FCT finite difference forward simulation of the submarine viscoelastic seismic wavefield

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Abstract. The actual seafloor is the typical viscoelastic medium, covered with unconsolidated geological bodies like sand, gravel, sludge, and detritus on the surface. When the seismic wave is propagating therein, viscosity of the seafloor strata will cause seismic wave energy loss, amplitude attenuation and gradual frequency reduction at the wavelet center, and then the accurate subsurface information and high-resolution images cannot be obtained directly from the seismic data due to the reduced signal resolution and SNR. Considering seabed viscoelastic media properties, a model including quality factor, density, and other physical parameters, the flux corrected transport (FCT) algorithm is established to describe the target seafloor and solve the wave equation, in which, the finite difference numerical simulation method of FCT is used to suppress the numerical dispersion generated by differential calculation in coarse grid, improve the seismic wavefield simulation accuracy and computational efficiency. Based on the submarine ancient channel types and the basic characteristics of the real and typical marine geological phenomena, the seismic responses to the three types of submarine ancient channel models, which are straight, curved and braided, are calculated, with good results acquired.

1. Introduction
With the epoch development and technological advance, a new era of ocean development is approaching. The production and construction activities in the marine engineering are increasingly frequent, (e.g., land reclamation, construction of the terminal, channel dredging, nuclear power plant building in shallow water, exploration and development of offshore oil, large-scale offshore wind farm, laying of submarine cables). With continuous ocean construction, the risk of submarine geological disasters is significantly increased. Compared with the land area, the submarine area has complex terrain and variable sediments, which brings great difficulties to construction. The use of advanced geophysical technologies to detect sediment distribution and stratigraphic distribution in shallow seas will provide important guidance for subsea engineering construction. Exploration of marine geological hazards and the reduction of offshore engineering losses require the careful detection and evaluation of shallow sea environments and close monitoring of existing buildings on the seafloor [13]. Therefore, it is of great significance to study the detection methods and techniques of shallow sea environments.

Seismic exploration technology has been widely used because of its high resolution, high efficiency, and low cost compared with geological engineering methods such as offshore engineering geological drilling and underwater static sounding [2, 13]. Numerical simulation is of significance to strengthen the wavefield characteristic analysis of different geological hazards, the rational processing and interpretation of data, as well as the density, void ratio, standard penetration number, characteristic value of bearing capacity, thickness and quality factors such as seafloor media, attribute parameter inversion [3].
The seabed surface is mainly covered with non-consolidated geological bodies such as sludge, silt, and silty clay, which have the property of the viscoelastic medium. When the local seismic wave propagates in it, the absorption effect caused by the seafloor's viscosity is one of the main factors for the attenuation of seismic waves [6]. Conventional seismic processing technology generally assumes that the earth medium is a completely elastic medium in which the propagation of seismic waves satisfies the Alembert equation. In this way, there will be no energy loss and waveform distortion during the propagation of the seismic waves, and the resolution of the pulse waveform received by the detector will be higher. However, this is an ideal state. In reality, it is difficult to do so. The geophone receives a seismic composite wave with a certain delay and a low frequency. Besides, when being far away from the source, the received low-frequency components are more abundant than the high-frequency components. The frequencies of the waves are different, so is the phase velocity during propagation. Earth's attenuation and absorption of seismic waves, especially the absorption of high-frequency components, will cause the resolution of seismic data to decrease [8]. Both scalar and elastic equations in isotropic media assume that the medium has no absorption attenuation to seismic waves. The viscoelastic wave equation takes into account the viscous absorption and attenuation of the elastic wavefield by the actual underground media. Therefore, the viscoelastic wave equation can more accurately describe the propagation law and wavefield characteristics of the elastic wave in the actual underground media.

The finite difference method has high simulation precision and fast calculation speed while occupying little memory, which makes it one of the most popular methods to solve seismic wave equations [4]. However, the finite difference discretizes the time and space and replaces the differential with the difference, which will produce the numerical dispersion phenomenon in the process of solving. The main frequency of the wavelet will decrease rapidly after passing through the near-surface because of the low-quality factor of the near-surface and the serious absorption of the geofilter [3,7]. The air gun excitation is carried out in the seawater, and since the quality factor of the seawater is large, there is almost no absorption of the wavelet. Therefore, the frequency of air gun source wavelet is higher, even up to about 200Hz. In this way, there are very few sampling points at each wavelength, which will inevitably produce severe numerical dispersion. Although it can be improved by reducing the space mesh or improving the accuracy of the finite difference, it will greatly increase the computation. Boris et al. Boris et al. (1997) [1] proposed a flux-corrected transmission (FCT) algorithm to solve the acoustic wave equation in the process of solving the continuous equation of fluid dynamics, which on the one hand effectively suppressed the numerical dispersion resulting from the difference calculation under coarse mesh [5, 9, 11]. On the other hand, the method of extracting formation quality factors based on the wavelet domain also provides necessary conditions for forwarding modeling of viscoelastic media [10].

