Application of surface wave in reinforced concrete invert detection

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Abstract. The thickness of reinforced concrete is an important parameter for tunnel safety, so it is necessary to detect it by non-destructive testing method. We used the multi-channel surface wave (MASW) method to derive velocity of tunnel lining structure in depth and detect thickness of reinforced concrete. The numerical experiment for irregularly dispersive media is conducted to simulate Rayleigh wave. The mode-kissing phenomenon in velocity spectrum is shown, and the modal dispersion curve can be inevitably misinterpreted. The field measurement is carried out on a new construction tunnel site and some Rayleigh wave data are acquired. We compute their velocity spectra. An alternative full velocity spectrum misfit function and a Bayesian inversion scheme are employed to retrieve tunnel lining structure. This study demonstrates that MASW method can effectively retrieve shear velocity of each layer in lining structure and detect the thickness of reinforced concrete inverts.

1. Introduction
Tunnel is an important part of the transportation network in southwest China. And tunnel lining structure stability is an important factor for traffic safety. Tunnel lining is, in general, divided by two- or three-layers structure with a reinforced concrete invert which plays a role in resisting the reverse force from the bottom of the tunnel and ensuring the function of tunnel stability. Reinforced concrete invert detection and evaluation provide technical support for tunnel construction and maintenance, which help to find defects in advance and prevent all kinds of possible hidden disease problems.

In recent years, Ground Penetrating Radar (GPR) and drill core sampling are widely applied for inspection of concrete lining structure. However, these techniques are individually not suitable for reinforced concrete invert detection. Drill core sampling is a kind of in-situ testing technique and can obtain the most intuitive results by drilling samples at the target site. But this method is low-efficiency and destructive testing. Though GPR is efficient nondestructive testing (NDT), there is small dielectric constant difference between the invert concrete and the filling layer concrete, which leads to weak electromagnetic wave reflection. The interface identification[1] and the thickness evaluation of lining structure can fail. Surface wave method capable of determining material velocity and stiffness of layered media has been frequently utilized for geotechnical engineering applications. For Rayleigh wave, most of the energy exists within one wavelength of depth and obvious dispersion appears in layered media. Based on dispersion curves or velocity spectra, S-wave velocity of concrete structure in depth was assessed for nondestructive testing. And MASW method has been gaining increasingly more attention and has become one of the main surface wave methods to determine shear wave velocity profiles for applications in geophysics and civil engineering. Surface wave method was successfully applied in ground crack detection[2], urban earthquake response prediction [3] and soil
compaction detection [4,5] measured the thickness of the aging layer of the concrete surface by using the frequency dispersion characteristics of Rayleigh wave in the layered medium. Ayolabi et al. [6] used the MASW method to study the causes of highway damage and to measure the cause of the damage to loose compaction of road-based materials. Because of special model structure, MASW method is largely neglected for tunnel lining structure detection with reinforced concrete invert. Liu et al. [7] detected the uncompact area of tunnel elevation by surface wave method, which proves the validity of surface wave testing.

In this study, the feasibility of MASW method in reinforced concrete invert detection is investigated. Rayleigh wave simulation of tunnel lining structure is performed by using finite difference in time-domain (FDTD) technique. Dispersive characteristics of Rayleigh wave are analyzed in full velocity spectrum domain. An alternative Full Velocity Spectrum (FVS) and a Bayesian inversion scheme are employed to retrieve tunnel lining structure. Field tests are carried out in a new construction tunnel of known lining structure.

2. Surface Wave Dispersion Analysis and Inversion

The typical tunnel lining section and profile are illustrated in Figure 1, where the filling layer is poured by C15 concrete, the reinforced invert layer is poured by C30 concrete and put on the bedrock. The elastic parameters of different medium are shown in the Table 1. This is a vertically heterogeneous media with low velocity in deep depth, which is irregularly dispersive media. When the Rayleigh wave is excited on the free surface of filling layer and exhibits dispersive behaviour, different frequency components will travel at different velocities and sample different depths of the subsurface based on their corresponding wavelength. The phase velocity is relative to the mechanical properties of the subsurface strata from the ground surface to a depth of approximately 1/3-1/2 the wavelength ($\lambda$).

