FDTD Numerical Simulation and Detection Capability Analysis of Small Loop Transient Electromagnetic Method in Shallow Water

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Abstract. The small loop transient electromagnetic method (TEM) in shallow water has strong adaptability and high resolution and is one of the current research hotspots. In this paper, a shallow-water model of a typical low resistance anomaly is established, which can be obtained through numerical simulation analysis. In the early time, the shallow water layer has large response and the low resistivity abnormal body has small response; In the late time, the shallow water layer has small response induction response and the low resistivity anomaly has larger response, and the response curve shows "double peak" attenuation law; The effects of different thicknesses of shallow water layers on the response of low resistivity abnormal bodies show "single peak", "double peak", and "peak wave trough" attenuation laws; However, the effect of different resistivity in shallow water layer on the response of the low resistivity abnormal body only shows the attenuation pattern of "single peak" and "peak wave trough". Finally, the article takes the highway site selection survey as an example, combined with the high density resistivity method comparison analysis, and verifies the reliability and accuracy of the detection results of the small loop TEM in shallow water. The research work provides a theoretical reference for the qualitative analysis of the response characteristics and data processing interpretation of the small loop TEM in shallow waters.

1. Introduction
In recent years, the construction of the “the Belt and Road” infrastructure project proposed by China has continued to flourish and develop. In the face of shallow water on land and ocean, exploration work has become more and more difficult. To accurately detect the information of the underwater stratum structure For the special working environment of shallow water construction, a safe, fast, convenient and economical method is needed[1].

Water exploration is an important area for the development of TEM. The domestic and abroad research has focused on marine TEM [2,3,4]. Marine TEM working devices mainly adopt deep-sea towed horizontal emission fixed-array receivers (>500 m) and shallow-sea towed horizontal emission-horizontal receivers (100 m-400 m). The detection targets are mainly submarine high resistivity oil and gas reservoirs. There has been no systematic research on the detection of small scale abnormal bodies and geological structures (<100 m) that are shallowly buried underwater. For lakes and rivers in shallow waters, the width of the water surface is generally in the range of tens of meters, and the water depth is shallow, which is not suitable for using the marine TEM working device. Therefore, the detection of small scale anomalous bodies near the shallow coast or in the shallow waters of lakes and rivers is one of the difficulties in the TEM of water exploration. It is necessary to research the working
device suitable for the TEM of water in the shallow water area to systematically analyze the transient electromagnetic signal response characteristics.

At present, traditional TEM surveying devices are usually large loop or center loop with side lengths of hundreds of meters or tens of meters, which usually require a wide area and flat terrain to achieve the best detection effect. For special construction sites such as lakes and rivers in shallow waters, it is not convenient or even impossible to construct large scale loop installations. Therefore, it is of great significance to apply the small loop TEM device to geological exploration in shallow waters.

2. FDTD simulation of the small loop TEM in shallow water

In a homogeneous medium, the displacement current induced in the ground is negligible compared with the conduction current, that is, it is approximately quasi-static. Therefore, under quasi-static conditions, in passive, lossy, non-magnetic media, the formula for Maxwell's equations in (5):

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
(1)

\[ \nabla \times \mathbf{H} = \sigma \mathbf{E} \]  
(2)

\[ \nabla \cdot \mathbf{B} = 0 \]  
(3)

\[ \nabla \cdot \mathbf{H} = 0 \]  
(4)

Where \( \mathbf{B} \) is the magnetic induction strength, \( \mathbf{E} \) is the electric field strength, \( \mathbf{H} \) is the magnetic field strength, and \( \sigma \) is the conductivity of the medium. Since the displacement current is ignored, the derivative term of the electric field versus time is missing in equation (2), so it cannot be solved using an explicit method that is satisfied by the finite differences time domain. In order to continue to use the explicit format of the DuFort-Frankel method, a virtual displacement current parameter is introduced, and the Maxwell equation (2) is written as the following form (4):

\[ \nabla \times \mathbf{H} = \gamma \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} \]  
(5)

