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Evaluation and Control of Subgrade Compaction Uniformity Based on Spatial Interpolation and Regression Analysis

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Abstract: In this paper, the compaction uniformity of subgrade is studied by single point subgrade com-paction detection index. The subgrade compaction test section of Jingde Expressway and Jingxiong Expressway is selected. PFWD and GeoGauge are used to detect subgrade pressure, and two detection indexes of resilience modulus and Young's modulus are obtained. According to the local statistical principle, the spatial interpolation of different subgrade detection indexes is carried out. Through the comparison of simulation accuracy and cartographic analysis, it is found that the ordinary kriging interpolation has higher accuracy and better visualization effect. By integrating the results of Kriging interpolation with the preliminary exploratory data analysis, it is concluded that the overall compaction uniformity of the subgrade is relatively concentrated, and the uniformity on both sides of the cross section is relatively discrete and the middle is relatively concentrated.

1. Introduction

In the process of expressway construction, the construction quality of roadbed is the key to obtain a solid and stable roadbed and ensure the overall good performance of roadbed pavement. However, due to the large variability in the spatial distribution of construction technology and subgrade fill, the evaluation of compaction uniformity has always been a major problem in subgrade compaction quality inspection and control. How to quickly and reliably evaluate subgrade construction quality, effectively carry out quality control during subgrade construction, and timely eliminate hidden dangers in subgrade construction quality? It is one of the key technologies to ensure the service quality and life of the roadbed pavement in the construction of subgrade expressways. For this reason, scholars at home and abroad have carried out a lot of research [1].

Nie Zhihong et al. proposed the quadrat analysis (QA) method based on point density and the nearest neighbor point index (NNI) method based on point distance to determine the spatial distribution characteristics of the unqualified area of railway subgrade compaction. Xu Guanghui et al proposed an evaluation method of compaction uniformity based on the "3σ" criterion. Yao Ke et al. obtained large sample test da-ta during pavement construction by using non-destructive testing method, and used grayscale evaluation method and statistical analysis evaluation method to analyze the uniformity of test data to evaluate the construction quality of asphalt pavement. Based on geostatistics theory, Wang Xiang et al. established a semi-variance function model to describe the spatial variability of continuous compaction detection data.

However, these methods are based on continuous compaction and only compaction detection data. For single-point field detection data, the variation degree of detection parameters in statistical distribution and the distribution characteristics of data cannot be reflected[2]. When the uneven area of subgrade compaction is distributed, it will lead to uneven settlement of highway subgrade, which will affect the stability and durability of subgrade pavement structure, and even endanger the safety of driving. Therefore, the analysis of spatial distribution characteristics and variation degree of single point detection parameters can provide theoretical basis for the evaluation of subgrade compaction uniformity. At present, there are few researches on the analysis of subgrade compaction uniformity by using single point detection index, and there is no clear regulation on the uniformity standard, which is easy to cause uneven sub-grade compaction in the construction process.

In this paper, K24+400-K24+600 platform backs, road-bridge transition sections and general subgrade sections of ZT2 section of Jingde Expressway are selected as test sections. PFWD is used to test the test sections, and the platform backs, road-bridge transition sections and general subgrade sections of K11+800-K11+850 of SG1 section of Jingxiong Expressway are selected as test sections. The soil modulus stiffness instrument GeoGauge was used to test the test section. Based on the field detection parameters such as resilience modulus and Young's modulus, the best results of simulation distribution of single point detection parameters are explored by using four different spatial interpolation methods, and then the distribution and variation rules of subgrade compaction uniformity in the test section of Jingde Expressway and Jingxiong Expressway are obtained, providing a scientific reference for the detection, evaluation and control of subgrade compaction uniformity[3]. At the same time, it analyzes the influence of different subgrade compaction test indexes, different subgrade structure forms and different subgrade fillers on the subgrade compaction quality test results, and analyzes the reliability of the equipment. Data collection and comparative analysis were carried out during the whole construction process from rolling construction to meeting the design requirements, and the relationship between the tested roadbed stiffness and the degree of compaction was obtained through regression analysis. Combined with the existing roadbed compaction standards, the stiffness technical index of GeoGauge rapid non-destructive testing of roadbed compaction quality was initially established, and the uniformity of roadbed construction quality was effectively evaluated. The research method and flow chart of this paper are shown in Figure 1:

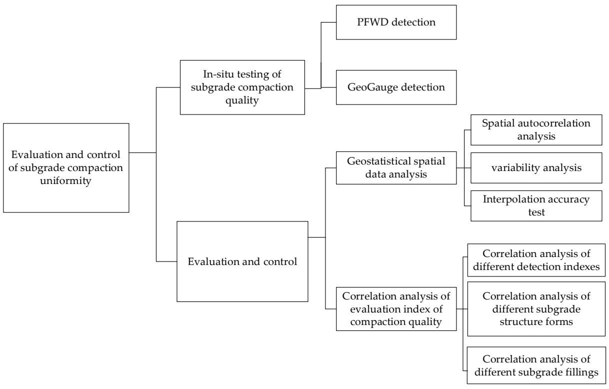


Figure 1: Flowchart of the research methodology.

2. Subgrade compaction quality test method

2.1. Subgrade compaction quality test parameter

The subgrade compaction detection parameter is an index reflecting the compaction state of each part of the subgrade in the process of subgrade filling and rolling by using PFWD and GeoGauge, a soil modulus stiffness instrument, to detect the singlepoint compaction quality of each subgrade rolling layer and analyze the compaction uniformity of subgrade in the process of subgrade construction. Based on the analysis and feedback control of subgrade compaction uniformity by subgrade com-paction detection parameters, real-time dynamic monitoring and control of the whole compaction uniformity of the rolling surface can be realized[4]. The elastic modulus and Young's modulus are used as the measurement parameters of subgrade pressure field, which can represent the compaction degree of soil. Therefore, for the same rolling surface, the spatial distribution rules of different subgrade compaction detection parameters reflect the degree of subgrade compaction uniformity. The arrangement method of detection points is shown in Figure 2.

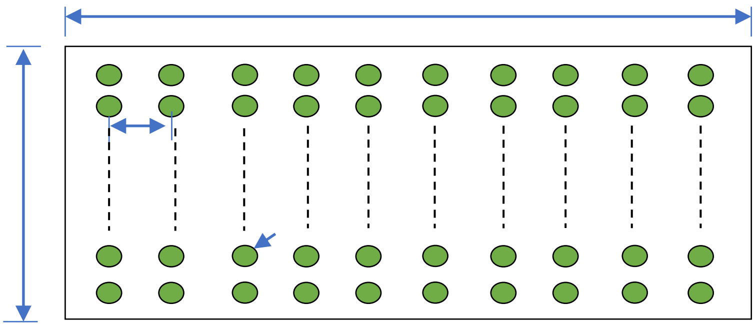


Figure 2: Subgrade compaction quality detection point layout method.

2.2. Subgrade compaction quality testing scheme

The test sections selected in this paper include three types of subgrade sections, such as platform back, road bridge transition section and general subgrade section. Jingde Expressway subgrade has a transverse width of 34.5 meters and is a two-way six-lane highway. Each compacted layer along the subgrade cross-section is used as a detection point every 3 meters, and 11 points are detected. For the general subgrade section, every 3 meters along the longitudinal 30 meters of the subgrade is used as a detection point, and 10 points are detected. The total number of measuring points is 110. For the back of the platform and the transition section along the embankment longitudinal 10 meters each 1 meter as a detection point, 10 points are detected. The total number of measuring points is 110. The subgrade of Jingxiong Expressway has a transverse width of 42 meters and is built as a two-way eight-lane expressway. The detection points and detection frequency are as follows: every 2 meters of each compacted layer along the subgrade cross section is used as a detection point, and 20 points are detected; For the general subgrade section, 10 points are detected along the longitudinal 20 meters of the subgrade every 2 meters as a detection point. The total number of measuring points is 200. For the back of the platform and the transition section along the embankment longitudinal 10 meters each 1 meter as a detection point, 10 points are detected. The total number of measuring points is 200. When testing, it should be ensured that the rolling of the test section is completed, and it is best to close the traffic after the rolling of each structural layer, and test the next day

2.3. Exploratory spatial data analysis

In order to analyze the uniformity of detection parameters from the perspective of spatial distribution, the spatial distribution state of detection data is analyzed based on the regionalized variable theory and semi-variance function model. In order to correctly and reasonably conduct statistical analysis and modeling of spatial sampling point data, understand the inherent law of data and whether it meets the Kriging interpolation conditions, exploratory spatial data analysis of detection parameters, including global trend analysis, spatial autocorrelation row analysis and spatial variability analysis, should be carried out before statistical analysis of spatial sampling point data[5]. It provides the basis for the selection of the relevant parameters and model of the subsequent interpolation method. The geostatistical analysis process is shown in Figure 3:

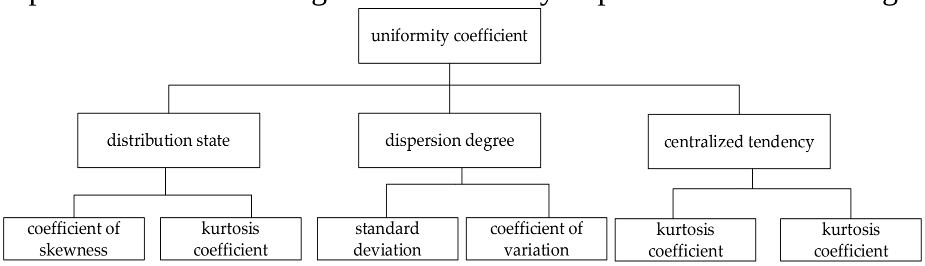


Figure 3: Statistical analysis of subgrade compaction quality detection index.

Synchronous statistical test can perform a series of tasks such as checking data distribution, finding outliers and analyzing global trends. The premise of spatial statistical analysis method is that the analysis data obey the normal distribution, and Kriging method has the highest prediction accuracy for the normal distribution data, so it is usually necessary to analyze the data distribution in the early stage of simulation. The histogram can well reflect the law and shape of the data distribution, so as to infer its overall distribution characteristics. The normal QQ chart is a statistical graph used to test the similarity of the data distribution in the normal distribution, and the detection data are in line with the normal distribution, and the more clustered in a straight line. The trend analysis chart is mainly used to analyze whether there is a trend in the data and display the trend visually[6,7,8]. The X and Y planes are used to represent the position of the detection point, and the Z-axis is used to represent the data attribute value. The trend projected by the Z-axis attribute value to the X and Y plane scatter curve is observed. If the fitted curve is flat, it indicates that no trend exists. If there is a trend, the best fitting polynomial can be found to interpolate the scatter points in the region and get the trend surface.

2.4. Interpolation method

Due to the limited number of detection points in the test section, the distribution of subgrade compaction detection data is not uniform due to the regionality of detection index variables, and the types of fillers and rolling processes are different. The da-ta distribution is dense in one area while sparse in another area. Such data with low density and uneven distribution is more in line with Kriging interpolation method. To obtain the distribution of the whole data in the test section, it is necessary to carry out spatial interpolation[9,10,11,12]. There are various methods of spatial interpolation, each of which has its own characteristics and applicability. By interpolating the test parameters with various methods, the error rule can be compared to ensure the applicability of the prediction results, and the factors that have strong correlation with the detection index can be explored, which provides a reference for the prediction and control of the subgrade compaction uniformity.

2.4.1. Inverse distance weighted

Inverse distance weighted method (IDW) is an interpolation method with the distance between the interpolation point and the sample point as the weight. The closer the sample points are to the interpolation points, the greater the weight is assigned, and the weight contribution is inversely proportional to the distance. The inverse distance weighting method assumes that the influence of the measured point on the pre-diction results decreases with the increase of the distance from the predicted point. The formula is as follows:

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{1}$$

Where $Z^*(x_0)$ is the predicted value at x_0; $Z(x_i)$ is the measured value at point i; N is the number of measured points around the predicted points; λ_i is the weight assigned to each measured point.

2.4.2. Kriging interpolation

Kriging interpolation method is analyzed on the basis of spatial statistics. The spatial relationship between data points is calculated using the semi-variance function. The Kriging interpolation method not only considers the spatial distance relationship between the predicted points and the adjacent sampling points, but also considers the position relationship. Based on the theoretical analysis of regionalized variables, the method uses semi-variance function as a tool to estimate the value of regionalized variables in a finite region[13].

2.5. Interpolation test

2.5.1. Cross validation

The purpose of cross-validation is to determine how accurately the model predicts unknown values. In this paper, the cross-validation tool in the Geo-statistical Analyst module of ArcMap10.8 software was selected to adjust the parameters of the interpolation method, and the statistical data calculated according to the prediction error could be used for diagnosis to determine the most suitable semi-variance function model for Kriging interpolation. To judge whether the prediction of the model is accurate, it is necessary to ensure that the prediction is unbiased, and the judging condition is that the average prediction error is close to 0. The standard error is accurate, and the criterion condition is that the root-mean-square standardized prediction error is close to 1. The deviation between the prediction and the measured value is small, and the criterion is that the root-mean-square error and the average standard error are as small as possible.