![Figure 1. Schematic of tunnel lining section and profile](image)

| Table 1. Model Parameters |
|---------------------------|
|                           | Shear wave velocity(m/s) | Density (kg/m3) | Layer thickness(m) |
| Filling layer(C15)        | 2000                      | 2.36             | 1.5                |
| Invert layer(C30)         | 2500                      | 2.38             | 0.5                |
| Bedrock                   | 1300                      | 2                | INF                |

The simulation is an effective way of studying the propagation and dispersive properties of Rayleigh wave. A two dimensional (2D) staggered grid FDTD scheme is employed to simulate Rayleigh wave propagation of tunnel lining model. In a MASW survey, a set of receivers are deployed as a linear array and surface waves are actively introduced (e.g., impacts of a sledgehammer) from a location relative to the closest receiver, and acquisition parameters are shown in Table 2.
Table 2. Acquisition parameters

| Number of channels | Sampling rate | Record time | Geophone spacing | Min offset |
|--------------------|---------------|-------------|------------------|------------|
| 24                 | 0.01ms        | 10ms        | 0.2m             | 1m         |

The Rayleigh wave data in space-time (x-t) domain are transformed into the frequency-phase velocity domain which represents the amount of accumulated energy at different frequency phase velocity values. In Figure 2, Rayleigh waveform data was processed by phase shift method to extract dispersion information. The dispersion velocity spectrum has its energy concentrated along a smooth and continuous “ridge” and contains evidence of tunnel lining structure feature. We add array length with 100 Geophones and find dispersive mode-kissing phenomenon ranging from 500Hz to 600Hz in velocity spectrum image. A fundamental-mode dispersion curve can be extracted by picking the spectral maxima along the ridge, but can be misinterpreted.

Due to irregularly dispersive media different from that of near surface media, the fundamental mode dominates the wave field, but higher order modes can become equally or more energetic in this model. To examine energy distribution among these modes, theoretical modal curves are calculated by Knopoff decomposition method and superimposed on the corresponding dispersion spectra. There is a clear difference between the theoretical dispersion curve and the measured dispersion curve. The root-finding method, in principle, is only applicable to normally dispersive media. For an irregularly dispersive medium, the quantitative accuracy of the dispersion curves is degraded to various extents.

![Figure 2](image)

Figure 2. The model set: a) Rayleigh waves and b) its full velocity spectrum with the peak curve (the black line) and the theoretical dispersion curve (the blue line) ; c) the full velocity spectrum of the array length model ; d) compact representation of the two velocity spectrum (background contours represent the velocity spectrum of the model data, whereas the overlaying black lines relate to the inversion results).

In the tunnel lining testing, the long array is difficult for high lateral resolution and fast surveying. So the conventional inverse misfit function using dispersion curve is not suitable for tunnel invert detection. We choose an alternative full velocity spectrum as inverse misfit function. Dal Moro[8] introduced this approach based on the analysis of velocity spectrum rather than the interpretation of the dispersion curves. This method takes into account the entire velocity spectrum of the surface wave and is therefore called full velocity spectrometry. The analysis of full velocity spectrum consists of three steps:

1. The field wavefield in the offset-time (x-t) domain is transformed into the frequency-velocity (f-v) domain data;
2. Based on global inversion scheme, the candidate model is used to simulate Rayleigh wave and the full velocity spectrum is also computed as the step (1);
(3) Calculate the fit error of the above velocity spectrum. And next candidate model is selected by heuristic method.

Because the inverse problem is nonlinear, its misfit function usually has multiple local minima rather than a single well-defined global minimum. Bayesian inference is employed for a derivative-free global-local search scheme, which provides rigorous uncertainty estimates by quantifying the posterior probability density (PPD) of model parameters. The PPD is estimated by numerical, multi-dimensional integration via non-linear sampling methods that produce an ensemble of parameter-vector values. The most common and efficient sampling methods for high-dimensional problems are based on a Markov chain Monte Carlo (MCMC) scheme. For the velocity spectrum in Figure 2(b), we use the MCMC scheme to invert model parameters shown in Table 3. The result demonstrates that tunnel lining structure obtained by using full velocity spectrum inversion is closer to the model.

3. Field Test
At a new construction tunnel site, The tunnel is located in Yunnan province and has a total length of 300m with an arched-gate cross section. The width of the tunnel is 10 m and the height of its vertical is 7.2 m. The tunnel lining is made with C15 concrete of the filling layer and C30 concrete of the reinforced invert. An overview of the tunnel is shown in Figure 3. Due to the dense interior and exterior reinforcement of the concrete lining section, the steel bars strongly interfere with the GPR signal and the interface between the fill layer and invert layer cannot be distinguished. So the MASW method is introduced for testing the quality of the lining.

