Research progress of turbulence characteristic parameters in bottom boundary layer

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Abstract: The bottom boundary layer in estuaries and coastal waters is an area where water flows interact with the bottom bed, and its flow structure is very complex. The influence on the bed morphology, energy and material exchange, circulation and other processes cannot be ignored. With the rapid development of technology, the measurement methods of the parameters of the bottom boundary layer are more mature, and the measurement and analysis of turbulence are more in-depth. In addition, the study of the bottom boundary layer has a great role in promoting the development of other similar disciplines, and its application value is increasingly obvious. This paper presents the latest progress in the study of turbulent characteristic parameters of the bottom boundary layer in estuaries and coastal waters, including measurement methods, frictional velocity, bottom roughness length and bottom drag coefficient. These achievements are summarized and analyzed, and the shortcomings of the current research are discussed, and the future research is prospected.

1. Introduction
The bottom boundary layer refers to the water layer whose flow structure is obviously affected by the bottom boundary. It is formed by the interaction between the bottom non-uniform flow and the irregular bed bottom. It has the characteristics of strong turbulence and shear. It has an important influence on the dynamic characteristics of the boundary layer flow, the changes in bed morphology, the re-suspension and transport of fine particles, the transport of salt and other chemical substances, etc. It is one of the difficult and hot issues in the international estuary and coastal dynamics research\textsuperscript{[1, 2]}. With the efforts of researchers and the deepening of research methods, the research scope of the bottom boundary layer is also more extensive than before, but within a certain range of the bottom interface. It also highlights the necessity of studying the bottom boundary layer for understanding and analyzing the flow characteristics, material transport, energy exchange and other phenomena in estuaries and coastal areas. Bottom boundary layer can usually be characterized by bottom stress, velocity profile, boundary layer thickness and other parameters. Among them, bottom stress, friction velocity and drag coefficient are the basic physical quantities to describe the friction characteristics of the bottom boundary layer. In the shallow sea area, turbulent energy dissipation in the bottom boundary layer play an important role in energy balance, affecting the circulation structure of the whole sea area, and controlling the processes of sediment resuspension\textsuperscript{[3]}. In addition, the bottom boundary layer of coastal oceans is also affected by wind, wave, tide, vertical eddy viscous distribution\textsuperscript{[4, 5]}, and stratification related to temperature and
salinity. It also provides mechanisms for energy transport, resuspension and transport of bottom sediments, and produces submarine ripple and other bed morphologies, which have an impact on water flow and biochemical processes. Therefore, the understanding of ocean flow, sediment transport, pollutant diffusion and ecological processes depends on the understanding of turbulence characteristics in the bottom boundary layer.

2. Measurement methods
With the development of observation instruments, research methods is becoming more diversified, and the research, observation and treatment methods of the seabed boundary layer are also more widely applied. With the wide application of acoustic Doppler velocimeter (ADV), acoustic Doppler Current Profiler (ADCP) and other high-frequency and high-resolution acoustic flow measurement instruments, the measurement and analysis of estuarine turbulence has gradually deepened. ADV are capable of rapid, accurate and three-dimensional velocity measurement, and the resulting velocity point measurement has high spatial and temporal resolution. In many cases, turbulence parameters such as Reynolds stress can be calculated directly and dissipation rate can be estimated indirectly. It can also measure the turbulent flux of temperature and salinity, and estimate the dissipation rate of temperature and salinity changes. Its post-processing function has good reliability and adaptability. ADCP is usually used for large-scale velocity measurement. It can measure the radial velocity, that is, the water velocity part parallel to the acoustic beam emitted by the acoustic transducer, and then calculate the water velocity according to the angle between the acoustic beam and the direction of the water flow. ADCP can measure the velocity profile of the cross section, calculate the inertial distance wavenumber spectrum and estimate the dissipation rate, and generate turbulent Reynolds shear stress profile by variance method. It has the characteristics of no disturbance of flow field, short test time and wide range of velocity measurement. Particle image velocimetry can generate two-dimensional velocity images, which can be used to estimate the spatial statistics of turbulence. Modern sensors have been greatly improved to accurately measure and analyze turbulent Reynolds stress and turbulent flux, as well as the corresponding dissipation rate. However, the successful application of these methods requires resolution of the appropriate scales. Acoustic Doppler velocity profiler can not solve the problem of Sufficiently small scale, and the field of view of particle image velocimetry can not solve the problem of large scale. In addition, surface waves has a very complex influence on the measurement of turbulent Reynolds stress, which makes it more difficult to accurately measure turbulent Reynolds stress. Moreover, the velocity variation associated with surface waves is one order of magnitude larger than that of turbulence, which makes it difficult to extract relatively small turbulence action. The role of the bottom boundary layer in land slope exchange is still poorly understood, especially in the boundary layer formed by wave action. Up to now, there is still a lack of field observation data. Therefore, it is indispensable to improve the observation technology and research means in the study of the bottom boundary layer.

