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Separable Online System of Dike Monitoring Based on a Parallel-Serial Mode of Signal Measurement

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ABSTRACT In the traditional system of dike monitoring, the acquisition apparatus is usually adopted with lots of built-in multiple data acquisition units. Each sensor is connected to the acquisition unit by wire, leading to the intensive use of wires. As a result, it is easy to cause inter-wire interference and signal distortion, compromising the accuracy and efficiency of dike monitoring. We have described and demonstrated a novel mode of signal acquisition that involved the integrated use of digital communication and human-computer interaction, and developed a separable online system of dike monitoring. Specifically, a parallel mode was adopted between the acquisition apparatus and the acquisition units; a serial mode was adopted between the acquisition unit and sensors; and a human-computer interface was used to control the monitoring process. Our research findings have shown that the parallel-serial mode not only proves to have a higher level of precision and efficiency than the serial mode, but also a simpler structure than the parallel mode under the same conditions. The acquisition unit adopting the parallel-serial mode could be separated from the acquisition apparatus and set up at nearby monitoring sites. This mode helps avoid such problems as massive amount of wiring as well as severe attenuation and interference of sensor signals in the serial mode, and is thus suitable for the linear dike monitoring. The parallel-serial mode has been successfully applied to the dike monitoring of the Yangtze River, and can also be used for scattered, linear, regional, and wide-range monitoring of engineering projects.

INDEX TERMS Monitoring, data acquisition, signal processing, digital communication, parallel processing, human-computer interaction.

I. INTRODUCTION

Engineering monitoring refers to the use of monitoring apparatuses to supervise the control indexes of key parts during construction and operation of the building structure, to examine and ensure the safety of engineering projects [1]. The dike is one of the earliest critical flood control projects widely used around the world, and it also serves as the major measure of preventing issues of flooding, and protecting residents as well as industrial and agricultural production [2]. The monitoring range of dike is both long and large. Compared with the system of dams, the system of dike monitoring is still in its initial period of establishment given that the existing monitoring systems mainly feature the serial mode of signal measurement [3]–[5], and that comprehensive monitoring systems are still yet to be established. In the traditional acquisition apparatus that adopts the serial mode, the same set of acquisition and processing unit is shared between data acquisition and signal transmission. All the connected sensors are directly connected to the acquisition apparatus through wires, whereas the signals are analog both in data acquisition and transmission. Nevertheless, numerous problems exist in the serial mode, such as massive amount of wiring, severe attenuation, and interference of sensor signals, limited precision, and low efficiency. These problems are particularly aggravated for long linear dikes. Furthermore, most of the field acquisition apparatuses of dike monitoring have no human-computer interaction function. The absence of this function

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not only poses a negative impact on the practice of monitoring dike engineering projects, but also makes it harder to meet the technical needs of IT-based water conservancy projects. The main challenge of our research is how to construct a signal measurement mode of dike monitoring and overcome the technical problems existing in the traditional mode of dike monitoring. We described and demonstrated a novel mode of signal measurement for the dike online monitoring based on the integrated use of digital communication and human-computer interaction, which improved monitoring accuracy and efficiency and was more suitable for linear dike engineering.

Numerous novel monitoring technologies have been introduced into dike monitoring, such as tomography [6], [7], ground-penetrating radar [8], interferometry satellite radar [9], [10], interferometric satellites [11], and unmanned aerial system [13]. These technologies are mainly adopted to monitor the dike safety by measuring the changes in relevant images on the surface or interior of dikes, and enhance the capacity and efficiency of dike monitoring. However, most of these technologies are still in the exploratory stage. Such facilities as the optical fiber [14], [15], time-domain reflector [16], and GPS [8] are introduced into the monitoring system as new sensors. For instance, the optical fiber and time domain reflectometer help improve the accuracy of monitoring temperature and humidity of the soil in dikes, and GPS can realize automatic monitoring of surface displacement. Nevertheless, the monitoring accuracy still has room for improvement. Therefore, acquiring data from the embedded sensors in dikes still serves as a main method of dike monitoring, and the monitoring system controlled by a computer still comprises the main technology in dike monitoring. Major modes of signal measurement in data acquisition include the serial [17], [18], parallel [19], [20] and distributed [21], [22], etc. The serial mode has found more applications such as in river dikes [23], [24], sea dikes [25], [26] and road dikes [27], [28]. The distributed mode has found certain applications [14], [15]. In addition, the parallel mode has not been applied in dike monitoring yet. Studies need to be conducted to address the question of which method is more suitable for dike monitoring. In such areas as civil engineering, water conservancy, traffic, and agriculture engineering, several new technologies have been introduced into the monitoring system, including but not limited to GIS [29], human-computer interaction technology [30], [31], parallel computing [32], [33], cloud computing [34], [35], wireless networks [36]–[39] and APP [40], which have also found applications in dike monitoring to some extent [29], [34]. It is thus particularly necessary to use advanced technologies to improve the performance of the dike monitoring system.

Both the serial and the distributed measurement modes are used in dike monitoring. Specifically, the field monitoring has been applied in evaluating the dike performance of the Qwuloolt River (Washington, U.S.A) under the climatic and tidal variations [5]. The signal measurement mode of the monitoring system is serial, and the acquisition apparatus is directly connected to the sensors. In addition, the signal in both acquisition and transmission is analog. However, the sensors will encounter particularly severe issues of signal attenuation and interference when the length of the dike monitoring is long and the number of monitoring sections is large. In such circumstances, the acquisition apparatus is connected with numerous sensors whereas a large amount of wires and cables are used, undermining the accuracy and efficiency of monitoring. We have introduced the field measurement conducted for almost 20 years (1994-2013) at the Petten sea dike in the Netherlands. The land-based instruments, in addition to the sea-based instruments located at MP6, MP67, MP7, and MP8, were connected to a computer through a cable based on the coaxial protocol and RS485. Furthermore, the Qinsy online system was in place to ensure synchronic, real-time, and remote data transmission [25]. In the dike monitoring system, the serial mode is adopted for data acquisition, but the coaxial protocol and RS485 are used for data transmission, which is categorized as the quasi-distributed mode. The type of signals in data transmission for the coaxial protocol is analog, whereas the type of signals in data transmission for RS485 is digital. However, due to the co-existence of two types of signals at the same time, the system is complex and the mode of signal measurement still has room for improvement. The distributed mode of signal measurement has been applied in dike monitoring. For instance, the monitoring technology of distributed optical fiber is used in monitoring the dike seepage. This method involves the use of the optical fiber as the sensitive element in sensing and the medium for signal transmission at the same time, so as to detect the change of temperature along with varying positions of the optical fiber, to quantitatively monitor the seepage of the porous media, and to realize truly distributed measurement [14], [15]. This technology has a good prospect for being applied in monitoring. However, currently, the main monitoring indexes are temperature and stress, and the limited number of monitoring indexes makes it difficult to reflect the safety situation of dike comprehensively, leading to a limited scope of application. The parallel mode of signal measurement has found initial application in such fields as industry and medicine. For instance, a parallel hardware structure is proposed to accelerate periodic / frequency measurement [19]. Numerous parallel wireless sensing systems are adopted to continuously monitor the size variation of the microtissue spheroids [20]. The parallel mode has high efficiency in signal acquisition and good prospects of application. However, due to its complicated wiring, the parallel mode is suitable for fewer types of signals, resulting in the limited application in dike engineering projects that involve various types of monitoring indexes and signals. Therefore, it is necessary to develop an accurate and efficient mode of dike monitoring by leveraging the advantages of various modes of signal measurement.