| Table 3. Inversion result and error |
|-------------------------------------|
| Shear wave velocity(m/s) | Error(m/s) | Layer thickness(m) | Error(m) |
| Fill layer | 1996.5 | 3.5 | 1.51 | 0.01 |
| Invert layer | 2509.2 | 9.2 | 0.52 | 0.02 |
| Bed rock | 1294.5 | 5.5 | INF | / |

Surface wave records were collected using a linear array of 24 vertical geophones in order to evaluate the feasibility of the MASW method. The geophones are arranged near the middle line. The array of geophone is shown in Figure 3. The near offset is 1m and receiver spacing is 0.2m. The sampling interval is 3μs. A recorded data (2K-160-1) and the full velocity spectrum calculated by phase shift method are shown in Figure 4(a) and (b). In the dispersion spectrum, a prominent bulge ranging from 400Hz to 500Hz is observed. This dispersive mode-kissing phenomenon is similar to that of the simulation. The FVS is used for inverse misfit function. The model from designed engineering parameters is chosen as the initial model. We conduct 1500 MCMC samplings for Bayesian inference. The lining structure is obtained from the arithmetic mean of 1500 samples and its theoretical FVS is shown in Figure 4(c). The theoretical FVS conforms well to that of field data (Figure 4(d)).
Figure 4. The data set (2K-160-1): a) Rayleigh waveform and b) its phase-velocity spectrum; c) the theoretical velocity spectrum; d) superimposition representation of the two velocity spectrum (color represent the velocity spectrum of field data and contour the theoretical velocity spectrum).

Table 4. Inversion result and the designed value.

|                  | 2K-160-1 | 2K-160-2 | Designed layer thickness (m) |
|------------------|----------|----------|-----------------------------|
| **Filling layer**| 1688.4   | 1665.5   | 1.59                        |
| **Invert layer** | 2196.2   | 2204.0   | 0.49                        |
| **Bed rock**     | 1110.9   | 1198.1   | INF                         |

Figure 5. The filed data set (2K-160-2): a) Rayleigh waveform and b) its phase-velocity spectrum; c) the theoretical velocity spectrum; d) superimposition representation of the two velocity spectrum (color represent the velocity spectrum of field data and contour the theoretical velocity spectrum).

Another data (2K-160-2) is processed with the same method and flow. The inverted lining structure is shown in Table 2. The reinforced concrete invert has a higher shear wave velocity of about 2500m/s and its thickness is around 0.49m. Compared to designed layer thickness, the errors are less than 5cm, which demonstrates the feasibility of MASW method. Some factors, including concrete
inhomogeneity, geophone and noise, can contribute to lining structure difference for two testing sites 2K-160-1 and 2K-160-1.

4. Conclusions
We introduce the MASW method to detect the tunnel lining structure which is irregularly dispersive media. A Rayleigh wave simulation with FDTD scheme is achieved and the dispersive property is analyzed in full velocity spectrum domain. We find mode-kissing and no concentrated energy, which can lead to misinterpret dispersive curves. The FVS misfit function and Bayesian inference are employed to invert model parameters. Two field data sets are tested and the results show the feasibility of MASW method for detecting reinforced concrete invert.

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References
[1] Chen R 2016 Nondestructive testing for the density of a immersed tunnel foundation by the sand-flow method Modern Tunnelling Technology 53(3) 131-136 (In Chinese)
[2] Zhao S, Meng Y and Sun J 2018 Research in the Trend of ground rupture development in Gaoliying of Beijing based on the variation of the S wave velocities Advances in Geosciences 8(7) 1123-1130 (In Chinese)
[3] Boaga J, Renzi S, Vignoli G, Deiana R and Cassiani G 2012 From surface wave inversion to seismic site response prediction Beyond the 1D approach Soil Dynamics and Earthquake Engineering 36 38-51
[4] Donohue S, Forristal D and Donohue L A 2013 Detection of soil compaction using seismic surface waves Soil & Tillage Research 128 54-60
[5] Tsai W H, Lin Y C and Cheng C C 2018 Detecting the depth of weak layer in concrete using R-wave dispersion techniques Ndt & E International 98 161-170
[6] Ayolabi E A and Adegbola R B 2014 Application of MASW in road failure investigation Arabian Journal of Geosciences 7(10) 4335-4341
[7] Liu J, Zhang F and Wang X 2017 On application of transient surface wave method in quality inspection of tunnel invert Subgrade Engineering 3 208-211 (In Chinese)
[8] Dal Moro G 2019 Surface wave analysis improving the accuracy of the shear-wave velocity profile through the efficient joint acquisition and Full Velocity Spectrum (FVS) analysis of Rayleigh and Love waves Exploration Geophysics 50(4) 408-419