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Research Article

Research on Real-Time Supervisory System for Compaction Quality in Face Rockfill Dam Engineering

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Compaction quality control in filling construction is of great significance to the stability and durability of the face rockfill dam. The conventional method of quality control mainly relies on manual process control and inspection for a limited number of test holes, which cannot meet the high requirements of modern mechanized construction and schedule anymore, with increasing of scale of face rockfill dams. There is an urgent need to propose a new quality control method of face rockfill dams during the entire compaction process. In this paper, a supervisory system based on GNSS (Global Navigation Satellite System) technology, wireless data communication technology, Internet of things technology, and computer technology is developed to supervise the real-time roller compaction parameters of the working surface including rolling track, rolling times, rolling speed, thickness, and smoothness. The system obtains continuous and high-precision spatial position information of roller compaction machines through GNSS technology and then calculates the roller compaction parameter information. The compaction quality control for the face rockfill dam is achieved through the supervision of roller compaction parameters. The feasibility and robustness of the developed supervisory system are validated by a case study in the face rockfill dam of Shuibuya project in China. The practice shows that the system provides a new and effective method of process control for the construction quality of the roller compaction in dam engineering and realizes real-time, precision, and automatic supervising of roller compaction parameters and ensures better construction quality.

1. Introduction

In the construction of the face rockfill dam, the compaction quality of the filling material is very important to the stability and durability of the dam. Therefore, the quality control in the process of filling construction is the key point to ensure the quality of dam construction. Insufficient compaction and quality control result in decreased strength and bearing capacity and increased settlement, volume change, and permeability. And it will directly affect the operation safety of the dam [1]. How to supervise the rolling construction process and make it meet the corresponding requirements is an important research question for scholars and quality managers.

The quality control methods of "dual controls" are mainly adopted in the quality management of filling construction of the face rockfill dam [2], of which one is manually controlling the roller compaction parameters including rolling times and driving speed of compaction machines, thickness of filling layer, and smoothness of storehouse surface, and the other is inspecting the test holes sampled manually in the working surface. However, the conventional method is difficult to ensure construction quality, because it is hard to accurately control these roller compaction parameters, interfered by human factors and extensive managements. Moreover, with the increase of scale of face rockfill dams, it puts forward higher requirements on filling construction quality control. In a word, the conventional manual quality management mechanism cannot meet the high requirements of modern mechanized construction and schedule anymore. Considering the shortages of conventional quality control method, it is necessary to propose a real-time and automatic compaction quality supervising method, which can realize timely and quickly supervising and feedback control impersonally.

Recently, many scientific research institutions and university science and technology workers paid attention to the automatic quality control method of compaction supervising. Different supervising systems for compaction quality have been developed and applied in engineering practice. In the middle of the 1980s, GEODYN company developed a compaction documentation system (CDS) [3, 4]. The CDS is a system that conceptually controls the process of pressure implementation. The data needs to be entered manually by the driver during the compaction process. Moreover, the CDS does not use sensors to orient and move the mobile roller compactor, and the driver must follow a predetermined route. In 1996, Froumentin and Peyret developed a prototype system called MACC, whose basic goal is to define a man-machine interface for assisting the driver to complete the compaction construction of asphalt pavement [5]. In the early development of the MACC, a laser positioning system is used. However, due to the laser positioning system requires expensive infrastructure, the cost is too high to be accepted by the construction unit. Then the MACC uses the GPS (Global Position System) as its positioning system. On the basis of the MACC prototype system, the CIRC (computer integrated road construction) project supported by the European Union Brite/EuRam plan, for roller compaction machine, defined and developed a system called CIRCOM aided by driver construction [6, 7]. The user of MACC and CIRCOM is the driver, so only one roller compaction machine is supervised. In 1996, Krishnamurthy and other scholars developed a system called AutoPave that realized the roller compaction machine walking path design and real-time navigation function by using GPS technology, communication technology, and computer technology to reach the requirements of asphalt pavement compaction [8, 9]. The AutoPave system warns and guides the driver to drive according to the design path in the form of graphics and sound, which can achieve uniform compaction of the road surface. In 1996, Oloufa and other scholars developed the Compactor Tracking System (CTS) with the help of GPS technology. Through continuous improvement, CTS-II and CTS-III have been developed successively [10, 11]. Both CTS and CTS-II can only control one roller compaction machine. CTS-III has improved the composition of CTS-II from the point of view of the reality of the compaction of several compacting machines on the road surface and the reduction of equipment costs. Adding a remote processing unit for processing positioning data and using the data transmission wireless communication unit, four roller compaction machines can be tracked in real time. In 2003, the German company BMW, the world's most famous road roller equipment manufacturer, introduced a GPS applied to compacting compaction quality control system called BVC [12]. However, the BVC system is only developed for the driver of the roller compaction machine, and the construction management unit (such as the supervisor) cannot control it in real time, and the complete system is expensive. The system is only suitable for the use of the equipment of its own company. In summary, the research of compaction quality supervising system has undergone the transformation and development from manual to automation, single to multiple machines, from the driver to the construction management unit, and the laser positioning technology to the GPS technology. The researches mentioned above are mainly focused on the road construction. Compared with road construction, the dam construction has different roller compaction parameters and construction techniques; thus, the systems are not very suitable.

