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Preface

Sediment erosion and resuspension is a process in which soil particles on the surface of the seabed are activated by hydrodynamic force and eventually enter the overlying water body. It is the root cause of beach evolution as well as channel erosion and siltation, an important cause of instability of offshore engineering structures, and an important path of releasing and transporting seabed buried pollutants to the water body. Accurate prediction of sediment erosion and resuspension process has been a challenge for coastal engineers and scholars.

The traditional view is that sediment erosion and resuspension is induced by wave-current combined shear stress, and the quantitative evaluation method is mainly based on the balance between erosion force and erosion resistance. However, in a wave-dominant hydrodynamic environment, the fine-grained seabed is prone to accumulation of pore water pressure and even seabed liquefaction under the action of wave loading. Such characteristic of wave–seabed interaction causes constant changes in the composition, structure, physical, and mechanical properties of the seabed sediments, and thus further affects the erosion and resuspension process of sediments. Due to the complexity of the process and the interdisciplinary nature of the problem, there is not only a lack of systematic understanding of the physical mechanism but also a lack of a highly universal computational model for quantitative prediction of the sediment erosion and resuspension under such wave–seabed interaction, which seriously constrains the development of offshore engineering calculations and numerical simulations.

In this monograph, the Yellow River Delta was selected as the research area. With the funding of multiple projects, we combined in situ long-term observations, field investigations, laboratory simulation experiments, and theoretical calculations to systematically study the physical mechanism by which wave-induced liquefaction of fine-grained seabed affects sediment erosion and resuspension. Based on the understanding of the mechanism, we modified the traditional shear erosion model and proposed a calculation model of liquefaction erosion. Finally, we verified the applicability of the model by comparison with measured data and used the new model to calculate and predict the sediment erosion and resuspension, source ratios, and their influence on long-term beach evolution in the Chengdao sea area of the Yellow River Delta under different sea conditions. The research results of this monograph are of great scientific values to understanding the dynamic changes of the fine-grained seabed sediments in response to waves, analysis and evaluation of the engineering geological environment conditions of the seabed, prediction, prevention, and control of geological disasters in the estuary delta, and understanding the resuspension, long-distance transport, and fate of sediments from rivers into the sea.

This monograph consists of eight chapters. Chapter 1 mainly introduces the research progress in related fields. Chapter 2 mainly introduces the engineering geological environment and sediment properties of the Yellow River Delta as a representative research area, including the formation and evolution, topography and geomorphology, and marine dynamic environment of the modern Yellow River Delta, and the sediment types, distribution, geological strata, grain size composition characteristics, mineral composition characteristics, microstructure characteristics, and physical and mechanical properties. Chapter 3 introduces the current erosion status in the Yellow River Delta, including the current status of erosion in the intertidal zone and on the underwater delta. Chapter 4 introduces the erodibility characteristic of seabed sediments in the typical study area of delta lobes formed in different sedimentary ages in the Yellow River Delta. Chapter 5 introduces the occurrence process of sediment resuspension in the Yellow River Delta. Chapter 6 introduces the wave-induced pore pressure response in relation to sediment erosion and resuspension in the Yellow River Delta. Chapter 7 introduces the physical mechanisms of sediment erosion and resuspension in the Yellow River Delta under the action of waves. Chapter 8 introduces the theoretical prediction of wave-induced sediment erosion and resuspension in the Yellow River Delta.

The contents covered in this book include major research outcomes of numerous research projects sponsored by National Natural Science Foundation of China (40876042; 41072215; 41072316; 41402253; 41427803), Qingdao National Laboratory for Marine Science and Technology (QNLM2016ORP0110). Several postgraduate students from the Shandong Provincial Key Laboratory of Marine Environmental and Geological Engineering participated in relevant research work, including Xiangmei Meng, Zhongnian Yang, Lei Guo, Liping Zhang, Chaoqi Zhu, Mingzheng Wen, Hong Zhang, etc. The editors in charge of this book Dan Li and Xiaofei Li also contributed great effort for the smooth publication of this book. I am grateful to Prof. Dong-Sheng Jeng (School of Engineering, Griffith University, Australia) for his kind support and help during the completion of the monograph. We hereby express our sincere gratitude to them.

The study on wave-induced sediment erosion and resuspension on fine-grained seabed represented by the Yellow River Delta is the intersection of estuarine sediment dynamics, marine soil mechanics, and marine geology. Although we have tried hard to do some tentative research, as limited by the authors' academic realm, level of knowledge, and the complexity of the academic problems studied, there are inevitably some inadequacies in the book. We sincerely request readers to criticize and correct.

Qingdao, China
January 2019

Yonggang Jia

Contents

Chapter 1
Introduction

1.1 Sediment Dynamics in the World's Major Estuaries

Estuaries are the transitional zone from terrestrial to marine environment, becoming the most complex area of physical, chemistry, and biological processes on the earth. Therefore, nearshore and estuarial sediments dynamics are of common interests to the oceanographers, harbor and coastal engineers, environmental and fluid mechanics scientists.

To study the clay sediments transport, deposition, resuspension processes in estuary and near coastal areas, US Navy Research Center started the STRATAFORM (Strata Formation on Margins) plan at Eel River in 1994, and employed on-site monitoring and numerical modeling to investigate the clayey sediments transport process. This study is in-depth study of short-term- and long-term geological strata transformation of the estuary area (Charles 1999). European Union in its 4th Development Frame carried out coastal sediments, coastal environment, and engineering study under a project named "MAST III". A group of research institutions including Oxford University, Delft Technology University of Netherland, British HR Wallingford Centre, Wales University, Belgium Hydrology Research Institute, Holland Delft Hydrology Research Centre jointly conducted a research project about the sediment bed dynamics called "COSINUS" (Prediction of Cohesive Sediment transport and bed morphology dynamics in estuaries and coastal zones with integrated Numerical Simulation Models). This project involved the establishment of a sediment exchange equation, on-site sediment bed strength test, indoor deposition column test, sediment bed consolidation model, a sediment bed dynamic model based on Biot consolidation theory, as well as sediments erosion and transport indoor experiments. The project is accomplished with important founding (Dearnaley et al. 2002).

