Response characteristics of transient electromagnetic of fault structures in shallow stratum of underground space and its exploration

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Abstract: The key to detecting underground faults in shallow stratum of the city with transient electromagnetic method is the determination of the fault location and the characteristics of accurate underground parameters. In order to establish a field data acquisition device and method parameters suitable for the exploration of the fault structure in the shallow layer of the city, the corresponding numerical model is established based on the Shungeng mountain fault structure with shallow depth. The finite difference method is used to simulate and calculate the response characteristics of the transient electromagnetic field in the fault structure zone, which provides the basis for the field application of the method and technique. Then, based on the surface geological conditions of Dongshan section of the Shungeng mountain fault, by using the short-circuit transient electromagnetic method, field data acquisition observing system and relevant parameters suitable for transient electromagnetic prospecting of urban shallow fault structures were established through experiments on site technical conditions, and the geoelectric section. The structure and characteristics of shallow buried faults are judged and explained. The results show that the response characteristics of transient electromagnetic in the fault fracture zone are significant, and the location and structure of transient electromagnetic field can be easily distinguished. It can provide references for similar geological conditions.

1. Introduction
The fault structure has a certain influence on the safety of urban underground space, so it is necessary to find out the fault location and its characteristics in the process of urban construction. At present, the application of geophysical methods has been strengthened in addition to drilling methods in the exploration of fault structures. The transient electromagnetic method has high sensitivity and resolution of the geoelectric section in the near field source area, high working efficiency, low production cost advantages. It is generally considered that this method is a geoelectric sounding method that has a promising prospect from shallow to deeper layers and has broad application prospect[1].

The difficulty of using transient electromagnetic method to detect shallow fault structures in cities lies in the shielding of shallow surface with low resistivity layer and the existence of a large number of electromagnetic noise sources in the city. The presence of a low resistivity shield on the shallow surface leads to a longer discharge time in the shallow area, which interferes with the information gathering in the deep area. Meanwhile, the induced current distribution around the surface at the moment of power failure is not uniform, which has some influence on the shallow ground surface. The overlying low resistivity layer reduces the diffusion speed of the transient electromagnetic field,
shields the field and weakens the abnormal reaction of its abnormal body[2]. The transient electromagnetic method is related to the longitudinal resolution of low resistivity layer and the thickness of low resistivity layer. The smaller the thickness is, the higher the resolution is. It will take a long time to detect the same depth when the low resistivity layer is overlying[3]. The existence of a large number of electromagnetic noise interference sources in the city has an impact on the detection effect of transient electromagnetic method, and it is easy to produce large errors. In addition, due to the inherent causes of conventional transient electromagnetic detection system, the early transient electromagnetic signal distortion, resulting in transient electromagnetic method in the shallow detection of the presence of semi-blind area of about 20m, to improve transient electromagnetic shallow ground exploration resolution, and to reduce the exploration blind area, the most crucial point is to determine the turn-off time of the emission current. Turn-off time is an important factor affecting the quality of transient electromagnetic data processing and interpretation[4~6]. At the same time, the selection of data acquisition and processing methods, the selection of wire frame size and arrangement, the selection of emission current, and the reasonable choice of sampling interval will greatly affect the anti-interference ability of transient electromagnetic and the detection effect[7]. Therefore, the current experience of using transient electromagnetic method to explore is not suitable for urban shallow fault structure detection.

Based on this, combined with the structural features of Shungeng mountain fault in the region, the article constructs a numerical model, and discusses the response characteristics of its transient field by numerical simulation to provide the basis for the field detection. At the same time, field investigation and research were carried out, and the geoelectric section of fault structure was obtained, which accurately judged the location and characteristics of faults, aiming to provide reference for similar geological conditions.