Based on the existing research and our previous research achievements and according to the quality control needs of filling construction of the face rockfill dam, this paper mainly carries on proposing a real-time compaction quality supervising method by the application of GNSS technology [13], wireless data communication technology, Internet of things technology, computer technology, and data processing and analysis technology. A real-time supervisory system for compaction quality is developed, which is suitable for the quality management needs of roller compaction construction in filling engineering. Several benefits are conferred by the proposed method. First of all, the real-time supervisory system for compaction quality automates the acquisition of real-time roller compaction data by using sensor-based technologies and effectively reduces the interference between data collection activities and other construction activities. Then the proposed method can obtain the real-time compaction quality of the working surface, making timely feedback possible for construction control and quality improvement. This helps to ensure high-quality construction while reducing the chance of costly rework. Lastly, the system has comprehensive functions of being real time, continuous, automatic, high precision, and so on. It can be applied to real-time supervising compaction quality of filling construction for dam, highway, airport, and so on and has become an effective assistant to ensure the construction quality.

The rest of this paper is organized as follows: Section 2 presents the research methodology of this study. Section 3 delineates the principles and composition of the real-time compaction quality supervising system. Section 4 introduces the roller compaction parameter calculation method. Section 5 illustrates the application of the real-time compaction quality supervising system in the face rockfill dam of Shuibuya project in China. Finally, Section 6 summarizes the article with a discussion of conclusion and future research directions.

2. Research Methodology

The current research is devoted to the design and development of a software system. The research paradigm that suits this inquiry is design science research (DSR) [14, 15] in which a feasible software system addressing a relevant solution to an unsolved problem is developed and evaluated.

We conduct three phases of a typical DSR tailored for the purpose of this research, as delineated in the following:

Phase 1. Problem identification has been already described in Section 1, that is, how to supervise the construction process in face rockfill dam engineering and make it meet the corresponding requirements. Our research objective is set up as "developing of a new compaction quality supervising system of face rockfill dams during the entire compaction process, which has characteristics of real time, continuous, automatic, and high precision."

Phase 2. Design and develop through which, the system, constituting four core components, was developed. These components will be described in detail in Section 3.3.

Phase 3. Validate appraises the efficacy of the system resulting from phase 2 through a case study in the face rockfill dam of Shuibuya project in China, providing real-time roller compaction parameters to ensure the construction quality.

3. Principles and Composition of the Real-Time Supervisory System

3.1. Principles of the System. The quality control of roller compaction is mainly the control of roller compaction parameters. According to China Electricity Council [16], the roller compaction parameters, including rolling track, rolling times, rolling speed, thickness, and smoothness, must be supervised and compared with the quality standards during the whole process of roller compaction. These parameters have a common physical quantity: the spatial position. Thickness of filling layer is the elevation difference between two space surfaces. Smoothness of storehouse surface is the concave and convex of the space surface. Driving speed is the distance between two spaces in a unit time. Rolling times are the number of rolling machines through the same space position. Therefore, a real-time, continuous, automatic, high precision spatial positioning system can be used to achieve the quality control of roller compaction.

In the past few decades, automatic real-time positioning technology has developed rapidly. At present, there are mainly two kinds of automatic real-time positioning technology, one is laser positioning and the other is GNSS. GNSS is the standard generic term for satellite navigation systems that provide autonomous geospatial positioning with global coverage. This term includes, for example, the GPS, GLONASS, Galileo, BDS (BeiDou Navigation Satellite System), and other regional systems. Laser positioning accuracy is quite high, but the laser positioning needs a large number of beacon stations, which are expensive and therefore limits its application [5]. GNSS is cheap and the technology is very mature. As a new technology of modern spatial satellite navigation and positioning system, GNSS has gradually replaced the normal optical and electrical surveying equipment in many fields [17–20], and it has been more and more widely used in engineering field. The combination of GNSS technology and modern data communication technology and computer technology makes it possible for applying GNSS to high precision, real-time, continuous, automatic, and all-weather compaction quality control.

The real-time supervisory system for compaction quality is to place GNSS receivers on the main machines of roller compaction and to control rolling track, rolling times, driving speed, thickness, and smoothness by supervising the change of the spatial position of the roller compaction machines. The quality control method based on GNSS can record the construction process information automatically and in real time and avoid the disadvantages of traditional manual recording, which has the factual basis and strong reliability.

3.2. Precision of the System. The real-time supervisory system for compaction quality uses the carrier phase differential positioning technique, which is also called real-time kinematic (RTK). With the GLONASS system to realize the 24 satellite full deployment, China's BDS system has the ability to provide positioning services in China and the surrounding areas [21, 22]; compared with the original GPS single system RTK in the past, the three-system (GPS + BDS + GLONASS) RTK greatly increases the number of visible satellites, effectively enhancing the graphic intensity of the observed satellite and improving the accuracy and reliability of the positioning result [23–25]. At present, the nominal accuracy of RTK plane positioning is 1 cm+ 1 ppm. As long as the construction area is in the service range of GNSS reference station, the plane position precision of the system fully meets calculation precision needs of rolling track, rolling speed, and rolling times, which is less than 10 cm. The positioning accuracy of elevation is 2~3 times lower than the plane precision. Considering the data acquisition method and the reasonable elevation fitting model, the elevation precision can achieve ±(1~2) cm, which can fully meet the quality control needs of thickness of filling layer and smoothness of storehouse surface.

