Application of Sub-Bottom Profiler to Study Riverbed Structure and Sediment Density

Wang Rui\textsuperscript{a} Li Changzheng\textsuperscript{b} Yan Xiaofei\textsuperscript{c}

Yellow River Institute of Hydraulic Research
Zhengzhou, 450003, China
\textsuperscript{a}E-mail: 7488918@QQ.com  \textsuperscript{b}E-mail: hnlzl@163.com  \textsuperscript{c}E-mail: yxf513@126.com

Abstract. In this paper, we present a study on the riverbed structure and sediment density in-situ test by using sub-bottom profiler. Compared with traditional direct observation methods, the sub-bottom profiler method based on sonar technology is non-contact, low-disturbance and high-efficient. We finish the investigation of several sections in Sanmenxia and Xiaolangdi reservoirs, which located on the main channel of lower reaches of Yellow River. Collected data show a detailed layered structure of the riverbed sediment which believed caused by sedimentary processes in different periods. Further more, we analyse the reflection coefficient of water-sediment interface and inverse the sediment density data from the raw wave record. The inversion method is based on the effective density fluid model and Kozeny-Carman formula. The comparison of the inversion results and sample tests shows that the in-situ test is reliable and useable.

1. Introduction
Riverbed structure and sediment density are important and basic information in research river sedimentation problems. As the sedimentation management has become an important challenge in river and reservoir operations, modern geophysical equipment such as sub-bottom profiler, side-scanning sonar and multi-beam sounding are playing more and more important roles. A lots of geophysical methods have been applied to study science and engineering problems in flood control, river ecology, engineering safety and etc.

In recent decades, sub-Bottom profiler has been widely used in underwater terrain measuring, hidden structure exploration, buried objects searching [1]. Beside the structure information in the data collected by profiler, the property of bottom sediment in shallow water also can be found out by inversion process. In early 1990's, LeBlanc used CHIRP sonar signals to determined major parameters of underwater sediment, including particle density, particle compressibility and rigidity constant[2]. Panda used the frequency variation of the received signals to inverse the impedance of the underwater sediment medium[3]. The theory of Biot assumes the sediment is two-phases medium includes solid particles and pore fluid. The two kinds of components of the medium move at different displacements[4]. The theory make it applicable that the sediment deposits having elastic and porous traits. Hovem and Ingram proved the high-permeability pore model plays an important role in viscosity attenuation[5]. Stoll improved the Biot model and discussed two typical situations of acoustic attenuation mechanisms in porous medium[6]. Schock used Biot theory to computer the sediment's density and porosity[7]. Chiu inversed the first-layer sediment at river bottom based on the effective density fluid model(EDF)[8].
In 2016 and 2017, Yellow River Institute of Hydraulic Research complete a series experiments on detecting riverbed structure and sediment density by sub-bottom profiler. The explored area are located at Xiaolangdi and Sanmenxia reservoirs on the Yellow River. The researchers also take sediment samples in mechanical way and test the density of samples in lab to evaluate the accuracy of in-situ investigation by sub-bottom profiler. The inversion of sub-bottom profiler data are developed from the Kozeny-Carman formula and the EDF model. It was found from the experiment that the sampling process squeezed the sediment samples and introduced error to the measurements. But the sediment gradation obtained by sampling sediment was still considered reliable.

The 3200-XS sub-bottom profiler from the U.S. Edgetech Corporation is adopted, which consists of towing fish, towing line and deck unit. The towing fish is of the type SB-216S and comprised of 1 transmitting transducer and 2 receiving transducers. The transmitted signal has a beam angle of 24°(-3dB). Sound boarding is used to separate the transducers in order to prevent the downward sound wave from interfering the received signal and to minimize surface reflection. The transducer transmits frequency modulated signal to the deep water right beneath it. The transmitted signal is able to penetrate into the stratum layers and will be reflected when the wave impedance changes. The reflected signal is received by the receiving transducer and sent to the deck unit through the towing line. A Topcon GPS system was connected with the host machine of the deck unit. The GPS coordinate corresponding to each measuring point is extracted using the collection software.

2. Theories and Methods

Sub-Bottom profiler method is a branch of acoustic method. The profiler sends acoustic signals by transmitters and record the echo signals. The received signals are proceeded and presents as time-position sections. The Edgetech sub-bottom profiler was operated with CHIRP pulse and achieved a penetration up to 25m in sandy bottom.