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British HR Wallingford Hydrology Centre conducted clayey sediments deposition characteristics investigation and modeling. In September 1998, they performed on-site monitoring at Calstock at Tamar River Estuary. Meanwhile, indoor deposition experiment was carried out at Delft University and Oxford University. The deposition column experiment was used to examine the relationship between deposition type and sediment bed density and strength. Sills (1997) discussed the clayey sediments deposition process based on the Oxford University deposition column test, measured sediments density and stress at bottom, middle and surface and their change over time; Ariathurai and Arulanandan (1986) employed on-site electric method tested the sediment density. The Netherlands is well known for its land reclamation from filling out the coastal sea area. They conducted detailed studies on marine land reclamation engineering including sediment consolidation process. Verbeek et al. (1993) investigated the sediment consolidation, transformation trend of the natural deposited silty sediments in the Netherlands; Mimura (1993) observed the erosion and deposition rates of the clayey sediments under the wave action; Merckelbach et al. (2001) tested the consolidation degree and strength of the bottom sediments using indoor experiments; Winterwerp et al. (2001) explored fast settlement of the saturated silt suspension; Kesteren and Kessel (2002) from WLP Delft Hydraulics studied the integration and extension of air traps in clayey sediments; Van (2002) from Rijakswaterstaat Limburg Directorate studied the suspended clay layer at Ems Estuary. Their results indicated that (1) the suspended clayey layer includes fluid and consolidated parts; (2) the key to investigate the sediments density along the vertical column including the bottom suspended clayey layer is the dissipation and mixing of the deposition and non-Laminar current.

1.2 Sediment Erosion and Resuspension

Sediment erosion and resuspension is the initial process of marine sediment dynamics, which is of great engineering, scientific, environmental, or economic significance, especially in the coastal zones, where distribute most of the world's population and cities. The global material cycle, maintenance of coastal construction, release of buried pollutants and the aquaculture which is strongly influenced by the turbidity and nutrition of seawater are all closely related to this process. Therefore, better understanding the magnitude and mechanism of sediment resuspension in the coastal area is quite important.

Sediment erosion and resuspension generally refers to the process of wearing away coastal materials due to the imbalance in the supply and export of material by natural forces and human activities, such as the high winds, waves, currents, tides, trawling, and dredging (Mohan et al. 2011). In coastal areas, this process generates an important redistribution of sediments and has particular indications for regional particulate matter budgets and export to deeper marine environment. Specifically speaking, erosion and resuspension can be divided into different items. Sediment resuspension and seabed erosion are two aspects of the same physical process, "sediment resuspension" is often discussed in the area of sediment dynamics, whereas "seabed erosion" is more mentioned in marine engineering. Sedimentologists are more concerned with how sediments move in the water, while marine engineers are more concerned with the evolution of seabed after the sediment leaves and suspended. Erosion refers to the response of seabed, as the seabed surface is lowed by hydrodynamics. However, lowing of seabed surface is now necessary during the resuspension of sediments in fluffy layers. Moreover, when sediments are resuspended in the interior of the seabed which is an important topic in this book, terminology "resuspension" is more appropriate than "erosion".

The physical mechanism of sediment erosion/resuspension has been mainly attributed to the tidal currents or the waves (Van Raaphorst et al. 1998). Tidal currents erode the bottom sediments by the friction between flow speed and the seabed surface, while waves are assumed to cause resuspension through the wave orbital velocity and resultant wave orbital shear stress. For the conditions with both presence of waves and currents, coupled wave-current shear stress was frequently argued to control sediment resuspension (Brand et al. 2010).

Historically, sediment resuspension mechanisms are either studied using controlled laboratory experiments or field observations and both the approaches have advantages. For example, in situ data is closer to the real law of the nature while the controlled indoor tests are more reliable for establishing quantitative relationship between detected parameters. Hence numerous investigations regarding sediment resuspension have been conducted around the globe, including site-specific instrumented tripod observations and benthic flume experiments, trying to characterize either the site-specific erosive property or spatial and temporal (seasonal) patterns of sediment resuspension within a scope of study area.

The subaqueous modern Yellow River Delta (YRD) is one of the world's most turbid sea, not only at the present river estuary due to the massive sediment discharge, fast deposition and disperse of plume front (Li et al. 2000), but also in the northern abandoned lobes, where distributes large numbers of offshore platforms of the Shengli Oilfield. In fact, the abandoned lobe has exposed to serious coastal erosion since 1976 when the river channel moved southward to the present estuary (Chu et al. 2006). Although parts of the coast are successfully protected from recession due to breakwaters, submarine seafloor are still experiencing severe erosion and an offshore water zone with high turbidity always exist in this area (Fig. 1.1).

With the objective of finding the physical mechanism for the serious erosion and massive resuspension in the modern Yellow River Delta, to finally improve the modeling effect of silty sediment erosion and resuspension, the research works of this book is conducted in the past decades.

Fig. 1.1 The modern Yellow River Delta (YRD), Chengdao sub-sea, Bo-hai Bay, China

1.3 Research Advance

1.3.1 Research Advance on Sediment Erosion and Resuspension

(1) ***Erosion Power—Bottom Shear Stress of Hydrodynamics***

Sediment resuspension refers to the progress of particles or agglomerates of seabed moving away from the seabed into the overlying water by hydrodynamic forces (Henry and Minier 2014). Its occurrence mechanism is often different in different types (e.g., shape or hydrodynamic conditions) of the gulf or estuary delta. The coast/delta can be divided into tidal-controlled and wave-controlled coast/delta based on different hydrodynamic conditions. Erosion and resuspension of sediment in tidal-controlled coast is mainly controlled by the friction between tidal friction velocity (U_*) and seabed sediment particles (Van Raaphorst et al. 1998):

$$\tau_c = \rho U_*^2 \tag{1.1}$$

When the near-bottom shear stress τ_c is greater than the critical shear stress (τ_{cr}) of the seabed surface sediments, the equilibrium state of the sediments is broken. Sediment will be suspended into the overlying water, and becomes resuspended materials. In wave-controlled coast/delta, many studies have found that the contribution of wave to sediment erosion/resuspension was much greater than that of tidal current (Brand et al. 2010). It is generally considered that the orbital velocity (U_w) is the main driving force.

$$\tau_w = \frac{1}{2}\rho f_w U_w^2 \tag{1.2}$$

where ρ is the density of seawater, f_w is friction coefficient of wave, and U_w is the horizontal component of the maximum wave orbital velocity in a wave period (T). When the turbulence is well developed in the wave boundary layer, the friction coefficient of wave and the roughness of bed(k_b)are related to the radius of major axis of the near-bottom wave orbit (A_b).