3.3. Composition of the System. The system hardware unit mainly includes the following three parts:

(1) GNSS satellite signals receiving equipment

(2) Wireless data communication equipment

(3) Computers

According to the requirements of compaction quality for filling engineering and construction quality management to system, the system is composed of supervisory center, data center, GNSS reference station, and mobile terminals. Figure 1 is the schematic diagram of the GNSS real-time construction quality supervisory system for filling construction project.

3.3.1. Supervisory Center. Supervisory center is the core of the system, receiving the real-time position information from the mobile stations through wireless data communication and automated processing. From the electronic display screen equipped in the supervisory center, the accurate position and speed of the roller compaction machines in construction and the state of compaction quality of filling engineering can

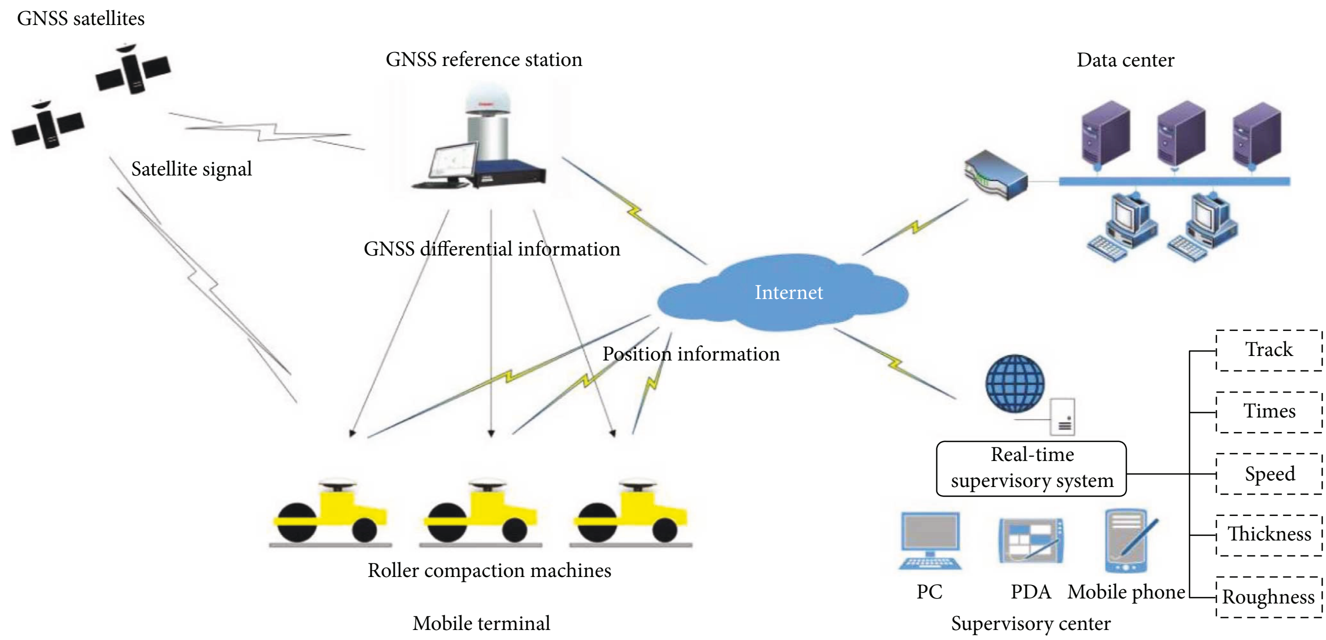

FIGURE 1: Schematic diagram of the real-time supervisory system.

be viewed in real time. The supervisory center is responsible for the data processing, analysis, and other work of the system and runs the information platform for all parties to visit through the Internet to view the real-time construction quality information.

3.3.2. Data Center. The data center is responsible for the storage and management of all data in the system to ensure data security and stability. The supervisory center accesses data center for data access operations through the Internet.

3.3.3. GNSS Reference Station. In order to improve the positioning accuracy, the GNSS reference station is established at a point with known coordinates to provide the carrier phase differential information. The real-time differential data of GNSS reference station is continuously sent to the GNSS mobile stations. GNSS reference station needs to be built in a place that can meet close to the construction area, has a wide-open sky (with few things blocking it like trees and buildings), has a solid foundation, and has a stable network and power supply.

3.3.4. Mobile Terminal. A mobile terminal is mainly composed of an integrated system unit, a GNSS receiver antenna, and a wireless communication antenna. The system unit integrates GNSS receiver, communication module, power module, and so on (Figure 2). Mobile terminal is installed in a roller compaction machine as a GNSS moving station and is responsible for collecting data. With the real-time positioning data, the roller compaction parameters for quality control can be calculated.

3.4. Work Flow of the System. The work flow of the real-time supervisory system for compaction quality is shown in Figure 3.

4. Supervising of Roller Compaction Parameters

4.1. Rolling Track. Rolling track, in fact, is roller wheel's track. As the GNSS antenna is placed on the top of the cab of roller compaction machine, it is necessary to calculate the axis midpoint and the left and right end coordinates of the roller wheel from the coordinates of the GNSS antenna according to the relative position relationship between the GNSS antenna and the roller wheel. After confirming the position of wheel axle of roller compaction machine, the rolling track in the passing sampling time is described by constructing the quadrangle continuously by connecting the roller wheel axis in chronological order. As is shown in Figure 4, it is a schematic diagram of rolling track within a continuous period of time. In the diagram, there are four black thick solid lines of L_1R_1, L_2R_2, L_3R_3, and L_4R_4, and each of which is the roller wheel axis of the roller compaction machine at four sampling times t_1, t_2, t_3, and t_4. And T_1, T_2, T_3, and T_4 are the points of the GNSS antenna at each moment, P_1, P_2, P_3, and P_4 are the center points of the rolling wheel axis at each moment, and L_1, R_1, L_2, R_2, L_3, R_3, L_4, and R_4 are the left and right end points of the roller wheel axis at each moment.

