A Cyber-physical System for Multi-roller Control in Mega Infrastructure Projects

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ABSTRACT

In mega civil and infrastructure projects such as dams, airports, and expressways, multiple rollers are usually used to simultaneously compact the same work zone to accelerate the construction progress. Quality control in such a multi-roller compaction scenario is a demanding task because it requires collaborative control of the roller fleet to enable the right type of roller to compact the right position at the right time with the right compaction parameters. Traditional intelligent compaction is mainly devised for single roller, and hence falls short of multi-roller control that requires real-time information sharing between rollers. To enable the collaborative control of a roller fleet, a cyber-physical system has been developed for multi-roller compaction monitoring. This paper systematically illustrates the system architecture by dividing the system into five modules, i.e. data collection module, wireless communication module, cloud-based data processing module, feedback control module, and monitoring client. The corresponding managerial mechanism based on the system is explained, which can enable effective information sharing between multiple rollers and different project stakeholders. Two case studies have been carried out respectively in a concrete slab rockfill dam project and an asphalt expressway project in China. In each case, the specific implementation workflow is introduced, and the results are analyzed. The results demonstrate effectiveness of the developed cyber-physical system in compaction process control and thus ensuring compaction quality.

Keywords: Intelligent compaction; Multiple rollers; Cyber-physical system; Mega infrastructure; Quality control; Lean construction.

INTRODUCTION

In the construction of mega infrastructure such as dams and highways, compaction is a critical step for the structures to gain the required strength, stability, and stiffness. Since these mega projects cover large areas and are under tight schedules, multiple rollers are usually operated simultaneously in the same work zone to accelerate the compaction process. Such a multi-roller compaction technique is a complex process that requires the roller fleet to work coordinately with the right compaction parameters at the right time. Table 1 lists compaction schemes for two typical mega infrastructure projects. A typical rockfill dam construction process requires the rollers to compact the materials in the mode of low amplitude with high frequency for the first 2 passes, high amplitude with low frequency for the subsequent 5 passes, and low amplitude with high frequency for the last pass. As for asphalt expressway, the construction process typically includes three stages, i.e., initial rolling, repeated rolling, and final rolling. Compliance with the compaction schemes is of the essence for ensuring compaction quality.

Table 1. Examples of multi-roller compaction scheme for mega projects

Rockfill dam		Asphalt expressway	
Stages	**Operations**	**Stages**	**Operations**
First 2 passes	Low amplitude with high frequency	Initial rolling	4 times by vibratory rollers in static mode with low speed
Subsequent 5 passes	High amplitude with low frequency	Repeated rolling	2 times by pneumatic rollers with medium speed ; then 6 times by vibratory rollers with medium speed, high frequency and large amplitude
Last pass	Low amplitude with high frequency	Final rolling	4 times by vibratory rollers in static mode

Quality control in multi-roller compaction scenarios is a demanding task. Traditional manual supervision is difficult to track multiple rollers that are simultaneously operated, and thus often prone to biases. The post compaction spot tests can only be conducted in a limited number of samples, and thus cannot reflect the ground-truth compaction quality of the entire work zone that covers a large area (Mooney et al. 2007). Emerged by the late 1970s, intelligent compaction (IC) provides effective means for compaction quality control. However, since IC is originally devised for single roller, it lacks necessary hardware and software supports to enable real-time information sharing and collective data processing between rollers, which is essentially important for multi-roller compaction monitoring because the compaction outcomes (e.g., roller passes) in this circumstance are determined by the mutual operation of multiple rollers.

To enable the collaborative control of a roller fleet, this paper develops a cyber-physical system for multi-roller compaction monitoring. A managerial mechanism based on the system is set up, which can enable effective information sharing between multiple rollers and different project stakeholders. Two case studies have been carried out for demonstration purposes, which indicate that the developed cyber-physical system can effectively control the compaction process, thus ensuring the compaction quality.

LITERATURE REVIEW

Intelligent Compaction

Conventional compaction quality control for infrastructure projects (e.g., dams and highways) relies on on-site supervision during compaction and random spot test after compaction, which are laborious and time-consuming, and can yield unreliable results with limited sampling. Intelligent Compaction (IC) technology has been developed to tackle the challenges and aims to provide a compaction quality evaluation method with 100% coverage (Mooney et al. 2009; Oloufa 2002).