The Biot model includes a large set of parameters so that it is almost an impossible mission to inverse the properties of sediment directly by the Biot model. In order to simplify the problem, Williams proposed the EDF model, which has more less parameters and make it practicable to inversion sediment's physical parameters from sound wave data. According to Williams, the frame module $K_h$ and the fluid module $\mu$ is much smaller than the sediment grain module and can thus be set to 0. The sound speed and attenuation estimated by the EDF model are very approximate to the result estimated by Biot theory.

When $K_h$ and $\mu$ are equal to 0, there is only one independent module for the pore medium. Hence, the equivalent fluid module is:

$$H = (\frac{1-\beta}{K_r} + \frac{\beta}{K_f})^{-1} \quad (2.1)$$

where $\beta$ denotes the porosity, $K_r$ and $K_f$ denote the bulk module of the sediment grain and the bulk module of the pore fluid. Then the sound speed in the medium can be written as:

$$c = \sqrt{\rho_{eff}(\tilde{\omega})} \quad (2.2)$$

where

$$\tilde{\omega} = 2\pi f \quad (2.3)$$

$$H = \frac{K_r^2}{D-K_b} \quad (2.4)$$

$$D = K_r[1 + \beta(K_r/K_f - 1)] \quad (2.5)$$

The equivalent density $\rho_{eff}(\tilde{\omega})$ is:

$$\rho_{eff}(\tilde{\omega}) = \rho_f \frac{\alpha(1-\beta)\rho_s + \beta(\alpha-1)\rho_f + \frac{ib\rho F\eta}{\rho_f \omega \kappa}}{\beta(1-\beta)\rho_s + (\alpha-2\beta+\beta^2)\rho_f + \frac{ib\rho F\eta}{\omega \kappa}} \quad (2.6)$$

where $\tilde{\omega}$ denotes the angular frequency, $f$ denotes the frequency, $\rho_f$ and $\rho_s$ denote the pore fluid density and sediment grain density, $\rho$ denotes the sediment bulk density; $\alpha$ and $\eta$ denote the tortuosity and pore
fluid viscosity respectively, \( k \) denote the permeability, and \( F \) denotes the viscosity correction to account for frequency-dependent viscous losses of the oscillating flow in the sediment pores\(^\text{[9]}\).

The relationship between sediment permeability and other parameters can be determined through experimental analysis. And the mean grain size of the sediment was used to represent the relationship between permeability and porosity. Considering the surface area \( S_0 \) of sediment grain and \( K \) the estimated empirical constant, the kozeny-carman formula can be written as:

\[
\kappa = \left( \frac{1}{K_S \delta^2} \right) \beta^2 (1-\beta)^2
\]

Many evidences and research achievements show that the Equation(2.7) is valid for grain in a large range of size. The permeability \( \kappa \) can be determined given the sediment's porosity \( \beta \) and \( S_0 \). Obviously, \( S_0 \) is related with the shape of grains. In real world, the shape has no fix pattern. But generally, it can be regarded as spherical and in the case of spherical grain, \( S_0=6/d \) where \( d \) is the diameter of grain. For the cluster of sediment grains, its average surface area is:

\[
\bar{S}_0 = \sum_{n=1}^{N} (6/d_n \times X_n)
\]

where \( d_n \) denotes the different grain diameters, \( X_n \) denotes the gradation of sediment grains. After than, we decide on the specific form of Equation (2.7) and computer the property of sediment using the EDF model. The gradation is measured in this paper based on relevant sediment testing regulations.

Before inversion of the sediment's density, the on-site reflection coefficient \( R(f) \) for the water-sediment interface must be calculated. During the exploration of sub-bottom profiler, the linear frequency modulation signal is transmitted by the transducer; and the signal received by the profiler is pulse compressed to improve the signal/noise ratio. The reflection coefficient is computed using the secondary reflection wave received by the profiler. The secondary reflection refers to the echoed signal from the riverbed is reflected by the air-water interface and then by the riverbed again. The secondary wave signal cannot be received effectively if the duration of the received signal is insufficient during on-site test.

It is rapid to obtain the distribution and wave impedance of riverbed sediment's using acoustic methods such as sub-bottom profiler. But it is a real challenge to calculate the sediment's porosity, density and wave velocity. A applicable method is using EDF model which involves porosity, permeability and other basic parameters. The calculation has three steps: (1) For a exploration area, sampling several sediment sample in mechanical way and test the gradation in laboratory. Computer the grain surface area \( S_0 \); (2)Establish template of relationship between reflection coefficient and porosity. Estimate the sediment's porosity by the reflection coefficient determined through testing results; (3) Combine the Kozeny-Carman formula and the EDF model. Define \( \beta_0 \) as the original value of porosity and substitute it into the EDF model. Then, defined the objective function presents the difference between the computed reflection coefficient \( R \) and the on-site tested reflection coefficient \( R(f) \). The porosity which minimized the value of the objective function is the best inversion result. Finally, the porosity can be exploited to compute sediment density, wave velocity and permeability.