Figure 4 shows that the real rolling track is with a width. In the specific rolling track when painting, in order to express the graph simply and clearly and recognize the mechanical path clearly and legibly, a line is generally used to constantly connect the midpoint of drum axle line to describe. As shown in Figure 4, these lines made by connecting P_1, P_2, P_3, and P_4 and marked with arrows indicate more sections.

4.2. Rolling Times. Rolling times, which are an important parameter of construction quality, refer to the number of roller compaction machines through the same space position. If the number of rolling times is too small and packing

Figure 2: Schematic diagram of mobile terminal.

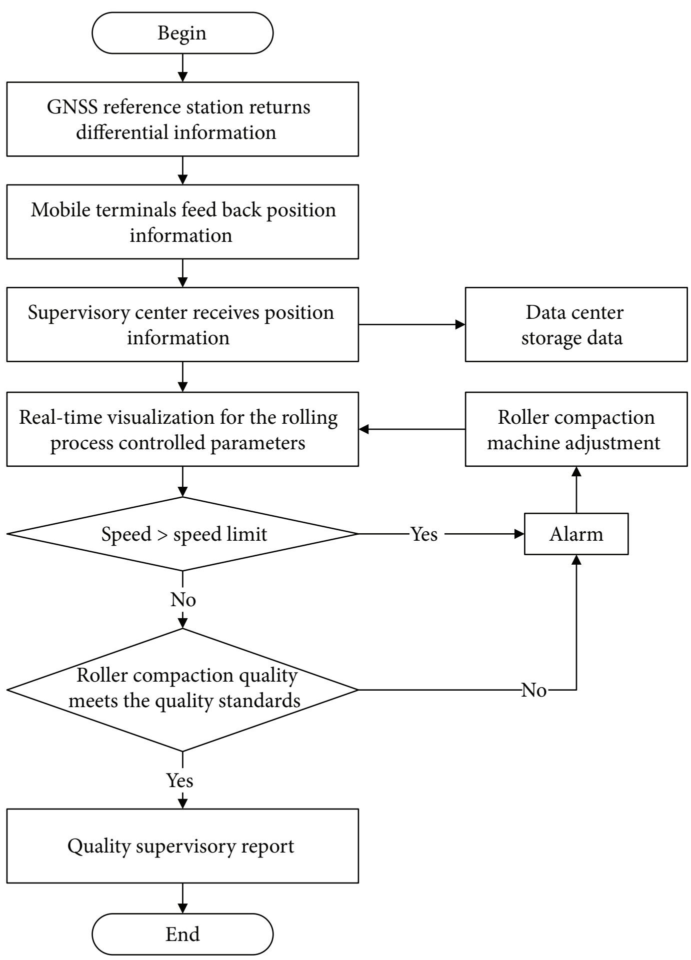

Figure 3: Flow chart of the real-time supervisory system for compaction quality.

compression deformation does not reach the standard, it will lead to the consequence that the final compaction, dry density, and other quality evaluation indicators fail to meet the requirements. Therefore, how to get the crush number of the current area quickly and accurately is the focus of the roller compaction quality monitoring system. The GNSS

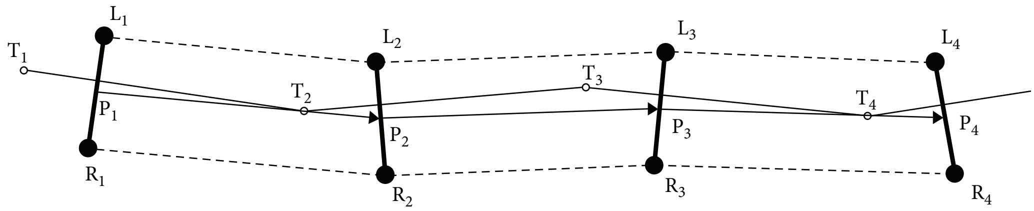

FIGURE 4: Real rolling track in continuous time.

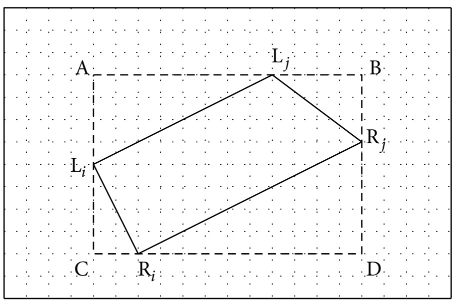

FIGURE 5: Schematic diagram of rolling times calculation by grid method.

real-time supervisory system adopts the grid method to calculate the rolling times.

