Application of FCTEM60-1 Instrument in Invert Rebar Testing for Highway Tunnel

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Abstract: The invert of a highway tunnel is the foundation for the entire tunnel structure. Its quality has a direct influence on the stability of tunnel structure. However, in practice the tunnel invert has various defects for a variety of reasons. FCTEM60-1 instrument is able to rapidly cut off the current using constant voltage clamping technique, thus significantly reducing the shallow dead-zone effect of transient electromagnetic (TEM). In this study the instrument is applied to testing invert rebar execution in a highway tunnel. The study result shows FCTEM60-1 instrument successfully detected the invert rebar, demonstrating its feasibility and reference value to tunnel quality test.

1. Introduction

As an important component of the highway tunnel and the foundation for the entire tunnel structure, the invert is an inverted arch structure provided at the bottom of tunnel to improve the loading conditions of tunnel support structure. Tunnel invert is one of the main components of the tunnel structure. It can effectively transfer the pressure from the tunnel above ground or load from the pavement to the ground below the tunnel via tunnel sidewalls. Meanwhile, it can effectively withstand the pressure from the ground below. The invert in combination with secondary lining improves the stability of tunnel structure. However, in actual the various defects of construction in the invert structure tend to result from inadequate knowledge and attention to the invert, poor understanding of geological conditions of the tunnel site area or other reasons. These defects include tunnel instability, pavement subsidence or heaving, cracking and mud pumping. Consequently, it is particularly important to conduct invert quality NDT to help the Owner control the quality of invert construction, for ensure the safety in tunnel operation and save maintenance cost from defect remedying.

At present tunnel invert is frequently tested by GPR method. Facts show GPR detection results are greatly affected by site conditions and design parameters of the invert itself. Additionally, GPR, based on the principle of electromagnetic wave, offers antennas with different frequencies but there exists a trade-off between its detection depth and resolution. High-resolution EM waves are mostly consumed in shallow part of the invert whereas low-frequency EM waves have low resolution despite the ability to penetrate to great depths. As a result, when inspecting invert quality by GPR the inspector cannot correctly assess rebar execution in the invert structure and hence achieve the goal of invert quality NDT in the case of deep invert or large amounts of loose debris in the shallow backfill due to EM wave wastage in the shallow part.

This paper investigates the use of TEM in testing rebar execution in tunnel invert structure in an effort to make up for the drawback of existing testing methods and increase the reliability of invert quality test.
2. Methods

2.1. Introduction to TEM
The transient electromagnetic (TEM) method, alternately called time-domain EM, is a geophysical exploration technique in which electric and magnetic fields are induced in rock/ore in the ground by transient pulses of electric current and EM field distribution in space and time is observed and studied to identify good conductivity orebody or solve relevant geological problems. The TEM method begins with transmitting a time-domain, square-wave signal into a large ungrounded loop to produce an EM field which induces the conductive geologic body to generate eddy-currents. Because the conductive geologic body is nonlinear, the pulse current changes from peak to zero, resulting in immediate disappearance of primary magnetic field whereas the eddy-current attenuate with time depending on electric properties of the conductor. Induced currents in good conductors decay slowly due to smaller heat loss of the eddy currents. This transient change process of eddy currents forms corresponding transient magnetic field in space (Figure 1). By observing the transient magnetic field and secondary magnetic field when the pulse current is cut off, we can identify abnormal geologic body in the subsurface and determine the electric properties and spatial distribution of the subsurface conductor.

Figure 1 Schematic diagram of eddy currents and transient magnetic field induced by primary pulse

Based on its theoretical basis the TEM can be used for near-surface exploration in theory. However, instruments at home and abroad are mainly designed for mineral exploration and have some cut off time, causing dead zone in shallow applications. Because it takes generally dozens of microseconds to several hundred microseconds to turn off the transmitter loop, the transient EM signal picked up by the receiver loop is affected by its transmitting current for a considerable time. This leads to distortion, making the results unsuitable for interpretation. As a result in practice the inspector would abandon the distorted signal and only record later signals after complete turnoff. This limits its shallow detection ability, creating dead zones.

2.2. Introduction to new TEM adopted in this study
This study uses FCTEM60-1 instrument developed by Chongqing University. This instrument has prominent advantages in system operation performance, quick turnoff, highly dynamic signal collection, GPS synchronous control and active magnetic probe design. In particular, the transmitter loop of its constant voltage clamping technique for quick turnoff is illustrated in Figure 2. The transmitter loop is composed of full bridge converter, clamping circuit and DC stabilized voltage supply. When outputting pulse current the full bridge converter supply power positively while the clamping circuit stops working, with load voltage equal to supply voltage. When power supply is
interrupted, the clamping circuit plays its role in making load voltage equal to the clamping voltage. At this point the load current drops linearly.