In space rectangular coordinate system, the electric and magnetic field components are defined on the hexahedron element, the electric field components \( E_x, E_y, E_z \) are defined at the midpoint of the hexahedron edge, and the magnetic field components \( H_x, H_y, H_z \) are defined on the surface of the hexahedron. Upper center. Each magnetic ring contains four magnetic field components. These four magnetic field components are respectively composed of the magnetic fields on the adjacent four grid cell surfaces. Similarly, each electrical ring also contains four electric field components. The electric field consists of four edges on a grid surface. Each electric ring surrounds a magnetic field component, and each magnetic ring also surrounds an electric field component. The electric field and the magnetic field are thus staggered and coupled in the model. The non-uniform meshing technique is used to divide the area calculated by the forward model into several small cuboids. The continuous electric and magnetic fields in the infinite area are transformed to solve the discrete nodes and face centers of the small cuboids in the limited area Field value. Equation (3) is written in the form of each component, and the principle of magnetic flux continuity is applied. Finally, the differential iteration format of each component of the magnetic field in the x-direction, y-direction, and z-direction is derived as (6):

\[ B_x(i,j,k) = B_x(i,j,k) - \Delta t \left[ \frac{E_x(i,j,k+1/2) - E_x(i,j,k-1/2)}{\Delta y} - \frac{E_x(i+1/2,j,k) - E_x(i-1/2,j,k)}{\Delta z} \right] \]

\[ B_y(i,j,k) = B_y(i,j,k) - \Delta t \left[ \frac{E_y(i+1/2,j,k) - E_y(i-1/2,j,k)}{\Delta z} - \frac{E_y(i,j,k+1/2) - E_y(i,j,k-1/2)}{\Delta y} \right] \]

\[ B_z(i,j,k) = B_z(i,j,k) - \Delta t \left[ \frac{E_z(i,j+1/2,k) - E_z(i,j-1/2,k)}{\Delta y} - \frac{E_z(i+1/2,j,k) - E_z(i-1/2,j,k)}{\Delta z} \right] \]
3. Analysis of the Small loop TEM response in the shallow water of typical low resistivity anomaly

Figure 1 shows the schematic diagram of the shallow water model of typical low resistivity anomaly. Set the upper part of the model as the shallow water layer and the lower part as the sedimentary layer. The shallow water layer has a water depth of 20 meters and a resistivity of 10 Ω·m. The thickness of the sedimentary layer is 140 meters and the resistivity is 200 Ω·m. The field source is excited by the small loop source with a radius of 1m, the number of turns is 10, and the current is 50 A. The size of the low resistivity anomaly is 10 m × 10 m × 10 m, the resistivity is 10 Ω·m, which is located directly below the transmitting coil, and the vertical distance from the transmitting coil is 90 m.

Figure 2 shows the 3-D slice graph of the magnetic field strength of typical low resistivity abnormal body. It can be seen from Figure 2 that at the initial moment, the transient electromagnetic field is mainly concentrated on the shallow surface and uniformly distributed; the large value gradually spreads downward and outward and affected by the low resistivity anomaly, and the transient electromagnetic field is distorted.

Figure 3 shows the magnetic field strength attenuation curves of the transient electromagnetic field in the shallow water layer of typical low resistivity anomaly at different times. The upper shallow water layer has a resistivity of 10 Ω·m and depth of 20 m. The resistivity of the lower deposition layer is 200 Ω·m, the resistivity of the low resistivity abnormal is 10 Ω·m, and the emission current is 50 A.
Six groups of different moments were selected to analyze the attenuation law of the magnetic field strength. It can be seen from Figure 3 that the magnetic field intensity decay curve first increases and then decreases and the curve change shows a “double peak” decay law. The corresponding position of the first peak of the curve (z=15 m) is located in the shallow water area. Because the shallow water layer has a low resistivity and the "skin effect" effect, the magnetic field strength is mainly concentrated in the shallow water layer. The position of the second peak (z=95 m) of the curve corresponds to the low resistivity anomaly. As the electromagnetic field propagates through the shallow water to the deep, it induces a response at the low resistivity body and the amplitude of the curve increases. At 0.050 ms, the response of the shallow water layer is large, and the response of the low resistivity abnormal body is small. At 0.060 ms, the response of the shallow water layer is small, and the response of the low resistivity abnormal body is increased.

