Application Analysis of Rayleigh Wave Method in Compactness Detection of Railway Subgrade

Xiaolin Wang[1], Wei Yin[2]

[1] School of Civil and Environmental Engineering, City College of Southwest University of Science and Technology, Mianyang, Sichuan, 621000, China

[2] China Railway 20 Bureau Group Third Engineering Co., Ltd, Chongqing, 400000, China

Keywords: Rayleigh Wave, Railway Subgrade, Compactness, Detection

Abstract: survey technology in the engineering field and the good results achieved, it is necessary to use rayleigh wave method to detect the degree of compaction of railway subgrade, and compare it with the conventional sand filling method and circular knife method to verify its feasibility and reliability. Through studying the theory and experiment of rayleigh wave, the paper discusses the application of non-destructive detection technology of surface wave in the detection of compaction degree of railway subgrade. It is believed that this method is feasible, reliable in precision, non-destructive and efficient, and is a practical technology worthy of wide popularization and application.

1. Introduction

With the opening of high-standard projects such as railway construction and high-speed rail project construction, the detection content of detection units is more and more diverse, the detection standard is higher and higher, and the time limit for a project is more and more tight [1]. For railway engineering, quality problems such as bumping at bridgehead, road surface subsidence and fracture often occur, which will seriously affect the comfort and safety of driving, and reduce the service life of the railway, while the cost of maintaining the railway increases, which is often caused by insufficient compactness of railway subgrade. The traditional detection methods for the compactness of railway subgrade [2] include ring cutting method or sand filling method. Points are randomly selected according to regulations, and then indoor analysis and treatment are carried out. Conventional detection methods are labor intensive and slow, causing damages to railway subgrade, and the detection results are covered with dots, which is difficult to truly reflect the real situation of the site [3]. With the rapid development of chinese railway industry, the traditional testing methods for the compaction degree of railway subgrade can no longer meet the needs of today. It is of great significance to study new pavement nondestructive testing equipment and technical means. Rayleigh wave testing technology is a new nondestructive, high-speed and fast testing technology, which can better complete the rapid testing for the compaction degree of railway subgrade.

2. The Basic Principle of Rayleigh Wave Method

There is a wave type in the surface wave. The propagation direction of the wave particle is perpendicular to the in-plane vibration, and the vibration track is elliptical. Its amplitude depth in the medium shows exponential attenuation. The propagation speed of the surface wave is slightly lower than the wave speed of the transverse wave [4]. Because it was first discovered by the British scholar Rayleigh, this wave was named Rayleigh wave, or Rayleigh wave [5]. When the seismic source strikes at the surface, longitudinal wave, transverse wave and surface wave will be generated simultaneously. Rayleigh wave is the vibration of a particle in a plane perpendicular to the medium interface in the propagation direction. The vibration trajectory of the particle is an ellipse rotating counterclockwise. The amplitude of the particle decays exponentially with depth and the propagation speed is slightly lower than that of transverse wave. There is a Rayleigh wave (i.e. surface wave) generated by the interference of compression wave and shear wave in semi-space

  DOI: 10.25236/acete.2019.080

elastic medium, which is the only vibration signal easy to identify [6]. The basic method of Rayleigh wave detection is that n + 1 detectors are arranged at the same detection distance Δ along the wave's propagation direction, and surface waves within the length of $n\Delta t$ can be received. Rayleigh waves have different penetration abilities with different wavelengths; Rayleigh wave propagation speeds have a good correlation with shear wave propagation speeds. Shear wave propagation speed is closely related to the physical and mechanical characteristics of the medium.