Aiming at the typical marine geological phenomenon of the ancient submarine channel, this paper studies the numerical simulation method of the two-dimensional seismic wavefield of the submarine viscoelastic medium. Through modeling analysis, the seismic wavefield profile characteristics of three different types of ancient submarine channels, i.e., straight, curved, and braided, were obtained, which provided reference for seismic exploration and image interpretation of submarine media.

2. FCT finite-difference algorithm

In the process of marine seismic exploration, high-frequency sources are used for obtaining higher resolution. When the quantity of sampling points in a wavelength is very small, the numerical dispersion phenomenon will occur. Although reducing the size of the spatial grid can improve part of the effect, the amount of calculation will be greatly increased. FCT finite-difference algorithm can solve this problem. To apply FCT algorithm to solve the viscoelastic wave equation, we take the velocity component \( V_x (v_{ij}) \) as an example, and the calculation steps are as follows [11, 13]:

1. Calculate the diffusion flux at the time \((k-1)\)
$$Q_{a_{i+1/2, j}}^{k-1} = \eta_i \left( V_{i+1/2, j}^{k-1} - V_{i, j}^{k-1} \right) 0 \leq \eta_i \leq 1$$
$$Q_{a_{i, j+1/2}}^{k-1} = \eta_j \left( V_{i, j+1/2}^{k-1} - V_{i, j}^{k-1} \right) 0 \leq \eta_j \leq 1$$

(1)

Where, $0 < i < N_x$ and $0 < j < N_z$, $N_x$ and $N_z$ are the horizontal and vertical grid points of the model respectively; $Q_{a_{i+1/2, j}}^{k-1}$ and $Q_{a_{i, j+1/2}}^{k-1}$ are respectively the diffusion fluxes of components at time $(k - 1)$ in the X and Z directions; $\eta$ is the diffusing factor, whose value is generally $0.02 - 0.1$, which can be obtained by some numerical calculations of amplitude changes tested according to the actual situation.

(2) Calculate the diffuse flux at the time $(k + 1)$

$$\tilde{Q}_{x_{i+1/2, j}}^{k+1} = \eta_i \left( V_{i+1/2, j}^{k+1} - V_{i, j}^{k+1} \right)$$
$$\tilde{Q}_{z_{i, j+1/2}}^{k+1} = \eta_j \left( V_{i, j+1/2}^{k+1} - V_{i, j}^{k+1} \right)$$

(2)

In the formula, $\tilde{Q}_{a_{i+1/2, j}}^{k+1}$ and $\tilde{Q}_{a_{i, j+1/2}}^{k+1}$ are the dispersion fluxes of the $V_x$ components in the X and Y directions at the time $(k + 1)$, $\eta_i$ is the anti-diffusion factor which is usually $0.01 \leq \eta_i < \eta_j \leq 0.1$.

(3) Correct the velocity component $V$ using the diffuse flux at the time $(k - 1)$

$$\tilde{V}_{i, j}^{k+1} = V_{i, j}^{k+1} + \left( Q_{a_{i+1/2, j}}^{k-1} - Q_{a_{i, j+1/2}}^{k-1} \right)$$

(3)

In the formula, $V_{i, j}^{k+1}$ and $\tilde{V}_{i, j}^{k+1}$ are the speeds before and after the correction $(k + 1)$. This step is to correct the waveform of the velocity variable by smoothing.

(4) Calculate the diffusion difference of $\tilde{V}_{i, j}$

$$X_{i+1/2, j} = \tilde{V}_{i+1/2, j}^{k+1} - \tilde{V}_{i, j}^{k+1}$$
$$Z_{i, j+1/2} = \tilde{V}_{i, j+1/2}^{k+1} - \tilde{V}_{i, j}^{k+1}$$

(4)

In the formula, $X_{i+1/2, j}$ and $Z_{i, j+1/2}$ are the diffusion differences in the X and Z directions, respectively.

