laws of the nearshore beaches of Haizhou Bay.

Key words: Nonlinear waves, XBeach, sediment transport, beach erosion, Haizhou Bay, SWAN model.

1. Introduction

In recent years, the increasing scope and severity of coastal erosion have severely impacted the ecological environment and economic activities in coastal regions worldwide, making it imperative to conduct in-depth research on the influence of coastal dynamic conditions on beach profile morphological changes [1]. Numerical simulation, with fewer spatial scale limitations and relatively short time cycles, has gradually become an important research tool in marine dynamics [2].

Nearshore wave nonlinearity is a significant phenomenon in coastal dynamic processes, while tidal currents, as persistent nearshore dynamic factors, interact with waves to influence sediment transport. Through mechanisms such as wave asymmetry and crest shape changes, they significantly affect beach evolution, sediment transport, and coastal erosion. As nearshore waves shoal and break, they exhibit waveform asymmetry and near-bottom flow asymmetry. Tidal currents alter the persistent direction of sediment transport through periodic flow movements. Their superposition leads to changes in sediment transport intensity and direction. Under nonlinear wave action, beaches often exhibit characteristics such as sand wave migration and adjustment of erosion/deposition patterns. Green M. et al. [3] analyzed the regulatory role of wave nonlinearity on sediment resuspension in estuaries and nearshore areas, noting that wave energy significantly alters sediment transport pathways and deposition patterns by enhancing turbulence and flow asymmetry. Van Rijn et al. [4] proposed theories indicating that wave shape skewness and asymmetry parameters can quantify wave asymmetry, both closely related to the Ursell number. Chen Daxi et al. [5] analyzed model outputs of wave skewness and asymmetry parameters to reveal the response mechanism of headland-bay beach morphology under typhoon conditions. Cai Daxin et al. [6]

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conducted in-depth research on the erosion mechanism of Longxi Bay beach, providing a basis and reference for coastal management and restoration projects. Overall, wave nonlinearity promotes lateral sediment transport by enhancing flow turbulence and asymmetry, thereby shaping the beach profile morphology.

XBeach is a structured-grid, two-dimensional coastal hydro-morphodynamic numerical model originally developed to simulate hydrodynamic and morphodynamic processes in specific areas of sandy coastlines under storm conditions. Currently, the model is being extended to address other types of coastal problems, offering advantages such as high modularity, parallelization, and ease of integration with other models [7, 8]. As an important tool for simulating coastal dynamic processes, it can parameterize nonlinear wave effects and couple wave propagation, tidal current movement, sediment transport, and morphological evolution. Bruno D et al. [9] detailed the mechanisms within the model for coupling wave propagation, sediment transport, and morphological evolution, providing a core tool for simulating coastal dynamic processes. Gong Yumeng et al. [10] used a one-dimensional XBeach model to simulate the changes in erosion and deposition after sand replenishment on the beach, verifying the importance of nonlinear parameters in erosion prediction; Zhang Hongyan [11] studied the impact of vegetation on the evolution of sandy coast profiles by adjusting the parameter values in the one-dimensional XBeach model. Cai Li et al. [12] described the reasons for varying degrees of seabed surface sediment coarsening. Xia Zhuying et al. [13] used XBeach to study the evolution characteristics of the coastal beaches in the nearshore area and verified that the sedimentation and erosion at the sand dunes were significantly affected by regular waves. Hu Pengpeng et al. [14] used XBeach to study the occurrence of jet streams in the nearshore region. In summary, this model has been widely used to simulate beach profile erosion changes and predict beach erosion/deposition development.

Based on the widely used Stationary mode in the XBeach model, this paper utilizes parameterized calculation of wave nonlinear parameters, presents the method for determining wave nonlinear parameters in the XBeach mathematical framework. Combined with multi-year continuous beach profile observation data from the sandy coast of Lianyungang, a one-dimensional XBeach beach profile evolution mathematical model was constructed. A preliminary comparison was made between measured data and calculation results. The movement patterns of nearshore sand waves under wave action were analyzed, and the influence of nonlinear parameters in the calculation model on beach sand wave movement was discussed.

