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Technology and application of real-time compaction quality monitoring for earth-rockfill dam construction in deep narrow valley

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ABSTRACT

Compaction quality is one of the most important aspects of the construction quality control of earth-rockfill dams. In recent years, real-time compaction quality monitoring technology based on a global navigation satellite system (GNSS) for earth-rockfill dams has realized effective control for earth-rockfill dam construction quality. However, many high earth-rockfill dams have been built in deep, narrow valleys, where the satellite signal is blocked by the tall, steep slopes such that the accuracy of the location is not satisfactory or that determining the location is fully impossible, thus seriously affecting the continuity and accuracy of real-time monitoring. The existing monitoring technology cannot meet the monitoring requirements in deep, narrow valleys. This paper establishes the theory and a mathematical model of real-time compaction quality monitoring in deep, narrow valleys and proposes a new method for real-time compaction quality monitoring based on positioning compensation technology (PCT), which combines GNSS and Robotic Total Station (RTS). An all-terrain and whole-process compaction quality monitoring of earth-rockfill dam construction is realized through this new method, making up for the shortcomings of the monitoring of the compaction process that relies solely on GNSS. Practical application shows that the method guarantees the objectivity and integrity of the real-time monitoring results, which ensures the compaction quality of earth-rockfill dam construction in deep, narrow valleys.

1. Introduction

The earth-rockfill dam, which is the earliest dam type in the history of human dam-making due to its use of local materials, simple structure, low requirement for foundation, and other characteristics, has become one of the most widely used and fastest-growing type of dam [1,2]. With the continuous development of dam-making technology, 200-m- or 300-m-high earth-rockfill dams have emerged, thus imposing more stringent requirements on their construction quality [3,4]. Compaction quality control is essential and crucial in the process of earth-rockfill dam construction quality control, which directly affects the dam's stability and durability [3,5]. Compaction parameters, including pavement thickness, soil material properties, compaction passes, roller speed, and vibration status, together with a compaction physical index that includes compaction or dry density, the water content and materials gradation are the quality control indexes for earth-rockfill dam construction [6]. The conventional compaction quality monitoring methods, including supervision engineer patrol and test pits detection [7,8], which rely primarily on human labor, are low-efficiency and easily affected by human factors. In contrast, though it belongs to the field sampling test, test pit detection cannot reflect the compaction quality of the whole compaction unit, so it is easy to miss quality defects that are difficult to find and cannot be made up. Therefore, the traditional monitoring methods have been unable to meet the increasingly stringent earth-rock dam construction quality control requirements.

The compaction process real-time monitoring method based on the real-time monitoring of the related construction parameters can help the constructer take control of the construction process continuously, precisely, and in real time. The method was first proposed and applied in the field of road construction. Oloufa and Do et al. [9–11] developed a global positioning system (GPS)-based automated quality control system for tracking pavement compaction. Minchin et al. [12], Anderegg et al. [13], Camargo et al. [14], Hossain et al. [15], Rinehart et al. [16], Xu et al. [17,18], Liu et al. [19] proposed and developed Intelligent Compaction (IC), which automatically adjusted the vibrations of compactors to optimal performance for the respective compaction status of the soil, based on a vibratory roller with measurement and control technology as well as GPS technology. Similar to Intelligent Compaction, a specific technology, named advanced compaction technology (ACT), has been developed, which is an automatic control technology for the road compaction process [20]. The technique

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effectively improves the work efficiency and prevents the road from being over- or under-compacted. Thompson and White [21,22] and Mooney et al. [23] proved the effectiveness of ACT technology in experiments that verified that the soil compaction performance has a strong correlation with the ACT monitoring index.

However, because the earth-rockfill dam construction technology and quality control standard differ from those of road construction, the research papers mentioned above are not completely suitable for earth-rockfill dam construction quality control. With many high earth-rockfill dams being constructed in China in recent years, Chinese scholars have expended a great deal of effort and made important contributions to real-time dam compaction monitoring research. Hung and Wu et al. [24–26] developed a GPS monitoring system for the concrete-faced rockfill dams (CFRDs) used to construct the Shuibuya dam, and this system is a beneficial extension to the quality control methods of large-scale rockfill dams. Wu et al. [27] proposed a location-based service platform to control roller compaction quality for rock-fill dams based on real-time kinematics (RTK)-GPS and WebGIS (Web-based GIS) and applied it to a core rockfill dam in Pubugou. Zhong, Liu and Cui et al. [6,28–30] put forward the theory and real-time monitoring method for high core rockfill dam construction quality and established a real-time monitoring and control system. By applying GPS technology, general packet radio service (GPRS) technology, network technology, and database technology, the system realized the precise automatic online entire-process monitoring of the compaction parameters, including compaction passes, compaction trajectory, roller speed, vibration status, and rolled pavement thickness. The system has been applied in the compaction construction process of the Nuozhadu Dam and plays an important role in compaction quality control.

