Evaluation method of continuous compaction quality of highway water stable base

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Abstract. This article summarizes several commonly used real-time monitoring indicators of compaction quality, proposes the methods for evaluating compaction quality of water stable bases. Two methods, the Kriging interpolation method and the geostatistical analysis method, are proposed for evaluating the spatial uniformity of compaction mass. The results show that: the Kriging interpolation method has strong extrapolation ability, and can consider the spatial correlation of data; the geostatistical analysis method can not only describe the structural variation of continuous compaction detection parameters, but also describe its random variation. It would provide reference suggestions for the compaction quality evaluation of water stable base.

1. Introduction
Cement stabilized macadam base is an ideal base material for high-grade highway pavement, because of its good physical and mechanical properties such as high strength, good anti-permeability, frost resistance and water stability. In recent years, cement stabilized macadam base has been widely used in China's highway construction. Compaction quality is an important factor that affects the road performance and durability.

The traditional compaction quality control mainly uses destructive tests such as sand filling method, or non-destructive testing methods such as nuclear densitometer and nuclear densitometer to check the compactness, then measure the compactness by taking "points" afterwards. These quality inspection methods have limitations, cannot be able to characterize the uniformity of compaction, and the problems of leakage, under pressure and overpressure are prone to appear.

At present, a method for real-time inspection and control of compaction quality using a vibratory roller as a tool has attracted much attention. The method of using the vibration signal generated by the vibratory roller during the compaction process to continuously control the compaction quality is called Intelligent Compaction [1]. Specifically, during the rolling process, according to the interaction between the vibrating roller and the material, the vertical vibration response signal of the vibrating wheel is continuously measured and technically processed. Sensors are installed on the vibrating wheel to detect the dynamic response of the vibrating wheel in real time and obtain the relevant parameters of the compaction quality. After processing, the detection results are displayed in the cab.

Many researchers have used the compaction indicators obtained by smart rollers to study the soil compaction characteristics. Pavana [2] confirmed that the compaction control value has a poor correlation with the relative density of the soil and a good correlation with the soil elastic modulus. It
is pointed out that both the compaction control value and the drop weight deflection value are affected by the support conditions of the soil under the compaction layer. Zhong [3-4] adopted the real-time monitoring system of filling compaction quality to realize the monitoring of driving speed, rolling pass number, the state of the exciting force, and the compaction thickness. White [5-6] compared the two technical indicators of CMV and MDP, concluded that both technologies can well obtain compacted and uncompacted areas. It also points out that the geostatistical variation function of the smart compaction measurement value can be used for construction process control and can also be used to analyze the changes of the supporting soil layer below.

2. Real-time compaction index analysis

Many companies have launched their own intelligent compaction real-time monitoring systems, such as the rolling variable control system BVC (BomagVario Control) launched by BOMAG in Germany, ACE (Ammann Compaction Expert) launched by AMMANN in Switzerland, CMV (Compacto Meter Value) launched by Geodynamik of Sweden and MDP (Machine Drive Power) launched by Caterpillar of the United States.

2.1. Soil stiffness index KB

According to the principle of vibration mechanics, the AMMANN company in Switzerland uses the stiffness coefficient \( K_B \) as a quality control index and considers the compact as a discrete element model. The research results are applied to its own vibratory roller [7]. Ammann's compaction expert system (Ammann compaction expert, ACE) automatically adjusts the amplitude and frequency of the roller according to the stiffness of the soil. The soil stiffness \( K_B \) is calculated as follows:

\[
K_B = \frac{m_d u_d a^2 \cos(\omega t) + (m_f + m_d) g - m_d \ddot{u}_d}{u_d}
\]  

where \( m_d \) is mass of vibration wheel, \( m_f \) is mass of wheel frame, \( u_d \) is vertical displacement of vibrating wheel, \( \ddot{u}_d \) is the vertical acceleration of vibrating wheel, \( m_e \) is eccentric mass, \( r_e \) is eccentricity, \( g \) is gravity acceleration, \( \Omega = 2\pi f \), \( f \) is the frequency.

\( K_B \) can reflect the soil compaction quality. When the \( K_B \) is small, the soil is soft, when the \( K_B \) is larger, the soil becomes harder, and the density becomes greater.

2.2. CMV (Compacton Meter Value)

Geodynamik first introduced the vibration acceleration frequency domain analysis index CMV based on the vibrating wheel parameters and construction parameters [8]. Sakai Company further expanded on this basis to obtain compaction control value CCV. The principle is to install an acceleration sensor on the vibrating wheel, and reflect the soil compaction status in real time by analysing the harmonic response of the acceleration during the vibration compaction process. The formula is shown in Equation (2).

\[
CMV = C \cdot \frac{A_{2\Omega}}{A_{\Omega}}
\]  

where \( A_{\Omega} \) is the amplitude of first harmonic in the accelerated frequency domain spectrum, \( A_{2\Omega} \) is the second harmonic amplitude in the accelerated frequency domain spectrum, \( C \) is the constant.