2. Research statuses
So far, scholars at home and abroad have made some researches on the detection of shallow anomalies by TEM and have accumulated some experience[7~10]. However, these studies are mainly focused on areas where there are few sources of electromagnetic noise in the field. Liu et al.[11] used the transient electromagnetic method to explore the water cut fault structure in the loess layer and loose sand layer with larger coverage area. It further verified the validity and reliability of transient electromagnetic method for water cut fault structure and data interpretation. Zhang et al.[12] did the joint research of fault exploration by the nano-transient electromagnetic method and EH4. On the basis of EH4 large-scale exploration to identify the general location and occurrence of faults, detailed investigation using nano-transient electromagnetic to accurately determine the location and occurrence of faults. Zhang et al.[13] is simulated by physical simulation experiment with multiple turns of the same small loop and multi turn overlapping small loop device. The change rule of transmitting magnetic moment, turn off time and induction signal with the turn of the transmitting coil is studied, and the relationship between the detection effect and the number of turns of the coil is analyzed. The comparison of the two small loop devices is made, which provides a certain experimental reference for the rational selection of the transient electromagnetic observation system and the field construction design. Jiao et al.[14] by making multiple antenna device, this paper analyzes on the problem of detecting ultra-shallow anomaly electromagnetic method based on physical model experiment, for each antenna device were carried out experiments of physical model, the results show that the change of antenna size and device type, the transient electromagnetic method can detect the ultra-shallow. In the above research, the application of transient electromagnetic field shallow surface anomaly structure exploration is studied, and the feasibility and effectiveness of its exploration are analyzed. Using the transient electromagnetic method to explore the fault structure in the shallow stratum of the city, in addition to the feasibility, it should be more efficient.

In order to further study the application of transient electromagnetic method in shallow fault structure exploration, a small number of scholars have studied the suppression of electromagnetic noise and the detection accuracy [15~17]. But the technology is not mature, and has not been applied
to engineering cases very well. Therefore, aiming at the characteristics of the existing research, this paper takes the shallow buried Shungeng mountain fault as the research object, discusses the data acquisition device and its exploration application, and carries out the theoretical and practical research on the transient electromagnetic detection of the shallow fault structure next to the city.

3. Research methods

3.1. Test area overview
The Shungeng mountain fault in the study area is an east-west thrust fault and about 300km long. The urban construction attaches great importance to the occurrence characteristics of the fault. The fault is inclined to the south, and the dip angle of the near ground is 60 ~70 degrees, and the deep part slows down to 20 ~30 degrees.

![Figure 1. Schematic diagram of Shungeng mountain fault](image)

Figure 1 is the structural section map of the study area. Now, combined with the shallow characteristics of the Shungeng mountain fault, we carry out corresponding exploration technology research, and establish effective working methods, further get the parameters such as the depth and location of the fault zone, so as to provide parameters for the investigation of urban geological hazards.

3.2. Numerical simulation

3.2.1. Simulation algorithm. The response characteristics of transient electromagnetic fields in geological conditions are the basis of detection. In the research, the numerical simulation method is applied to discuss its theoretical rules, and the response characteristics of transient electromagnetic fields in fault structure areas are discussed, which provides a basis for the on-site application of methods and technologies. The three dimensional finite difference time domain method is one of the main methods to calculate the transient electromagnetic field in time domain. In Cartesian coordinates system, electric field and magnetic field equations are written in the form of components:

$$\begin{align}
\frac{\partial H_x}{\partial y} - \frac{\partial H_y}{\partial z} &= \gamma \frac{\partial E_y}{\partial t} + \sigma E_z \\
\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial z} &= \gamma \frac{\partial E_x}{\partial t} + \sigma E_z \\
\frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial y} &= \gamma \frac{\partial E_z}{\partial t} + \sigma E_x \\
\frac{\partial H_x}{\partial t} &= \frac{1}{\mu} \left( \frac{\partial E_y}{\partial y} - \frac{\partial E_z}{\partial z} \right) \\
\frac{\partial H_y}{\partial t} &= \frac{1}{\mu} \left( \frac{\partial E_x}{\partial x} - \frac{\partial E_z}{\partial z} \right) \\
\frac{\partial H_z}{\partial t} &= - \frac{\partial H_x}{\partial x} - \frac{\partial H_y}{\partial y} \\
\end{align}$$