Grid method is to grid the entire rolling area into an array of regular grid, as shown in Figure 5. In real time, we determine the real rolling track in the time of t_i to t_j is illustrated as quadrangle $L_iR_iR_jL_j$ in Figure 5. Whether or not the grids' centers are in $L_iR_iR_jL_j$ should be identified. If the center of grid is in $L_iR_iR_jL_j$, the rolling times of this grid should be added one more time. The detailed calculation steps are as follows:

(1) According to the rolling range, the rolling area is divided into lots of grids, and the rolling times of the grid unit are initialized to 0.

(2) The grid analysis area ABCD is determined according to $L_iR_iR_jL_j$.

(3) The ray method is used to determine whether the central point of the grid unit in the ABCD is within the quadrangle $L_iR_iR_jL_j$.

(4) According to the rolling times of grid units, the corresponding color is filled and the rolling time graph (Figure 6) is obtained.

4.3. Rolling Speed. Assuming that two consecutive sampling times t_1 and t_2, and $P_{t_1}(x_{t_1}, y_{t_1}, h_{t_1})$ $P_{t_2}(x_{t_2}, y_{t_2}, h_{t_2})$ are the center points of the rolling wheel axis at each moment, the driving speed of roller compaction machine can be calculated as follows:

$$v = \sqrt{\frac{(x_{t_2} - x_{t_1})^2 + (y_{t_2} - y_{t_1})^2 + (h_{t_2} - h_{t_1})^2}{(t_2 - t_1)}}. \quad (1)$$

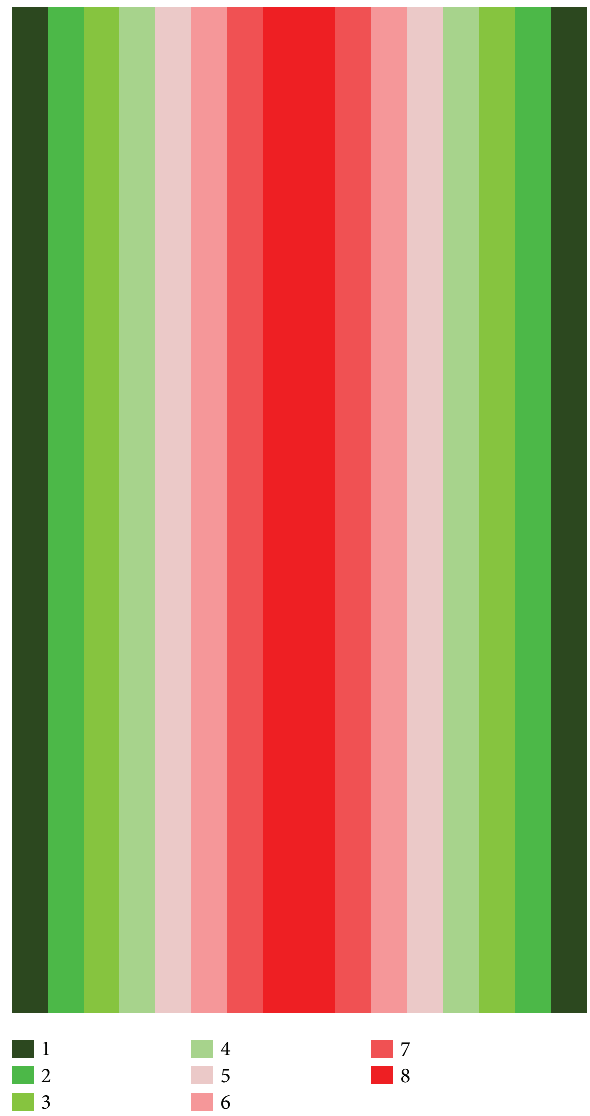

FIGURE 6: An example of the rolling times graph.

In this paper, the speed measurement method is called average speed method, which is long as the selected speed sampling period Δt and the two positioning data P_{t_1} and P_{t_2}, and does not require other new observations. Average speed method is very effective for low speed (usually not more than 4 km/h). With time as the abscissa axis, the velocity as the vertical axis, it can be plotted in a rolling speed diagram (Figure 7).