With the advancement of IC technology, major roller manufacturers have developed various intelligent compaction systems featured with different Intelligent Compaction Measurement Values (ICMV). DYNAPAC Compaction Analyzer (DCA) system (DYNAPAC 2003) adopted a frequency-based index called Compaction Meter Value (CMV). Ammann Compaction Ltd. developed the Ammann Compaction Expert (ACE) system (Anderegg et al. 2006), which uses a soil stiffness index denoted by k_s to assess the compaction quality. SAKAI designed the Compaction Information System (CIS) (Hennion 2009) which applied Compaction Control Value (CCV). Although the intelligent compaction systems developed by different manufacturers have significantly expedite the quality control process, they are mainly designated for single roller scenarios, and hence are not adequate for multi-roller compaction quality control of mega projects, which requires real-time information sharing between rollers and efficient data collaboration between different project stakeholders. Therefore, it is necessary to find a new solution feasible for the roller fleet control in mega infrastructure.

Compaction Process Monitoring Systems

Little research effort has been focused on multi-roller control in mega projects. One of the few research attempts in the area features the development of compaction process monitoring systems in dams and pavements. Zhong et al. (2009) conducted a theoretical research on real-time monitoring techniques of compaction quality for core rockfill dams. Zhong et al. (2011) developed a real-time monitoring system of compaction quality for Nuozhadu dam project, which can track, monitor and document the compaction parameters (i.e. roller velocity, vibration status, roller passes and compaction thickness) of different rollers during compaction process. Liu et al. (2016) introduced compaction power per unit volume (E) into the real-time monitoring system for highway compaction quality, which improved the reliability and precision of compaction quality evaluation. Liu et al. (2019) developed a system for collaborative operation and real-time control of roller fleet for asphalt pavement compaction. However, none of existing researches have systematically address the problem of multi-roller control in the broad context of mega infrastructure construction.

CYBER-PHYSICAL SYSTEM FOR MULTI-ROLLER CONTROL

System Architecture

Figure 1 presents the overall architecture of the cyber-physical system for multi-roller control, which consists of five modules, i.e., data collection module (DCM), wireless communication module (WCM), cloud-based data processing module (CDPM), feedback control module (FCM) and monitoring client (MOC).

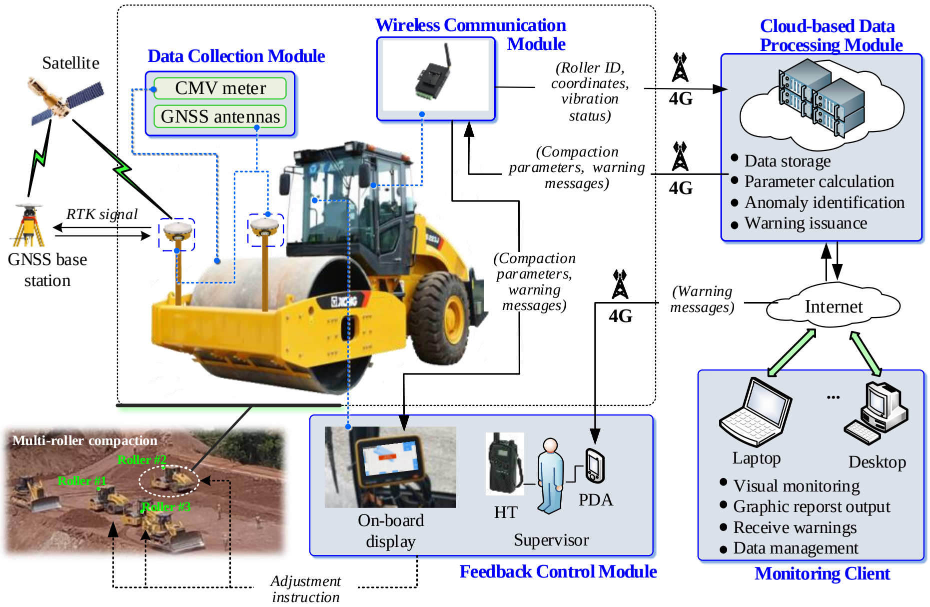

Figure 1. Overall architecture of the proposed cyber-physical system

The DCM includes a Global Navigation Satellite System (GNSS) positioning module and a CMV meter. The real-time kinematic (RTK) technique was adopted to improve the accuracy of the GNSS positioning module with a centimeter-level precision. The CMV meter is mounted in the vibration drum to obtain the vibration status of the drum (i.e., amplitude and frequency) and the CMV of the compacted materials.