With the increase of soil compactness, the distortion degree of the vibration wheel acceleration signal become greater, and more harmonic components occur. When the CMV is small, the soil is soft, and the larger the CMV value, the denser the soil.

2.3. MDP (Machine Drive Power)

Caterpillar defines the mechanical drive power as a quality control index. MDP uses rolling resistance and indentation deformation to determine the energy required to overcome the rolling resistance [9]. MDP can be calculated by the following equation:

\[
MDP = P g - W V \left( \sin \alpha + \frac{a}{g} \right) - (mV + b)
\]
Pg is the total working power of the machine, W is the mass of vibration wheel (KN), a is acceleration (m/s²), α is slant angle, V is velocity, b(KJ/s) is machine internal loss coefficient.

MDP is a relative value, in the detection surface, MDP=0KJ/s. When the value of MDP is a positive number, the compactness is less than the detection surface, and when the value of MDP is a negative number, the compactness is greater than the detection surface.

In addition to the above three compaction indicators, according to the elastic half space theory of the double cylinders’ interaction, Bomag Company in Germany proposed the modulus index after technical processing, which is called vibration modulus $E_{\text{vib}}$. The performance has been used in BOMAG single-drum and double-drum vibratory rollers, making them a vibratory roller with automatic frequency and amplitude modulation.

3. Evaluation method of vibration compaction quality for water stable base

Using the intelligent compaction monitoring system, the real-time monitoring values can be obtained. The parameters are obtained through experiments, and then perform correlation analysis on the experimental data, which can realize the evaluation of the compaction quality of the entire working face. The specific evaluation steps are as follows:

1. Real-time collection of the compaction monitoring value (CV).
   During the roller compaction, the continuous compaction control system is used to collect the quality monitoring index CV at the compaction position in real time and store the data.

2. Parameter selection.
   There are many factors influencing the compaction quality of water stable base, such as material gradation, compaction times, speed, excitation force and so on. Studies [10] have shown that the more rolling passes, the denser the soil, the slower the rolling speed, the better the compaction effect and the greater the excitation force, the greater the impact of the vibrating wheel on the soil. There is a positive correlation between CV and rolling passes and excitation force, and a negative correlation with construction speed. In addition, factors such as material moisture content, dry density, compaction thickness, and frequency changes will also affect the quality of water stable base compaction. The parameter index needs to be determined before the field test.

3. Field test and sample collection.
   Set up the test strips and test points on the strips. The GPS on the roller can locate the coordinates of the test belt and obtain the CV value at each test point. Sampling at the test point for testing, the water content, compaction, elastic modulus and other parameters can be measured.

4. Correlation analysing and build the regression model.
   Analyze the correlation between the parameters measured in the test and the CV value. The relevant specifications [11] require that the measurement equipment must be strictly verified before use, and the correlation coefficient cannot be lower than 0.70. According to the correlation analysis result, the parameter index is matched with the CV value, the evaluation model $CV=f(n,h,v,EFWD,\omega,\ldots)$ is established, and the model is tested for significance.

5. Evaluation of compaction quality space uniformity.
   In the process of collecting continuous testing parameters of compaction quality by vibratory roller, due to the anisotropy of material and the difference of detection process parameters, the continuous detection parameters of the compaction quality have a large spatial variability on the rolling surface. It is clear that the spatial distribution of the compaction quality continuous detection parameters is the precondition for the evaluation of the compaction quality uniformity. In order to evaluate the compaction quality of the water stable base at any position of the full working face, it is necessary to conduct the compaction quality inspection on the full working face.

3.1. Kriging interpolation method

Related research [12-13] uses Kriging interpolation method to perform spatial difference on discrete sampling points. Kriging interpolation method has the advantages of high approximation, strong extrapolation ability, and can consider the spatial correlation of data. The coefficient of variation is
used to measure the compaction uniformity of the construction pavement [14]. The coefficient of variation is calculated as:

\[
COV = \left( \frac{K_{SD}}{K_{MN}} \right) \times 100\%
\]

(4)

\(COV\) is the coefficient of variation, \(K_{SD}\) is the standard deviation of compactness, \(K_{MN}\) is the average of compactness. The whole working area after Kriging interpolation is divided into sufficiently small grids, the compactness values in each grid are obtained, and the value of \(K_{SD}\) and \(K_{MN}\) can be obtained by statistics. The smaller the coefficient of variation, the better the uniformity of compaction quality.