(5) Anti-diffusion processing to find the corrected velocity component $V$

$$V_{i, j}^{k+1} = \tilde{V}_{i, j}^{k+1} + \left( X_{i+1/2, j}^{c} - X_{i, j-1/2}^{c} \right)$$
$$Z_{i, j+1/2}^{c} = S_{x} \max \left\{ 0, \min \left[ S_{x} X_{i, j-1/2}^{c}, \text{abs} \left( \frac{\tilde{V}_{i, j+1/2}^{c}}{S_{z}} \right), S_{x} X_{i+1/2, j}^{c} \right] \right\}$$
$$X_{i, j-1/2}^{c} = S_{x} \max \left\{ 0, \min \left[ S_{x} X_{i, j+1/2}^{c}, \text{abs} \left( \frac{\tilde{V}_{i, j-1/2}^{c}}{S_{z}} \right), S_{x} X_{i+1/2, j}^{c} \right] \right\}$$

(5)

Seismic wavefield simulation of ancient submarine channel

The ancient river channel is the abandoned river channel as a result of river diversion. The most important feature of the ancient river channel is its associated bed facies deposition, with a pebble or coarse sand layer at the bottom and sand or silt layer at the top. In the vertical section, the particle size is thick at the bottom and thin at the top; in the longitudinal section, the upstream is thicker than the downstream.
Buried ancient rivers are formed by ground subsidence. As for rivers that are not prone to sedimentation on riverbeds, the ancient rivers are buried by ground material. Concerning the exposed ancient channels, the exposed surface is not buried by material filling. According to the plane development mode of the modern river and the section shape characteristics of the river course, Leopold divides the ancient river course into three types: straight, curved, and braided [12].

2.1. Model parameters

| Parameters     | Submarine sediment | loose rock | bedrock | seawater | shallow gas pressure (MPa) |
|----------------|--------------------|------------|---------|----------|---------------------------|
| Density (g/cm³)| 1.4                | 1.8        | 2.4     | 2.6      | 1.03                      |
| $v_p$ (m/s)    | 2000               | 2500       | 3000    | 3500     | 1500                      |
| Quality factor | 20                 | 50         | 100     | 130      | 300                       |
| $\theta$       | 320                |            |         |          |                           |

The model parameters are shown in Table 1. The model is uniform 500m×500m in size, and 20Hz in wavelet frequency, in which common offset observation is adopted.

2.2. Wavefield characteristics of different types of ancient submarine rivers

Next, numerical simulation of the seismic wavefield is carried out for different models of the submarine ancient channel.

1) Straight type ancient channel

The boundary profile of the ancient river section shows that the slopes of both sides of the river valley are roughly equal, the bottom of the river valley is gentle or narrow, and the section is shaped like “u” or “v”. The boundary shape of this symmetrical channel section is single, and the sedimentary texture and filling structure are also relatively simple. There are no fluvial sedimentary bodies such as a floodplain, point bar, and sandbar in the valley, which reflects that the river is in the young forming period. Generally, it is a small branch river of the straight type that generates traceable accumulation in the transgression period [12].

Figure 1. Stratigraphic profile record of straight ancient channel [12]

Figure 2 (a) is a straight ancient river channel model based on the basic form of Figure 1. The ancient river channel is filled with sediment. Figure 2 (b) is the wave field response obtained by simulation.

In Figure 2 (b), because the diffraction effect of the ancient river channel on the seismic waves, two very obvious hyperbolic shapes have been formed on the seismic wave profile. The intersection of the two hyperbolas and the stratum reflection surface of this layer forms an inverted triangle shape. The
position of the triangle is the same as that of the ancient river channel in the model. At the two ends of the top of the ancient river channel, there are diffraction hyperbolas in bow shape due to the existence of intersections, which is caused by the diffraction effect of seismic waves. Under the hyperbola, there are weak interference waves, which can be eliminated by data processing.

![Image](image-url)

(a) The straight ancient river model  (b) Wavefield simulation results

**Figure 2.** Numerical simulation of the seismic wavefield of the Zhishun-type ancient channel.

(2) Braided paleochannel

The braided channel often shows a kind of complicated channel section in the seismic section. In addition to the development of symmetrical and asymmetric river sections, there are also more complex river sections [12].

![Image](image-url)

**Figure 3.** Multiple braided ancient river sections [12]

In Figure 3, three braided paleochannel sections are developed. According to their basic forms, we have established a braided paleochannel model. As shown in Figure 4 (a), the three ancient river channels are respectively distributed in different positions on the seafloor in different sizes, and the interface between the filler and the overlying silt layer is undulating.