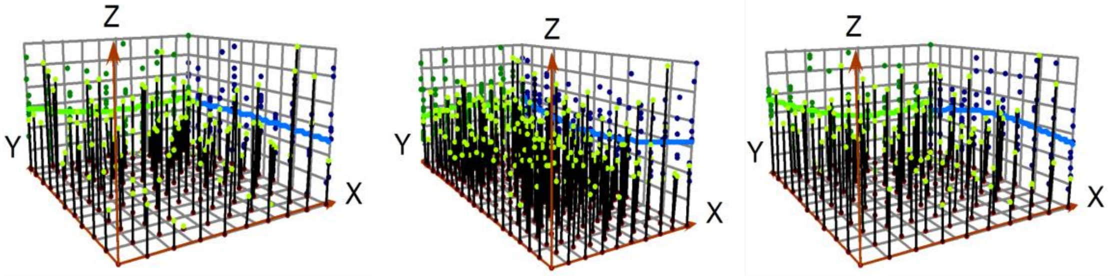
2.5.2. Subset verification

In this paper, the accuracy of four different interpolation methods is compared by means of subset verification, the detection data in the test section is interpolated, and the accuracy of different interpolation results is compared by means of average abso-lute error and root-mean-square error. When the average absolute error is equal, the smaller the root-mean-square error is, the better[14].

3. Interpolation application procedure

Firstly, the results of exploratory spatial data analysis were observed, as shown in Figure 4. It can be seen from the histogram that the median of detection indicators is basically close to the average value, indicating that the data is close to normal distribution[15]. Through the normal QQ chart, it can be seen that the detection index data tends to be normally distributed, and no corresponding data conversion is needed be-fore interpolation. Through the trend analysis, it can be found that each detection index data in the test section has a certain correlation, and its basic trend is high in the middle and low on both sides or low in the middle and high on both sides.

Ordinary kriging interpolation does not consider the removal trend, and its accuracy is mainly affected by the semi-variance function. In this paper, on the premise of ensuring that the step size of variance function is equal to about half of the maximum distance between all points in the test section, four semi-variance function models, including spherical model, Gaussian model, exponential model and power function model, are selected respectively for Kriging interpolation. After comparing the cross-verification results, the exponential function model is selected as the semivariogram model of Kriging interpolation to fit the semi-variogram results of subgrade compaction detection parameters. The pan-Kriging method combines the results of exploratory data analysis to remove the trend characteristics of the data, selects the removal order of the trend as 1, and determines the exponential function as the kernel function suitable for the surface. The cokriging method considers the close correlation between the detection index and the detection location, analyzes the cloud image of the orthogonal covariance of the two, and selects the detection index of the subgrade with different structural forms as the added regional variable. The modeling process of the semi-variance function of the pan-Kriging method and the co-Kriging method is consistent with that of the common Kriging method. The inverse distance weighting method needs to determine very few parameters. Here, after debugging, the index is set to 2, and the weight is taken from 15 adjacent elements.



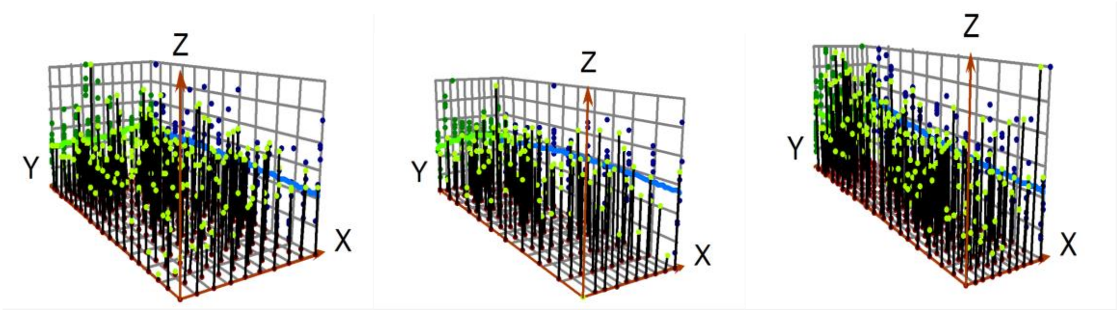


Figure 4: Exploratory data analysis of detection indicators.