3. Friction velocity and roughness length

3.1. Friction velocity
Frictional velocity is indispensable in hydraulic calculation. It is a function reflecting wall shear stress and plays an important role in many shear stress analysis. Song assumes that the vertical distribution of tidal current obeys logarithmic rate based on the governing equation of three-dimensional tidal current movement, and thus obtains a revised expression of friction coefficient which can comprehensively reflect the factors of water depth, water level gradient and flow direction. Nouh and Townsend studied the distribution law of bed shear stress in open channel with curved channel by experiment, and revealed the following law: in open channel with curved channel, the resistance coefficient of flow will increase due to the strong secondary flow, resulting in the increase of bed shear stress. Zhang, et al. Through experimental analysis, it is pointed out that when roughness suddenly increases, the frictional velocity will suddenly increase at the sudden change point, and under the same conditions
According to the current research status of friction velocity, there are several methods to determine friction velocity in experimental research. (1) extending the vertical distribution of Reynolds stress to the bed surface to obtain the shear stress of the bed surface so as to calculate the friction velocity; (2) using the measured velocity distribution to calculate the friction velocity; (3) high frequency observation method; (4) resistance balance method. Friction velocity can also be determined by Preston tube directly measuring wall shear stress. Researcher analyzed (1) and (2) these two different determination methods through uniform flow experiment, and obtained more consistent results. Chen, et al. discussed the influence of sample size of vertical velocity distribution in open channel on the fitting of logarithmic formula. He used laser Doppler velocimeter to carry out flume test. The friction velocity, integral constant, correlation coefficient of statistical variables and variation coefficient obtained by logarithmic formula fitting will change with the size of sample size.

3.2. Roughness length

The application of boundary layer model needs to determine the hydrodynamic roughness length. The correlation between roughness length and particle size, fluid viscosity and shear velocity has been studied extensively for uniform fixed sand. Roughness length is related to Reynolds number, thickness of boundary layer and shape of bottom. If the boundary is more complex and the bed is erodible, the roughness length will be difficult to determine. Moreover, the effect of wave-current interaction on bed roughness is very obvious. In addition, there are similar characteristics in some studies of atmospheric science and engineering science, which is of great help and important reference to the study of complex boundary layer roughness.

Because of the frictional action of the bottom bed, the flow in the bottom layer of the estuary and coast is quite different from that in the upper layer. In the early years, many scholars have studied and described the bottom roughness of mobile sediment bed type. Friction velocity and roughness length are important parameters in the study of bottom boundary layer. Therefore, accurate estimation of roughness length and friction velocity plays an important role in the study of water flow in Estuary and coastal bottom boundary layer. Field observations conducted by Anwar show that the instability of tidal current has a strong influence on the turbulence mechanism and related hydrodynamic parameters such as turbulent diffusion coefficient, drag coefficient and roughness length. Xu estimates the bottom stress and roughness length of Chesapeake Bay near the bottom by means of inertial dissipation method. The results show that when the wave action is not obvious, resistance coefficient and roughness length can be used to characterize the bed properties. Konsoer, et al. explores the length scales and statistical characteristics of form roughness along the outer banks of two elagant bends on a large meandering river by calculating the root-mean-square of normal distances from a Triangulated Triangular Network surface and Hilbert Huang Transform spectral analysis. These studies pointed out that the scalar roughness length and laminar resistance are necessary for calculating scalar fluxes. Nikura under different Reynolds number, pipe diameter and sediment particle size conditions, it was found that the velocity of flow decreased to 0 at the position of $d_{50}/30$ from the bed with median particle size of $d_{50}$. And the parameter $k_s$ is defined as Nikura roughness, which links $K_s$ with $z_0$.

3.3. Relationship between them

The research on the relationship between friction velocity and roughness length has made great achievements. Zhu et al. based on the Nikuraz experiment and combined with Schifflinson's resistance formula, discussed theoretically the relationship between friction velocity $u^*$ and roughness length $z_0$, and concluded that there is a linear relationship between $z_0$ and $(u^*^2)/g$ in tidal channel.