Figure 2 Block diagram of constant voltage clamping transmitter loop

2.3. Field test of tunnel invert quality inspection

(1) Overview of test site

The test site is located in a 42m stretch and 32m stretch respectively at the portal and interior of a tunnel in the urban area of Chongqing. Measurements are made at 2m intervals to compare rebar distribution in the invert at the portal and inside the tunnel.

Figure 3 displays the top view of survey line 1 in the first test. The survey line is 16m long outside the tunnel and 26m long inside the tunnel. In this test measurements are made both in and out of the tunnel because TEM varies depending on full space and half space scenarios. In full space since the part above the tunnel pavement is also part of the tunnel structure, the effect of the upper structure on the test process should be understood so as to correctly assess test results. Figure 6 shows the starting point of survey line 1 on the site.

Figure 3 Top view of survey line 1
Figure 7 displays the top view of survey line 2 which passes a 16m stretch with invert and a 14m stretch without invert. The red zone indicates an area with a small amount of accumulated water where a mist spray machine is located. (see Figure 8)
(1) Results

In the test measurements at 22 points at 2m intervals along the 42m long survey line 1 were made. Measurements at 16 points at 2m intervals along the 30m long survey line 2 were made. Apparent resistivity images for survey lines 1 and 2 are shown below:

Figure 7 Image for survey line 1 (note: the apparent resistivity denotes relative value only and does not represent actual value)

Since the front half of survey line 1 (point 1 to point 8) is on the bridge leading to the portal and over rail transit viaduct, local low resistivity is observed. The rear half (point 9 to point 22) is in the tunnel approach section without rebars at the bottom, so high resistivity is observed, with apparent resistivity of surface layer above 2,000.

Figure 8 Image for survey line 2 (note: the apparent resistivity denotes relative value only and does not represent actual value)

The front half (point 1 to point 9) of survey line 2 as shown in Figure 8 is in the main tunnel with rebars and invert at the bottom. The rear half (point 10 to point 16) is also in the tunnel without invert but with steel plate on the pavement. Additionally, a mist spray machine was working during measurement producing lots of mist in the air and there was considerable water on the pavement, having a big effect on measurements. Therefore, its apparent resistivity is lower than the front half. Comparison of the rear half (without rebars at the bottom) of survey line 1 and the front half (with...
rebars at the bottom) of survey line 2 shows the latter's apparent resistivity of surface layer (around 1600) is lower than the former's 2100.

3. Discussion and Conclusions

The test results show the apparent resistivity varies greatly between presence and absence of low resistance objects underground and that shallow information is identifiable, meeting technical requirements for tunnel invert detection. From uniform apparent resistivity it can be inferred that the underground rebars are distributed continuously. However, for a stretch with unevenly distributed rebars underground (because of cheating on workmanship and materials or varying rebar spacing), the effectiveness of imaging remains to be verified. The presence of such structures as fan room and guard house near the tunnel almost had no effect on test results, demonstrating this method is adaptable to test environment in the tunnel. But its resistance to interference from excessive interferents remains to be verified. Generally, interferents in an operating tunnel are few and the proposed method in the test is therefore feasible for detecting rebars in invert structure.

TEM detects the transition of eddy current field in the conductor. Observations are made in the interval of pulses without interference from primary field. Meanwhile, the use of independently developed weak inducting coil technology can eliminate the effect of self-inductance and mutual inductance of wire frame to some extent, making almost all observation parameters come from secondary field. TEM is the only method that uses same-point device among various types of electromagnetic prospecting methods including GPR method. It provides the tightest coupling with detection target and the strongest response and generates an EM wave who propagates into the subsurface through an ungrounded loop of wire. This characteristic makes TEM very suitable for NDT on concrete asphalt pavement or cement pavement in an operation tunnel and the non-contact characteristic makes TEM a cutting-edge technique in line with the trend toward rapid NDT technology for modern highway projects. The successful application of the constant voltage clamping technique for quick turnoff in FCTEM60-1 instrument used in this study eliminates dead zones in shallow ground faced by traditional TEM and fundamentally changes TEM applicability in highway testing. Through interpretation of its early signal full analysis of variations in apparent resistivity in shallow ground is possible, without the trade-off between detection accuracy and depth in radar detection due to different frequencies of EM waves.

To sum up, the proposed TEM instrument can not only detect rebars in highway tunnel invert, but also has greater potential in the field of highway NDT. Further study on its applicability to different detection targets is needed to help solve more quality test problems.

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