Nielsen (1992) suggested that the friction coefficient of wave was estimated by the following relationship:

$$f_w = \exp\left[5.213(k_b/A_b)^{0.194} - 5.977\right] \tag{1.3a}$$

$$A_b = U_w T/2\pi \tag{1.3b}$$

Soulsby (1997) suggested that the friction coefficient of wave was estimated by the following relationship:

$$f_w = 1.39(k_b/A_b)^{-0.52} \tag{1.4a}$$

$$A_b = U_w T \tag{1.4b}$$

Based on the linear wave theory, the near-bottom wave orbital velocity (U_w) is related to wave height (H), wave period (T), and water depth (h).

$$U_w = \frac{\pi H}{T\sinh(kh)} \tag{1.5}$$

$$\omega^2 = gk\tanh(kh) \tag{1.6}$$

where $\omega = 2\pi/T$ is the angular frequency, $k = 2\pi/L$ is the wave number, $L = g\mathrm{T}^2/\pi\tanh(kh)$ is the wave length.

As sediment erosion and resuspension in many sea areas controlled by coupling effect of wave and tidal current, a series of coupled wave-current shear stress models are developed (Soulsby 1997).

$$\tau_{wc} = \sqrt{(\tau_{c,wc} + \tau_w\cos\psi)^2 + \tau_w\sin\psi^2} \tag{1.7}$$

$$\tau_{c,wc} = \tau_c\left\{1 + \left[1.2(\frac{\tau_w}{\tau_w + \tau_c})^{3.2}\right]\right\} \tag{1.8}$$

where τ_{wc} is the coupled near-bottom shear stress under the interaction of waves and currents, $\tau_{c,wc}$ is the flow-induced shear stress enhanced on the basis of pure flow shear stress (τ_c) under the interaction of waves and currents, and ψ is the angle between waves and currents.

(2) ***Erosion Resistance—Critical Entrainment Threshold Stress of Sediments***

Critical shear stress for sediment entrainment (τ_{cr}) is an important parameter to estimate erosion rate or resuspension flux. For sandy sediments, τ_{cr} can be characterized by a dimensionless Shields parameter θ (Fig. 1.2).

For cohesive sediments, many laboratory experiments and field studies have found that τ_{cr} is significantly affected by a series of seabed properties (Aberle et al. 2004) such as density, water content, particle size and biological indicators, and varies with time and space. Making the estimation of the critical erosion state of cohesive sediments quite complicated, even some scholars have questioned whether the critical erosion shear stress really exist? Therefore, most of the critical erosion problems of cohesive sediments depend on laboratory or in situ measurements. The mainstream methods/tools are annular flumes, Cohesive Strength Meter (CSM) (Tolhurst et al. 1999), and remote sensing (GOCI) (Ge et al. 2015), etc.

Even though, there are still some empirical methods trying to calculate the critical shear stress of cohesive sediments (Taki 2000):

$$\tau_{ce} = 0.05 + \beta\left\{\frac{1}{\pi/6(1+sW)^{1/3}-1}\right\}^2 \tag{1.9}$$

where W is the water content, $s = \rho_s/\rho_w - 1$, β is the empirical coefficient.

Considering the cohesion and particle weight of cohesive sediments, Nouwakpo and Huang (2010) proposed that

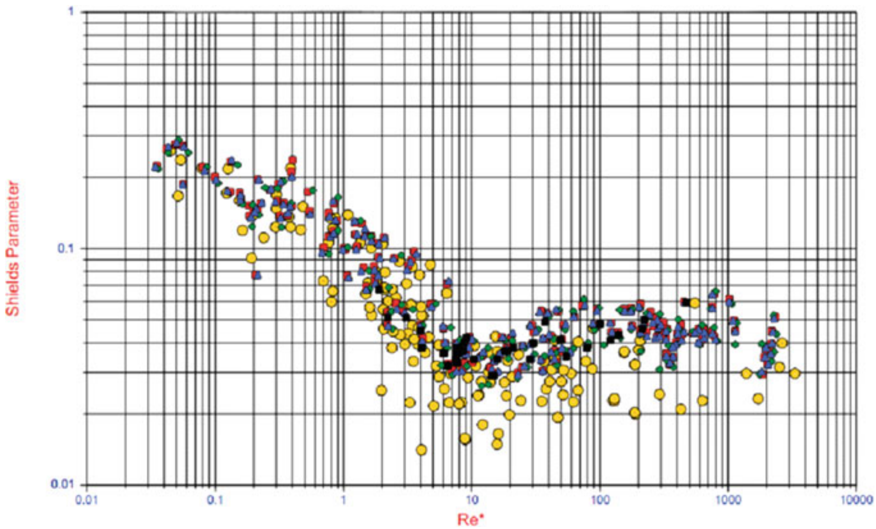

Fig. 1.2 Shield parameter curve

$$\tau_{cr} = \sqrt{\left(\frac{\frac{C_o}{L} D_{psm}}{2}\right)^2 + \left(\frac{\frac{4}{3}\pi\left(\frac{D_{psm}}{2}\right)^3 (\rho_s - \rho_w) g}{\frac{1}{2}\pi D_{psm}^2}\right)^2} \tag{1.10}$$

where C_o is the cohesion, D_{psm} is the Sauter average particle size which characterizes the uneven degree of the sediment particles.