The monitoring systems can be developed by leveraging the technologies of embedded human-computer interaction [30], [40] and online communication [36]. For instance, the acquisition apparatus for slope monitoring is developed with multiple functions, which features human-computer interaction [30]. The Android interface is developed for wireless data acquisition and control, providing a flexible graphical user interface populated entirely from a remote instrument [40]. Studies are conducted on the application of a wireless sensor network for landslide monitoring [37]. The indication system for horizontal-plane settlement is developed for freeway health monitoring based on the digital technology of RS485 communication [41]. However, for most of the field acquisition apparatuses of dike monitoring, computers are still needed to support the setting of systems and adjustment of parameters. Consequently, these apparatuses are inconvenient to use and have an improvement in terms of their simplicity and maneuverability. Furthermore, as analog signals are adopted in the majority of the communication between sensors and the acquisition unit, there is room for improvement in the quality of communication. Therefore, according to the characteristics of dike monitoring, and based on the technical gaps for the mode of signal measurement and the apparatus for field acquisition, we need to propose a monitoring system suitable for the linear dike engineering by adopting the advanced technologies accordingly.

By taking a holistic view of the dikes and related monitoring technologies, we can see from the perspective of the signal acquisition mode of dike monitoring that the serial mode is used more frequently at present, whereas the parallel mode has not yet been applied. The monitoring system of the serial mode features a simple structure, and has found more applications while accumulating rich experience. However, there is a large amount of wiring, resulting in a limited level of accuracy [23]. The parallel mode has a high level of efficiency in terms of signal acquisition, but relatively few monitoring parameters and a complex structure [19], [20]. Nevertheless, currently, there is neither a parallel mode of signal measurement in dike monitoring, nor a combination of serial and parallel modes. Therefore, while studying the monitoring systems, we should focus on addressing the issue of how to leverage the characteristics of both the serial and parallel modes to establish an accurate and efficient mode of signal measurement suitable for linear dike monitoring. Judging from the field acquisition apparatus used in dike monitoring, the wireless communication technology has already been popularized [29]. Nevertheless, the human-computer interactive equipment is not adopted in most of the field acquisition apparatuses of dike monitoring, complicating the configuration of parameters and operations of adjustment [29]. The rapidly developed technologies on human-computer interaction and network communication lay a technical foundation for the remote and intelligent development of the dike monitoring system. Current studies need to address the issue of how to integrate the technology of human-computer interaction [42] with the technology of network communication, so as to build a field acquisition apparatus convenient for application in the linear dike monitoring. Therefore, it is an inevitable trend for the development of dike monitoring technologies that we should determine how to combine the advantages of both serial and parallel modes and make use of the technologies of human-computer interaction and network communication, so as to optimize the existing dike monitoring systems, and to enhance the efficiency and accuracy of signal acquisition and transmission.

In this paper, our objectives are to put forward the mode of signal measurement and acquisition apparatus suitable for dike monitoring, to analyze the rationality of the proposed mode theoretically, and to verify the feasibility of the proposed mode. Based on the principles of parallel processing and the technology of human-computer interaction [19], [42], we have put forward a parallel-serial mode of signal measurement. Specifically, the parallel mode of communication was adopted between the acquisition apparatus and the acquisition unit, and the serial mode of communication was adopted between the acquisition unit and the sensors. In addition, the process of dike monitoring was under the control of the human-computer interface. We have carried out both indoor and field tests to compare the parallel-serial mode with the serial and parallel modes. The main contributions of this study were to transform the signal measurement mode of dike monitoring from the serial mode to the parallel-serial mode, which was more suitable for dike monitoring. Our research findings have shown that the parallel-serial mode that we proposed for the signal measurement for the dike monitoring met our goals. Compared with the serial mode alone, the digital signal was used between the acquisition apparatus and the acquisition unit in the parallel-serial mode. Consequently, we could effectively improve the accuracy and efficiency of signal measurement, and avoid such problems as the massive amount of wiring, attenuation, and interference of the sensor signals, limited precision, and low efficiency. In addition, we could separately arrange the acquisition unit, and it would be easier to operate and popularize the monitoring system based on the technology of human-computer interaction, which can provide the technical support for the monitoring of dike engineering projects and other similar projects.

II. EXISTING MODES OF SIGNAL MEASUREMENT ON DATA ACQUISITION OF DIKE MONITORING

A. BOUNDARY OF THE MODES OF SIGNAL MEASUREMENT AND METHOD OF EVALUATING THE SYSTEM ERROR

1) BOUNDARY OF THE MODES OF SIGNAL MEASUREMENT

According to the actual circumstances of dike engineering and relevant experience in dike monitoring, we preferably arranged the acquisition apparatus along the dike line while setting up the dike monitoring system. In addition, we connected the acquisition apparatus with the acquisition unit, which was further connected with sensors. For the serial mode of signal measurement, the acquisition unit was placed in the acquisition apparatus, and analog signals were transmitted not only between the acquisition apparatus and the acquisition unit, but also between the acquisition unit and sensors. The acquisition unit could be separated from the acquisition apparatus for either the parallel mode or the parallel-serial mode. In such circumstances, digital signals were transmitted between the acquisition apparatus and the acquisition unit, whereas analog signals were transmitted between the acquisition unit and sensors. For an easier comparison, the distance between sensors and the acquisition apparatus was assumed to be 1,020 m in aggregate, including the 20-meter distance of the connecting cable between sensors and the acquisition unit, and the 1,000-meter distance between the acquisition unit and the acquisition apparatus. For the serial mode, the acquisition unit was built into the acquisition apparatus, and there was a distance of 1,020 m between sensors and the acquisition unit along with the acquisition apparatus.

2) METHOD OF EVALUATING ERRORS OF THE DIKE MONITORING SYSTEM

We have analyzed the errors of the dike monitoring system based on the dynamic error modeling theory of the whole system [43]. For the monitoring object, operating environment, and working mode of a complete monitoring system, it all included the following five key links, namely, signal coupling, signal preprocessing, signal acquisition, data transmission, and data processing. Based on the modeling principle of the dynamic precision theory of the whole system [43], when the five components formed a serial relation, the transmission chain function of the whole monitoring system could be expressed as follows.

$$F(f_1, f_2, f_3, f_4, f_5) = f_1 \cdot f_2 \cdot f_3 \cdot f_4 \cdot f_5 \tag{1}$$

where, $F(\ )$ refers to the transfer chain function of the whole system. Index 1-5 refers to signal coupling, signal preprocessing, signal acquisition, data transmission, and data processing, respectively. f_i (i = 1-5) refers to the transfer chain function of the unit. f_1 refers to the component of the signal coupling of the transfer chain function. f_2 refers to the component of signal preprocessing of the transfer chain function. f_3 refers to the component of the signal acquisition of the transfer chain function. f_4 refers to the component of the data transmission of the transfer chain function. f_5 refers to the component of the data processing of the transfer chain function; "·" refers to the symbol of multiplication.

Judging from our analysis, the errors were not only incurred by the internal components of the measurement system, but also caused by the disturbances both internally and externally. The model of the total error transmission of the system, i.e., the model of the overall dynamic accuracy of the monitoring system, could be shown as follows.

$$e_y(t) = n_x(t) \cdot F(f_i) + e_F + n_y(t) \tag{2}$$

where, $e_y(t)$ refers to the total output error of the monitoring system $n_x(t)$ refers to the interference signal at the input. $n_y(t)$ refers to the interference signal at the output. e_F refers to the total output error caused by the error of each component in the monitoring system.

During our analysis of the errors incurred in the monitoring system, we need to take into account numerous influencing factors, such as signal coupling, signal preprocessing, signal acquisition, data transmission, and data processing. For the serial, parallel, and parallel-serial modes of signal measurement, they feature basically the same methods for the same dike monitoring system from the aspects of signal coupling, signal preprocessing, signal acquisition, and data processing. The main difference among the three modes lies in the distance of data transmission between sensors and the acquisition unit, and the varying types of signal transmission. For the serial mode, the path of data transmission extends from sensors to the acquisition apparatus, whereas the type of transmission was the analog signal. For the parallel mode or the parallel-serial mode, the path of data transmission is divided into two segments. The first segment extends from sensors to the acquisition unit with analog signals to be transmitted. The second segment extends from the acquisition unit to the acquisition apparatus with digital signals to be transmitted via the RS485 communication mode. As a result, the second segment features an extremely low distortion rate of the signal transmission, along with the almost negligible errors during signal transmission.