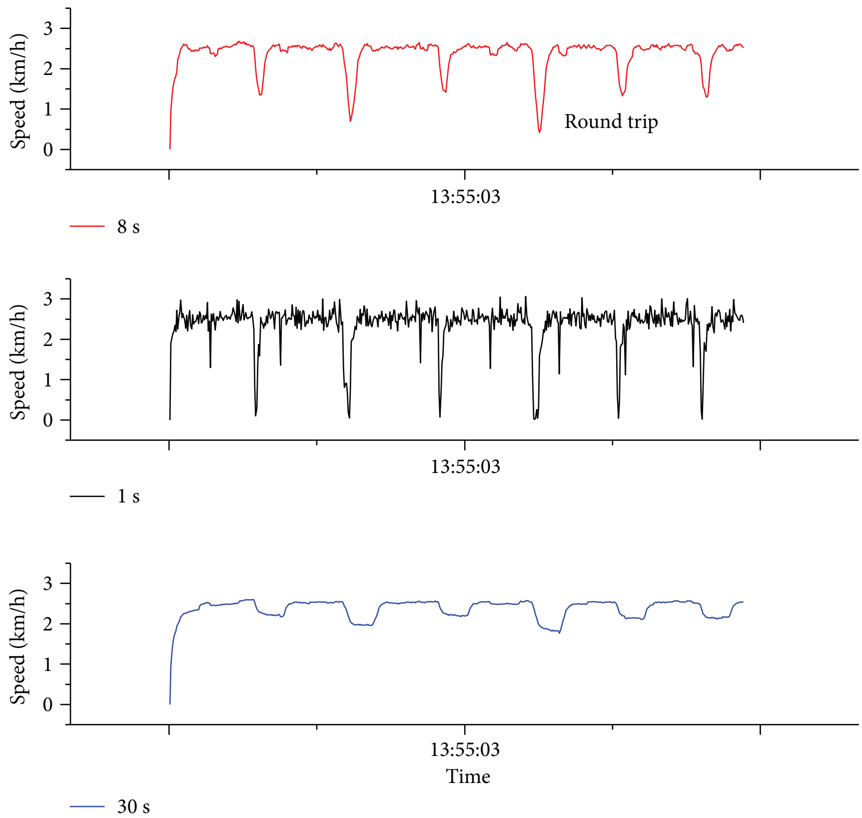

Figure 7: Rolling speed diagram.

When using the average speed method, it should be noted that the sampling period Δt should be suitable. If the period is too long or too short, it will not accurately represent the actual speed. In the actual calculation of rolling speed, the value of Δt was tested. When $\Delta t = 1$ s, rolling speed is abrupt, and it is shown in the velocity diagram with a large sawtooth, which is not consistent with the actual speed. When $\Delta t = 30$ s, rolling speed is almost invariable, and it is a straight line in the velocity diagram. After repeated experiments, it is concluded that Δt is suitable for 6~15 s. As shown in Figure 7, it is a typical rolling speed diagram when $\Delta t = 8$ s.

4.4. Thickness of Filling Layer. Thickness of filling layer is the elevation difference between the elevation of the surface after the filling and the elevation of the surface before the filling. The average elevation of a storehouse surface is H_1, and the average elevation of the previous storehouse surface is H_0, then the thickness of the filling layer shall be $H_1 - H_0$. As shown in Figure 8, the thickness of the upper filling layer can be obtained at 60 cm.

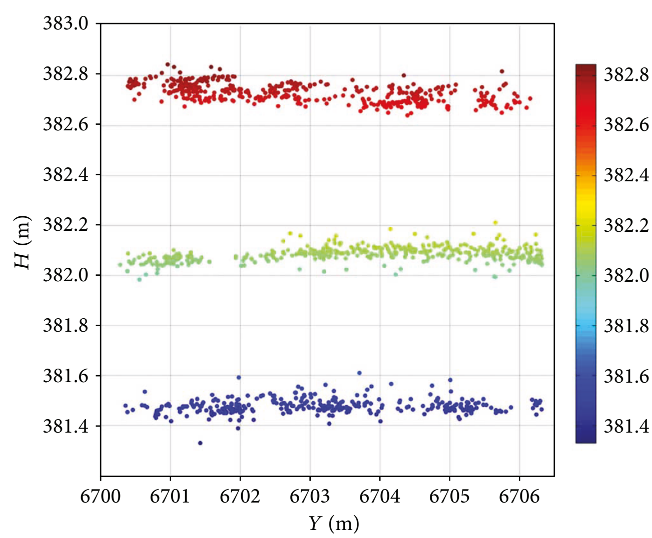

Figure 8: An example of thickness calculation.

4.5. Smoothness of Storehouse Surface. Smoothness of storehouse surface is a very important quality control index. The smoothness reflects the concave and convex condition of rolling storehouse surface, which further reflects the distribution of the compaction of the storehouse surface. Through GNSS positioning, it can continuously collect the coordinate information of roller compaction machine. But if the points are discrete and irregular, it is necessary to use some interpolation methods to generate regular grid digital elevation model (DEM). And then DEM visualization can graphically describe the smoothness of storehouse surface. In this paper, moving least square surface fitting algorithm is adopted. This method has high fitting precision and smooth surface, which can reflect the smoothness of storehouse surface directly and accurately (Figure 9).

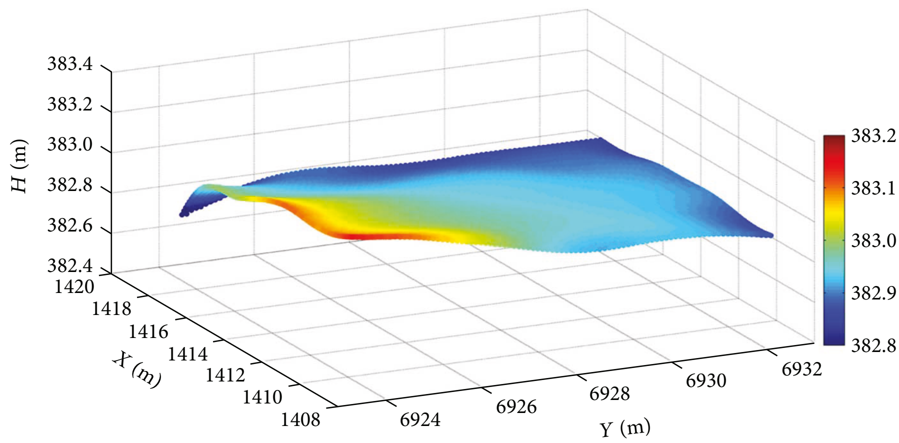

Figure 9: An example of storehouse surface after fitting.