(3) ***Erosion and Resuspension Parameter I—Suspended Sediment Concentration***

Suspended sediment concentration (SSC) can be estimated based on the Shear Erosion Theory above. In early stage, some scholars found that there was a good relationship between SSC and wave orbital velocity or wave orbital shear stress (Clarke et al. 1982):

$$C_{ref} = C_a + \beta(u_w - u_{cr}) \tag{1.11}$$

where C_a is the SSC near the observation point, u_w is the wave orbital velocity, u_{cr} is the critical wave orbital velocity, β is the empirical coefficient.

Wright et al. (1988) proposed an parameterization equation based on Shields parameters

$$C_{ref} = A\rho_s\theta_{sf}'^3 \tag{1.12}$$

where θ_{sf}' is the surface friction Shields parameter defined by Nielsen (1986)

$$\theta_{sf}' = \frac{0.5\rho f_w U_w^2}{(\rho_s - \rho)gD} \tag{1.13}$$

Glenn and Grant (1987) proposed

$$\overline{C_{ref}} = \frac{\rho_s C_{bed}}{T} \int_{t=0}^{t=T} \frac{\gamma_0 \psi'(t)}{1 + \gamma_0 \psi'(t)} dt \quad \psi'(t) > 0 \tag{1.14a}$$

$$\psi'(t) = \frac{\tau' - \tau_{cr}}{\tau_{cr}} \tag{1.14b}$$

where γ_0 is the resuspension coefficient, C_{bed} is the volume density of bed, T is the wave period.

Lee et al. (2004) introduced the effect of settling velocity of particles and proposed a prediction relationship applicable for sandy sediments

$$C_{ref} = A\left[\theta_{sf}\frac{u_{*sf}}{\omega_s}\right]^B \tag{1.15}$$

where ω_s is the settling rate, u_{*sf} is the friction velocity, A, B are all empirical coefficients.

(4) ***Erosion and Resuspension Parameter II—Erosion Rate (Resuspension Flux)***

Resuspension flux and erosion rate of sediments mentioned in this paper can be considered as the same concept, but when we compare our results with experts from different fields, we consider the choice of pronouns.

As early as the 1960s–1970s, erosion of riverbed had become a hot issue in the field of hydraulic engineering and was extensively studied. It was generally believed that erosion rate can be expressed as a function of flow-induced near-bottom shear stress and critical shear stress (Dyer 1986)

$$E_{\mathrm{r}} = M_{\mathrm{e}} \left\{ (\tau/\tau_{\mathrm{cr}})^{\Phi} - 1 \right\} \tag{1.16}$$

where E_r is the erosion rate, M_e is the erosion constant, Φ is the bed parameter.

Later on, research results of hydraulic riverbed sediment transport in open channel were adopted by marine engineers to study the transport of seabed sediments. Considering the significant influence of wave action in coastal ocean environment, the coupled wave-current bottom shear stress parameters are introduced to form the calculation method for erosion and resuspension of seabed sediment in wave-current coexistence environment. Lavelle et al. (1984) derived an empirical relationship $E_{\mathrm{r}} = \alpha\tau^{\beta}$ based on field data. Later on, calculation form has been unified (Sanford and Maa 2001)

$$E_{\mathrm{r}} = M_{\mathrm{e}} (\tau - \tau_{\mathrm{cr}})^{\Phi} \tag{1.17}$$

Until now, the numerical simulation of sediment transport in the field of sedimentary dynamics still mainly uses this form of erosion model. The calculation method of erosion rate above attributed the sediment resuspension process to the stability of sediment particles on the seabed surface. When the continuous action of horizontal current-induced shear stress (Fig. 1.3a) or reciprocating wave-induced orbital shear stresses (Fig. 1.3b), exceeds the critical shear stress of sediments, the steady state of sediments is broken, erosion, and resuspension occur. This can be defined as waves lift up sediments and then currents transport them (Chen et al. 2004).

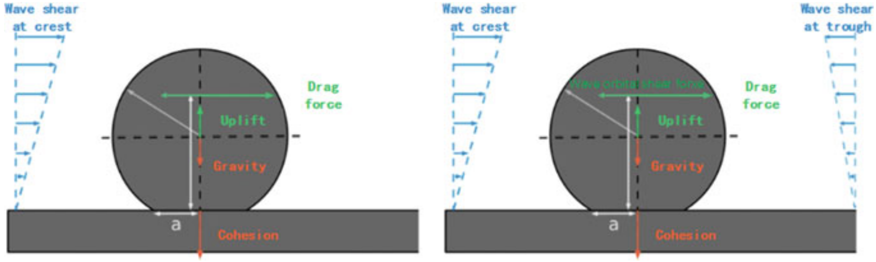

Fig. 1.3 Schematic diagram of mechanism of sediment erosion and resuspension

1.3.2 Research Advance on Wave-Induced Seabed Response

(1) ***Wave-Induced Excess Pore Pressure***

According to the principle of effective stress of saturated soil, the deformation and strength of soil are closely related to the effective stress. Only the stress transmitted through the contact point of the particle can cause the deformation of the soil and affect the strength of the soil. The pore water pressure (u), the effective stress (σ') and the total stress (σ) of the normally consolidated seabed are in equilibrium $\sigma = \sigma' + u$ (Terzaghi 1924). When an external load acts on the soil bed, a part of the additional stress is borne by the pore water, so that the pore pressure rises and the excess pore water pressure (P_{exc}) is generated. Seismic load can induce excess pore water pressure in the soil, and the rapid release of the excess pore pressure will lead to liquefaction, sand boiling, and then cause geological disasters such as earthquakes. In the marine environment, waves act as an additional cyclical dynamic load (Fig. 1.5a), which can also induce excess pore water pressure in seafloor sediments (Ishihara and Towhata 1983). The resulting pore pressure response mode is related to factors such as sediment type, density, initial stress state, and reciprocating stress intensity and frequency. The pore pressure response mechanism of the silty soil seabed under wave action is mainly divided into two types (Jeng 2013): one is the oscillating excess pore water pressure (P_{osc}), also known as the transient excess pore water pressure, the other is the residual excess pore water pressure (P_{res}), also known as the cumulative excess pore water pressure (Fig. 1.4b).