2. Study Area

Haizhou Bay is located on the coast of the Yellow Sea in the northeastern part of Jiangsu Province. The tidal regime is primarily regular semi-diurnal, with significant shallow water constituents. The duration of ebb tide is longer than that of flood tide. The average tidal range in the area is relatively large, reaching 3.6 m. The tidal current direction in Haizhou Bay is generally southwest-northeast. In the southern part of the bay, the tidal current direction gradually shifts from north-south to northwest-southeast. The flood current velocity is greater than the ebb current velocity. Current velocities farther offshore are greater than those nearshore, ranging from 0.4 to 0.65 m/s [15]. The tidal characteristics of Haizhou Bay vary in different regions. Considering that the northern coast is affected by tidal currents and other dynamic factors, the signs of undererosion on the beach surface are obvious. In order to study the evolution law of the beach under specific dynamic conditions, the study transect is located on the beach in the northern part of Haizhou Bay, as shown in Fig. 1.

2.1 Beach Topography and Sediment Grain Size

The terrain was based on RTK beach surface monitoring data (85 national elevations) from 2018, 2020, and 2021. The data results of surface sediment collection, screening, and laser particle size analysis at appropriate locations on the forebeach and outer beach of the monitoring profiles in April and September 2021 are shown in Fig. 2.

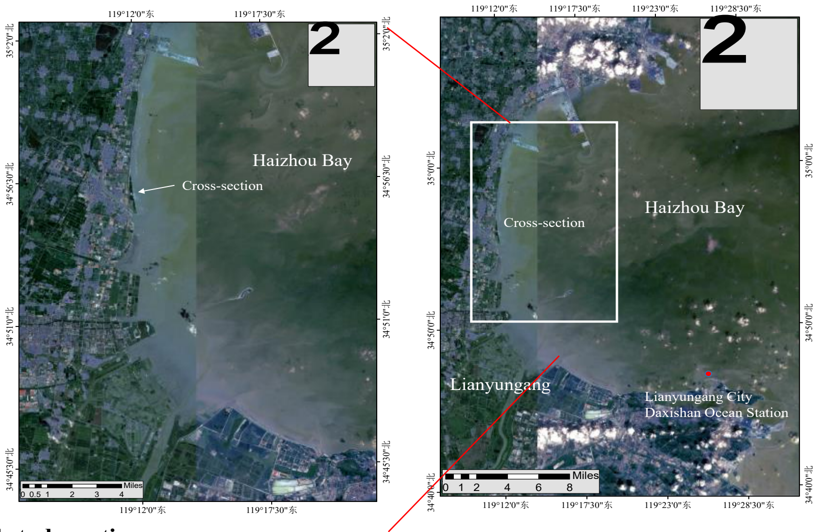

Fig. 1 Study area and study section.