Suppose its frequency is f_i, the time difference of Rayleigh surface waves recorded by adjacent detectors is Δt, and the phase difference is Δh, then the wave velocity of Rayleigh surface waves within the length of adjacent channels Δx is [7]:

$$V_r = \frac{\Delta x}{\Delta t} \, or \, V_r = 2\pi f_i \frac{\Delta x}{\Delta h} \quad (1)$$

The measurement range $n\Delta x$ average speed is:

$$\overline{V}_r = \frac{n\Delta x}{\sum_{i=1}^{n} \Delta t_i} \, or \, \overline{V}_r = \frac{2\pi f_i n\Delta x}{\sum_{i=1}^{n} \Delta h} \quad (2)$$

When a heavy hammer is used to apply the excitation force on the ground, Rayleigh waves of different frequencies f correspond to wave speeds V r of different depth ranges, so as to obtain V_r-H curves no. ie, dispersion curves). Laminar wave velocity V_r. When a transient state is produced on the ground (thumping or exploding), Rayleigh waves of a certain frequency range are generated. Rayleigh waves of different frequencies are superimposed together and propagate forward in the form of pulses. These are superimposed by the ground detector After receiving the signal, through analysis of frequency spectrum and phase spectrum, the Rayleigh waves of each frequency are separated to obtain a V_{Ri} -f curve.

3. Detection of Railway Structural Layer Thickness by Rayleigh Wave Method

For the ordered waveform signals received by multi-channel detectors, Rayleigh wave propagation velocity is a population velocity synthesized by Rayleigh waves with different frequencies. In order to obtain the corresponding frequency curve, it is necessary to adopt mathematical means to process Rayleigh waves in the time domain. Whether the frequency component of the source signal is rich or not and its energy is directly related to the effectiveness of the transient method, so the source should be carefully selected according to the testing requirements. In a half space with uniform directions, Rayleigh wave velocity does not change with the change of frequency. In horizontal layered media, Rayleigh wave phase velocity V_r is related to the physical and mechanical parameters of each layer of media. V_r varies with frequency. This characteristic is called Rayleigh wave dispersion. Using the dispersion information of Rayleigh wave, the parameters of each layer can be inversed. Using Rayleigh wave method to detect the thickness of each structural layer of railway is based on the variation law of dispersion curve of Rayleigh wave propagation in layered medium. It is not only related to the physical parameters of each layer, but also closely related to the thickness of each layer, especially the inflection point of dispersion curve has a direct correspondence with the interface of each layer. The interface depth of each layer can be calculated by the following formula [8]:

$$h_i = \beta \lambda_{Ri} \, or \, h_i = \beta \frac{V_{Ri}}{f_i} \quad (3)$$

In the formula, hi is the depth of the bottom interface of layer I of the layered medium, and m and f_i are Rayleigh wave frequencies, Hz, corresponding to inflection points of dispersion curves. λR_i is the Rayleigh wave wavelength corresponding to the inflection point of the dispersion curve, m; Beta is the wavelength and depth conversion coefficient of Rayleigh wave.

If Rayleigh wave method is used to detect the compactness of railway subgrade, detectors shall be arranged according to the specific conditions of the project and the characteristics of the site. The Rayleigh wave velocity at each depth is mainly detected by a detector, and the compactness of each filling layer is determined by using the relationship between density and Rayleigh wave velocity. When analyzing the time domain signals of the measured waves, the time interval range of the surface wave vibration data is determined to avoid being influenced by interference signals and create conditions for smooth spectrum analysis. At present, the geophones used include moving coil electromagnetic velocity sensors and piezoelectric crystal acceleration sensors. In the test, the corresponding main frequency detector is selected according to the excitation frequency. There is a relatively appropriate excitation frequency to completely cover the depth range of the detection target; There are enough small frequency intervals so that each structural layer on the measured V_{Ri} -f curve can correspond to several data points. Appropriate frequency interval is a relative concept, which is closely related to the depth of the target body and the average velocity $\overline{V}_R$ of the medium above it. In principle, all the results of the steady-state method can be obtained only by one impact on the ground. The steady-state method not only has a large workload on site, but also is susceptible to human error when determining the phase on the oscilloscope. In general, survey lines shall be arranged along the longitudinal section or cross section of the railway subgrade, and all factors in the project shall be comprehensively considered in the actual operation process.

In the formula, hi is the depth of the bottom interface of layer I of the layered medium, and m and fi are Rayleigh wave frequencies, Hz, corresponding to inflection points of dispersion curves. λR_i is the Rayleigh wave wavelength corresponding to the inflection point of the dispersion curve, m; Beta is the wavelength and depth conversion coefficient of Rayleigh wave.