3.2. Geostatistical analysis

There are two main reasons for the spatial variability of the monitoring data. One is that under the influence of complex factors such as the initial formation and local action of the base, there are spatial structural variations in the properties of the soil at different locations; the other is the uncertainty factors of the measurement system, which lead to random variation in the detection parameters. The semi variogram model based on the geostatistics can not only describe the structural variation of continuous compaction detection parameters, but also describe its random variation [15-16]. The semi variogram equation is:

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [CV(x_i) - CV(x_i + h)]^2 \quad (i=1,2,\ldots,N(h))
\]

(5)

\(N(h)\) is the number of detection points, \(CV(x_i)\) and \(CV(x_i+h)\) are the actual observation values at the spatial position \(x_i\) and \(x_i+h\) with the distance \(h\), respectively. The semi variogram function \(\gamma(h)\) is a monotonically increasing function, as shown in Figure 1. When \(h\) exceeds a certain value \(a (a>0)\), \(\gamma(h)\) does not continue to increase, but tends to a limit value \(C_0 + C\). In geostatistics, \(a\) is defined as Range, and \(C_0 + C\) is defined as Sill.

**Figure 1.** The semi variogram model.

When \(h\) tends to 0, \(\lim_{h \to 0} \gamma(0) = C_0\), \(C_0\) called Nugget. \(C_0\) reflects the random variation degree of the continuous compaction detection value. When \(h\) tends to endless, \(\lim_{h \to \infty} \gamma(x) = C_0 + C\), \(C\) is partial abutment value. It reflects the structural variation degree of the continuous compaction detection value, that is, the unevenness of soil compaction.

Find out the \(CV(x_i)\) and \(CV(x_i+h)\) data pairs that conform to different sampling intervals \(h\), and put them into the equation to obtain the semi variogram value \(\gamma(h)\) corresponding to different sampling intervals \(h\). However, the scatter points calculated by the semi variogram cannot intuitively describe the spatial variation characteristics of continuous compaction parameters, therefore we need to fit the semi variogram. Exponential function [17] is used for fitting:

\[
\gamma(h) = \begin{cases} 
0 & h = 0 \\
C_0 + C \left[ 1 - \exp\left( -\frac{h}{a} \right) \right] & h > 0
\end{cases}
\]

(6)

Turn the exponential function into a linear model, set \(x=h, y=\gamma(h), k=C_0 + C, m=-C, n=-1/a,\) then \(y=me^{ax}+k\). Set \(X=x\), then \(Y=lg(y-k)=lgm+(nlg)eX\). For the semivariogram, the distance between the
first few points is small, which plays a more important role in reflecting the spatial variability, and its importance should be considered. Therefore, the weighted regression method is used for fitting. In addition, \( b_0=\lgm, b_1=nlge \), the unary linear regression equation is \( Y=b_0+b_1X \), the parameter solution equation is:

\[
\begin{align*}
    \beta_0 &= \bar{y} - b_1 \bar{x} \\
    b_1 &= \frac{\sum_{i=1}^{N} N(h_i) (x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{N} N(h_i)(x_i-\bar{x})^2} \\
    \bar{x} &= \frac{1}{n} \left[ \sum_{i=1}^{N} N(h_i) x_i \right] / \sum_{i=1}^{N} N(h_i) \\
    \bar{y} &= \frac{1}{n} \left[ \sum_{i=1}^{N} N(h_i) y_i \right] / \sum_{i=1}^{N} N(h_i)
\end{align*}
\] (7)

\( N(h) \) is weight, the number of samples with a small interval \( h \) is more than that with a large \( h \), that is to say the weight when the model is fitted is greater. The \( C \) obtained after fitting is the index of compaction uniformity.

6. Feedback of compaction quality assessment results.

According to the compaction quality and quality control standards at any position of the water-stable base, the qualified and unqualified areas can be analyzed, marked with different colors, and the evaluation results will be fed back to the construction site to repair the unqualified areas, ensure the compaction quality of water stable base in the whole section. The qualified rate of compaction quality of the whole working section can be calculated according to the following equation:

\[
\mu = \frac{S_D}{S_A} \times 100\% 
\] (10)

\( \mu \) is compaction quality qualification rate, the larger the \( \mu \), the better the compaction quality control. \( S_D \) is the area where the compaction quality real-time monitoring index \( CV \) is greater than the qualified value in the compaction quality cloud map. \( S_A \) is the area of the entire working surface.

4. Conclusions

Water stable bases are widely used in the construction of high-grade highways because of their good performance. Its compaction performance is key factor affecting the road performance of water stable bases. The emergence of intelligent compaction technology provides new ideas for the quality control and evaluation of water stable base compaction. This article summarizes the current common intelligent compaction real-time monitoring systems, puts forward a method for evaluating the compaction quality of water stable bases, and proposes the method for evaluating the compaction uniformity of the full face of the water stable base. It is hoped to provide a reference for the evaluation of compaction quality and on-site construction guidance of water stable base in the future.

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