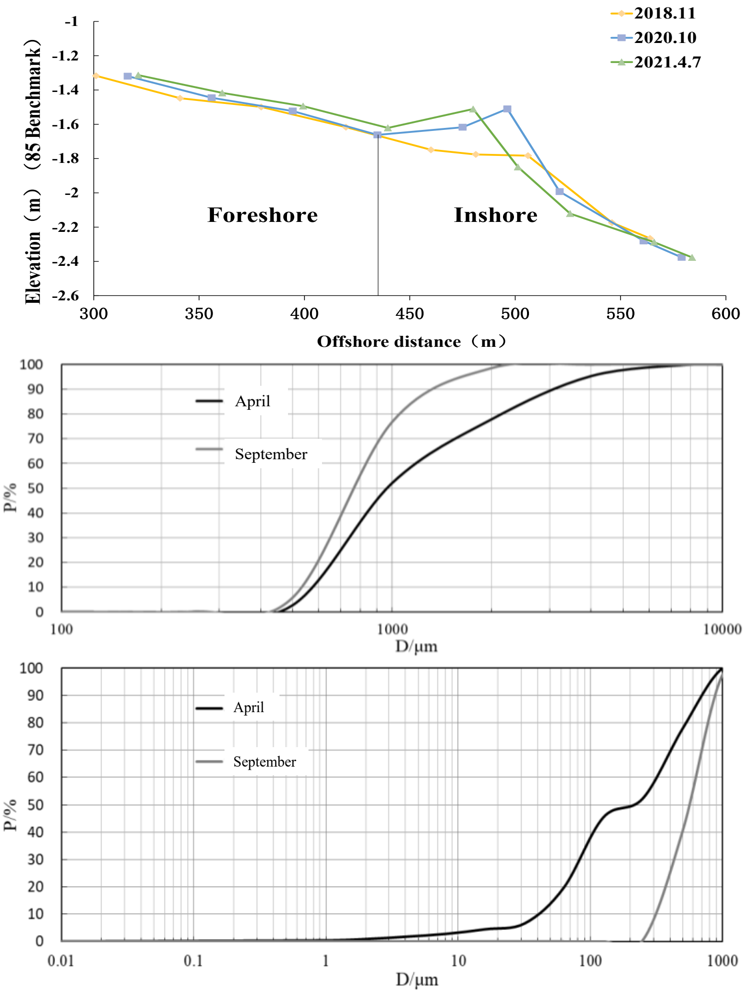

Fig. 2 shows the distribution curves of sediment particle size in the front and outer beaches of the measured and monitored beach sections.

From the topographic monitoring and grain-size analysis results: A sand wave exists approximately 500 m from the seawall, with a width of about 170 m and an average height of about 0.4 m. Influenced by wave action, it shows a tendency to move onshore, with the crest position continuously advancing landward and the crest elevation increasing annually and tending to stabilize. Between the sand wave and the seawall, slight sediment accumulation occurs, while slight scouring is observed between the sand wave and the subtidal zone. Regarding grain size analysis, the gradation curve indicates that D_{50} at the calculation transect is 0.22 mm. Surface sediments from different profiles mainly consist of three types: sand, gravelly sand, and silty sand, with a low clay component. Furthermore, the average grain size of surface sediments in the offshore area first increased from 0.09 mm to about 0.86 mm and then decreased to 0.01 mm, indicating that the profile sediments underwent a process from very fine sand to coarse sand to fine silt, with poor sorting.

3. Research Methodology and Model Validation

Wave action balance equation:

$$\frac{\partial A}{\partial t}+\frac{\partial c_x A}{\partial x}+\frac{\partial c_y A}{\partial y}+\frac{\partial c_\theta A}{\partial \theta}=\frac{D_w+D_f+D_v}{\sigma} \quad (1)$$

Where: A is wave action; c_x, c_y and c_θ are wave action propagation velocities; θ is the wave incidence angle (relative to the x-axis), with the positive x-axis direction parallel to the wave incidence direction; Dw is wave energy dissipation; D_f is bottom friction; D_v is energy dissipation due to vegetation; σ is wave frequency.

Waves in the nearshore zone exhibit skewness and asymmetry. Near-bottom water particles perform asymmetric horizontal oscillatory motions. Superimposed with the periodic flow of tidal currents, the asymmetry of the oscillatory flow is further intensified, significantly affecting sediment transport intensity. Sediment transport equation considering asymmetry and tidal current action:

$$\frac{\partial hC}{\partial t}+\frac{\partial hC(u^E-u_a\sin\theta)}{\partial x}+\frac{\partial hC(v^E-u_a\cos\theta)}{\partial y}+\frac{\partial}{\partial x}\left[D_h h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_h h\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{Ta} \quad (2)$$

Where, C is sediment concentration; c_{eq} is equilibrium sediment transport rate; u^E and v^E are tidal current velocities; D_h is sediment diffusion coefficient; θ is wave angle; T_a is duration of action. The method proposed by Van Rijn is used to describe wave skewness and nonlinearity:

$$u_a = (f_{SK}S_K - f_{AS}A_S)u_{rms} \quad (3)$$

Where, u_a is calculated from the wave skewness parameter S_K, wave asymmetry parameter A_S, root-mean-square velocity u_{rms}, and two calibration factors f_{SK} and f_{AS}. Larger values of u_a indicate stronger onshore sediment transport. Wave skewness parameter S_K and wave asymmetry parameter A_S reflect the degree of oscillatory flow asymmetry. Wave skewness parameter S_K and wave asymmetry parameter A_S:

$$S_K=\frac{\overline{u_m^3(t)}}{\sigma_{u_m}^3} \quad (4)$$

Where, σ_{u_m} is the standard deviation of $u_m(t)$. The wave asymmetry parameter A_S is calculated by replacing $u_m(t)$ with its Hilbert transform. Current analysis of nonlinearity mainly relies on the relationship between the Ursell number and nonlinear parameters. Ruessink et al. fitted a large amount of experimental data. This paper integrates these analyses to establish the relationship between S_K, A_S and the Ursell number U_r.