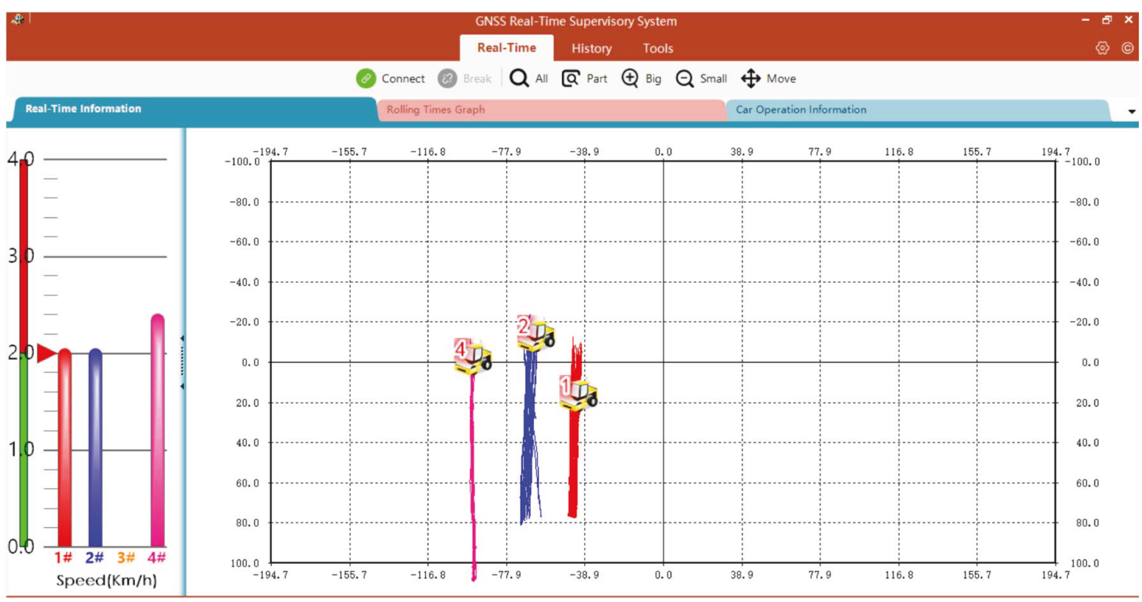

Figure 10: Main interface of the real-time supervisory system.

5. Case Study

The face rockfill dam of Shuibuya project in Qingjiang River of Hubei Province, China, ranking first in dam height of the same type in the world, is as high as 233 m. The project has a total filling volume of $1.6 \times 10^7\,m^3$ and more than $6 \times 10^5\,m^3$ for peak filling volume of a single month. So the filling construction of the dam needs all-weathered 24 hours without break, and many roller compaction machines work simultaneously. Therefore, the supervisory system has a great meaning for improving the construction quality of Shuibuya project.

The real-time compaction quality supervising system (described in Section 3) is applied in the actual construction process of the Shuibuya dam. The whole operation is in good condition. The main interface of the system is shown in Figure 10, which illustrates the supervising of running speed of roller compaction machines and rolling times at any position. With the use of this system, the 4 roller compaction machines served for the project are all under supervising real timely. The field supervisors can conduct roller compaction machines to make complementary compaction if poor quality is found in some places. When the compaction process is finished, the charts of rolling tracks (Figure 11), rolling times (Figure 12), and rolling speed will be reported as the supporting documents of construction quality inspection.

6. Conclusions and Future Work

With the development of dam construction technology, face rockfill dams are playing an increasingly significant role in hydraulic and hydroelectric projects. The quality control during the filling construction process is of great significance to the stability and durability of the face rockfill dam. The conventional method obtaining the compaction quality mainly based on some test holes cannot reflect the quality

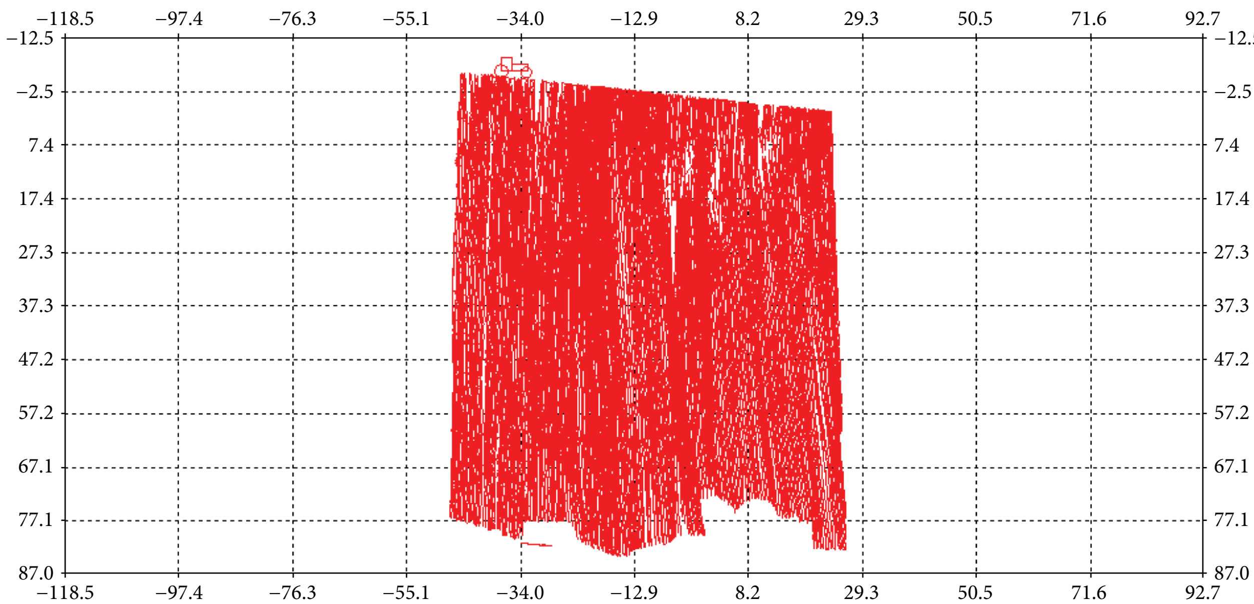

Figure 11: Rolling tracks of storehouse surface.