Equations (1) and (2) are the basic equations for the electromagnetic field in the passive zone in
Figure 2. Distribution of every field quantity in single cellular of Yee

For a spatial grid cell, Yee sets the electric field component at each edge of the cell and the magnetic field component at the center of each cell of the cell (see Figure 2). In this way, the six components of the electromagnetic field are discretized into the following to show the difference equations so that they can be solved iteratively in the time domain.

The 6 component forms after the discrete are

$$E_x^{(i+\frac{1}{2},j,k)} = CA(m) \cdot E_x^{(i+\frac{1}{2},j,k)} + CB(m)$$

$$E_y^{(i,j+\frac{1}{2},k)} = CA(m) \cdot E_y^{(i,j+\frac{1}{2},k)} + CB(m)$$

$$E_z^{(i,j,k+\frac{1}{2})} = CA(m) \cdot E_z^{(i,j,k+\frac{1}{2})} + CB(m)$$

Among them

$$CA(m) = \frac{2\gamma - \sigma(m)\Delta t}{2\gamma + \sigma(m)\Delta t}$$

$$CB(m) = \frac{2\Delta \mu}{2\gamma + \sigma(m)\Delta t}$$

Similarly, the spatial-temporal difference form of the x, y, and z components of the magnetic field is
\[
H_i^{\nu+1}\left(i+\frac{1}{2},j,k+1\right) = H_i^{\nu+1}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right) + \Delta z \times \frac{E_i^{\nu} \left(i,j+1,k+\frac{1}{2}\right) - E_i^{\nu} \left(i,j,k+1\right)}{\Delta y}
\]

\[
H_i^{\nu+1}\left(i+\frac{1}{2},j+1,k\right) = H_i^{\nu+1}\left(i+\frac{1}{2},j+\frac{1}{2},k+1\right) + \Delta x \times \frac{H_i^{\nu+1} \left(i+1,j,k+\frac{1}{2}\right) - H_i^{\nu+1} \left(i,j,k+1\right)}{\Delta y}
\]

In the formula (1) - (11), H is the magnetic field strength; x, y, z is a unit vector; γ is the reflection coefficient; E is electric field intensity; T is the thickness of conductor tape; σ is electrical conductivity; μ is the permeability coefficient; i, j, k, m, n are variables; Δ is the amount of change; l on behalf of the length; s is the area.

### 3.2.2. Model Construction and Parameter Design

The model was designed according to the strata and producing conditions exposed locally from the Shungeng mountain fault. Fig. 3 is a shallow-burried fault structure model under half-space ground conditions. For the numerical simulation of the model, set the transmit and receive wireframe side length are 20m. In the simulation, the current of the wire frame is set as 1A, the resistivity of the soil layer is 200 Ω·m, the resistivity of the rock formation is 800 Ω·m, the resistivity of the fault is 2000 Ω·m and 20 Ω·m. By calculating the electrical parameters of a given model under different states of faults, it is convenient to compare the electromagnetic response characteristics of fault structures.
3.3. Field exploration test

The whole field transient electromagnetic exploration is carried out at the fault hill section of the Shungeng mountain, and the geoelectric section of the fault structure is obtained, so as to get the field data acquisition and observation system suitable for the shallow fault structure in the city, and the related parameters. As a non-contact probing method, it uses the ungrounded return line or ground return line to send a pulse field to the ground once (referred to as a primary field). The conductive medium will generate eddy current under the excitation of a field. During the interruption of the emission current, the eddy current will disappear immediately, but form a secondary magnetic field that decays with time in the space around it. The law of the secondary magnetic field decaying with time mainly depends on the conductivity, size, depth of the medium, and the shape and frequency of the emission current. Therefore, the attenuation characteristics of the secondary field measured by the receiving coil can be used to understand the electrical structure of the underground medium. Due to the horizontal or vertical inhomogeneity of the shallow underground geological conditions, the physical properties are obviously different, resulting in different distributions of the induced fields and the exploration and analysis of the underground space fault conditions.

