# 3D Constrained Resistivity Inversion with Prior Information in Tunnel Advanced Detection

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## Abstract

Geological conditions and adverse geological structures ahead of the tunnel face need to be known beforehand in the tunnel construction, so the 3D resistivity detection method introduced into the tunnel advanced detection. In order to suppress the multiplicity of inversion results, the inversion methods with inequality constraints and spatial shape constraints are combined. The 3D constrained inversion with prior information in tunnel advanced detection is developed. In the proposed method, anisotropic smooth constraints with prior boundary information can be imposed on the boundaries of the adverse geological body to improve the accuracy of the adverse structure's boundary. Inequality constraints with prior information of resistivity range can make the background and adverse zone in inversion results close to the true situation. This method can theoretically improve the inversion result. The numerical tests are implemented, and inversion results with the proposed inversion method are more close to the true situation than the traditional method with smooth constraints. The 3D constrained resistivity inversion with prior information in tunnel advanced detection is feasible and effective.

## Keywords

Tunnel Advanced Detection, 3D Constrained Resistivity Inversion, Prior Information, Numerical Model.

## 1. Introduction

The scale of tunnel construction in the world is growing, especially in the developing countries. More and more tunnels are built in areas with complex terrain and complex geological conditions, and often pass through areas with the development of fault zones, weak strata, karst caves, and other adverse geological bodies. The water and mud inrush are easy to happen in soluble or water-rich rock formations during tunnel construction [1]. The possibility of tunnel collapse is also very high in the fault zones. The constructions are all delayed due to the geological disasters in the diversion tunnel at Dul Hasti Hydropower Station in India [2], the Maluqing Tunnel in Hubei Province, China [3]. Therefore, it is necessary to carry out advanced geological detection during tunnel construction and to find out the adverse geology conditions ahead of the tunnel face. This can provide supports for the decision of the tunnel construction.

The resistivity method is a geophysical detection method based on the difference of dielectric resistivity. The resistivity of the water-filling cave, water-conducting channel and so on, which are concerned with the tunnel advanced detection, is quite different from the resistivity of the intact surrounding rock. The resistivity method is then introduced to detect the adverse geological bodies in front of the tunnel face [4]. Due to the narrow space of the tunnel, the observation device is adjusted based on the one of ground detection. Nie, et al [5, 6] use 3D resistivity method with the multi-source array observation in the tunnel advanced detection. And the research in this paper is taken based on this observation device.

Resistivity detection is required to reflect the state of the adverse geological body accurately. However, as a mean of geophysical detection, non-unique solutions of the inversion result are inherent problems in resistivity detection. The problems get more serious when faced with the adverse geological bodied in tunnel detection, which can easily lead to wrong interpretation. Sasaki [7] introduced the smooth constraints into the least squares inversion, minimizing the resistivity difference of the adjacent grids, and the ill-conditioned inversion equation is improved. Oldenburg, et al [8,9], Liu, et al [10] use the variation range of polarization/resistivity obtained from the geological interface geological drilling and other methods as the prior information, and the information is imposed into the inversion equation as equality or inequality constraints as model parameterization, obstacle function and so on, which improve the inversion result further. Kaipio [11], Li, et al [12] translate the anomaly boundary information obtained from other detection methods into the prior spatial shape constraints and impose them into the resistivity inversion equations, which removes the false anomalies and redundant structures in the inversion results effectively.

This paper offers a 3D constrained resistivity inversion method with prior information in tunnel advanced detection. This method is based on the equality constraints and the spatial shape constraints. The boundary information of the adverse geological bodied and the dielectric resistivity information is translated into constraints and then imposed into the 3D resistivity inversion equation. In the constrained inversion results, the anomalous boundaries are more accuracy, the anomalous resistivity values are closer to the true geological conditions than in the traditional smooth constrained results.

## 2. 3D constrained inversion method with prior information

### 2.1 3D observation device of the resistivity method in tunnel advanced detection

In the thesis [5, 6], the 3D resistivity method with the multi-source array observation in the tunnel advanced detection is proposed. The measuring electrodes array M is arranged on the tunnel face, and 4 current electrodes A are arranged around the tunnel profile. Electrodes B and N are situated at relative infinity of the rear tunnel. When the detection is carried out, 4 current electrodes A supply the currents, and the measuring electrodes array M collect the useful information. Then the current electrodes A move away from the tunnel face with a certain distance, the measuring electrodes array M repeat collecting. This observation device has the advantages of forward focusing and backward shield, which is sensitive to the abnormal body ahead of the tunnel face and can shield interference from the backward [5, 6].