The WCM allows multiple rollers to communicate with each other via the cloud-based data processing module (CDPM). On one hand, it sends the roller information collected by the DCM to the CDPM, which includes the roller ID, position coordinates, vibration status and CMV. On the other hand, the WCM receives compaction parameters (i.e., vehicle speed and roller passes) and warning messages of abnormal operations from the CDPM. WCM uses 4G networks for the wireless communication with the CDPM.

The CDPM collectively analyzes the data acquired from multiple rollers in real time. The roller information (i.e., roller ID, coordinates) is processed to obtain roller passes, and vehicle speed for each roller. In addition, the CDPM will compare the obtained compaction parameters (i.e., roller passes, vehicle speed and vibration status) with pre-determined criteria to identify abnormal operations. Once such an abnormal operation is detected, a warning message will be generated and fed back to the monitoring client (MOC) and the feedback control module (FCM).

The FCM includes personal digital assistants (PDA), handheld transceivers (HT), and on-board displays. On-site supervisors use the PDA to receive warning messages and coordinate the operations of multiple rollers via HT. The on-board displays present the real-time compaction parameters and warning messages of a single roller, and remind roller operators to adjust improper compaction operations.

The MOC provides a holistic overview of the compaction process to different project stakeholders, which include owners, supervisors, and contractors. The MOC dynamically displays the compaction trajectories of multiple rollers and the real-time compaction parameters. A color-coded map can also be generated to visualize the roller passes of the entire compacted area. Stakeholders can use the MOC to export the compaction graphic reports (e.g., compaction trajectories and roller passes) as quality acceptance materials.

Managerial Mechanism

As presented by Figure 2, a managerial mechanism that involves different project stakeholders (i.e., owner, supervisor, contractor, and operators) is proposed to apply the abovementioned cyber-physical system for multi-roller compaction control.

First, the supervisor inputs the control criteria in advance for the area to be compacted (denoted by a compaction unit). The control criteria include a speed control criterion, a vibration status criterion and a roller pass criterion, which are determined based on a series of trial compaction experiments. Once the control criteria have been set, the roller operators are allowed to start rolling the compaction unit cooperatively. During the process, the data collected by multiple rollers are constantly transmitted to the cloud-based data processing module (CDPM) for compaction parameter calculation. The calculated compaction parameters are sent to the owners, supervisors and contractors by monitoring client (MOC) for process monitoring. The CDPM compares the vehicle speed and vibration status of the rollers with the control criteria for compliance checking. When anomalies (e.g., overspeed, abnormal vibratory status) are detected, the on-site supervisors will receive warning messages issued by the CDPM. From the messages, the supervisor can identify ID of the roller that is under improper operation, and give corresponding adjustment instructions to the operator of the roller. The rectified compaction parameters will be re-examined after the adjustment. If the vehicle speed and vibratory status are qualified, the CDPM will evaluate the roller passes of the entire compaction unit, which is then compared with the roller passes criterion. The roller passes criterion is formulated as the fraction of the area that attains the desired roller passes out of the area of the entire compaction unit. If the roller passes does not meet the criterion, the rolling will continue and go through another cycle of the abovementioned process. The operators can end rolling after the roller passes meets the criterion. As the final step, the owners will evaluate the overall compaction quality and conduct quality acceptance for the unit.

The proposed cyber-physical system provides an integrated multi-roller control platform for the engagements of different parties in a mega project. The owners can grasp the overall compaction process without leaving their office, and can have a better control over the compaction quality. Supervisors can use a less labor-intensive way to ensure the compaction operation compliance. The contractors can use the tool to prevent roller operators cheating in the work.