If Rayleigh wave method is used to detect the compactness of railway subgrade, detectors shall be arranged according to the specific conditions of the project and the characteristics of the site. The Rayleigh wave velocity at each depth is mainly detected by a detector, and the compactness of each filling layer is determined by using the relationship between density and Rayleigh wave velocity. When analyzing the time domain signals of the measured waves, the time interval range of the surface wave vibration data is determined to avoid being influenced by interference signals and create conditions for smooth spectrum analysis. At present, the geophones used include moving coil electromagnetic velocity sensors and piezoelectric crystal acceleration sensors. In the test, the corresponding main frequency detector is selected according to the excitation frequency. There is a relatively appropriate excitation frequency to completely cover the depth range of the detection target; There are enough small frequency intervals so that each structural layer on the measured V_{Ri} -f curve can correspond to several data points. Appropriate frequency interval is a relative concept, which is closely related to the depth of the target body and the average velocity $\overline{V}_R$ of the medium above it. In principle, all the results of the steady-state method can be obtained only by one impact on the ground. The steady-state method not only has a large workload on site, but also is susceptible to human error when determining the phase on the oscilloscope. In general, survey lines shall be arranged along the longitudinal section or cross section of the railway subgrade, and all factors in the project shall be comprehensively considered in the actual operation process.

4. Rayleigh Wave Method for Compactness Test of Railway Subgrade and Pavement

In time and space, surface waves are more superimposed and interspersed. Wave energy of surface wave can be directly identified by longitudinal observation in frequency wavenumber domain, and dispersion data of single mode can be directly obtained from this. In order to obtain the dispersion curve of phase velocity, the Rayleigh wave in the time domain must be processed mathematically in the ordered waveform generated by the transient vibration source received by the multichannel detector. The compaction degree of railway subgrade is detected by transient Rayleigh wave method and evaluated by sand filling method. The on-site test shall be carried out after the rolling of the railway subgrade base and before the paving of the next layer of railway subgrade soil. Then the equivalent half-space method is used to calculate and obtain the Rayleigh wave velocity of each layer, and then the corresponding relation between the Rayleigh wave velocity and the dry density of the railway subgrade soil is established, so that the compaction degree of the railway subgrade soil can be obtained from the measured Rayleigh wave velocity. Compaction degree is the main test item for railway subgrade, pavement base and flexible pavement. Compaction degree is called compaction coefficient, and its physical meaning is the ratio of medium dry density and maximum dry density actually achieved through compaction during construction, namely

$$k = \frac{\rho}{\rho_0} \times 100\% \quad (4)$$

In-situ compaction test using elastic wave velocity is based on the good relationship between elastic wave velocity of medium and density of medium. In elastic theory, density and elastic wave velocities V_P, V_S, V_R have the following relationship:

$$V_P = \sqrt{\frac{E}{\rho} f(\sigma)} \quad (5)$$

$$V_S = \sqrt{\frac{\mu}{\rho}} \quad (6)$$

$$V_R = (0.92 - 0.95)\sqrt{\frac{\mu}{\rho}} \quad (7)$$

In the formula, wave velocities V_P, V_S and V_R are longitudinal wave, transverse wave and Rayleigh wave velocities, m/s respectively; E and μ are elastic modulus and shear modulus respectively, Pa; For Besumbi.

The wavelength of surface wave can be decomposed into sine signal and cosine signal in time and space, which is easy for two-dimensional spectrum conversion. Time frequency fluctuation can be obtained by measuring the fluctuation times within 1s, marked as frequency (f), and the unit is defined as hertz (Hz). Analyzing the above formula, it seems that when the density ρ increases, the wave velocities V_P and VR should decrease, but in fact they are not, because for soil media, the density ρ is a function of the porosity of the media, the porosity decreases and the density ρ increases, while the elastic modulus E and shear modulus G will also increase, and the increasing speed of E and G is much faster than ρ. Rayleigh wave propagation velocity is a group velocity composed of Rayleigh waves with different frequency components of a certain frequency band width generated by transient excitation. In order to obtain the dispersion curve of phase velocity, necessary mathematical treatment must be made for Rayleigh wave in time domain. Therefore, it is necessary to convert the apparent velocity of Rayleigh wave into the layer velocity of Rayleigh wave and give the velocity of shear wave. As a result, when ρ increases, the wave velocities V_P and V_R also increase correspondingly. According to this, the correlation between V_R and ρ can be established for specific media:

$$\rho = A V_R^B \quad (8)$$

In the formula, A and B are coefficients, which are constant for a specific medium.