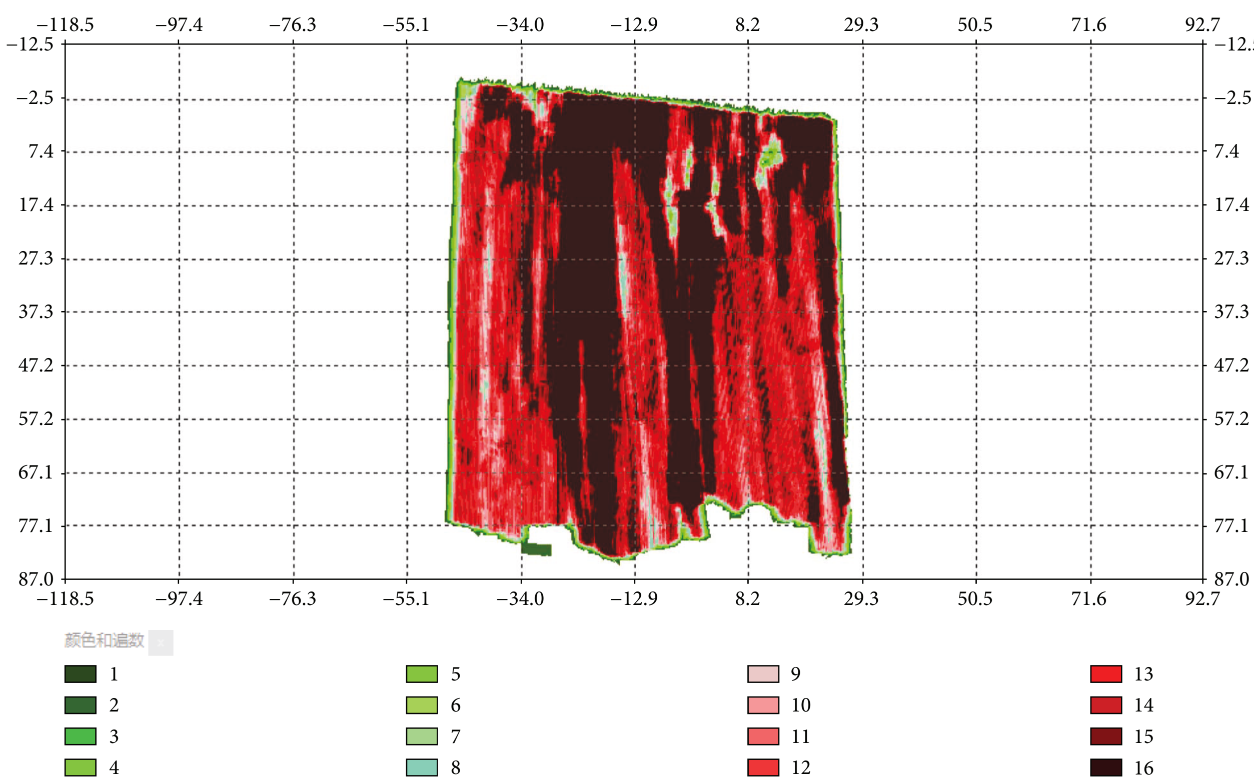

Figure 12: Rolling times of storehouse surface.

of an entire construction area. At the same time, the conventional manual quality management mechanism cannot meet the high requirements of modern mechanized construction and schedule anymore. In this study, a real-time compaction quality supervising method with the application of GNSS technology, wireless data communication technology, Internet of things technology, and computer technology was proposed, which involves data collection, data transmission, data integration, and data analysis. The method solves the real-time roller compaction parameter information by supervising the change of the spatial position of the roller compaction machines to realize monitoring of the rolling construction process. And the method overcomes the shortcomings of traditional methods, realizes the on-site quality control and process control in all aspects, and has a factual basis in the construction quality monitoring through data recording and storage. A real-time construction quality supervising system for face rockfill dams is developed, and the construction process of the Shuibuya dam is taken as a case study. The results show that the system is effective for construction quality control of face rockfill dams.

However, the compaction quality of face rockfill dams is affected by many factors, including not only the roller compaction parameters listed in this paper but also the excitation force of compaction machines and the water content of the material Therefore, using more sensors to obtain additional construction information is a clear area for further research. Meanwhile, in order to apply to various compaction machines and benefit supervision of construction quality, the system needs to be further improved and perfected in the aspect of unit bodily form and module integration of mobile terminal.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Shengxiang Huang devised the research, and Wen Zhang and Gen Wu designed the methods and developed the program. All authors wrote the paper. All authors have read and approved the final manuscript.

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