We have analyzed the errors incurred in the three modes of measurement control in a simplified manner. By assuming that the input end is the same as the output end of the system in terms of signal interference, signal coupling, signal preprocessing, signal acquisition, and data processing, we focused our analysis only on the difference in the data transmission and did not consider the interaction among various links. In this way, the model of the overall dynamic accuracy of the monitoring system could be expressed by the following formulas.

$$e_y(t) = e_4(t) = e_{41}(t) + e_{42}(t) \tag{3}$$

$$e_{41}(t) = f(l_1) \tag{4}$$

$$e_{42}(t) = f(l_2) \tag{5}$$

where, $e_4(t)$ refers to the system error incurred during data transmission. $e_{41}(t)$ refers to the error of data transmission between the acquisition unit and sensors. $e_{42}(t)$ refers to the error of data transmission between the acquisition apparatus and the acquisition unit. l_1 refers to the distance of data transmission between the acquisition unit and sensors. l_2 refers to the distance of data transmission between the acquisition apparatus and the acquisition unit.

When l_1 is not greater than 20 m, the error of data transmission for the general wire could be negligible, i.e. $e_{41}(t)$ is almost equivalent to 0. When l_1 is greater than 100 m, the error of data transmission for the general wire is to increase dramatically. When the distance of data transmission is not more than 1,000 m between the acquisition apparatus and the acquisition unit through the RS485 communication, the data transmission error could be negligible, i.e. $e_{42}(t)$ is almost equivalent to 0.

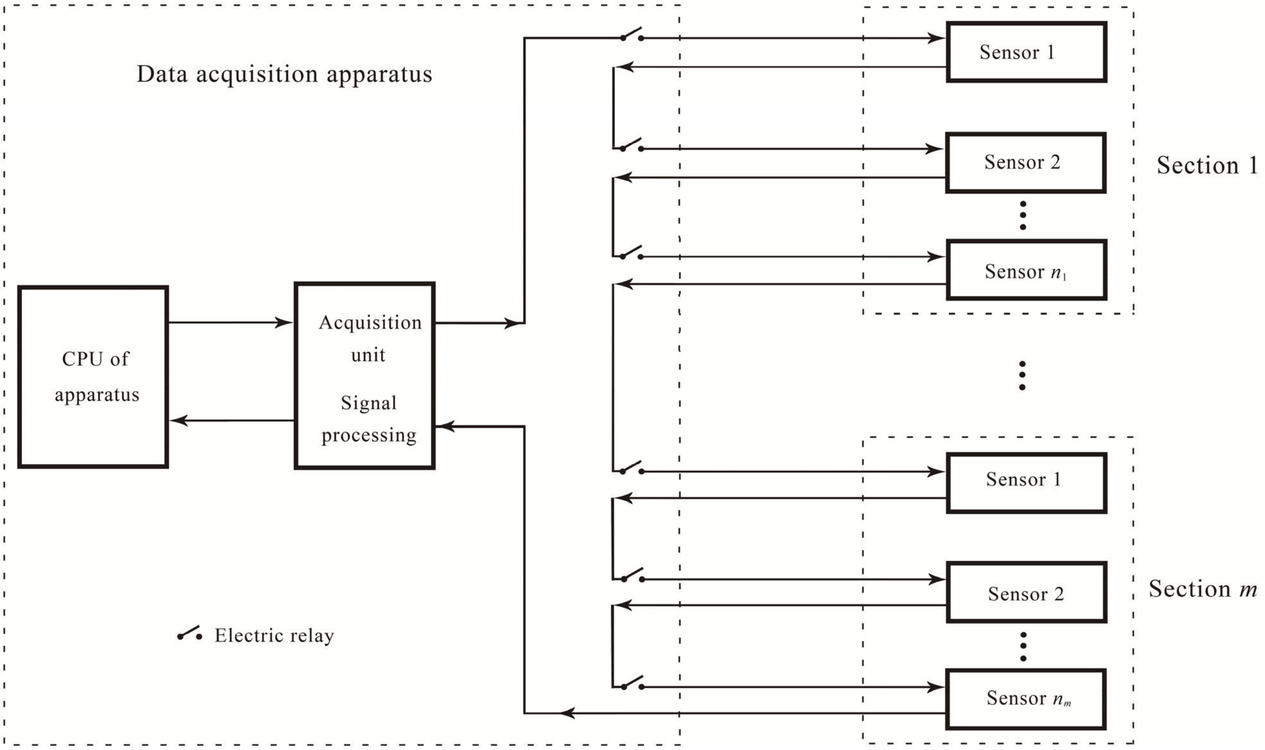


FIGURE 1. Schematic diagram of the serial mode of signal measurement.

B. SERIAL MODE OF SIGNAL MEASUREMENT ON DATA ACQUISITION OF DIKE MONITORING

1) PRINCIPLE OF THE SERIAL MODE

In the traditional system of dike monitoring that adopts the serial mode, the signal acquisition, and processing of the acquisition apparatus are integrated into the main module. In addition, sensors are connected with the acquisition apparatus through the acquisition unit (Fig. 1). The acquisition apparatus and the signal acquisition unit are connected as a whole with only a signal processing unit in the acquisition apparatus. The switching of the channel of signal acquisition for all sensors is completed in turn by the electric relay, and the signals are collected from sensors one by one until the signal acquisition is completed in all sensors [1].

The time it takes for the sensor to collect signals is closely related to the type of sensors, which varies by the type of sensors. Specifically, it takes less time to collect signals in the form of a current, voltage, or pulse, whereas it takes longer to collect signals from a vibrating wire since more time is needed for its sensors to emit the vibration signal. Assuming that the serial mode is adopted for the signal measurement, the time it takes for a single sensor to collect signals could be shown as follows.

$$t_{\mathrm{ij}} = f(r_{\mathrm{ij}}) \tag{6}$$

where, r refers to the type of sensors. j refers to the sequence number of sections. i refers to the sequence number of the sensors at the section. r_{ij} refers to the type of signals for the i^{th} sensor in the j^{th} section. $f(\,)$ refers to the function between r_{ij} and t_{ij}. t_{ij} refers to the time it takes for the acquisition apparatus to collect signals from the i^{th} sensor in the j^{th} section.

If the total time it takes for the system to adopt the serial mode to collect signals from all sensors is set as $t_{\mathrm{a}1}$, then we could obtain the following formula.

$$t_{a1} = \sum\nolimits_{j=1}^{m} \sum\nolimits_{i=1}^{n} (t_{ij}) \tag{7}$$

where, m refers to the total number of monitoring sections. n refers to the total number of monitoring sensors at each section. t_{a1} refers to the total time it takes for the dike monitoring system adopting the serial mode of signal measurement to collect signals from all sensors.

The total output error of the monitoring system that adopts the serial mode of signal measurement could be expressed by the following formula.

$$e_{1y}(t) = e_{141}(t) + e_{142}(t) \tag{8}$$

where, $e_{1y}(t)$ refers to the total output error of the monitoring system that adopts the serial mode of signal measurement. $e_{141}(t)$ refers to the error of data transmission of the serial mode between the acquisition unit and sensors. $e_{142}(t)$ refers to the error of data transmission of the serial mode between the acquisition apparatus and the acquisition unit, it can be expressed by the function of the distance between the acquisition unit and sensors as (10). The acquisition unit is built in the acquisition apparatus adopting the serial mode. In such circumstances, $e_{142}(t)$ can be negligible, i.e. $e_{142}(t)$ is almost equivalent to 0, and the total output error of the system could be expressed as follows.

$$e_{1y}(t) = e_{141}(t) \tag{9}$$

$$e_{1y}(t) = e(l_1) \tag{10}$$

where, $e(l_1)$ refers to the error of data transmission of the serial mode between the acquisition unit and the sensors. l_1 refers to the distance between the acquisition unit and the sensors.