The basic calculation formula for the compactness of railway subgrade is as follows:

$$K = \frac{\rho}{\rho_0} \quad (9)$$

Where ρ0 is the maximum dry density (kg/m3) reached by standard compaction test. Substituting equation (3) into equation (4) yields:

$$K = \left(\frac{V_R}{V_{R0}} \right)^B \quad (10)$$

Where: V_R is the measured Rayleigh wave velocity value after actual compaction of railway subgrade; V_{R0} is the Rayleigh wave velocity measured after the standard compaction test.

In actual work, the longitudinal wave velocity V_P is greatly affected by the medium water content, while the Rayleigh wave velocity V_R is almost not affected by the medium water content, so the Rayleigh wave velocity V_R value can be used to determine the compaction degree of railway subgrade.

5. Inspection Effect of Compactness of Railway Subgrade

5.1 The Corresponding Standard Rayleigh Wave Velocity

There are many methods to determine the standard Rayleigh wave velocity. According to the actual situation of Sanling Railway, the same point and ring knife method are used for comparative tests. After the compaction of a certain layer is completed, the compaction degree by ring knife method and Rayleigh wave method are respectively detected at the same point, and the average wave velocity VR and the corresponding average compaction degree k in the evaluation stage are respectively obtained. A total of 20 same point tests were carried out. After the dispersion data are processed hierarchically, the corresponding average Rayleigh wave velocity value can be determined according to the dispersion data points of each segment through debugging and fitting. To ensure that the fitted data points are consistent with the measured data points as much as possible, only by this can the same Rayleigh wave velocity value as the actual project be obtained. Rayleigh waves with different frequencies have different wavelengths, and their average velocities reflect the properties of media in different depth ranges. Taking 1.5 times the mean square deviation as the control standard, after eliminating the 5th and 11th points with obvious errors from the 13 measuring points, the regression empirical formula for the measured Rayleigh wave velocity and the dry density of railway subgrade soil is re-fitted as follows:

$$\rho = 0.8573 V_R^{0.1443} (g / cm^3) \quad K = \left(\frac{V_R}{V_{R0}} \right)^B \quad (11)$$

The correlation coefficient of linear regression is r= 0.732. The correlation coefficient of formula (11) is tested for significance, with r= 0.732>r0.95= 0.602 1 at the level of confidence a= 0.05, indicating that the density of railway subgrade soil is linearly related to Rayleigh wave velocity V_R, and the reliability of regression empirical formula is greater than 95%.

5.2 Standard Rayleigh Wave Velocity At Different Evaluation Stages

At the later stage of railway subgrade construction, the high-speed railway adopts hydraulic dynamic compaction machinery to tamp all abutment backs, and the backfilling quality of abutment backs is evaluated by settlement difference before and after tamping. The size of the track spacing should not be less than the thickness of the minimum layer of the detected railway subgrade. If the track spacing is small, the bathymetry will decrease correspondingly, but the signal resolution is high. If the distance between tracks is large, the opposite is true. During the construction of railway subgrade, more than 90 cross-section tests have been completed in the whole line using this method. The quality problems of deep filling of railway subgrade have been found in a timely and effective manner. The test results are good and provide the basis for management units to take remedial measures. Although the maximum dry density obtained from indoor heavy compaction tests in various soil fields is slightly different, it will not change the relationship between dry density ρ and Rayleigh wave velocity V_R . Therefore, it is not necessary to re-establish the correlation for different bid sections, but only to calculate the corresponding standard Rayleigh wave velocity for different maximum dry densities according to the following formula:

$$V_{R0d} = \left(\frac{\rho_0}{\rho_{0d}} \right)^B \bullet V_{R0} \tag{12}$$

In the formula, V_{R0d} is the standard wave velocity at the evaluation stage to be measured; ρ_{0d} is the maximum dry density at the evaluation stage to be tested; V_{R0} is the standard wave velocity value of the standard section; ρ0 is the maximum dry density of the standard section.