a. Transient (Oscillating) Excess Pore Water Pressure

The transient excess pore water pressure is periodically cyclically reciprocated around the equilibrium position (Fig. 1.4c). This excess pore water pressure is directly related to the transmission of sea surface wave pressure along the depth of the seabed and is therefore unique in the marine environment (Wang 2014). When the crest passes, the oscillating pore water pressure is at the peak, and when the trough passes, the oscillating pore water pressure is at the bottom. Zen and Yamazaki (1990) pointed out that the oscillation amplitude of transient pore water pressure decreases with the increase of seabed depth, which is related to the attenuation of the wave infiltration pressure with depth (Fig. 1.4d). Recent studies have shown that the distribution of transient pore water pressure is not absolute. The experimental results of Wang et al. (2014) show that the amplitude of the oscillating pore water pressure below the antinode of the standing wave decreases with depth, which is in accordance with the above rules. In the certain depth range below the standing wave node, there is no oscillating pore water pressure, but after exceeding a certain depth, the oscillating pore water pressure appears. The experimental results of Zhang (2016) also show that the maximum value of transient pore water pressure appears at a certain depth below the seabed surface, not the surface of the seabed. In essence, the transient pore water pressure response corresponds to the elastic deformation of the seabed soil (Wang et al. 2014), and the residual pore water pressure response corresponds to the plastic deformation of the soil (Sekiguchi et al. 1995). The generation of excess

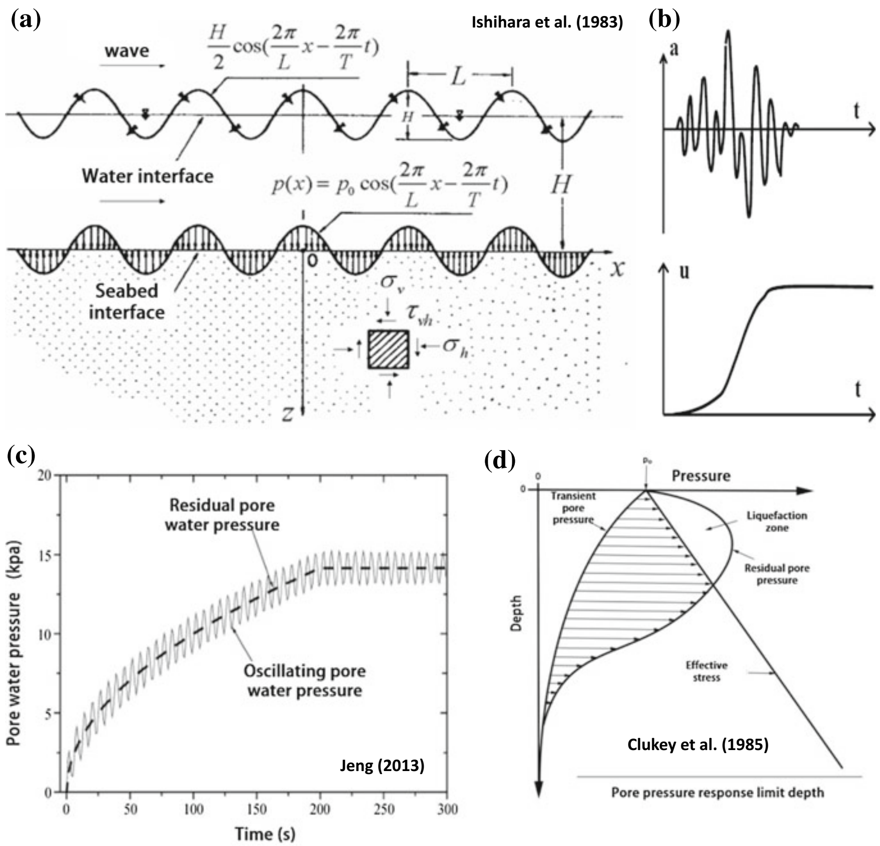

Fig. 1.4 Stress and pore pressure response in the seabed under wave action **a** Wave loading mode **b** Two pore pressure response modes **c** Pore pressure response time history curve **d** Pore pressure response depth profile

pore water pressure originates from the elastic and plastic deformation of the seabed under external loads.

$$\varepsilon = \varepsilon^e + \varepsilon^p \tag{1.18}$$

In the formula, ε^e and ε^p are elastic and plastic body changes, respectively. The elastic body can be recovered instantaneously, corresponding to the transient excess pore water pressure response; the unrecoverable plastic body deformation accumulates under the action of wave load cycle, and the incompressible pore fluid does not reach the drainage, which means that the cumulative pore water pressure increases, corresponding to the plastic body deformation of the soil (Sekiguchi et al. 1995). The centrifuge experiments of Sassa and Sekiguchi (1999) and the flume experiments of

Kirca et al. (2013) and the flume experiments of Wang et al. (2014) show that: both the antinode and the node of progressive wave and standing wave can generate transient and residual two kinds of excess pore water pressure can generate both transient and residual excess pore water pressure. It indicates that the cyclic normal stress or shear stress can simultaneously cause two kinds of pore water pressure responses. This recognition has led to an advancement in the view that initial residual pore water pressure originates from seabed shear stress and shear strain (Yamamoto et al. 1978).

