Review on Tunnel Concrete Invert NDT Methods

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Abstract: Tunnel concrete invert is very important to the stability of the entire tunnel structure. However, invert’s quality is usually insufficient due to various reasons. Traditional approaches to detecting tunnel concrete invert focus on inefficient coring. The results of detection often cannot reflect all realities of the invert and concrete fill layer. These approaches are short of meeting current detection requirements for concrete invert. In order to increase the effectiveness and accuracy of invert test this paper summarizes technical features of GPR method and Rayleigh wave method according to concrete structure NDT and tunnel invert test technologies at home and abroad. The results show: the GPR method is simple and efficient and capable of qualitative test of tunnel invert, though with a trade-off between detection depth and accuracy; the Rayleigh wave method provides high accuracy and the qualitative test ability for tunnel invert thickness and unconsolidated fill, though inefficient due to a lack of pertinent equipment.

1. Introduction
As an important component of tunnel lining structure, the invert plays a vital role in increasing the bearing capacity of the lining structure, inhibiting surrounding ground deformation and improving structural safety performance. Therefore, the overall quality of invert structure has a direct influence on the overall stability and operation safety of the tunnel. However, construction quality in western China cannot be strictly controlled due to its complex geology and construction challenges. This leads to common quality problems of tunnel invert, e.g. loose backfill layer and execution of the invert not in accordance with design requirements. A comprehensive test method is currently not available for tunnel invert [1]. It is therefore necessary to review and describe tunnel concrete invert test methods. This paper provides a description of GPR and Rayleigh wave methods.

2. GPR Method
Since the 1990s GPR (ground penetrating radar) has been used for concrete NDT. With upgraded GPR data acquisition and processing software and hardware, foreign experts and scholars applied the GPR technique in detecting defects of tunnel lining and invert in actual projects as well as simulation test. These applications produced good results.

A GPR transmitter and antenna emits high-frequency electromagnetic waves in the form of broadband short pulses into the ground. The waves are absorbed by ground material and reflected by abnormal bodies back to the surface. A receiving antenna can then record the variations in the return signal, generating radar waveforms containing abundant information of the ground. Through offset and other processing of the radar waveforms received, distribution of underground media and abnormal bodies can be obtained, as shown in Fig. 1. The travel time of radar pulse wave can be expressed as
\[ T = \sqrt{4z^2 + x^2} \cdot v^{-1} \]  

(1)

where \( T \) is the travel time measured by radar; \( z \) is the depth of abnormal body; \( x \) is the spacing between transmitting and receiving antennas; \( v \) is wave velocity in media. Radargrams are commonly recorded as reflected pulse waveform. Fig. 1 (b) displays the schematic diagram of radar waveform record. Fig. 1 (a) displays a simple geological model. Waveforms in vertical direction of survey line at measuring points are recorded in the waveform record to form radar profile.

![Figure 1 GPR detection schematic diagram](image)

Since the 1980s Australia has used GPR for geophysical exploration and engineering NDT and achieved remarkable results in tunnel quality test, laying the groundwork for GPR application in tunnel inspection and test. In early 21st century a study team in the US conducted simulation experiment on using GPR for tunnel defect detection. As a latecomer China set foot in such research in the 1970s. At present, GPR is mainly used for detection of tunnel lining thickness, lining/original rock failure, lining crack, lining deformation and backfill compactness and water leakage. In 2014 Huang Xiaogang \[3\] verified the hyperbola characteristic with equal imaginary axis and real axis for karst cave radargram via physical simulation. He also performed field test on tunnel invert in karst cave and verified the effectiveness of GPR in tunnel invert detection in karst cave. In 2015 Yang Zhuo and Zhang Xia \[4\] discussed lining loosening and invert thickness problems in rail tunnel lining quality inspection by GPR method, identified the use of radar for invert test as the cause of large error and noted use of radar alone for invert test is of limited effect.

Over the past decade with progressing GPR technology, commercial radars represented by GSSI and SSI have matured, making GPR technique a key means of NDT for tunnel concrete invert structure. In 2012 Fan Pusheng et al. \[5\] studied how to assess unconsolidated concrete fill in tunnel invert using GPR method and applied this method in invert test for a tunnel in Qinghai. The radar imaging result was highly consistent with destructive test result, thus verifying the effectiveness of invert test by GPR method. This contributed to valuable experience in high-precision invert test and of significance to practical guidance. Subsequently Du Sheng and Zhou Bin \[6\] at China Railway Southwest Research Institute further explored invert, fill layer thickness and compactness test by GPR method and noted its high accuracy in qualitative test of invert compactness and deficiency in depth detection.
The GPR method has not been effectively applied in invert test for mountain tunnels due to geological complexity and detection difficulties. However, it has been used in lining test for mountain tunnels. In recent years taking into account high elevation, coldness, water richness and complex geology of high altitude mountain tunnels Zhang Mingchen et al. [7] took Yuximolegai Tunnel as an example to analyze technical issues of GPR lining test for alpine mountain tunnels, offering great reference value to future invert test by GPR in cold areas. In view of multiple defect types in actual invert fill layers Mu Pengyu and Ma Ruitao [8] analyzed waveforms for loose gravel fill, unevenly compacted concrete and mud interlayer and noted non-destructive and economical advantages of GPR in preliminary assessment of concrete defects, providing a reference for tunnel invert looseness detection.