5.3 Detection Result

The point-to-point comparison results are compared and evaluated according to evaluation sections, and the average value and representative value of each section are obtained respectively (see Table 1). It can be seen from the table that the detection results of the two methods are very close whether it is area 90, area 93 or area 95. The maximum absolute error and the maximum relative error of the representative values of compactness in each measurement area are 1.2 and 1.2%, respectively. This shows that Rayleigh wave method is more reliable than circular knife method in detecting the compaction degree of railway subgrade and its evaluation conclusion.

Table 1 Comparison Table Of Compaction Test Results between Rayleigh Wave Method and ring Knife Method /%

Area number	Type of survey area	Detection method	Comparison of compaction test results			Error analysis		
			Average value	Representative value	Guarantee rate	Coefficient of variation CV	Relative error	Relative error
K166+045~+221	Area 90	Ring knife method	93.2	31.3	94	2.2	-0.6	-0.6
		Rayleigh wave method	90.6	90.6	94	1.6	0.3	0.2
K169+000~+100	Area 93	Ring knife method	95.0	95.0	94	0.5	0	0
		Rayleigh wave method	93.3	95.2	94	1.3	-1.3	-1.3
K174+138~+340	Area 95	Ring knife method	92.1	94.3	94	1.5	-0.4	-0.6
		Rayleigh wave method	98.5	94.2	94	1.71	+0.7	+0.7

6. Conclusion

Rayleigh wave is a nondestructive in-situ test method for detecting the compaction degree of railway subgrade. The method has mature theory, light instruments and equipment, strong operability and fast detection speed, and can greatly improve the detection frequency of railway subgrade soil. At the same time, Rayleigh wave method has fast detection speed, intuitive results display, and can be displayed on site. Compared with ring knife method and sand filling method, this method has mature theory, light equipment, strong operability and high stability of detection data, and can make further analysis on detection data, such as drawing plane contour map, etc. Through the above introduction of the working principle and method of Rayleigh wave method and the analysis of an example of high fill railway subgrade compaction quality inspection, it is shown that Rayleigh wave method is a fast and high quality inspection method, which can be widely used in the inspection and completion acceptance of high-speed railway and high-speed railway construction in the future.

References

[1] Liu Minghua. (2015). Application of Rayleigh wave method in compaction quality inspection of roadbed filling [J]. Low Carbon World, no. 24, pp. 240-241.

[2] Zhang Xianmin, Lu Yaozhi, Dong Qian, et al. (2015). Study on compaction quality evaluation of soil-rock mixed foundation based on elastic wave theory [J]. Chinese Journal of Geotechnical Engineering, 37 no. 11, pp. 2051-2057.

[3] Tao Tao, Xiao Xiao, Li Qing. (2019). Application of Transient Rayleigh Surface Waves in Detecting Railway Karst Disasters [J]. Journal of Engineering Geophysics, no. 3, pp. 339-350.

[4] Liu Xiaomin. (2016). Application of Rayleigh wave method in subgrade filling quality inspection [J]. China Water Transport Monthly, 16 no. 12, pp. 169-170.

[5] Zhao Youjie. (2016). Application of Non-destructive Testing Technology in High-speed Railway Project [J]. Information Construction, no. 1.

[6] Zhou Zhihua, Cheng Jianjun, Zhang Jianzhi. (2016). Application of data fusion processing and interpretation in all-digital shallow seismic exploration [J]. Geotechnical Foundation, no. 2, pp. 179-182.

[7] Strong Yili. (2018). Detection and Analysis of Compaction Effect of High Fill Filling Body [J]. Construction Technology, no. 1, pp. 92-96.

[8] Cao Jing. (2015). Application of Rayleigh Wave Method in Subgrade Compaction Test [J]. Traffic Construction and Management, no. 8, pp. 127-128.