![Figure 3. Curves of magnetic field strength attenuation at different times](image1)

![Figure 4. Magnetic field strength attenuation curve for different shallow water layers](image2)

Figure 4 shows the transient magnetic field strength attenuation curve of the shallow water layer of a typical low resistivity anomaly when the thickness of the shallow water layer is different at 0.05 ms. Set the upper shallow water layer resistivity to 10 Ω•m. The resistivity of the sedimentary layer is 200 Ω•m, the resistivity of the low resistivity abnormal is 10 Ω•m, and the emission current is 50 A. Six different groups of shallow water depths were selected to analyze the attenuation of magnetic field strength. It can be seen from Figure 4 that when h=0 m and h=5 m, the magnetic field intensity decay curve shows a “single peak” change law. This is because at h=0 m, in this case, it is equivalent to a uniform half space model containing low resistivity anomaly. The magnetic field strength is the strongest at the low resistivity anomaly; At 0.05 ms, the electromagnetic field has penetrated the shallow water layer, and the induction response is strongest at the low-resistivity abnormal body. When h=10 m, 15 m, and 20 m, the magnetic field intensity decay curve shows a "double peak" change law. The corresponding positions of the “double peak” maximum value are located in the shallow water area and the low-resistivity anomaly, respectively; when h=50 m, the magnetic field intensity decay curve shows a “wave peak and valley” change law. This is due to the large depth of the shallow water layer. At 0.05 ms, the electromagnetic field is mainly concentrated in the shallow water layer and does not completely penetrate the shallow water layer. Therefore, the magnetic field intensity curve presents a peak response at the shallow water level and a valley response at the low resistivity anomaly.
Figure 5 shows the transient magnetic field strength attenuation curve of a shallow water layer of a typical low resistivity anomaly when the resistivity of the shallow water layer is different at 0.05 ms. The upper shallow water layer is set to a depth of 20 m, the resistivity of the sedimentary layer is 200 Ω•m, the resistivity of the low resistivity abnormal is 10 Ω•m, and the emission current is 50 A. Six groups of different shallow water resistivity cases were selected to analyze the attenuation law of the magnetic field strength. It can be seen from Figure 5 that when the resistivity of the shallow water layer is less than 10 Ω•m, the curve shows a "wave peak and valley" change law; when the resistivity of the shallow water layer is greater than 10 Ω•m, the curve shows a "single peak" change law. This is because the smaller the resistivity of the shallow water layer, the greater the intensity of the induced magnetic field, the slower the downward propagation speed of the electromagnetic field, and the weaker the response of the low resistivity abnormal body at the same time. When the resistivity of the shallow water layer is greater than 10 Ω•m, the electromagnetic field can penetrate the shallow water layer more easily, and a peak response appears at the low resistivity anomaly.

4. Analysis of Practical Application of the Small Loop TEM in Shallow Water
In order to illustrate the detection effect of the transient electromagnetic device of the small loop TEM in shallow water, a karst survey of a highway subgrade in Guizhou Province is taken as an example, and a comparative analysis is conducted in combination with the high density resistivity method. The project is located 6 kilometers southwest of Jiangkou County, Guizhou Province. The bedrock in the work area is mainly limestone, dolomite, and shale. The terrain is relatively flat, and the survey line crosses a river. The river has a water surface width of about 40 meters, a water depth of about 10 meters, and a slow water flow. In order to find out the geological conditions within 80m below the roadbed and bridge basement surface, as well as the bad geological distribution of karst, broken belts, and weak layers. Due to the special environment of the worksite, other geophysical methods are difficult to carry out construction. Therefore, the TEM and high density resistivity methods on the water are selected for detection.
The measured data is filtered and pre-processed, and then the data inversion processing is performed to obtain the apparent resistivity profile (Figure 6). Combined with the analysis of the high density resistivity inversion results, we can obtain:

a) The stratum section can be divided into three layers in the vertical direction (Figure 6a). The apparent resistivity of the surface layer is 10~300 $\Omega \cdot m$, which is interpreted as the reflection of the Quaternary overburden and gravel soil. The layer thickness is generally about 5m; the apparent resistivity of the second layer is generally 500~800 $\Omega \cdot m$, and the layer thickness is relatively stable at 20–25 m; the apparent resistivity of the third layer is 800~1600 $\Omega \cdot m$, which is inferred to be a more complete limestone. At the interface of strong and weak weathering lithology, the horizontal apparent resistivity is less than 800 $\Omega \cdot m$ between the horizontal distance of 120 m-200 m. It is inferred that the rock mass has different degrees of dissolution development.

b) The stratum section can be divided into three sections of electrical units in the horizontal direction (Figure 6a). With the boundary between the mileage of 40m and 120 m, the limestone with large differences in lateral electrical properties can be divided into three electrical units. The first electrical unit is located between the horizontal distance of 0-40 m, the apparent resistivity contour line is regular and continuous, and the rock mass is estimated to be complete; the third electrical unit is located between the horizontal distance of 100-290 m, the apparent resistivity contour line morphology More regular and continuous. Between the horizontal distances of 120 m-200 m, the low-resistivity contours are bent downward, and the high-resistivity and low-resistivity rock masses are staggered with each other. It is speculated that rock integrity is poor and karst development may exist. In the horizontal distance of 180 m -200 m, an upright low-resistivity abnormal body is present, with a burial depth of more than 40 m. It is speculated that the rock formations in this area are broken and cracks develop. The third electrical unit is located at a horizontal distance of 40-100 m, and the apparent resistivity is between 10~400 $\Omega \cdot m$. The scale of the low resistivity anomaly is large, and the buried depth exceeds 70 m, which is consistent with the inversion results of the high density resistivity method. (Figure 6b), it is speculated that karst development is likely in the low resistivity anomaly range, rock formations are broken, and the possibility of water cut is extremely high. The small loop transient electromagnetic method inversion results are consistent with the high density resistivity method inversion results. At local details, the inversion results are finer and higher resolution than the high density resistivity method.

5. Conclusions
In this paper, the shallow water layer model of a typical low resistivity anomaly is established, and numerical simulation is performed using FDTD. The response characteristics of the shallow water model of a typical low resistivity anomaly are analyzed, and the analysis shows that: in the early time, the response of the shallow-water layer is large, and the response of the low resistivity anomaly is small; at the late time, the response of the shallow water layer is small, and the low resistivity The response of the abnormal body increased, and the response curve showed a "double-peak" attenuation.
rule. The effect of the low resistivity anomaly on the response characteristics of the low resistivity anomaly body was analyzed when the thickness of the shallow water layer was different. The attenuation curve, when the thickness of the shallow water layer is $5 \text{m} < h < 50 \text{m}$, the response curve shows a "double peak" attenuation law; when the thickness of the shallow water layer is $h > 50 \text{m}$, the response curve shows a "peak wave valley" attenuation law; the resistivity of the shallow water layer is analyzed At the same time, it affects the response characteristics of the low-resistivity abnormal body. The smaller the resistivity of the shallow water layer is, the more the response curve shows a "peak-to-valley" attenuation law. Otherwise, the response curve shows a "single-peak" attenuation law.

Finally, the thesis takes the highway location survey as an example, combined with the high density resistivity method comparison analysis, and verifies the reliability and accuracy of the detection results of transient electromagnetic devices in small loops in shallow water. The research work provides a theoretical reference for the qualitative analysis of the response characteristics and data processing interpretation of the small loop TEM in shallow waters.

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