The results showed that the value of $e_{141}(t)$ was closely related to the distance between the acquisition apparatus and sensors (our specific findings were listed in the results section). The value of $e_{141}(t)$ was small when l_1 was less than a certain distance l_{11} (e.g.: 100 m), the value of $e_{141}(t)$ was relatively large when l_1 was more than or equal to a certain distance l_{11}, and less than a certain distance l_{12} (e.g.: 300 m), and the value of $e_{141}(t)$ was huge when l_1 was more than a certain distance l_{12}. The values of l_{11} and l_{12} could be obtained from the test.

2) ADVANTAGES OF THE SERIAL MODE

The signal acquisition apparatus adopting the serial mode features a simple structure and has found wide applications. This mode is suitable for fewer monitoring points, smaller range, and centralized distribution of dike monitoring. For the engineering project that is relatively close to the monitoring sections, the acquisition apparatus could be set up in the location adjacent to the project.

3) DISADVANTAGES OF THE SERIAL MODE

When there are numerous monitoring points, large range, and wide distribution for the dike monitoring, along with a relatively remote distance from the monitoring section to the dike, the acquisition apparatus adopting the serial mode would require a pair of wires for each sensor. Consequently, the sensors would face such issues as excessively lengthy connective wires and huge amplitudes of signal attenuation that could lead to insufficient energy incentives under severe circumstances. Furthermore, it could impose a negative impact on the normal operation of sensors and even lead to serious distortion. In addition, the serial mode features massive interference among wires resulting from harmonic and high frequency, and suffers from the huge influence of the surrounding environment, undermining the accuracy of the signal measurement. Since it is necessary to set up a pair of wires between each sensor and the acquisition unit, there is a massive amount of workload and costs related to wiring. The acquisition apparatus adopts a polling mode while collecting signals from sensors, but with a low level of efficiency during data acquisition, and faces restrictions in terms of the number of connected acquisition units. Therefore, for dike engineering projects with numerous measuring points, large range, and wide distribution, the serial mode would face such issues as limited accuracy and lengthy time of data acquisition, which could not meet the requirements of linear and large monitoring for dikes.

C. PARALLEL MODE OF SIGNAL MEASUREMENT ON DATA ACQUISITION OF DIKE MONITORING

1) PRINCIPLE OF THE PARALLEL MODE

The working principle of a parallel mode of signal measurement is shown in Fig. 2 [1], [20]. The acquisition apparatus controls all the acquisition units to collect signals at the same time in the parallel mode. The acquisition unit has an independent signal processing unit, which can simultaneously collect signals from all connected sensors. In other words, the acquisition apparatus can achieve signal acquisition of all connected sensors at the same time. However, the number of signals to be collected by each acquisition unit is limited due to restrictions of the port line of the CPU, which is generally four-eight analog or eight-sixteen digital. The acquisition unit can be separately arranged in the parallel mode. The total time it takes for the slope monitoring system adopting the parallel mode to collect signals from all connected sensors could be expressed by the following formula.

$$t_{a2} = \max(t_{ij}) \quad (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{11}$$

where, $\max(t_{ij})$ refers to the maximal value among t_{ij}. t_{a2} refers to the total time it takes for the dike monitoring system adopting the parallel mode to collect signals from all connected sensors.

The total output error of the monitoring system in the parallel mode of signal measurement could be expressed as follows [43].

$$e_{2y}(t) = e_{241}(t) + e_{242}(t) \tag{12}$$

where, $e_{2y}(t)$ refers to the total output error of the monitoring system in the parallel mode of signal measurement. $e_{241}(t)$ refers to the error of data transmission between the acquisition unit and sensors in the parallel mode. When the distance between the sensor and the monitoring section is set as 20 m, the data transmission error is negligible, i.e. $e_{241}(t)$ is almost equivalent to 0. $e_{242}(t)$ refers to the error of data transmission between the acquisition apparatus and the acquisition unit in the parallel mode. The data between the acquisition apparatus and the acquisition unit in the parallel mode are transmitted through RS485 communication. When the distance between the acquisition apparatus and the acquisition unit is set as 1,000 m, the data transmission error is negligible, i.e. $e_{242}(t)$ is about equivalent to 0, and the total output error of the system could be expressed as follows.

$$e_{2y}(t) = 0 \tag{13}$$

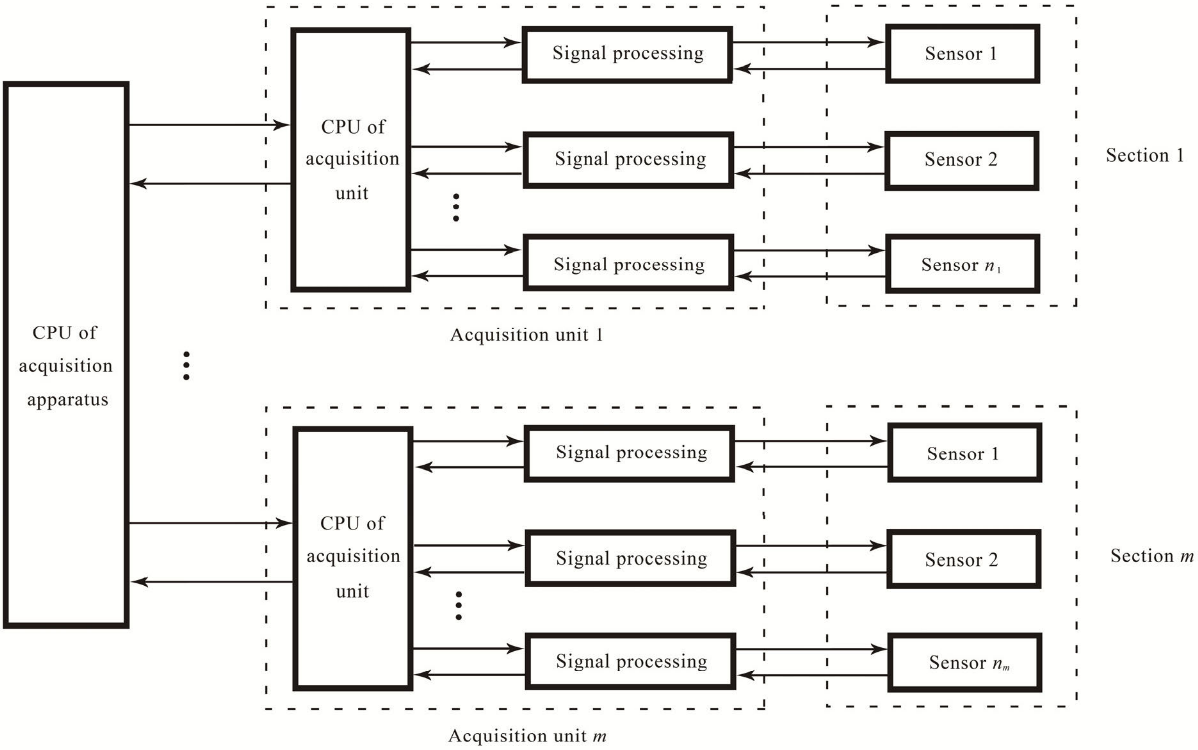


FIGURE 2. Schematic diagram of the parallel mode of signal measurement.

2) ADVANTAGES OF THE PARALLEL MODE

We could obtain (14) by comparing (7) and (11). Therefore, the total time of the parallel mode is less than that of the serial mode under the same conditions, and the parallel mode could improve the efficiency of data acquisition. The parallel mode of signal measurement has been widely used in industrial control, whereas the velocity of data processing of the central processing unit for all acquisition units is dependent on the transmission rate of the communication bus. The transmission rate is at the millisecond level in general. Therefore, the acquisition rate of the parallel mode is much higher than that of the serial mode.

We could obtain (15) by comparing (10) and (12). Therefore, the output error of the parallel mode is far less than that of the serial mode under the same conditions, and the parallel mode could improve the precision of data acquisition.

$$t_{a2} < t_{a1} \tag{14}$$

$$e_{1y}(t) \gg e_{2y}(t) \tag{15}$$

3) DISADVANTAGES OF THE PARALLEL MODE

The types of signals commonly used in dike monitoring mainly include current, voltage, resistance, vibrating wire frequency, and pulse. For instance, the signal of the pulse is not categorized as standard signals in the field of industrial control. There are stringent requirements for the signal processing unit to process signals in the parallel mode, resulting in extremely complex structures, high costs and poor versatility, and limited application in dike monitoring.