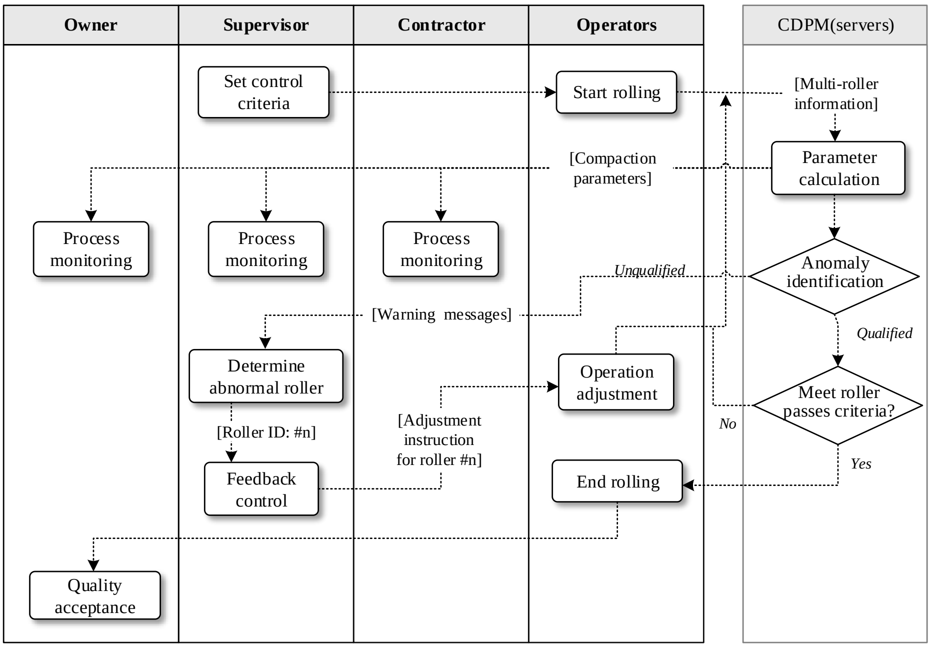

Figure 2. Multi-roller managerial mechanism involving different stakeholders

CASE STUDIES

Jiayan Concrete Slab Rockfill Dam

Jiayan concrete slab rockfill dam, with a height of 154.0 m and a rockfill volume of 5 million cubic meters, plays an important role in irrigation, water supply, and power generation in Southwest China. The materials in the project are compacted in the mode of low amplitude with high frequency for the first two passes, high amplitude with low frequency for the subsequent five passes, and low amplitude with high frequency for the last pass.

The proposed cyber-physical system has been applied in Jiayan concrete slab rockfill dam throughout the compaction process, as shown by Figure 3. In construction site, a front control station was set up near the dam crest elevation to cover the whole construction period. Both the supervisor and contractor have representatives stay at the station to control the whole compaction process with the monitoring clients (MOC) provided by the system. Once an anomaly is identified, the supervisor will guide the roller operators to rectify the abnormal operations via handheld transceivers (HT). Both the front control station and the data collection module mounted on rollers are connected via 4G network to the cloud-based data processing module (CDPM) placed at a rear control center, where the owners can access the MOT by local intranet.

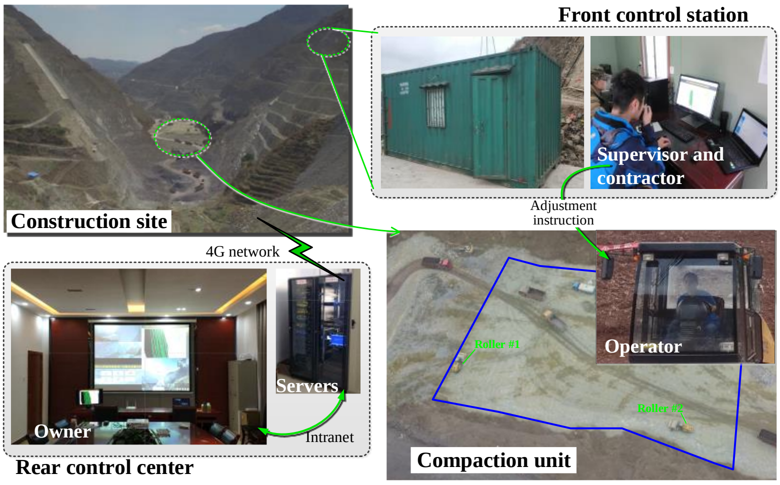

Figure 3. System setup at Jiayan concrete slab rockfill dam

Figure 4. Screenshot of the monitoring client at Jiayan project

Figure 4 presents a screenshot of the monitoring client, on which the roller ID, roller passes, vehicle speed, and CMV of multiple rollers are displayed in real time. The figure shows that the vehicle speed of roller #2 was over the upper speed limit, and hence a warning message was issued to remind the users.