The theoretical calculation of transient pore pressure response usually uses an elastic constitutive model (Yamamoto et al. 1978). The wave-induced pore pressure response of the sandy seabed only shows the characteristics of transient oscillations (Tzang 1992); and in the silty soil seabed with relatively poor permeability, the wave-induced pore pressure response also shows a cumulative rise, that is, residual excess pore water pressure response.

b. Residual (Cumulative) Excess Pore Water Pressure

Residual excess pore water pressure refers to the cumulative rise based on the initial pore water pressure, which tends to increase faster and dissipate relatively slowly. This excess pore water pressure is closely related to wave parameters (such as frequency, wave height, etc.) and the sediment properties. There are two necessary conditions for the generation of residual pore water pressure: (1) the soil skeleton has compressibility, some additional stress will be borne by the incompressible pore water, (2) the sediment permeability is poor, and the pore water can not freely leave the force zone in time under the cyclic extrusion. Silty sediments have a higher compressibility than clay because of their lower permeability than sand, and are relatively prone to residual excess pore water pressure (Clukey et al. 1985).

The generation and development of excess pore water pressure is related to the consolidation properties of the seabed. The Biot equation in the one-dimensional case has the same form as the Terzaghi equation:

$$\frac{\partial p}{\partial t} - c_v \frac{\partial^2 p}{\partial z^2} = f \tag{1.19}$$

where p is the excess pore water pressure, c_v is the consolidation coefficient of soil, z is the seabed depth, and $f = \partial u_g / \partial t$ is the source term, that is, the pore water pressure development mode. Based on the consolidation equation, the pore water pressure development model is added as the source term to calculate the cumulative pore water pressure. The pore water pressure development model is based on the empirical relationship between the number of dynamic load cycles and pore water pressure growth based on the indoor soil unit dynamic test, such as the anti-sinusoidal mode of sand (Seed and Rahman 1978):

$$u_{\mathrm{g}} = \sigma_0' \frac{2}{\pi} \arcsin \frac{N}{N_l}^{1/2\theta} \tag{1.20}$$

In the formula, u_g is the excess pore water pressure, σ_0' is the initial vertical effective stress, MN is the number of dynamic load cycles, and N_l is the number of dynamic load cycles when the liquefaction or pore water pressure stability is no longer rising, and θ is the empirical coefficient.

$$N = \frac{\mathrm{t}}{\mathrm{T}} \quad N_l = \left(\frac{1}{\alpha}\frac{\tau}{\sigma_0'}\right)^{-1/\beta} \tag{1.21}$$

where t is time and T is the wave period, and α and β are empirical parameters related to soil type and relative density. τ is the amplitude of wave-induced seabed shear stress, which can be obtained by the Biot elastic model. When the seabed depth is greater than L/2

$$\tau = p_0 \lambda z \exp(-\lambda z) \tag{1.22}$$

$$P = \frac{\gamma_w H}{\cosh(\lambda h)} \cos(\lambda x - \omega t) = P_0 \cos(\lambda x - \omega t) \tag{1.23}$$

In the formula, γ_w is the seawater bulk density, H is the wave height, the wave number is $\lambda = 2\pi/L$, h is the water depth, and the angular velocity is $\omega = 2\pi/T$.

The linear development model (McDougal et al. 1989) has the following form:

$$u_g = \sigma_0' \frac{N}{N_l} \tag{1.24}$$

In recent years, the newly developed hyperbolic development model using elasto-plastic constitutive relations can simultaneously calculate transient and residual excess pore water pressure (Dunn et al. 2006). The development mode of silty soil is hyperbolic model (Chen et al. 2004). Among them, the exponential hyperbolic development model has the following form:

$$u_g = \frac{\sigma_0' \left(\frac{N}{N_l}\right)^{\mathrm{a}}}{\mathrm{b}\left(\frac{N}{N_l}\right)^{\mathrm{a}} + \mathrm{c}} \tag{1.25}$$

In the formula, a, b, and c are the empirical coefficients. When a = 1, it is the conventional hyperbolic mode.

c. Seabed Liquefaction Discrimination Method

There are two types of liquefaction criteria: the first is the effective stress criterion. The soil liquefies when the wave-induced average effective stress is equal to the initial average vertical effective stress. It also includes one dimension (Zen and Yamazaki, 1990) and three-dimensional effective stress criteria (Tsai and Lee 1995):

$$(\gamma_s - \gamma_w)\mathrm{z} \le \sigma_z' \tag{1.26a}$$

$$\frac{1}{3}\left[(\gamma_s - \gamma_w)(1 + 2K_0)z\right] \le \left(\sigma'_x + \sigma'_y + \sigma'_z\right) \tag{1.26b}$$

In the formula, the first term represents the initial average vertical effective stress of the soil at the depth z, γ_s is the dry weight of the soil, K_0 is the static pressure coefficient of the soil, and the second term represents the average effective stress produced by wave.

Jeng (2013) pointed out that the effective stress standard does not apply to the liquefaction discrimination of a limited thick seabed. At present, the second criterion based on pore water pressure is adopted, that is, when the residual residual pore water pressure is equal to the initial average vertical effective stress, the soil is liquefied. Also includes one-dimensional and three-dimensional super-pore pressure criteria

$$(\gamma_s - \gamma_w)z \le P_{res} \tag{1.27a}$$

$$\frac{1}{3}\left[(\gamma_s - \gamma_w)(1 + 2K_0)z\right] \le P_{res} \tag{1.27b}$$

Tzang and Ou (2006) proposed that when the pore water pressure reached the static pressure of the overlying soil, the soil liquefaction would be

$$(1 - n)(\rho_s - \rho_w)gz \le P_{res} \tag{1.28}$$

In the formula, n is the porosity of soil, ρ_s is dry density of soil, and ρ_w is density of seawater.

When Wang (2014) proposed liquefaction discrimination, $P_{exc} = P_{res} + P_{osc}$ is used on the right side of the equation because the oscillation pore water pressure and residual pore water pressure tend to exist at the same time. When the two pore water pressures are superposed, the pore pressure is the largest, and the liquefaction is most likely to occur at this time.