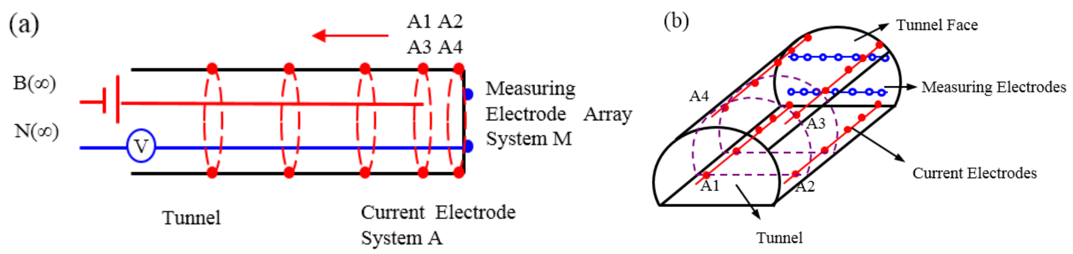


Fig. 1 Schematic diagram of observation model with multi-electrodes array resistivity method: (a) sectional view [5, 6]; (b) 3D schematic diagram [5, 6]

### 2.2 Existing constrained inversion methods

Priori information of resistivity range can be obtained in the 3D polarization/resistivity inversion [10~12]

$$\rho_i^{\min} \le m_i \le \rho_i^{\max} \tag{1}$$

where $m_i$ is the resistivity of the $i$-th grid; $\rho_i^{min}$ is the lower bound of the resistivity of the $i$-th grid, $\rho_i^{max}$ is the upper bound of the resistivity of the $i$-th grid.

The inequality constraints are added to the objective function with the obstacle function, and when the model parameter approaches the constraint boundary, the value of the objective function tends to infinity, so that the model resistivity is constrained within the known constrained range. The use of the inequality constraint method in tunnel resistivity detection is subject to many limitations. In tunnel advanced detection, resistivity information of adverse geological bodies can always be obtained by advanced geo-drilling. Only dielectric resistivity in a small range around the borehole can be revealed, and the spatial extension of the adverse geological body cannot be obtained. These limitations often result in that the background rock resistivity range can only be used in the inequality constrained inversion, and the adverse resistivity information revealed by geo-drilling are not fully exploited.

The adverse boundary information is imposed to the objective function with spatial shape constraints in the resistivity inversion [5, 12]. The boundary information can be obtained by the ground penetrating radar (GPR) in the tunnel engineering. An anisotropic smoothing constraint is applied on the boundary of the anomaly body in the spatial shape constrained inversion. The constraint weight in the normal direction of the anomaly boundary is small, and the resistivity value can change rapidly in this direction. The constraint weight in the tangent direction is large, and the resistivity value changes slowly in this direction. Thus, a better reflection of the anomaly boundary can be realized.

## 3. Numerical simulation and discussion

### 3.1 Detection devices of the numerical simulation in tunnel advanced detection

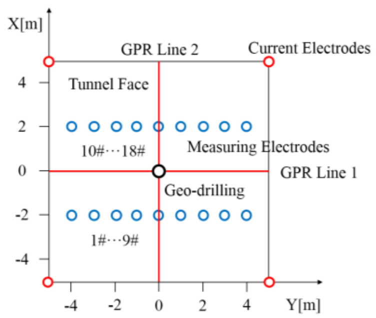


Fig. 2 Detection device on the working face

Advanced geo-drilling, GPR detection, and 3D resistivity method are used to simulate the exploration in the numerical examples. The detection devices are shown in Fig. 2. The tunnel face is 10 m×10 m, and the background resistivity is 1000 Ω•m. The geo-drilling is in the center of the working face and forward to the excavation direction with the depth of 30 m. The GPR detection is carried out with two 10m survey lines. The transmitting antenna has the center frequency 100 MHz, and the Back-Propagation algorithm is used to process the data. 3D resistivity detection with the multi-electrode sources array method is taken [5, 6]. The detection device has two survey lines on the tunnel face. The distance between these two lines is 4 m. 9 measuring points are arranged in each survey line, and the point-gap is 1 m.

### 3.2 Numerical model

There is one low resistivity body (4 m×4 m×6 m, 10 Ω•m) in front of the tunnel face, and the distance to the tunnel face is 10 m. The geologic anomaly in the depth range of 10 m ~ 16 m is obtained by simulated geo-drilling, and the resistivity range of abnormal body is 0 ~ 600 Ω•m. GPR detection gets the abnormal reflection in the range of x=-2~2m, y=-2~2m, and the reflection interface is 10m ahead of the detection face. The prior information of anomaly boundary and abnormal resistivity range obtained from this two methods, are applied to the 3D constrained resistivity inversion. Inverse results are achieved with 10 iterations. A low resistivity region appears in the range of x=-2~2 m, y=-2~2 m, z=10~16 m, and the resistivity value of the anomalous region is lower than 500 Ω•m, as shown in Fig. 3(c)(d).

Fig. 3(e)(f) show the inversion result with the traditional smooth constraints, and a low resistivity region appears in x=-4 m~4 m; y=-4 m~4 m; z=10 m~20 m, and the resistivity value is lower than 800 Ω•m.