Figure 5(a) and Figure 5(b) present, respectively, graphic reports of compaction trajectory and total roller passes for compaction unit 3B-1302.0-1. The qualification rate of roller passes for the unit is 97.46%. Figure 6 shows the qualification rates of roller passes for the compaction units that were compacted in 2018. The average qualification rate of vibratory passes is 94.29% (over that required 90%), which indicates that the whole compaction process was under good control.

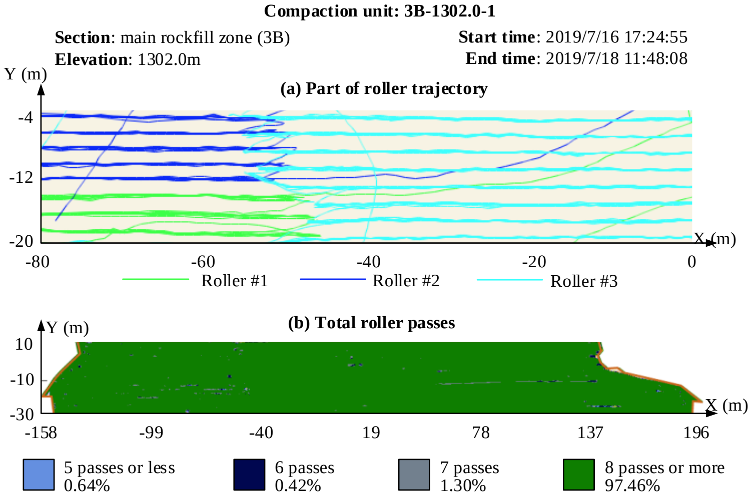

Figure 5. Graphic report for compaction unit 3B-1302.0-1

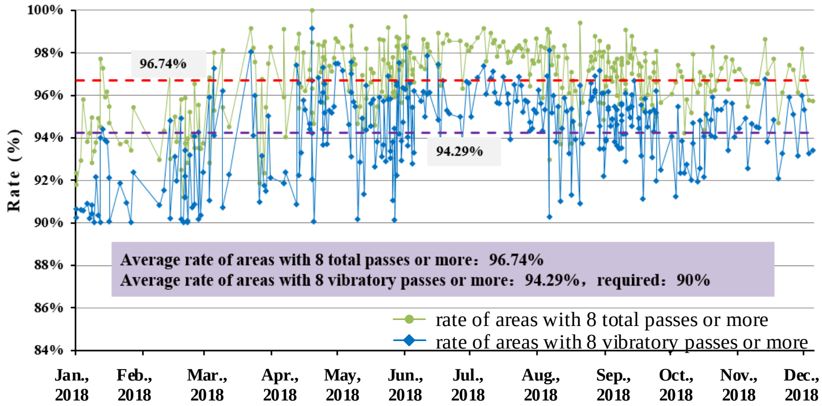

Figure 6. Qualification rates of compaction units in 2018

Binhai Asphalt Expressway

Binhai asphalt expressway is a key highway project to connect Tianjin Harbor to the North China region. The developed system was applied to the bottom surface layer of the pavement system, which is paved with 12 cm of asphalt treated base mixture. The asphalt materials are first compacted by steel wheel rollers in static mode for 4 times. The materials are then successively compacted by pneumatic rollers and vibratory rollers for 2 times and 6 times, respectively. Finally, steel wheel rollers are operated to compact the material with static mode for the last 4 times.

Figure 7 shows the system setup at the project. It is difficult to set up a control station in a fixed position to cover the whole construction period of pavements. Hence, we use a minivan as a mobile control station, where a supervisor controls the compaction process with the monitoring client. Due to the complexity of pavement compaction techniques, a supervisor or a manager from the contractor is also designated to stay at the compaction zone to guide the roller operations. The CDPM was placed in a rear office, where representatives from the owner can use the system to monitor the compaction process.