In addition, the hydraulics field has also proposed methods for determining soil bed liquefaction (seepage failure) based on hydraulic gradients, such as the Ergun formula (Yang 2003a, b), for non-cohesive soils

$$\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2 \mu V_s g}{\varepsilon^3 D_p^2} + 1.75\frac{(1-\varepsilon)\rho_w V_s^2 g}{\varepsilon^3 D_p} \tag{1.29}$$

In the formula, ε is porosity, L is bed thickness, μ is fluid dynamic viscosity coefficient, V_s is seepage velocity, D_p is particle size.

For cohesive seabed soils, the cohesion source term needs to be added to the Ergun formula

$$\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2 \mu V_s}{\varepsilon^3 D_{psm}^2} + 1.75\frac{(1-\varepsilon)\rho_w V_s^2}{\varepsilon^3 D_{psm}} = (\rho_p - \rho_w)g + \frac{C_0}{L} \tag{1.30}$$

In the formula, C_0 is the cohesive force and D_{psm} is the Sauter mean particle size, representing the inhomogeneity of the particles.

1.3.3 Research Advance of Sediment E&R Considering Wave-Seabed Response

(1) ***Physical Mechanism***

The applicability of sediment erosion/resuspension theory, which only considers horizontal shear stress, has been dubious in the wave-dominated hydrodynamic environment. Wave effect on the seabed sediment is not simply provide the horizontal reciprocating shear stress on the surface of the seabed produced by the orbital movement of water particles. Sea level fluctuations due to the passing-by of wave crest and wave trough also exerts vertical cyclic loading on the seabed, causing instantaneous and residual pore pressure responses, which in turn triggers oscillating and cumulative seepage flows in the seabed (Fig. 1.5). Transient seepage flows at the sediment–water interface can be subdivided into instantaneous infiltration flows and upwelling flows (Fig. 1.5a).

Infiltration flows in the surf zone has received widespread attention. Nielsen (1997) found that on the one hand, infiltration current would reduce the thickness of the bottom boundary layer and thus enhance the near-bottom shear stress; on the other hand, the downward drag effect of infiltration flows on the surface sediment would inhibit the sediment erosion process. Which effect dominates the entrainment determined by the balance of the sediment particle specific gravity and the seabed permeability. Based on the clear understanding of mechanism, Nielsen (1997) modified

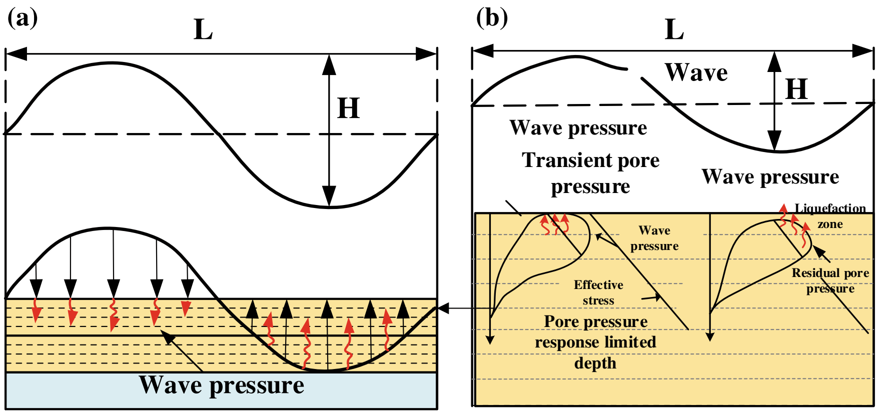

Fig. 1.5 Wave-induced seabed instantaneous (oscillation) and cumulative (one-way) seepage diagram

the traditional Shields parameters and successfully quantified the effect of infiltration flows on erosion and resuspension

Traditional Shields parameter

$$\theta = \frac{u_{*0}^2}{gd_{50}(s-1)} \tag{1.31}$$

Nielsen (1997) modified Shields parameter for considering the effects of downward seepage

$$\theta' = \frac{u_{*0}^2(1-\alpha\omega/u_{*0})}{gd_{50}(s-1-\beta\omega/K)} \tag{1.32}$$

where S is the grain specific gravity, K is the permeability coefficient, ω is the angular velocity, α, β are empirical coefficients.

The experimental results of Obhrai et al. (2002) supported the modification of Nielsen (1997) and found that infiltration flows can reduce sediment erosion amount up to 50%. Similarly, Myrhaug et al. (2014) also considered the wave-induced seepage from the perspective of Shield parameters and would not repeat them here.

More researches have been done on the effect of upwelling flows on erosion and resuspension, because not only the upwelling component of transient seepage flows, but also the nonuniform vertical distribution of wave-induced residual excess pore water pressure (P_{res}) in the seabed can generate vertical seepage (Fig. 1.5b). Since the seabed surface is the free drained boundary, seepage direction be vertically upward, as long as residual excess pore water pressure is accumulated large enough in the peak area of the P_{res}, to completely overcome the self-gravity of particles.

For sandy sediments, many studies have shown that the effect of vertical seepage is unimportant (Baldock and Holmes, 1999). Because the coarser and larger weight of sandy sediment particles make it not significantly affected by the slow seepage flows. However, some experiments also found that when the vertical seepage gradient is large enough, it does have a vertical injection effect on the surface sediments and further promotes the sediment erosion and resuspension (Cao and Chiew 2014). That is to say, the effect of the upward seepage flows is not absolute, there is a balance between seepage strength and the grain size of sediment or seabed permeability. It is noteworthy that anthropogenic vertical seepage flows in laboratory experiments are mostly used to simulate groundwater seepage (Smith et al. 2009), of which the intensity is often larger than that induced by the accumulation of pore water pressure, until it has liquefied the seabed. When the vertical seepage gradient makes the degree of liquefaction of the sediment reach 80%, the critical erosion flow speed decays by only 10% (Carstens et al. 1976).