Through these studies, it can be concluded that the accurate monitoring of compaction machinery spatial position is the core part of real-time monitoring technology. In addition to the vibration status of the compaction machines monitored by a sensor, the remaining monitoring of the compaction parameters is based on the spatial position of the compaction machinery, including compaction passes, compaction trajectory, roller running speed, and rolled pavement thickness. In previous studies, the global navigation satellite system (GNSS) technology, mainly referring to GPS technology, was used as the basis for the positioning of compaction machinery. However, the accuracy of positioning by GNSS is greatly influenced by the surrounding terrain and environment. Monitoring performance is usually affected by a reduction in accuracy for machine positioning. For high earth-rockfill dam construction in a deep, narrow valley, the position coordinates of the compaction machinery often cannot be obtained accurately because the satellite signal is blocked by the tall, steep slopes; thus, the real-time monitoring system cannot work normally. Therefore, developing a new method for solving the above problem and realizing real-time monitoring for high earth-rockfill dam compaction quality in deep, narrow valleys for the entire compaction process have been the concern of our researchers.

The main disadvantage of GPS-based positioning is its dependency on a direct line of sight with the satellites [31] and thus its accuracy is affected in deep, narrow valleys. Some local radio-based positioning technologies have been developed over the past years with advances in sensor technologies and wireless communications, such as Wireless Local Area Networks (WLAN, Wi-Fi), Bluetooth, ZigBee, Ultra-wideband (UWB), and Radio-frequency identification (RFID) technologies. These positioning technologies can adapt to complex environment, e.g. none line of sight (NLOS), due to the ability of radio signals to potentially overcome the presence of obstacles. The application of radio-based positioning technologies in civil engineering has been investigated by multiple researchers. These applications cater for various needs in the construction industry, and owners and supervisors of construction projects have been positive about the need for the utilization of such technologies on construction sites [32]. For instance, Lin et al. [33] developed a real-time tunnel location-based services (LBS) system based on WiFi tracking technology to provide workers' safety protection and various services in concrete dam site. Zhang et al. [34] used UWB to track the movement of the boom of cranes and further used the location data to identify the potential collisions of the crane and re-plan the path of the boom so that the collision would be avoided. Cheng et al. [35] used UWB for real-time, mobile resource location tracking in harsh construction environments in assisting the safety and productivity management of job sites. Song et al. [36] used RFID technology for automatically identifying and tracking individual pipe spools in laydown yards and under shipping portals. Montaser and Moselhi [37] proposed the application of RFID for the tracking of earthmoving equipment and automated the calculation of the cycle time of truck operations. However, there are obvious disadvantages of these technologies when they are applied to machine positioning in real-time dam compaction quality monitoring. For the WLAN and Bluetooth positioning technologies, signal propagation is easily affected by environmental factors and other signals. Multipath distortion and variability of signal strength in time limit the accuracy of such techniques [31]. The accuracy of the ZigBee positioning technology depends on the propagation model, but in the complex environment of dam construction, it is very difficult to establish an accurate propagation model [38]. UWB signals are less sensitive to multipath distortion and environment, so they can achieve higher accuracy. However, the high cost of UWB equipment and infrastructure deployment results in its limited availability for positioning. Because of short communication distance, RFID technology is usually with a small coverage. Its accuracy also depends on the density of tag deployment and RFID reading ranges [31]. In addition, these local radio-based positioning technologies usually need a dense network of devices and infrastructures, which usually interferes the dam construction.

In this paper, the Robotic Total Station (RTS) is selected as the GNSS positioning compensation measure. GNSS/RTS data fusion is used to overcome signal deficiencies in real-time compaction quality monitoring. RTS is a type of precision measuring instrument. Because of high accuracy, high efficiency, and easy using, it has been widely used in the construction of water resources and hydropower engineering, including in the monitoring of dam displacement [39], dam exterior deformation [40,41], rockslide deformation near a dam [42], and the controlled and detailed measurements of a dam [43,44]. In the above studies, RTS is used for static measurement but not for the continuous dynamic positioning measurement of construction machines. Moreover, no research has been reported that uses the total station in real-time dam compaction quality monitoring. However, there are some successful RTS dynamic measurement research results in other fields [45–47], which can be utilized in this research.

In this paper, the compaction quality real-time monitoring parameters and criteria are determined by analyzing the compaction quality control characteristics and requirements of earth-rockfill dam construction in deep, narrow valleys. First, this paper establishes the theory and a mathematical model of real-time monitoring for compaction quality in deep, narrow valleys. Second, this paper proposes a new technology, which we call positioning compensation technology (PCT), that combines GNSS and RTS. Third, based on PCT, a real-time compaction quality monitoring method is realized, which is an all-terrain and whole-process compaction quality monitoring method for earth-rockfill dam construction that makes up for the shortcomings of the compaction process monitoring that relies solely on GNSS. Finally, the new method has been applied in the real-time monitoring of a hydropower station dam compaction construction process in a deep, narrow valley in the southwest of China. It shows good adaptation to the deep, narrow terrain environment. The new method guarantees the objectivity and integrity of the real-time monitoring results, thus ensuring the compaction quality of earth-rockfill dam construction in the deep, narrow valley.