III. PRINCIPLES AND METHODS

A. BASIC PRINCIPLES OF THE PARALLEL-SERIAL MODE OF SIGNAL MEASUREMENT ON DATA ACQUISITION OF DIKE MONITORING

1) THE AIM OF THE PARALLEL-SERIAL MODE

The aim of the parallel-serial mode is to replace the serial mode of the traditional engineering projects of dike monitoring. The mode is expected to overcome the problems typical in the serial mode, such as massive amount of wiring, severe interference between cables, limited accuracy, and efficiency of dike monitoring. Thanks to the adoption of this mode, we aim to achieve less wiring as well as higher levels of accuracy and efficiency in dike monitoring.

2) WORKING PRINCIPLES OF THE PARALLEL-SERIAL MODE

Based on the technologies of signal acquisition and communication, we have proposed the principle of the parallel-serial mode of signal measurement as shown in Fig. 3 and Fig. 4. The parallel-serial mode has integrated the advantages of simple structure in the serial mode and high sampling efficiency in the parallel mode.

As shown in Fig. 3 and Fig. 4, the parallel mode is adopted between the acquisition apparatus and acquisition units. In addition, the acquisition apparatus has control over

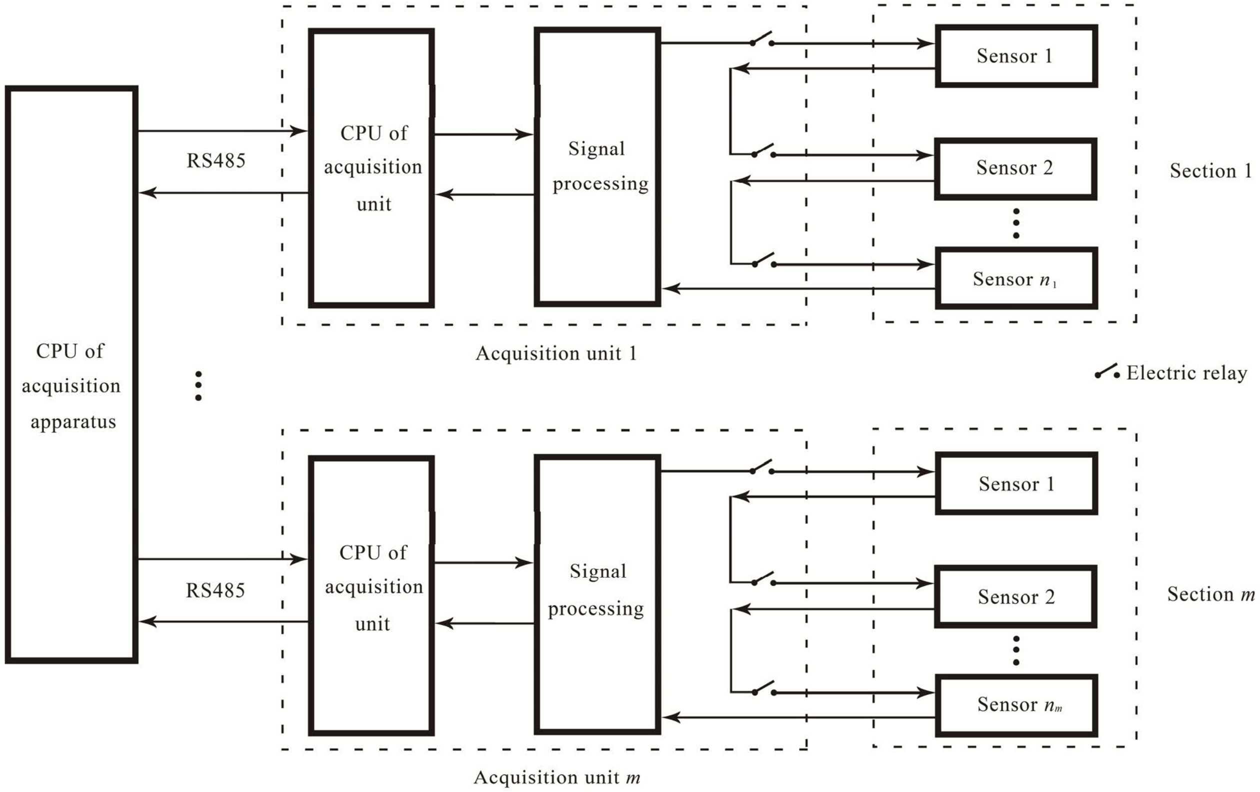


FIGURE 3. Schematic diagram of the parallel-serial mode of signal measurement.

all connected acquisition units so that they are operated at the same time. The serial mode is adopted between acquisition units and sensors in the parallel-serial mode, and each acquisition unit is a separate miniaturized unit of serial data acquisition, whereas the acquisition unit collects the signals from all connected sensors in turn.

The total time it takes for the dike monitoring system in the parallel-serial mode to collect signals from all connected sensors could be expressed by the following formula:

$$t_{a3} = \max \sum\nolimits_{i=1}^{n} (t_{ij}) \quad (j = 1, 2, \ldots, m) \tag{16}$$

where, $\sum\nolimits_{i=1}^{n} (t_{ij})$ refers to the time of collecting signals from all connected sensors in section j. max $\sum\nolimits_{i=1}^{n} (t_{ij})$ refers to the maximal value of the time it takes for the acquisition apparatus to collect signals from all connected monitoring sensors in every single section. t_{a3} refers to the total time it takes for the dike monitoring system to collect signals from all connected sensors in the parallel-serial mode.

The output error of the monitoring system in the parallel-serial mode of signal measurement could be expressed as follows [43].

$$e_{3y}(t) = e_{341}(t) + e_{342}(t) \tag{17}$$

where, $e_{3y}(t)$ refers to the total output error of the monitoring system in the parallel-serial mode of signal measurement. $e_{341}(t)$ refers to the error incurred in the parallel-serial mode during data transmission between the acquisition unit and sensors. $e_{342}(t)$ refers to the error incurred in the parallel-serial mode during data transmission between the acquisition apparatus and the acquisition unit.

When the distance reaches 20 m between the sensor and the monitoring section, the data transmission error can be negligible, i.e. $e_{341}(t)$ is almost equivalent to 0. The data between the acquisition apparatus and the acquisition unit could be transmitted through RS485 communication in the parallel-serial mode. When the distance reaches 1,000 m between the acquisition apparatus and the acquisition unit, the data transmission error could be negligible, i.e. $e_{342}(t)$ is almost equivalent to 0, the total output error of the system could be expressed as follows.

$$e_{3y}(t) = 0 \tag{18}$$

3) PROPERTIES AND NOVELTY OF THE PARALLEL-SERIAL MODE

We have analyzed the efficiency of data acquisition in different modes of signal measurement when the number of the acquisition units and the connected sensors to the acquisition apparatus was kept as the same for three modes of signal measurement. Judging from (7), (13), and (18) for the serial, parallel, and parallel-serial modes, the data acquisition time could be expressed as follows.