$$S_K = B\cos\psi \quad (5)$$

$$A_S = B\sin\psi \quad (6)$$

Where, S_K and A_S are related to the nonlinear parameters B and ψ. Their calculation formulas are as follows:

$$B=\frac{0.857}{1+\exp\frac{-0.471-\log U_r}{0.297}} \quad (7)$$

$$\psi=-90+90\tanh\left(\frac{0.815}{U_r^{0.672}}\right) \quad (8)$$

Where B and ψ depend on the Ursell number U_r:

$$U_r = \frac{3}{8} \frac{H_s k}{(kh)^3} \tag{9}$$

In model calculations, based on significant wave height H_S, wave period T, and water depth “h”, the Ursell number U_r is first calculated. Then, the nonlinear parameters B, ψ, wave skewness parameter S_K, and wave asymmetry parameter A_S are computed.

3.1 Determining Wave Conditions Using the SWAN Model

Nearshore sediment undergoes lateral transport under incoming waves, leading to sand wave movement and consequently causing erosion and deposition changes in the beach elevation within the breaker zone. To accurately simulate this process, offshore wave conditions need to be determined. The SWAN model was used to derive the offshore wave conditions for the XBeach model in this study, as shown in Fig. 3. The SWAN model domain covers part of the southern Yellow Sea, extending from Qingdao in the north to the abandoned Yellow River delta in the south, spanning 2.5° in latitude and 2° in longitude.

Table 1 shows the 10-year return period design wind speeds at Lianyungang Station. Table 2 compares the reference and calculated values for the 10-year return period significant wave height at Lianyungang Daxishan Ocean Station. Reference values are selected from the wave height reference values for Lianyungang Ocean Station in the *Port and Waterway Hydrology Code*. The calculation errors are all within 4.0%, indicating that the model parameters are reasonable and the calculated wave height data are reliable.

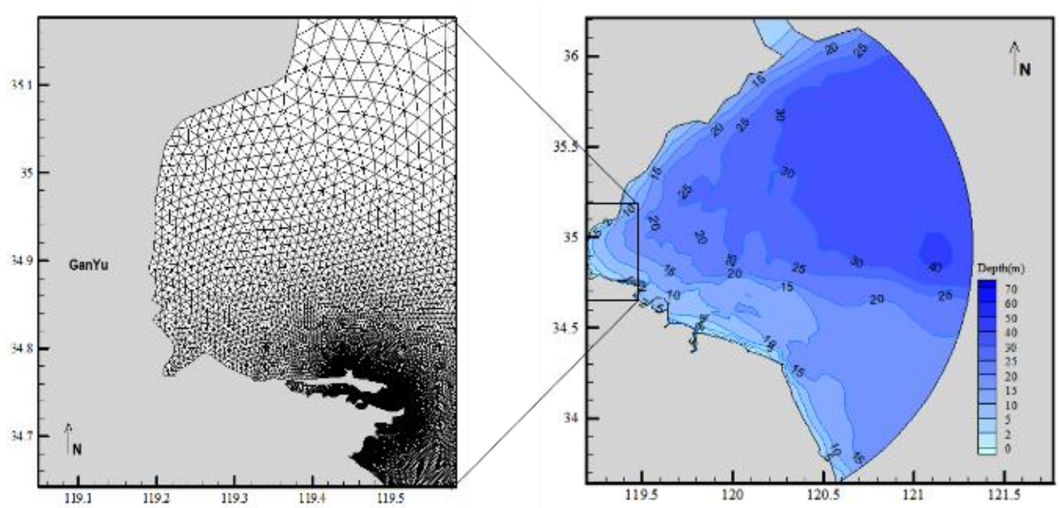

Fig. 3 Calculate the grid of the under the average wave conditions over the years.

Table 1 The design wind speed of Daxishan Ocean Station in Lianyungang is once in 10 years.