3. Results of Exploration and Inversion

Xiaolangdi and Sanmenxia reservoirs are both large-scale reservoirs areas in the middle reaches of Yellow River and are playing important roles in the task of flood control, sediment retaining and power generation. In 2015 and 2015, Yellow River Institute of Hydraulic Research carried on a series experiments of riverbed structure and sediment's density exploration by sub-bottom profiler. According to the on-site sediment characteristics, the selected CHIRP linear frequency modulation signal has a frequency band of 500Hz~7kHz and 700Hz~12kHz, the transmission frame rate is 5Hz and the towing fish moves at a speed of 1.2 m/s. The ship speed is adapted to the water flow during the test. The sampling and survey is studied with profile as the unit. The line segment that connects the left and right river bank is a profile along the direction vertical to stream current (the distance between neighboring profiles is about 2 km).

The profiler test lines are mainly along the existent hydrology testing sections. The sections are numbered in sort from the upper river. The profiler exploration results inherited the name system.
Figure 1 and Figure 2 show the depth-position acoustic sections of section No.11 and No.26. The images show the layered structure of the riverbed. The riverbed is basically smooth and the sound wave reflected from it can be regarded as vertically going back up to the profiler.

**Figure 1**: The profiler image of the 11th section

**Figure 2**: The profiler image of the 26th section

Figure 3 shows the calculation results (computed density and wave velocity) of 12 profiles. The gradation of sediment samples from each profile was tested. The computed wave velocity indicated that the surface layer of the silt has a thickness of 2.6±0.2m. The effective density is in the range of 1350kg/m$^3$~1500kg/m$^3$, and the speed range is 1470m/s~1500m/s. The results show that the percent of clay is high and the porosity is large, causing the small density. The density obtained from theoretical model is 1495kg/m$^3$, proving consistency of the result computed using the proposed method with the result computed using the empirical formula.

**Figure 3**: Calculation results of 12 profiler sections
4. Conclusion
Sub-Bottom Profiler is an efficient and reliable method to detect riverbed structure. Water-sediment interface and inner surface in sediment of different ages can be clearly recognized. Detect depth and the resolution are mutually exclusive of each other. The working frequency of profiler should be chosen carefully in consideration of the target of detection.

With the data collected by profiler, it is practicable to inverse the density, wave velocity and permeability of sediment near the water-sediment interface. When the riverbed is smooth and the wave impedance of the sediment at the riverbed varies slightly in horizontal directions, the results of inversion are more feasible.

In the future, we will continuously focus on the technology to test the density and other parameters in-situ with acoustic equipments, increasing the test accuracy. We also will try to inverse parameters of sediment beneath the water-sediment interface.

Acknowledgements
This study was sponsored by the “National Key R&D Program of China” (grant number 2016YFC0401608) and supported by the special funds for Yellow River Institute of Hydraulic Research (grant number HKY-JBYW-2016-29)

References
[1] Grelowska G., Kozaczka E., Szymczak W. Method of data extraction from sub-bottom profiler’s signal, Hydroacoustics, 13, 109-118 (2010)
[2] LeBlanc L.R., Mayer L., Rufino M., Schock S.G., King J., Marine sediment classification using the chirp sonar, The Journal of the Acoustical Society of America, 91(1), 107-115 (1992)
[3] Panda S., LeBlanc L.R., Schock S.G., Sediment classification based on impedance and attenuation estimation, The Journal of the Acoustical Society of America, 96(5), 3022-3055 (1994)
[4] Biot M.A., Theory of propagation of elastic waves in a fluid-saturated porous solid I. Low-frequency range, The Journal of the Acoustical Society of America, 28(2), 168-178 (1956)
[5] Hovem J.M., Ingram G.D., Viscous attenuation of sound in saturated sand, The Journal of the Acoustical Society of America, 66(6), 1807-1812 (1979)
[6] Stoll R.D., Acoustic waves in ocean sediment, Geophysics, 42(4), 715-725 (1977)
[7] Schock S.G. A method for estimating the physical and acoustic properties of the sea bed using chirp sonar data, IEEE Journal of Oceanic Engineering, 29(4), 1200-1217 (2004)
[8] Chiu L., Chang A., Lin Y.T., Liu C.S., Estimating geoacoustic properties of surficial sediments in the North Mien-Hua Canyon region with a chirp sonar profiler, IEEE Journal of Oceanic Engineering, 40(1), 222-236 (2015)