From Figure 4 (b) seismic wavefield numerical simulation section of braided paleochannel, it can be seen that the top of each ancient river course presents a hyperbolic shape with strong reflection at the inflection point, and the same characteristics appear at the bottom. The interval between the upper and lower hyperbolas is the depth of the ancient channel, and the interval between the left and right hyperbolas is its span.

In summary, the morphological characteristics of ancient rivers are different, so are the acoustic reflection characteristics. The acoustic reflection characteristics of the upper paleochannel in the acoustic profile are mainly manifested in the transverse or oblique cutting section, the overlying or underlying layer structure, the reflection characteristics of the filling in the channel, and the development of the channel deep channel. In addition to distinguishing and classifying the morphologic characteristics of paleochannel sections in the acoustic strata, it is more important to distinguish the engineering properties of the sediments filled in the channel, especially to judge whether the paleochannel deposits were formed by the continental environment or by the marine transgression. Many of the palaeo-channel
bodies accumulated in the continental environment are formed by flood alleviation, and some flood plain terraces have the following engineering characteristics: coarse and fine, poor separation, dense soil, good bearing capacity, and good water permeability. However, the ancient channel sand body traceable to the accumulation has fine sediment, good separation, large water content, high sensitivity, poor consolidation degree, poor bearing capacity, liability to liquefaction and deformation, and other engineering characteristics.

3. Conclusions
In submarine engineering, the exploration of typical marine geological phenomena is an important problem yet to be solved. We use the FCT finite-difference algorithm to simulate this typical marine geological phenomenon, which provides a feasible method for high-precision exploration of shallow sea engineering geology.

(1) FCT method is combined with staggered grid finite difference method to solve the acoustic wave equation of seafloor viscoelastic medium, through which the numerical simulation of the wave equation of seafloor viscoelastic medium is realized, effectively suppressing the numerical dispersion of staggered grid finite-difference and improving the accuracy and operational efficiency of wavefield simulation.

(2) FCT finite difference numerical simulation is used to simulate the propagation response of seismic waves in three types of submarine palaeo-channel models, namely straight, curved and braided, and the identification mark of its acoustic profile is obtained.

(3) Based on the acoustic reflection characteristics of the sediments in the paleo-channel, the structure and structural characteristics of the sediments can be analyzed, to infer the existence, nature, and scale of the paleo-channel.

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References
[1] Boris J P and Book D L 1997 Flux-corrected transport. SHASTA, a fluid transport algorithm that works Journal of Computational Physics-Special Issue: Commemoration of the 30th Anniversary 135 172-186
[2] Chand S, Rise L and Ottesen D 2009 Pockmark-like depressions near the Goliat hydrocarbon field Barents Sea: Morphology and genesis Marine and Petroleum Geology 26 1035-1042
[3] Cheng J, Gu H, Liu Li, Liu C and Liu Z 2011 FCT finite difference forward modeling of marine
viscoelastic medium Journal of Oil and Gas 33 83-88.

[4] Dong L, Ma Z and Cao J 2000 First order elastic wave equation staggered mesh high order difference method Journal of geophysics 43 411-419

[5] Li D 2012 Research on modeling method of wave equation FDTD seismic forward modeling (Chengdu: University of Electronic Science and Technology)

[6] Ma S and Chen T 2009 Marine disaster geology common in northern South China Sea wells site surveys South China Sea Geological Research 1 114-123

[7] Pan H and Sun P 2009 Dispersion analysis and correction strategy of staggered mesh wave field numerical simulation Marine geological dynamics 25 36

[8] Shan Q 2007 Forward modeling of viscoelastic wave equation and parameter inversion (Shandong: China University of Petroleum (east China))

[9] Yang D and Teng J 1997 FCT finite difference simulation of three-component seismic records in anisotropic media Petroleum geophysical exploration 2 181-190

[10] Yuan E and Gu H G 2010 Q is extracted from prestack seismic data based on wavelet domain Journal of engineering geophysics 7 190-196

[11] Yang N 2008 Application of FCT optimal difference method in forward simulation (Chengdu: Chengdu University of Technology)

[12] Ye Y 2012 China Marine disaster geology (Beijing: ocean press)

[13] Xi J 2006 Submarine medium seismic wave field simulation and engineering application research on typical geological hazards. Changchun:Jilin University.

[14] Zhao T 2011 High resolution acoustic detection of seabed and its application (Qingdao: Ocean University of China)