4. Analysis of test results

4.1. Spatial aggregation trend of detection indexes in each subgrade test section

In this experiment, DPS data processing system was used to calculate Moran's I index of the field detection index, and its spatial autocorrelation was analyzed. Moran's I index of each subgrade section detection index is calculated.It can be seen from FIG. 5 that the detection data set of the test section is distributed between -1 and 1, indicating that there is spatial autocorrelation and aggregation among detection points. The Moran's I index of detection data of each subgrade section of the test section was plotted as a scatter plot, as shown in FIG. 5.

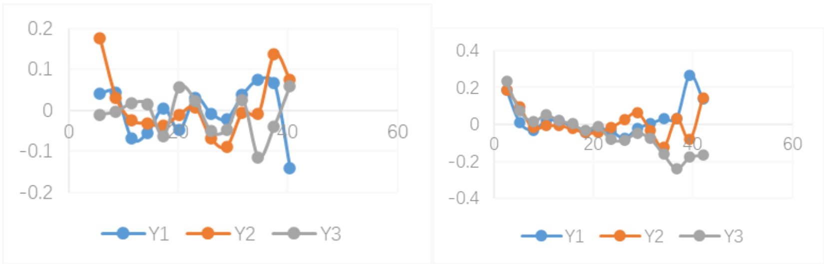


Figure 5: Moran's I index scatter plot of rebound modulus and rebound modulus.

Each dot in the figure represents a position pair, the horizontal axis represents the lag distance, and the vertical axis represents the Moran's I index of the detected data[16]. It can be seen from the scatter plot that the two short points of Moran's I index are relatively discrete, and most of the position pairs in the middle are concentrated between -1 and 1, and are relatively close to 0, indicating that the spatial correlation of the detected data is weak, and the spatial distribution is random. Therefore, the sub-grade compaction test data of each group of cross-sectional sections differ greatly at both ends of the cross section, are relatively discrete, and the middle is better concentrated, and the compaction uniformity at both ends of the subgrade is worse than that at the middle part.

5. Analysis of interpolation prediction results

5.1. Comparison of prediction results by different methods

Taking the ordinary Kriging interpolation method as an example, the spatial interpolation distribution images of the resilience modulus and Young's modulus of different subgrade sections were obtained by drawing the interpolation results, as shown in Figure 6. From top to bottom, the top of the embankment on the general subgrade section, the top of the road bed on the general subgrade section and the top of the road bed on the back of the platform were shown in sequence. It can be seen that the prediction result of Kriging interpolation is relatively smooth, but it can be clearly seen that the extreme value of the detection index only appears at the sampling point, which is greatly affected by different subgrade sections. In particular, many isolated abnormal pattern spots are generated on the edges of both sides of the test section, which is far from the actual distribution situation. In general, the results obtained by ordinary Kriging interpolation have a good transition and are more in line with the reality. It can reflect the changing trend of space, but the mapping has some blocky effect. The common Kriging interpolation method is obviously affected by different subgrade sec-tions and different detection indexes, which makes the simulated detection index values vary too much in some areas[17,18]. There are often isolated abnormal spots on the top of the road bed at the back of the platform, which is different from the actual situation, which also indicates that the actual distribution of detection index values is affected by many factors. The Kriging interpolation method is the best in visualization, and can accurately show the spatial distribution characteristics and change rules of detection indicators.

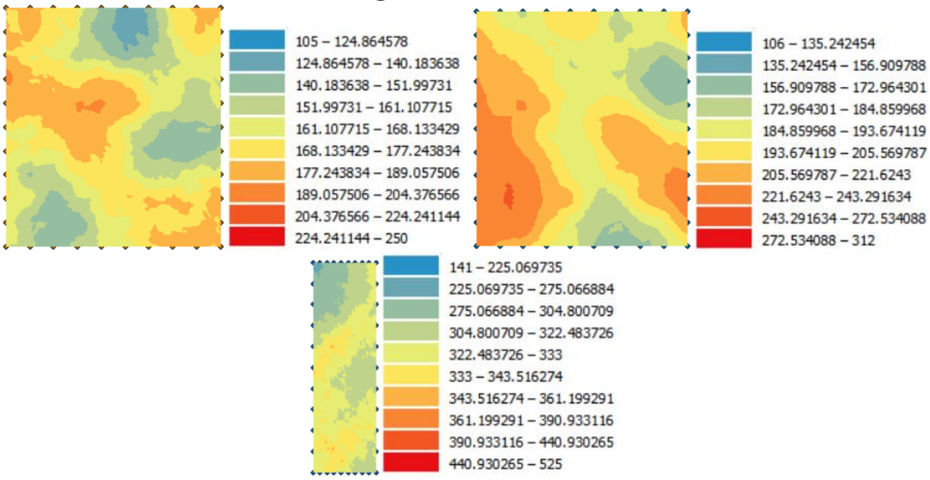


Figure 6: Kriging interpolation results of different subgrade detection indexes.