$$t_{a2} < t_{a3} < t_{a1} \tag{19}$$

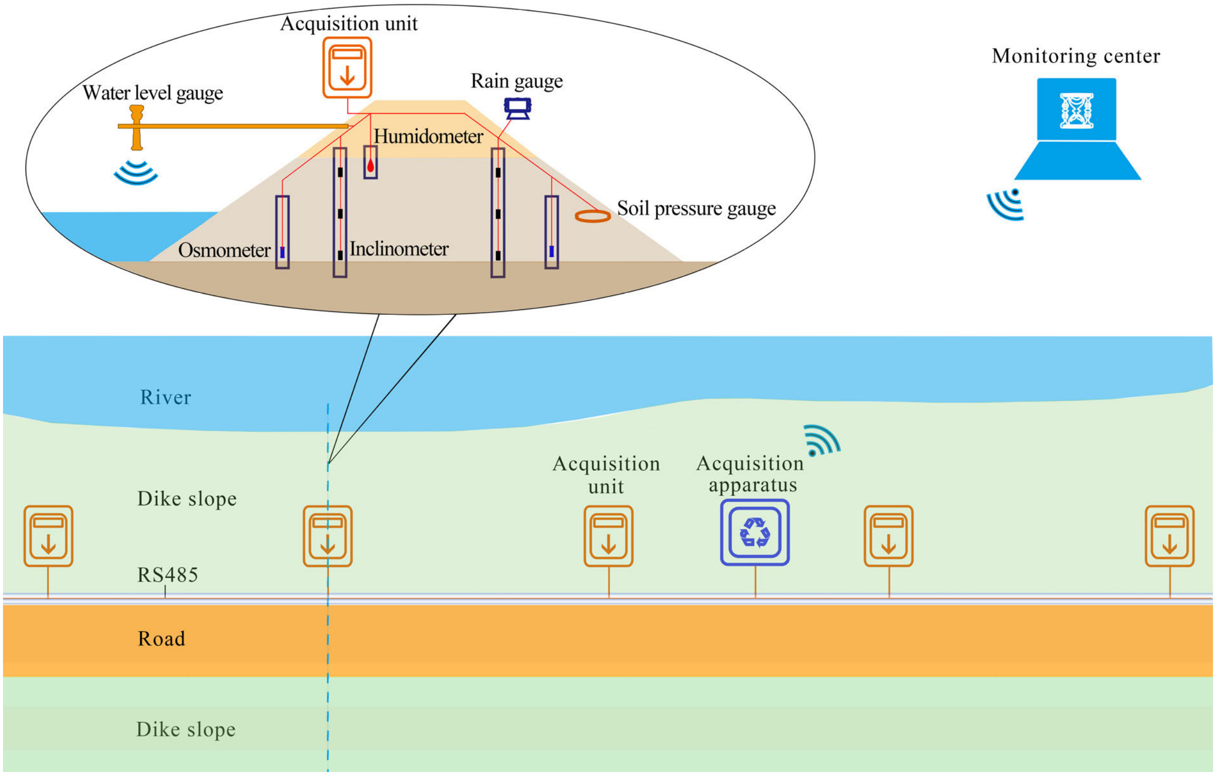


FIGURE 4. **Schematic diagram of the separable online system of dike monitoring based on the parallel-serial mode of signal measurement.**

t_{a3} is greater than t_{a2}, but it is less than t_{a1} by (19). The parallel-serial mode can effectively improve the velocity and efficiency of data acquisition compared with the serial mode. The parallel-serial mode has a lower speed and efficiency of data acquisition than the parallel mode, but it can also meet the monitoring requirements of dike engineering [44]. Therefore, the data acquisition efficiency of the parallel-serial mode is higher than that of the serial mode.

We have analyzed the accuracy of data acquisition in the different modes of signal measurement. The distance is kept at 1,020 m between the acquisition apparatus, the acquisition unit, and sensors for the serial mode. Specifically, the distance is kept at 1,000 m between the acquisition apparatus and the acquisition unit, whereas the distance is kept at 20 m between the acquisition unit and sensors for the parallel mode and the parallel-serial modes. On this basis, we have compared the data acquisition error by comparing the results of (10), (13), and (18) for the serial, parallel, and parallel-serial modes, and obtained the results as follows.

$$e_{1y}(t) \gg e_{2y}(t) \approx e_{3y}(t) \tag{20}$$

When the distance between sensors and the acquisition apparatus is less than 1,020 m by (20), the total output error of the parallel-serial mode is equivalent to that of the parallel mode, but far less than the serial mode. Therefore, the parallel-serial mode could effectively reduce the system output error. The overall output error of the parallel-serial mode was much smaller than that of the serial mode, thus the parallel-serial mode could effectively improve the monitoring accuracy.

We have transformed the method of signal acquisition and transmission from integration in the serial mode into separation in the parallel-serial mode. The acquisition unit and the acquisition apparatus could be arranged separately, and the sensors are only required to be connected with the acquisition unit. In addition, the connection between the acquisition unit and the acquisition apparatus could be realized through the RS485 communication mode, and only a pair of twisted-pair wires is needed to realize the data transmission. Compared with the serial mode, the parallel-serial mode proves to have greatly reduced the amount of wiring and prevented signal distortion and interference. Furthermore, the production cost of the parallel-serial mode with the same monitoring task is about 10-20% of that of the parallel mode, which is a significant reduction. Therefore, the parallel-serial mode is more suitable for the engineering projects of linear dike monitoring.

We have adopted the RS485 digital communication between the acquisition apparatus and the acquisition unit. In addition, the acquisition apparatus could also receive the data set from the acquisition unit or the remote server. The signal acquisition unit features the function of the two-way communication with the acquisition apparatus, whereas the remote server could realize the two-way exchange of

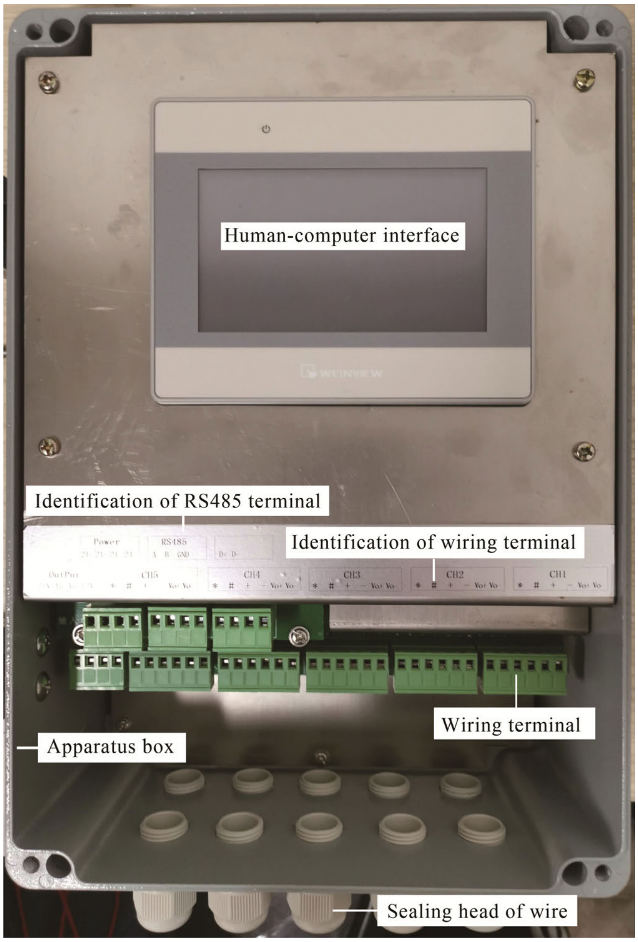


FIGURE 5. Physical picture of the acquisition apparatus of dike monitoring in the parallel-serial mode.

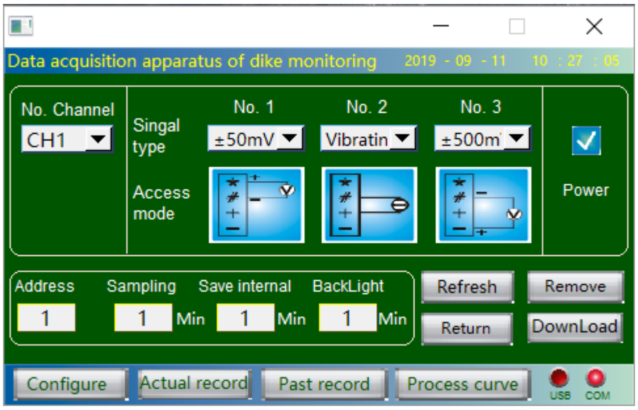
information between the acquisition apparatus and the acquisition unit, avoiding difficulties of the field operation in such aspects as parameter set and data reading. Therefore, this method can prevent the acquisition unit from becoming an isolated information island.