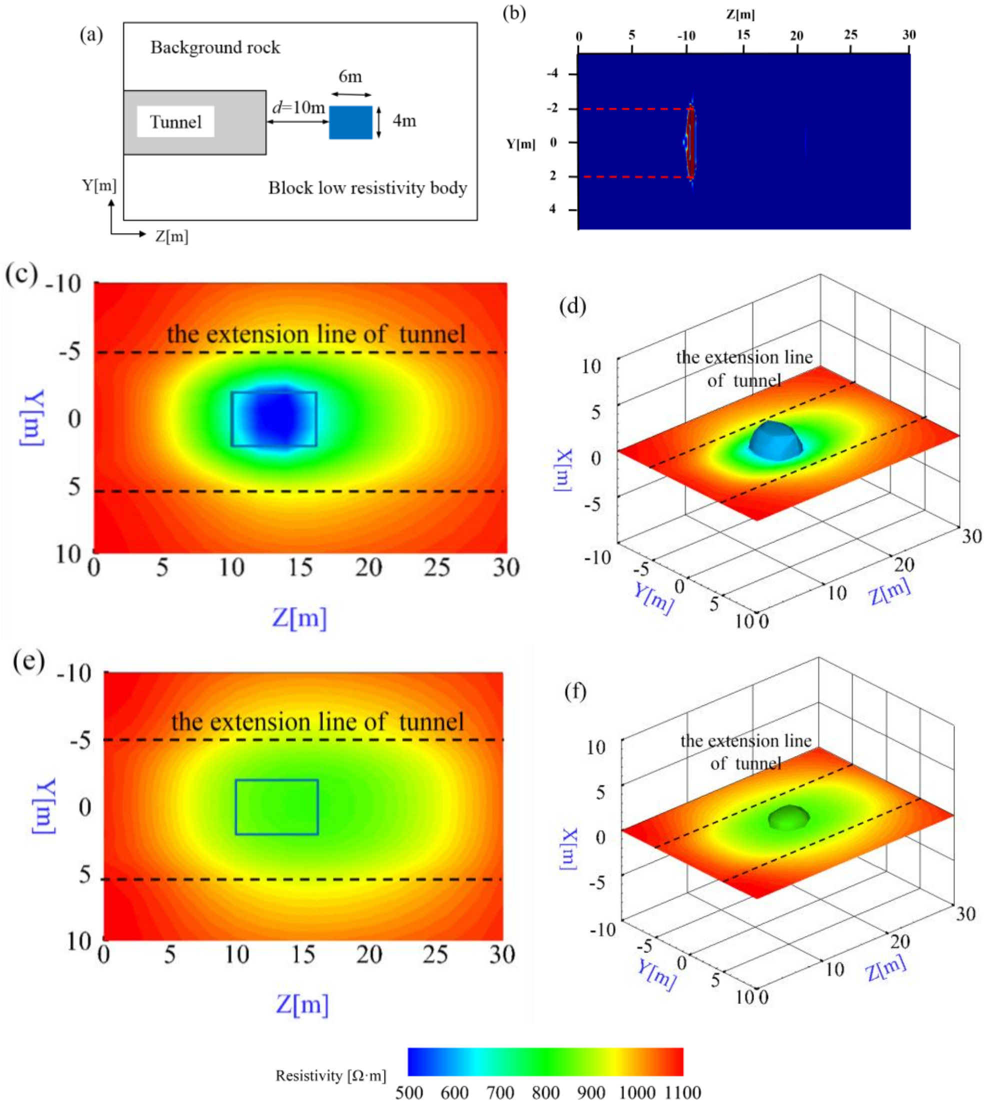


Fig. 3 Numerical model 1 and detection result: (a) projection of model 1 on yOz plane, and the projection on xOz plane is the same; (b) result of GPR Line 1, and the result of GPR Line 2 is the same; (c) section slice for X=0 m of the constrained inversion result with prior information; (d) 3D inversion result of the constrained inversion with prior information; (e) section slice for X=0 m of the traditional smooth constrained inversion result; (d) 3D inversion result of the traditional smooth constrained inversion

### 3.3 Discussion

In the proposed 3D constrained inversion, the abnormal boundary information from the GPR method and the dielectric resistivity information gained by geo-drilling are merged into the resistivity inversion. Finally, the position, scale, and resistivity value of the anomaly body in the inversion results are closer to the real state of the model in simulation model than in the inversion results with traditional smooth constraints.

Water-filled caves, water-bearing faults and other potentially damaging structures are the main targets in tunnel advanced detection. The blocky low resistivity body in model can be treated as a water-filled cave in actual geological conditions. The 3D constrained inversion method with prior information from the GPR and geo-drilling present the abnormal body close to the initial one in the numerical model.

## 4. Conclusion

(1) In tunnel advanced detection, results of GPR and geo-drilling as the prior information are merged into 3D resistivity inversion. This information is translated to the spatial shape constraints and inequality constraints and then added into the resistivity inversion function. Then a new 3D constrained resistivity inversion method with prior information is proposed.

(2) The prior information of constrained inversion is derived from the abnormal boundary information gained from GPR detection, and the dielectric resistivity value obtained by geo-drilling. The application of prior information to 3D resistivity inversion is helpful to improve the accuracy of the adverse boundary in inversion results and make the resistivity value closer to the real situation. Inversion results with this method are close to the prototypes in numerical examples.

(3) Geological anomalies in tunnel advance detection have different geophysical properties. In the following work, multiple detection methods should be carried out to get more abundant prior information. Thus, the 3D constrained resistivity inversion can get better results in tunnel advanced detection.

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