Wind Direction	N	NE	E
Wind Speed (m/s)	17.9	15.8	13.3

Table 2 Comparison of reference values and calculated values of 10-year effective wave height at Daxishan Ocean Station in Lianyungang

Direction	N	NE	E
Reference Value (m)	2.90	3.10	2.20
Calculated Value (m)	2.83	3.15	2.27
Relative Error (%)	-2.4	1.6	3.2

3.2 Model Validation

This study established a one-dimensional mathematical model for lateral sediment transport and beach profile evolution of the northern sandy coast of Haizhou Bay based on XBeach. The calculated beach profile length is 1,000 m, with a spatial step of 0.5 m, totaling 2,000 grids. The stationary wave mode was adopted. The sediment transport formula used was vanthiel_vanrijn, which is based on principles of sediment movement mechanics and considers the effects of currents, waves, and other factors on sediment transport. In the bed, D_{50} is taken as 0.22 mm. The initial water level z_{s0} is set to the long-term average sea level of 0.06 m. The significant wave height H_s is 0.78 m. Both offshore and landward boundaries use one-dimensional weakly reflective boundaries. The wave boundary condition uses the JONSWAP wave spectrum, an empirical spectrum commonly used to describe ocean wave spectral characteristics, capable of reasonably reflecting the distribution of wave energy across frequencies under different sea states.

The Brier Skill Score (BSS) quantifies the relationship between the variance of differences between measured data and model results and the variance of the data itself. The coefficient of determination R^2 measures the correlation between measured and modeled results. An R^2 value closer to 1 indicates a higher degree of fit between model results and measured data. The Scatter Index (SCI) normalizes errors, effectively avoiding abnormal results caused by small data averages and high variability. Generally, a smaller SCI value indicates better model performance.

$$BSS = 1 - \frac{\left(|z_c - z_m| - \Delta z_m\right)^2}{\left(z_0 - z_m\right)^2} \tag{10}$$

$$R^2 = \frac{Cov\left(z_m, z_c\right)}{\Delta z_m \Delta z_c} \tag{11}$$

$$SCI = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(z_{c,i} + z_{m,i}\right)^2}}{\frac{1}{n}\sum_{i=1}^{N} z_{m,i}} \tag{12}$$

Where: z_c is the computed beach elevation (m); z_m is the measured beach elevation (m); Δz_m is the standard deviation of measured beach elevations (m); Δz_c is the standard deviation of computed beach elevations (m); z_0 is the initial beach elevation (m). BSS values of 0.8-1.0, 0.6-0.8, 0.3-0.6, and 0-0.3 correspond to excellent, good, reasonable, and poor model prediction efficiency, respectively.

Field surveys of beach profiles in Haizhou Bay were conducted from 2018 to 2021. Profiles measured in November 2018, October 2020, and April 2021 were selected as measured profiles, as shown in Fig. 4. The figure shows that under hydrodynamic action, the sand wave approximately 500 m from the shore continuously moves landward. Its crest advances onshore under wave action, and the crest elevation increases annually. The calculation results can essentially reflect the Regularity of beach erosion and deposition, fitting well with the measured results.

After comparing the measured and calculated values for 2018, 2020, and 2021 using the BSS model, the statistical model errors are shown in Table 3. The predictions for 2018 and 2020 are rated as “good”, and for 2021 as “excellent”, indicating that the model effectively simulates the regularity of beach erosion and deposition.

From the comparison of the predicted three-year shoreline topography with the measured topography, the constructed mathematical model of lateral sediment transport of Haizhou Bay shoreline can accurately reproduce the lateral sediment transport and sand wave movement process. The characterization of nonlinear wave parameters in the model calculation is both convenient and relatively accurate. It provides a reference for the determination of nonlinear wave parameters in the research on lateral sediment transport along the Haizhou Bay beach and the establishment of the Xbeach model.

3.3 Results and Discussion

The shoreline profile of Haizhou Bay in Lianyungang is at the average sea level and is jointly affected by constant waves and tidal currents. About 500 meters from the shore, sediment transport is frequent and the bed surface elevation changes significantly. From the profile changes of the sand wave at different times (Fig. 5), it can be seen that the profile changes of the sand wave at different time points show a distinct dynamic