Hao et al. Starting from the principle of fluid mechanics, using Prandtl mixing length and Von Kanman self-similarity theory, a logarithmic linear model of tidal current velocity distribution near the bottom of Estuary and coast is established. The direct consistency of the two models is discussed by regression analysis between roughness length and frictional velocity. From the statistical point of view, the values of $z_0$ and the corresponding $u^*$ obtained by six vertical enumeration methods are used to
calculate the correlation between the bottom boundary layer $z_0$ and $(u^+)^2/g$ respectively. Li, et al. [39] Based on the tidal current observation data, the frictional velocity and roughness length of the boundary layer are analyzed by using Kaman-Prandtl model. It is concluded that the average velocity at different time scales has little effect on calculating the frequency of $u$-$ln(z)$ linear relation. The roughness length of the bed surface in the flood stage is longer than that in the ebb stage, and the frictional velocity in the flood stage is less than that in the ebb stage. Pan et al. [40] Based on the observed data of vertical current velocity profiles in Xiamen Bay during the period of typhoon Saint-Pa affecting the Taiwan Strait, the frictional velocity and roughness length were analyzed. It was found that the frictional velocity and roughness length during typhoon were larger than those during non-typhoon.

Researchers used logarithmic distribution model and enumeration method combined with least squares method to calculate the friction velocity and roughness length of power flow, analyzed the phase relationship between friction velocity and roughness length, and concluded that there is a good consistency in the phase relationship between friction velocity and roughness length with time, and both of them reach the maximum at the same time [41]. Qiao [42] analyzed five methods for calculating frictional drag velocity and roughness length. The results show that the logarithmic parabolic method is the best method for calculating the friction velocity and roughness length of tidal current in the Yangtze Estuary, and the consistency of the two parameters in physical connotation is analyzed. Wang [43] analyzed some important parameters such as bed shear stress $\tau_b$, friction velocity $u_*$ and roughness length $z_0$ in the near-bottom boundary layer based on ADP velocity observation data. Estuary flow is affected by many factors, such as tidal current, sediment stratification, dilute salt water mixing, surface wind, etc. Song, et al. [44] regards the flow as the superposition of tidal current and wind-driven current. By using enumeration combined with least square fitting method, the reasonable parameters of surface wind are obtained. Ni, et al. [45] took the above two factors into account, and added the effects of density flow and runoff, and achieved good results. The most important reason for the formation of velocity profile is the frictional effect of the bottom bed on the flow. It is this friction that forms the bottom boundary layer near the bottom, which makes the velocity in this region different from that far away from the bottom turbulent core. Therefore, it is a common method to obtain friction characteristic parameters from velocity profile for analyzing hydrodynamic mechanism.

4. Bottom drag coefficient

Resistance coefficient is an important parameter of the bottom boundary layer. Some factors, such as morphological drag caused by local topography, wave-current interaction and the transformation of mean flow pattern in the bottom boundary layer will have a great impact on the variation of drag coefficient [46]. The results of Liu [47] in the bottom boundary layer of tidal current in the Yellow Sea show that the drag coefficient decreases gradually with the increase of average velocity, and the range of $C_d$ varies from $5.0 \times 10^{-4}$ to $8.2 \times 10^{-5}$. Scully measured and studied the related parameters. The results show that the wave-induced velocity has a great influence on the change of $C_d$. The action process of drag coefficient has not been discussed in detail in theory. Moreover, drag coefficient has a very important influence on the formation of vortices on the continental shelf, and it is also very important for the trans-contour transport of water. Therefore, the study of drag coefficient needs longer time series observation data to analyze the turbulence characteristics in the bottom boundary layer under different tidal levels and structures. Some studies have shown that [46], the correlation between the numerical variation of drag coefficient and the size of the bed is not clear.

5. Conclusion

1. Modern measuring instruments can accurately measure turbulent Reynolds stress and turbulent flux, and estimate the corresponding dissipation rate of temperature and salinity changes. With the development of technology, the methods for dealing with turbulence scale problems of surface waves, ocean currents and complex topography are more mature.

2. In the case of wave-ocean current interaction with erodible seabed, the role of bottom boundary layer in slope exchange and the dependence of roughness length on Reynolds number and other flow
characteristics need further study.

3. Due to the limitation of data, the quantitative dependence of drag coefficient on mean velocity have not been clearly concluded and there are few studies on the variation of drag coefficient in tide.

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