B. APPARATUS AND CIRCUIT OF THE PARALLEL-SERIAL MODE OF SIGNAL MEASUREMENT ON DATA ACQUISITION OF DIKE MONITORING

1) APPARATUS OF THE PARALLEL-SERIAL MODE

We have established the human-computer interface of dike monitoring by using the technologies of human-computer interaction for the acquisition apparatus and the acquisition unit. Specifically, we have used the human-computer interface TK8070IH introduced from WEINVIEW Co., LTD of Taiwan in China, and we have developed the corresponding software based on the EasyBuilder Pro software as shown in Fig. 5 and Fig. 6.

Fig. 5 shows the hardware of the acquisition apparatus. It is mainly composed of an apparatus box, a human-computer interface, wiring terminals of sensors and RS485 signal lines, sealing heads of wire, and the supporting circuit (the circuit is below the human-computer interface). In addition, the acquisition unit can be connected with the acquisition apparatus through the RS485 wiring terminal.


Data acquisition apparatus of dike monitoring 2019 - 09 - 11 10 : 27 : 05

No. Channel: CH1

Singal type: No. 1 ±50mV; No. 2 Vibratin; No. 3 ±500m

Access mode

☑ Power

Address: 1

Sampling: 1 Min

Save internal: 1 Min

BackLight: 1 Min

FIGURE 6. Interface of the acquisition apparatus of dike monitoring in the parallel-serial mode.

Fig. 6 shows the software of the acquisition apparatus. The software mainly includes configuration, actual record, history record, process curve, and main operation keys to realize real-time monitoring of dike in the parallel-serial mode of signal measurement. The human-computer interface allows us to operate easily and achieve on-line monitoring.

2) CIRCUIT OF THE PARALLEL-SERIAL MODE

It is necessary to use the technology of the multi-sensor interface to realize the parallel-serial mode of signal measurement for the acquisition apparatus. In addition, we could realize the signal acquisition and transmission of sensors through the built-in CPU in the acquisition unit, and the specific circuit principle is shown in Fig. 7.

Fig. 7 shows the main parts of the acquisition apparatus, which mainly includes sensors, multiway switches (multi-channel of sensor input and the corresponding multi-switch of electric relay input), excitation switches (the optional switch for internal and external excitation), analog switches, amplifiers, ADCs (the conversion circuit from the analog to digital), photoisolators, CPUs of the acquisition unit, an acquisition apparatus, a monitoring server, and a power module.

The existing chip or circuit could be adopted in each part of the acquisition apparatus. For instance, the Microprocessor Unit could be used in the CPU of data acquisition units, namely, a small industrial embedded CPU. The interface RS485 could be adopted in the communication unit, and the electric relay could be used in the excitation switch for the internal and external sources. In terms of the Analog/Digital Converter, it is recommended to use a high-precision ADC with 24 bit. The sensor interface of the acquisition unit is classified by a wire slot, which could avoid interference. We have adopted the serial communication interface RS485 for the interface hardware of the acquisition apparatus, which had strong compatibility and high efficiency in communication. In addition, numerous acquisition units could be connected to the acquisition apparatus. The channels have *p* channels,

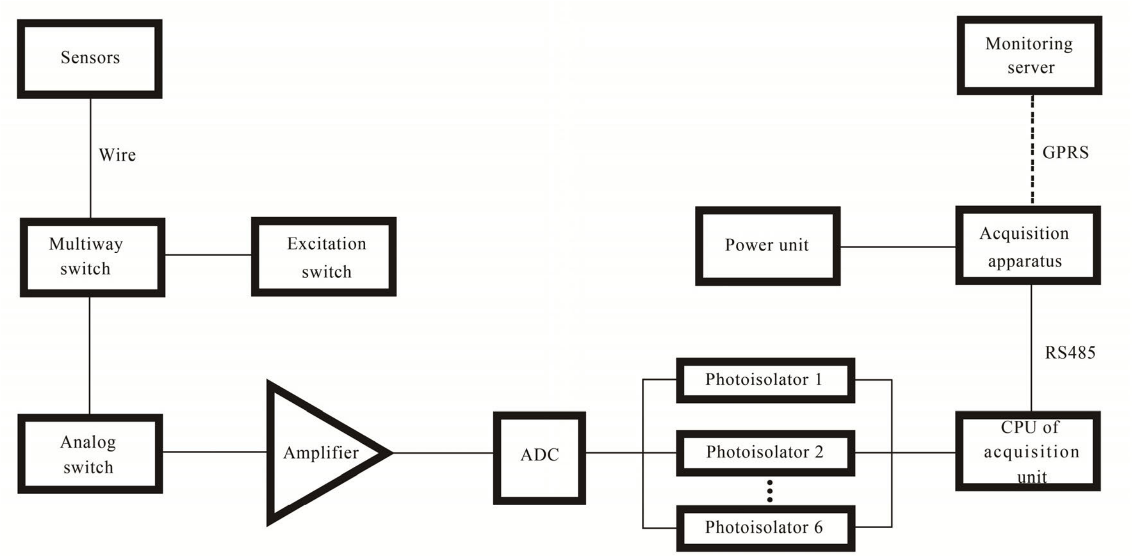


FIGURE 7. Schematic diagram of the circuit of the parallel-serial mode of signal measurement.

each consisting of four terminals and connected to the sensor through the terminal. Thanks to the different combinations of the four terminals, up to three analog signals or pulse signals could be input at the same time. Therefore, each acquisition unit could be connected to the $3p$ analog signals, and generally, p is set from five to ten. In other words, the number of connected sensors for each acquisition unit could range between fifteen and thirty. Since the working voltage of the integrated chip in the acquisition unit is not the same, the switching power module could be used in practice.

C. WORKING PROCESS OF THE PARALLEL-SERIAL MODE OF SIGNAL MEASUREMENT ON DATA ACQUISITION OF DIKE MONITORING

There are mainly two types of electrical signal response output of the sensor: (1) analog signal, i.e. voltage, current, or resistance signal (e.g. temperature, pressure, vibrating sensors, etc.); and (2) pulse signal (e.g. rain gauge signal). These two types of signals are processed in different manners, and the signal acquisition of sensors for every channel in the acquisition unit is shown in Fig. 7.

The processing of the analog signal is as follows. First, the CPU sends out the control signal through the coupling transmission of the No. 3 photoisolator, and the analog electronic switch is launched to generate the corresponding output of the sensor. The output signal of the analog electronic switch would then turn into the programmable apparatus amplifier. Second, the CPU sends out the control signal through the coupling transmission of the No. 2 photoisolator to control the signal gain of the programmable apparatus amplifier, thus the output signal of the programmable apparatus amplifier is consistently matched with the measuring range of the ADC. Third, the CPU sends out the control signal through the coupling of the No. 1 photoisolator to control the sampling of the ADC. After the completion of the ADC sampling, the CPU would read the sampling result of the ADC by the No. 1 photoisolator. Last but not least, the CPU would complete the digital filtering for the sampling results, and transform the range according to the characteristics of the sensor, then store the conversion value of the range.

The processing of the pulse signal is carried out by the following procedures. First, the CPU sends out the control signal through the coupling transmission of the No. 5 photoisolator to control the switching of the pulse signal selector, and the output signal of the sensor is amplified into pulse signal amplification, shaping the circuit module. Second, the shaping signal is transmitted to the CPU through the No. 4 photoisolator, and the signal is counted by the CPU and calculated to the output frequency of the pulse signal sensor (e.g. rain gauge), whose calculating values would be stored. The monitoring data of the separable acquisition unit could be transmitted to the acquisition apparatus when the acquisition apparatus is connected with the separable acquisition units through the communication port.