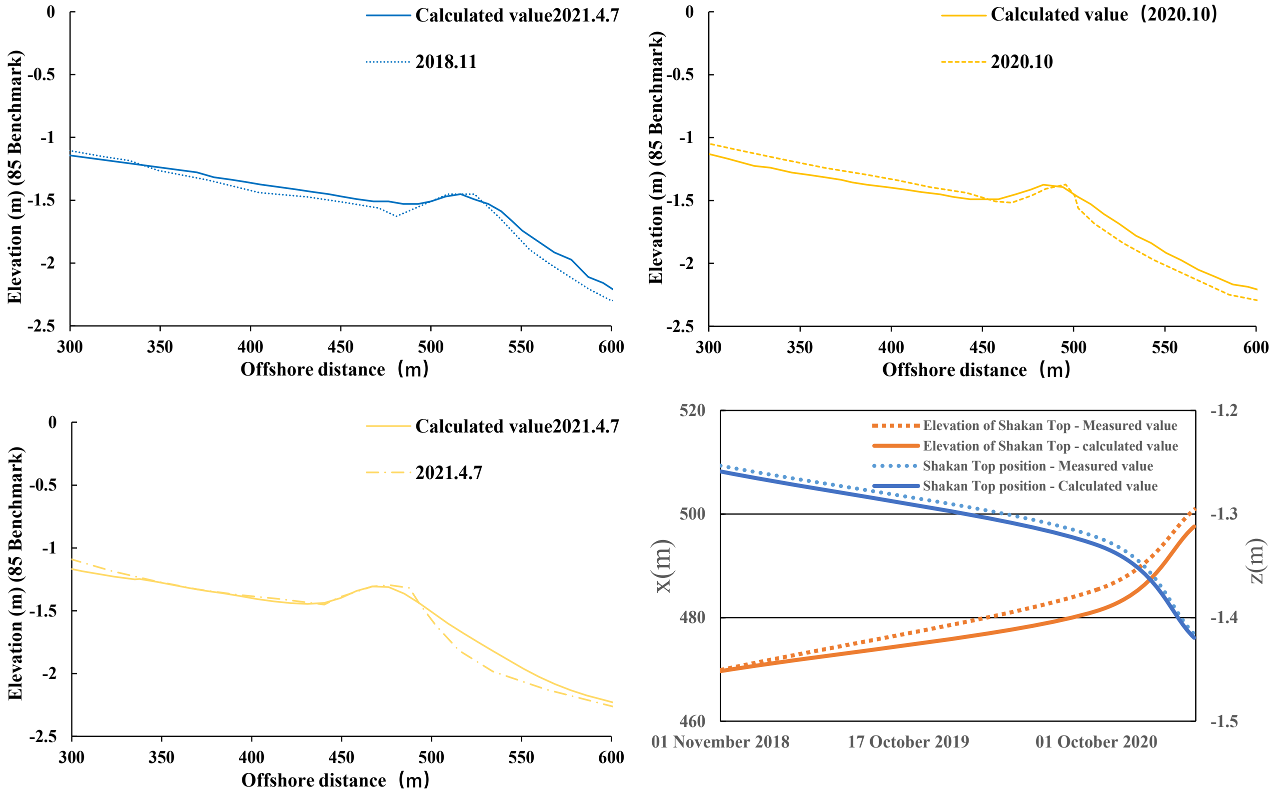

Fig. 4 Verification of the elevation of the beach profile and the annual change value of the beach profile elevation from 2018 to 2021.

Table 3 Model error statistics.

Year	BSS	R^2	SCI	Quality
2018.11	0.78	0.75	0.08	Good
2020.10	0.85	0.90	0.09	Excellent
2021.4.7	0.74	0.89	0.11	Good

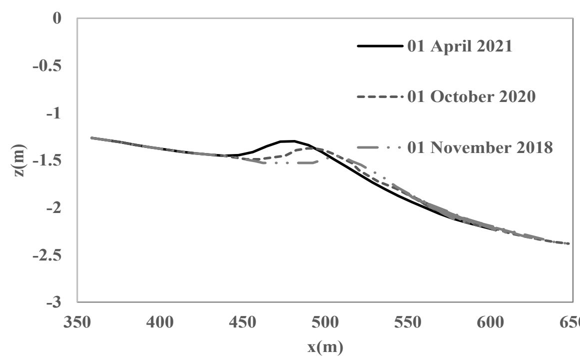

Fig. 5 Evolution of topography and constant wave conditions.

evolution trend. The elevation of the sand wave peak shows an increasing trend year by year. This phenomenon is mainly attributed to the nonlinear characteristics of the waves and the continuous effect of the tidal current force.