Baldock and Holmes (1999) found that the effect of vertical seepage on the starting of cohesive sediments is not obvious, because of its low permeability. On the one hand, the seepage velocity of pore water is relatively small. On the other hand, the water head pressure applied to the bottom of the bed takes a long time to reach the surface of the seabed. However, some studies have also found that pore water pressure gradient can cause overall slump of riverbed blocks (Fox et al. 2007) under the action of groundwater seepage. Simon and Collison (2001) pointed out that the occurrence of this process compliance with Moore's Kulun guidelines

$$S_{\mathrm{r}} = c' + (\delta - u)\tan\varphi' \tag{1.33}$$

where S_{r} is the shear strength of the bed, c' is the effective cohesion, $\delta = W\cos\beta$ is the total normal stress, W is the sliding block weight, β is the sliding surface angle, u is the pore water pressure, φ is the effective internal friction angle.

When the vertical seepage is in the limit case, that is, the vertical seepage gradient reaches the overlying effective stress (σ_{v}) and causes seabed liquefaction (Sumer 2014), its promotion effect on erosion and resuspension will become more significant. As early as the 1960s, some scholars pointed out that the critical erosion shear stress changed with time and was affected by the magnitude and duration of wave loadings (Alishahi and Krone 1964). Mehta et al. (1989) pointed out that the critical shear stress of sediments under unidirectional flow was one order of magnitude larger than the critical value under wave action. When the accumulation of wave-induced pore pressure equals the effective stress of overburden, sediments liquefy and are easily mixed into the overlying water in vertical direction by tidal currents. Indoor flume experiment of Tzang et al. (2009) more directly proved that seabed liquefaction can lead to a 10–20 times increase in suspended sediment concentration, but it has a certain lag effect, and its effect on erosion/resuspension is not significant in sandy sediments, because pore pressure accumulation is not obvious as silty ones.

(2) ***Numerical Simulation***

Considering the remarkable seepage effect in seabed when liquefaction occurs, some scholars have tried to take the influence of seepage effect into consideration in the traditional erosion model from different perspectives. Modify the formula of critical shear stress for erosion is a mainstream idea. By introducing seepage force into the force analysis of the sediments in the seabed boundary layer, Wang et al. (2014) derived the critical shear stress equation of surface sediment under seepage flow, and verified its rationality using an actual calculation example.

$$\tau_{\mathrm{e}} = \frac{\left\{\frac{\pi}{6}\mathrm{d}^3\left[(\rho_{\mathrm{s}} - \rho)\mathrm{g} - \frac{\Delta P}{\Delta L}\right]\right\}\tan\varphi}{\frac{\pi}{8}d^2(C_{\mathrm{d}} + C_{\mathrm{L}}\tan\varphi)} \tag{1.34}$$

where ΔL is the distance between two depth in seabed, ΔP is the excess pore pressure difference between the two points, τ_{e} is the critical shear stress, φ is the saturated soil static internal friction angle, d is the sand size (for the median diameter of d_{50}), ρ_{s} is the sediment particle density, ρ is the density of water, resistance coefficient $C_{\mathrm{D}} = 0.4$, uplift coefficient $C_{\mathrm{L}} = 0.1$.

Cheng et al. (2004) also carried out similar studies and will not be described here. Another representative modification method is Fox et al. (2007) who introduced the seepage velocity parameters into the traditional critical erosion shear stress formula

$$\tau_e = \frac{C_2 q}{(s - 1)\varepsilon K} \quad (1.35)$$

where C_2 is the empirical coefficient, s is the ratio of particle to fluid density, q is the percolation rate, ε is the porosity, K is the permeability coefficient.

To consider the influence of wave-induced seabed liquefaction on erosion/resuspension in the Yellow River Delta, we evaluated the decay law of critical entrainment flow velocity (u_{cr}) and critical shear stress (τ_{cr}) of liquefied sediments under waves of different recurrence period through laboratory experiments. It is reported that u_{cr} decays 6–32% and τ_{cr} decays 12–53% under the waves of 5-year recurrence period. Under the waves of 50-year recurrence period, the maximum u_{cr} attenuation is about 46% and the τ_{cr} attenuation is up to 72%. Zhang et al. (2017a) also attempted to parameterize the erosion resistance of liquefied sediments in Hangzhou Bay and found that the erosion rate of liquefied sediments was significantly affected by its yield stress

$$E_r = 0.00027\left(\frac{\tau_b}{\tau_c} - 1\right)e^{-0.00076\tau_y} \quad (1.36)$$

where τ_y is the yield stress, τ_b is the bottom shear stress, τ_c is the critical shear stress.

It is generally accepted that the effect of wave-induced seabed liquefaction on erosion and resuspension is to reduce the erosion resistance of surface sediments. Moreover, some scholars also argued that the vertical seepage flows caused by residual pore pressure will also cause vertical internal transport of fine particles. Clarke et al. (1982) was the first to propose that waves would cause the movement of pore water in surface sediments and carry fine sediments into the water to suspend. The effect of wave-induced pore water movement on sediment resuspension was initially proposed. Maa et al. (1998) proposed that the surface of cohesive seabed would form floating mud under the action of waves and the thickness of the floating mud layer would also be affected by the transient water level fluctuation. The floating mud can easily be suspended in the case of unidirectional flow, which has a significant impact on cohesive sediment transport process. Nichols et al. (1994) found that significant upwelling and overflow of pore fluid and sediment flow occurred after liquefaction. However, due to its simulation method of artificial hydraulic gradient applied in a tank, the true effect of wave-induced pore pressure accumulation cannot be completely simulated effectively (Clukey et al. 1985). Tzang (1998) suggested that wave-induced pore pressure response would promote the movement of pore water, resulting in "internal sediment suspension" in the seabed. Sterpi (2003) designed an flume experiment to study the grain size of the internal eroded sediments that carried by the vertical seepage erosion, and established a rough estimation of the erosion amount. Fine-grained sediments on the intertidal seabed of the Yellow River Delta after the storm surges and speculated that the source was the fine-grained material (5–8 φ) which was "pumped" from the interior of the tidal flat to the surface of the seabed during the dissipation of wave-induced residual excess pore pressure. According to the results of flume experiment, we found that the seabed liquefaction would