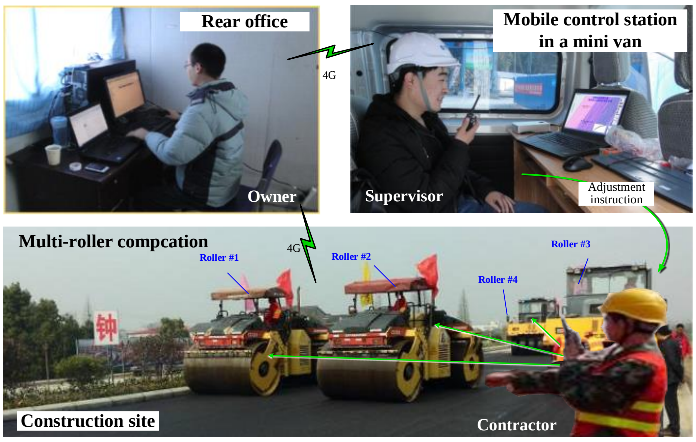

Figure 7. System setup at Binhai asphalt expressway

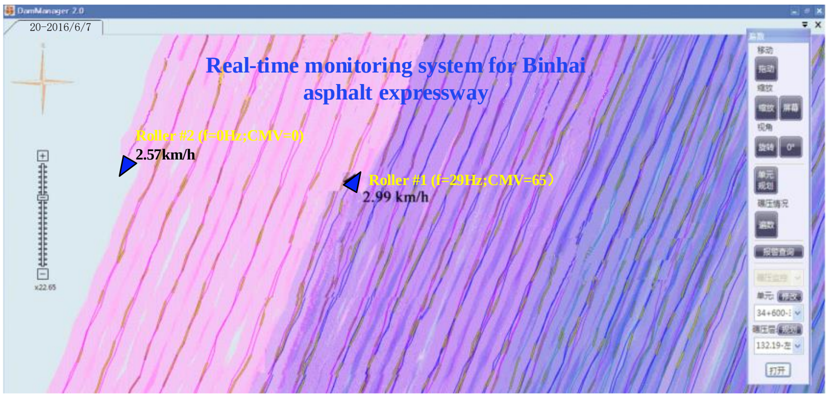

Figure 8. Screenshot of the monitoring client at Binhai project

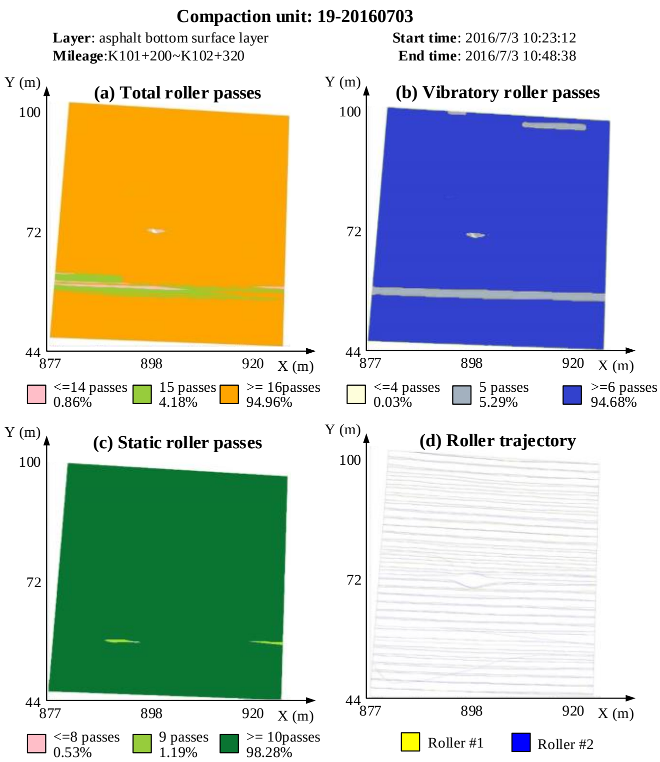

Figure 9. Graphic reports for a compaction unit

Error! Reference source not found. presents a screenshot of the monitoring client at Binhai project. **Error! Reference source not found.** shows the graphic reports of total roller passes, vibratory roller passes, static roller passes, and roller trajectory for a compaction unit. The qualification rates of roller passes for the unit are, respectively, 94.96%, 94.68% and 98.28%, which demonstrate a good compaction quality in the unit.

CONCLUSION

This paper proposed a cyber-physic system for compaction quality control in mega infrastructure projects, where multiple rollers are required to collaboratively compact the same area. The developed system consists of five modules, i.e. data collection module, wireless communication module, cloud-based data processing module, feedback control module, and monitoring client. A managerial mechanism based on the system have been proposed to engage different stakeholders of a mega project in the multi-roller control process. Case studies have been implemented for demonstration in two mega infrastructure projects, Jiayan concrete slab rockfill dam and Binhai asphalt expressway. The results indicate that the proposed system can effectively control the multi-roller compaction process and ensure the compaction quality.

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