When the tide rises, the tidal current pushes the waves to transport sand towards the shore. This causes some of the sediment to deposit on the side facing the shore, significantly enhancing the sediment deposition in this area.

During the model calculation process, it was found that due to the influence of phase difference, the suspended sediment carried by the offshore water flow does not decrease in the forward stage of the water flow. Instead, the sediment suspended in the water increases, leading to an increase in sediment content. As a result, more siltation occurs in the offshore area. Meanwhile, some suspended sediment will also move towards the shore with the rising tide, and the peak lines of the sand waves will gradually shift towards the shore year by year.

Through model calculation, it is found that nonlinear waves advance towards the shore, and the Essert number steadily increases, indicating a significant increase in wave energy and an enhancement of wave nonlinear characteristics. Coupled with the continuous transport effect of tidal currents, the impact frequency of waves on the shore increases, and at the same time, the sediment transport rate of the shore increases, thereby accelerating the rate of sediment loss. The nonlinear characteristics of waves are strengthened, leading to an increase in water turbulence. This intensifies the wave force acting on the sediment particles on the beach, causing more sediment to be suspended in the water and thereby affecting the transport of sediment. Meanwhile, the asymmetry of the waves intensifies. During the stage when the waves fall back, stronger offshore currents will carry sediment and transport it to the sea.

To analyze the influence of nonlinear wave motion on lateral sediment transport, during the evolution of the measured coastal profile in Haizhou Bay, based on significant wave height H_s, wave period T, and water depth h, the Ursell number at each grid point was calculated and output. The numerical model outputs changes in the S_k, A_s parameters and sediment transport rates (Fig. 6).

The larger wave energy is sufficient to overcome the settling force of sediment particles, causing the small particles and some large particles of sediment in the bottom bed to be suspended in the water again. Some of them deposit at the sand wave, and the sediment transport rate suddenly increases at this point. The sudden increase in the Ussel number (Ur) in the figure indicates that the impact of waves on the bottom