In terms of radargram analysis Huang Yang et al. [1] developed a spectrum-energy analysis method based on GPR principle that could achieve detection depths 2-3 times greater than conventional methods and improve the trade-off between GPR antenna frequency and resolution. Their work provided beneficial technical support for effective test of invert at great depths in complex geological conditions in mountain areas.

3. Rayleigh Wave Method
Rayleigh waves are a type of surface wave that travel in ellipses near the ground surface, characterized by low frequency, low speed, high Signal to Noise Ratio and dispersion. They are very sensitive to shear wave velocity in ground material. Therefore, the Rayleigh wave method is widely applied in near-surface detection and concrete structure NDT. The characteristic of Rayleigh wave dispersion is used in underground target detection. In actual applications, surface waves in a wide frequency band can be generated by a point source. Subsequently, the dispersive spectrum of the surface wave data can be derived. By inverting the dispersion curve the target at designated depths can be imaged. Normally the relationship between surface wave frequency $f$, wave speed $v$ and detection depth $h$ can be approximated as:

$$h \approx 0.5 \frac{f}{v}$$  \hspace{1cm} (2)
In 1887 a British scholar Lord Rayleigh discovered the existence of Rayleigh waves and described their propagation characteristics in elastic half space medium. In mid 20th century Rayleigh wave dispersion was discovered and began to be used in research on underground medium testing.

Constrained by computer technology development, no breakthrough was made in Rayleigh wave method in early 20th century. By 1983 Stokoe et al. [8] at University Of Texas developed Spectral Analysis of Surface Waves (SASW) and established near-surface shear wave velocity profile by proper interpretation of the dispersion curve of surface waves, thus gradually forming the theoretical foundation and application system of superficial exploration by Rayleigh wave method.

The Rayleigh wave method provides high resolution for near-surface detection and is mainly applied in geotechnical investigation of shallow strata, e.g. reinforcement assessment for soft ground, advance detection of railway subgrade strength and mine coal seam and rolling quality inspection for dam fill. As higher accuracy demands are placed on tunnel lining and invert testing, the Rayleigh wave
method has received increasing attention from researchers in concrete structure NDT at home and abroad in recent years.

In 2010 Antonin [9] investigated the application of high-frequency surface wave multi-ray analysis method in asphalt pavement through comparison of asphalt pavement NDT theories and developed appropriate equipment, promoting the application of the Rayleigh wave method in NDT field. Subsequently, V.Métais et al. [10] inverted the dispersion curve of Rayleigh waves using global neighborhood algorithm and applied it in concrete porosity testing. In 2018 R.Drelich et al. [11] analyzed the detection effect of multi-ray Rayleigh waves in heterogeneous concrete structure and generated high-resolution images of a 1-meter heterogeneous concrete structure.

China's research on concrete invert NDT by Rayleigh wave method is in the exploratory stage. In 2018 Zhao Qianjin [12] at South Yunnan Railway Headquarters tested concrete invert structure in the railway tunnel using wide-frequency multi-ray transient surface wave method and compared the detector, seismic source and other key parameters. The genetic algorithm based dispersion curve inversion results are roughly consistent with coring data, verifying the effectiveness of the Rayleigh wave method in testing concrete invert structure of the tunnel.

In the same year Liu Jibin et al. [13] at China Railway Southwest Research Institute systematically described the transient surface wave technique in tunnel concrete invert testing and pointed out the prominent advantage of this technique in quantitative assessment in concrete invert testing. In addition,
China Railway Southwest Research Institute [14] improved the conventional Rayleigh wave method and created a set of patented equipment for tunnel concrete invert test by Rayleigh wave method. This equipment is promising in wider applications.

4. Conclusions

From review and comparison of current tunnel concrete invert testing technology by GPR and Rayleigh wave methods, the following conclusions can be drawn:

(1) Thanks to its ease of operation, low cost and high efficiency the GPR method is widely applied in tunnel quality test and a major means of testing tunnel concrete invert. However given the great thickness of the concrete fill layer of invert the GPR method struggles to meet the detection requirements of great depths and high precision due to the trade-off between detection depth and precision. Furthermore, the invert itself is a RC structure and the presence of rebars interferes with GPR imaging quality of invert bottom. Therefore, the GPR method is deficient in quantitative analysis of invert and concrete fill layer.

(2) The Rayleigh wave method can accurately locate physical boundaries in tunnel concrete invert and due to its insensitivity to rebars in the invert structure, is capable of high-precision imaging of unconsolidated locations in the invert and its concrete fill layer. However, this method currently uses traditional geophysical observation system leading to low detection efficiency. Its high demands on personnel skills in data processing stage have prevented its wider applications.

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