![Figure 3. Sketch map of fault model](image)

### Figure 3. Sketch map of fault model

- **(a)** arrangement of measuring line
- **(b)** detecting photo

Figure 4. Field detection arrangement and data acquisition

In combination with site conditions, a survey line approximately perpendicular to the strike of the fault is laid out. Figure 5 shows the survey line layout and the test photograph. Among them, line AB is the strike of ShunGengshan fault, and the site acquisition location is marked as line a in the graph. MSD-1 transient electromagnetic instrument is used for data acquisition. In order to determine the best data acquisition mode in the field, different schemes are designed to compare the length of the transmitting and receiving coil frame, the number of coil turns and the different acquisition parameters. Finally, an overlap loop device with a length of 5m on the side of the wire frame is adopted. The coil turns are 9 turns, the working frequency is 8.3 Hz, the transmitting power supply voltage is 48 V, 128 times superposition, and the test point distance is 3 m. Through analyzing the response characteristics of electromagnetic field in shallow exploration media, the data acquisition scheme was drafted to realize the data acquisition of the fault zone. The data of the whole survey line induced field was of good quality.
4. Result Analysis and Discussion

4.1. Simulation results analysis
Based on the numerical simulation method in 3.2, the response characteristics of the transient electromagnetic field in the fault tectonic zone are analyzed. When using transient electromagnetic method to detect fault structure, the whole model is established with node-based magnetic field units. Because the actual problem belongs to open domain problem, numerical simulation is only applicable to the electromagnetic field calculation in the closed boundary area. Therefore, the simulation needs to deal with the open domain situation accordingly. The model applies parallel boundary conditions of magnetic field lines to all the outermost layers of air to simulate the state of infinite field to meet the requirements of finite difference calculation of electromagnetic field [22–24]. Fig. 4 shows the distribution of magnetic fluxes calculated from different electrical parameters. From the figure, it can be seen that the distribution of magnetic fluxes in fault zones with or without tectonic zones and in fault zones filled with or without water is obviously different. When the fault with water filling, lines from the rock into the fault position, the magnetic field was bent down; when the fault zone is not filled with water, the magnetic field will certainly change, but larger, and the distribution characteristics of different state water filling under contrast, can be found on the transient electromagnetic water filling fault induction is more sensitive to low resistance body. At the same time, combined with lateral comparison, it can be found that due to the great difference in resistivity between fault zone and surrounding rock, the magnetic force line has changed obviously at the fault zone, showing obvious transverse heterogeneity, which provides a basis for fault location judgement. The above simulation results show that the response characteristics of the transient field under the condition of the structure are significant. The transient electromagnetic method can effectively detect the specific location and the corresponding features of the fault, and have a good judgment on the water-filling conditions of the fault. This is for field exploration applications and the basic conditions of judgment.

![Figure 5. Magnetic force line distribution](image)

(a) Water-filled fault  (b) No water filled fault

4.2. Interpretation of the geoelectric section
Based on the field exploration test in 3.3, the feasibility and efficiency of transient electromagnetic exploration of the fault structure in the shallow layer of the city are analyzed. Data processing is done by self-compiled software, including data editing, coordinate establishment, data preprocessing and correction, apparent resistivity calculation and imaging, geological data comparison, interpretation of apparent resistivity anomaly, anomaly area delineation, etc. Figure 6 for the survey line apparent resistivity profile, we can see that there is a significant difference between the various layers within the region. In the figure, there is a distinct electrical interface at a distance of 30m from the starting point of the test, with large differences in resistivities between the two sides, of which 0-30m is characterized by high resistivity and has a value of 700 Ω·m or more and a resistivity of 30m to 110m relatively small, below 500 Ω·m. The electrical interface between the left and right has a certain change of inclination; from the survey line 30-110m to analyze, the vertical difference was significant, showing zonation.
Among them, the resistivity value of the loose layer is relatively small in the shallow part, and the bedrock layer in the lower part, and its resistivity value increases at 300-500 Ω·m. According to the comprehensive analysis of the on-site geological survey data, it is considered that the obvious interface of electrical difference is the location of the fault section, and the inclination size and tendency characteristics are easy to judge. Therefore, it is feasible to use the transient electromagnetic method to probe the geological structure of the shallow underground space, and the shallow structure exploration using the small wireframe and the multi-turn electromagnetic cable can obtain a good application effect.