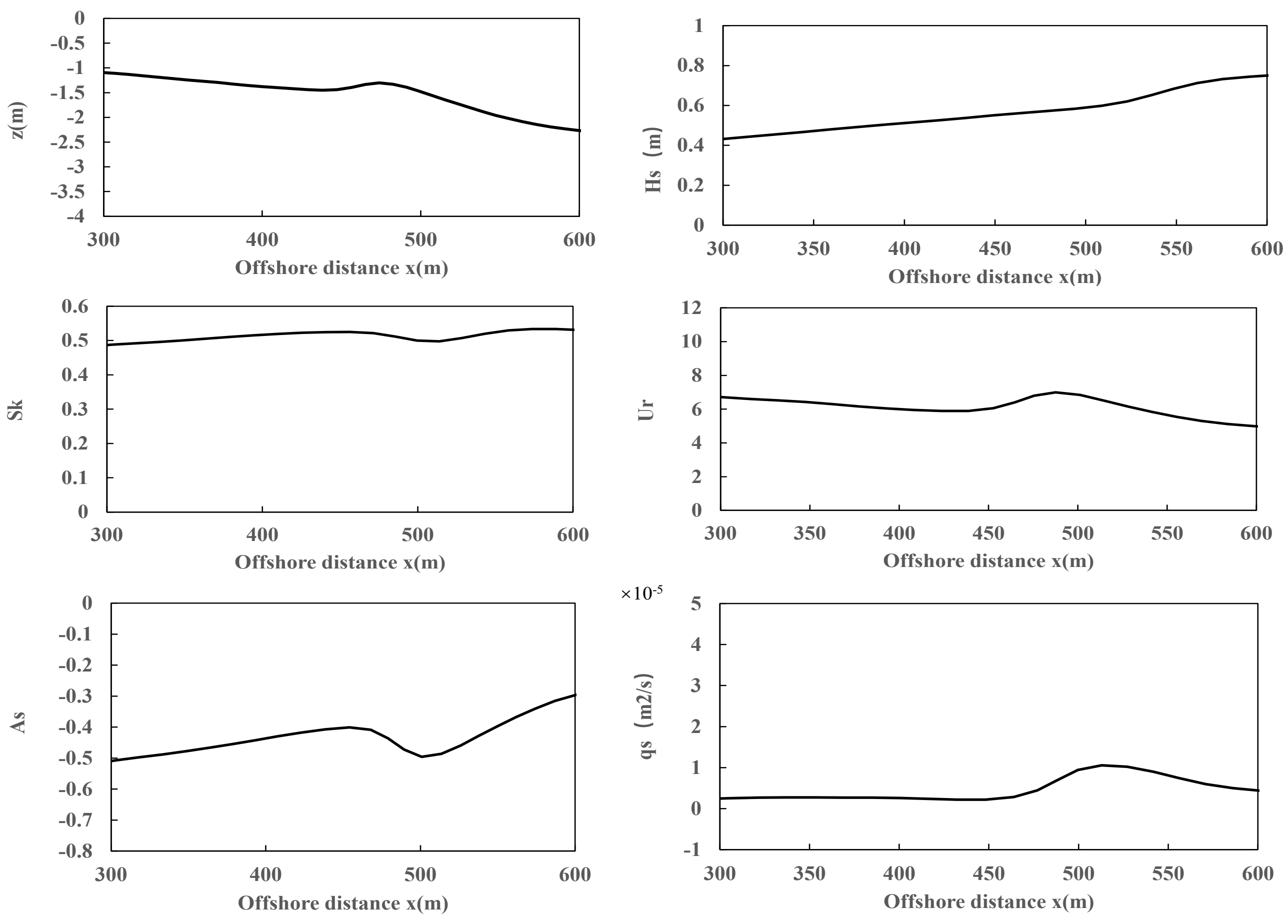

Fig. 6 Changes in nonlinear parameters and calculation results of sediment transport.

sediment is enhanced, and the intensity of sediment transport is improved, thereby increasing the sediment transport rate in this area. The Sk diagram indicates that the front of the wave is steeper and the back wave is gentler. An increase in positive skew means an increase in the risk of erosion. Sk mainly enhances the re-suspension and transport of sediment by affecting wave breaking and energy loss. The As diagram indicates a short ascending time and a long descending time, which simultaneously promotes the deposition of sand and soil. As alters the movement pattern and transportation efficiency of sediment by influencing the shape of waves and changes in flow velocity. As the nonlinearity of waves continues to increase, wave skew and asymmetry intensify, and the movement of near-bottom water quality points towards the shore gradually becomes stronger than the average offshore movement. The calculation results show that as the waves move towards the shore, affected by the terrain, the waveform changes significantly, and the degree of nonlinearity continuously increases, which further aggravates the wave skewing and asymmetry, making the evolution of lateral sand transport and beach sand waves more intense.

4. Conclusions

In order to better grasp the laws of lateral sediment transport and sand wave movement along the sandy coast of Haizhou Bay, a one-dimensional mathematical model of lateral sediment transport and beach profile evolution of XBeach was established. The nonlinear parameters of waves in the model were discussed, and the SWAN model was used to construct the wave field near the coast of Haizhou Bay. Based on the results of the model calculation, the movement law of sand waves on the shoreline was analyzed, and the influence of the nonlinearity of waves on the movement law of sand waves on the shoreline was also analyzed. Furthermore, the mechanism of erosion and siltation of sandy shorelines was explored. Research shows that the nonlinearity and asymmetry of waves are constantly increasing, and the movement of sediment in the bottom bed towards the shore is gradually stronger than the average offshore movement. About 500 meters from the shore, the sand wave moves towards the shore. The top elevation of the sand wave shows an upward trend. Sediment accumulates on the shore side and erodes the offshore side. The asymmetry of nonlinear waves can lead to the re-suspension of small particles of sediment, the deposition of large particles or the need for greater energy to move. Sediment forms in areas with strong waves, while erosion occurs in weaker areas. The research revealed the positive correlation between the Erseur number (Ur) and the sediment transport rate, verified the driving effect of wave shape offset parameters (Sk) and nonlinear parameters (As) on sand wave migration, and provided a method reference for the local configuration of nonlinear parameters of the Xbeach model in nearshore dynamic simulation. The research results have important reference significance for understanding the lateral sediment transport process, sand wave movement law and beach erosion of the sandy coast of Haizhou Bay under the action of nearshore nonlinear waves.

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