5.2. Spatial distribution and dynamic change of detection indexes in different subgrade sections

The four interpolation methods can all show the distribution and change law of each detection index in different subgrade sections. Based on the analysis results of the trend surface, the detection index data has a certain dispersion along the subgrade longitudinal, that is, along the driving direction, the overall compaction uniformity of the subgrade is better, while the data along the subgrade cross section has a discrete trend, and the overall compaction uniformity along the subgrade cross section is poor. The elastic modulus and Young's modulus of the top of the road bed at the back of the platform change gently compared with the general subgrade section, so the compaction uniformity of the top of the road bed at the back of the platform is better than that of the general subgrade section. In addition, the subgrade compaction detection index values are distributed in a certain area, indicating that the overall uniformity of the subgrade in the test section is good.

5.3. Interpolation precision analysis

Since the inverse distance weighting method does not estimate the prediction er-ror, it is not suitable for cross-validation. In this paper, the method of subset validation is used to compare the error, and the comparison results are shown in Table 1 and Table 2. Table 1~6 respectively represent the modulus and Young's modulus at the top of embankment on the general subgrade, the modulus and Young's modulus at the top of road bed on the general subgrade, and the modulus and Young's modulus at the top of road bed on the back of the platform. First, it is determined that there is no significant difference between the measured values and the estimated values of various interpolation methods.

Based on the estimated values of resilience modulus and Young's modulus and their overall conditions, it is concluded that Kriging interpolation method has the highest accuracy in the detection index of the test section. Although there is no significant difference in the interpolation accuracy between different interpolation methods, Kriging method is generally superior to deterministic spatial interpolation method.

Table 1: Average absolute error of detection index.

interpolation method	Mean Absolute Deviation					
	1	2	3	4	5	6
Common kriging	-0.0150	0.0178	-0.0049	-0.0049	0.0175	-0.0150
pan-kriging	0.0624	0.0182	-0.0044	-0.0041	-0.0219	-0.0085
cokriging	0.0611	0.0173	-0.0039	0.0087	0.0175	-0.0137
Inverse distance weight	0.0167	0.0170	-0.0093	-0.0075	0.0172	-0.0144

Table 2: Root mean square error table of detection index.

interpolation method	Mean Absolute Deviation					
	1	2	3	4	5	6
Common kriging	-0.0150	0.0178	-0.0049	-0.0049	0.0175	-0.0150
pan-kriging	0.0624	0.0182	-0.0044	-0.0041	-0.0219	-0.0085
cokriging	0.0611	0.0173	-0.0039	0.0087	0.0175	-0.0137
Inverse distance weight	0.0167	0.0170	-0.0093	-0.0075	0.0172	-0.0144

6. Conclusions

In this paper, six groups of roadbed pressure field detection data of Jingde Expressway and Jingxiong expressway test section are selected to analyze the distribution characteristics of sampling point detection data. Four methods, namely ordinary kriging, pan-kriging, collaborative kriging and inverse distance weight, are used to carry out spatial interpolation of detection indicators respectively. The spatial distribution images of the detection indexes of different roadbed test sections were prepared by various methods. The exponential function was determined as the optimal function of the regionalized variables of the ordinary kriging interpolation through cross-validation, and then subset validation was carried out. Combining the results of exploratory data analysis and ordinary kriging interpolation, a conclusion was drawn:

(1) The accuracy of kriging interpolation for different subgrade detection indexes is the highest, which can best reflect the spatial variation of subgrade compaction detection indexes;

(2) The subgrade compaction test data of each group of cross sections have a large difference at both ends of the cross section, are relatively discrete, and the middle is better concentrated, and the compaction uniformity at both ends of the subgrade is worse than that at the middle part.

(3) The mean value of the detection index predicted by the ordinary Kriging interpolation is close to the termination on the whole, and the detection index data tend to be normally distributed.

(4) The detection index data of the test section have a certain correlation, and the basic trend is high in the middle and low in the two sides or high in the middle and low in the two sides, so as to

provide a reference for the rapid non-destructive testing of the subgrade compaction quality of expressway.

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