![Survey of apparent resistivity profile of underground line](image)

**Figure 6.** Survey of apparent resistivity profile of underground line

### 4.3. Analysis of Factors Influencing Exploration

Through the comparison of different parameters and the investigation of influencing factors, we can further get effective application results, and we need to pay attention to several aspects for improving the quality of field exploration. First, the selection of test wire frame size should meet the requirements of field exploration. Within a certain range of side length, the anomalous amplitude of the geological body increases linearly with the increase of the side length. For the shallow underground space surrounding the city, the length of the return line is sometimes limited, so the site can be exploratory test investigation to determine the wireframe used and the corresponding parameters. Second, on-site interference conditions investigation. Electromagnetic noise mainly from the outside, high voltage wires around the test site and other electromagnetic interference survey to reduce the sensitivity and observational capabilities of the instrument. Third, the data processing needs to be based on the characteristics of the acquisition of induced electromotive force pre-processing, calculation of resistivity can be adjusted according to the test medium conditions coefficient. Geological interpretation can be combined with the exploration object, make full use of all kinds of geological data to make a comprehensive comparison and analysis. Fourth is the electrical conductivity of the geological body, depth and geometry parameters. The amplitude of anomaly is related to the electrical and geometric parameters of the geological body. The better conductivity of the geological body, the greater of geometric parameters, and the abnormal amplitude is high, the method of detection of the target body is strong. The use of transient electromagnetic method to detect shallow subsurface fault structure, due to the geometric parameters of the fault structure is relatively small, so we need to consider the impact of the method on the fault detection ability.

### 5. Conclusions

In this paper, based on the numerical simulation of the field measured, its aim is to establish a set of shallow transient electromagnetic exploration and interpretation of analytical methods. The characteristics of electromagnetic response of fault zone are discussed by numerical model. The
acquisition device and technical parameters are discussed through field test. The influencing factors of site construction detection and other improvements are analyzed. Finally, the following conclusions are obtained in the article.

1) For the regional shallow fault structure exploration, the application of full transient electromagnetic method to explore a certain feasibility. Fault zones and the two layers of the formation of different characteristics of its transient electromagnetic field response sensitive and different characteristics. High and low resistance of the electrical differences significantly. This provides a reference for exploration of similar geological conditions and also provides a new direction for the application of TEM.

2) The exploration of shallow geological conditions, the use of multi-turn small wireframe transient electromagnetic technology to better effect, minimize or avoid electromagnetic interference at the scene to ensure the effectiveness of data collection. As far as possible along the fault orientation laid a number of survey line, easy to carry out lateral contrast between the line and a comprehensive analysis. The exploration of the Shungeng mountain fault section in the study area established the basic occurrence of the fault plane and the characteristics of the two reservoirs, providing a reference for the formulation of safety measures in urban construction.

3) Due to the limitations of the test methods, some of the survey tasks of the survey line were completed on site. The fault extension state also needs to track and reconstruct the spatial occurrence characteristics of the fault with the combination of urban surface conditions and multiple vertical survey lines. In order to improve the overall resolution precision of the underground geological target body, it can also be combined with the methods of electric or seismic waves to carry out comprehensive exploration and verification. To further improve the fine resolution and judgment of fault tectonic conditions.

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