Data rates mainly include two parts: the data transmission rate and the data acquisition rate. The data transmission rate is mainly affected by the transmission mode. The data transmission could be completed in batches, and the acquisition apparatus or the acquisition unit could transmit all the signals connected to all sensors at the same time. It takes 30-50 ms for a batch of data to be transmitted within 1,000 m with the wired mode, and the distance has a limited effect on the data transmission rate, which is negligible. The data transmission rate is greatly affected by the network situation with the wireless mode, and the time it takes for a batch of data to be transmitted generally does not exceed 15 s. The connected sensors are generally required to collect signals in turn. The data acquisition rate is determined by the acquisition rate of the sensor of the acquisition unit or the acquisition apparatus. The time of data acquisition can be divided into three parts, namely, the starting time of the acquisition unit, the response time of sensors, and the time it takes to switch the sensors of the acquisition unit or the acquisition apparatus. The starting time of different acquisition units varies from each other, which is about 5-10 s in general. Different sensors vary in their response time. Generally, it would take about 30-50 ms to collect signal from 1 sensor, and about 450-750 ms to collect signal from 15 sensors. In addition, it takes a varying amount of time to switch sensors with different acquisition units or acquisition apparatuses. Generally, it takes about 0.1-5.0 s to switch 1 sensor, and about 1.5-75.0 s to switch 15 sensors, thus the acquisition time of 15 sensor signals is about 2.95-85.75 s. Therefore, the total time of acquisition and transmission is about 2.98-85.80 s with the wired mode, whereas the total time of acquisition and transmission is about 18.0-100.5 s with the wireless mode. The structure of the dike is similar to that of the earth-rock dam, currently, not less than 30 min is required according to the monitoring code for the earth-rockfill dam [44], and our proposed mode could meet the requirements of engineering monitoring.

D. EXPERIMENTAL DESIGN OF VERIFICATION AND ENGINEERING APPLICATION

To assess the performance of the parallel-serial mode of signal measurement, we have mainly carried out the tests in the following aspects, including the acquisition accuracy, acquisition efficiency, real-time performance, two-way communication, and the engineering application. Through comparison with the parallel and serial modes of signal measurement, we have properly evaluated the effectiveness of the parallel-serial mode.

1) EXPERIMENTAL DESIGN OF THE VERIFICATION OF ACQUISITION ACCURACY

Numerous sensors are connected to the acquisition unit with different lengths of wires, such as soil pressure gauges, osmometers, inclinometers, humidometers, and rain gauges, etc. We have analyzed the acquisition accuracy of the parallel-serial mode for dike monitoring. Moreover, we have compared the method of direct measurement with the results of the serial, parallel, and parallel-serial modes, thereby verifying the accuracy of data acquisition of different modes. By using the direct measurement method, we would connect the frequency meter directly to sensors. The corresponding physical value could be converted according to the output frequency index of the frequency meter. The relative error evaluation method is used to analyze acquisition accuracy. Taking the direct measurement value of a frequency meter as the benchmark value, the relative error can be calculated by the difference between the measured value of three modes (i.e., serial, parallel, and parallel-serial modes) and the direct measurement value of the frequency meter. We have verified the acquisition accuracy of the parallel-serial mode by using the seepage pressure test. To reduce the test error, we have set the wire length between the sensor and the acquisition unit to be 20 m for the parallel and parallel-serial modes, and only the length of the bus RS485 wire is changed during the experiment. The wire length between the sensor and the acquisition apparatus ranges between 20 m and 1,020 m for the serial mode. When the acquisition apparatus has control over three acquisition units, each acquisition unit is respectively kept connected with three soil pressure gauges, three osmometers, three inclinometers, and three humidometers, and the total number of sensors reaches twelve.

2) EXPERIMENTAL DESIGN OF THE VERIFICATION OF ACQUISITION EFFICIENCY

For a better comparison of the acquisition efficiency of dike monitoring in the parallel-serial mode, we have connected the acquisition apparatuses adopting the serial, parallel, and parallel-serial modes to a different number of signal acquisition units. To simplify our analysis and reduce the errors incurred during tests, the number and the type of sensors connected to the acquisition unit are kept consistent. Three same acquisition units and four types of sensors (soil pressure gauge, seepage gauge, inclinometer, and soil humidometer) are chosen. Furthermore, we have carried out the tests while connecting each acquisition unit to 1-3 sensors of the four types.

3) EXPERIMENTAL DESIGN OF THE VERIFICATION OF REAL-TIME PERFORMANCE

To test the real-time performance of the parallel-serial mode of signal measurement, we have read manually the display time of the sensors on the acquisition unit at different distances, and obtained the corresponding display time of each sensor on the acquisition apparatus. In addition, we have analyzed the real-time monitoring performance of the parallel-serial mode. To eliminate the influence of other factors, we have connected only one acquisition unit to the acquisition apparatus during the test with the same number, type, and arrangement order of sensors in the acquisition unit. Furthermore, we have verified the real-time performance of the parallel-serial mode through the seepage pressure test.

4) EXPERIMENTAL DESIGN OF THE VERIFICATION OF TWO-WAY COMMUNICATION FUNCTION

To test the two-way communication function of the parallel-serial mode, we have adjusted the acquisition frequency of sensors connected to the acquisition unit by using the acquisition apparatus, and observed the actual sampling frequency of the acquisition unit. In addition, we have compared the set frequency of the acquisition apparatus and evaluated the two-way communication function of the parallel-serial mode. Eventually, we have verified the two-way communication function of the parallel-serial mode through the seepage pressure test.

TABLE 1. Frequency results of the osmometer with different length of connected wires.

Length of wire (m)	Value of the meter (Hz)	Value of the serial mode (Hz)	Relative error of the serial mode (%)	Value of the parallel mode (Hz)	Relative error of the parallel mode (%)	Value of the parallel-serial mode (Hz)	Relative error of the parallel-serial mode (%)
10	2275.3	2275.5	0.01	2275.00	0.01	2275.5	0.01
30	2275.3	2276.8	0.07	2275.70	0.02	2275.7	0.02
50	2275.3	2253.4	0.96	2275.80	0.02	2275.8	0.02
100	2275.3	2232.7	1.87	2275.90	0.03	2275.8	0.02
300	2275.3	Jitter	/	2275.90	0.03	2275.9	0.03
500	2275.3	Jitter	/	2277.00	0.07	2276.1	0.04
800	2275.3	Jitter	/	2274.20	0.05	2276.6	0.06
1020	2275.3	Jitter	/	2281.50	0.27	2267.3	0.35
1520	2275.3	Jitter	/	2311.40	1.59	2240.7	1.52

5) EXPERIMENTAL DESIGN OF ENGINEERING APPLICATION

Taking the monitoring of the Zhangjiagang Dike of Yangtze River in Jiangsu Province of China in 2018 as an example, the field tests mainly include the tests of acquisition accuracy and acquisition efficiency to evaluate the engineering performance of the parallel-serial mode of signal measurement. We conducted these tests to properly assess the engineering effect of the parallel-serial mode. We set up two parallel-serial acquisition units respectively on the over dike and the back dike to monitor the stress and deformation of the dike, the seepage pressure, and the water level of the river during the monitoring process. To reduce the test error, we fixed the wire length between sensors and the acquisition unit to be 20 m while modifying only the length of the bus RS485 wire during our experiment.

We carried out the signal acquisition in the parallel-serial mode, and measured the frequency of the inclinometer directly by the frequency meter through the inclinometer test, thereby verifying the acquisition accuracy of the parallel-serial mode in engineering application. The acquisition apparatus was connected to 1-2 signal acquisition units respectively with the same type and number of sensors connected to the signal acquisition unit, and we have compared the influence of the number of the acquisition units on the acquisition time. In addition, we have verified the acquisition efficiency of the parallel-serial mode in engineering application.

IV. RESULTS

A. VERIFICATION OF ACQUISITION ACCURACY

We have assessed the acquisition accuracy of the parallel-serial mode by using direct measurement and contrast methods (Table 1). When the distance between the sensor and the acquisition apparatus is kept at 100 m, the relative errors of the serial, parallel, and parallel-serial modes are 1.87%, 0.03%, and 0.02%, respectively, and the relative error of the parallel, parallel-serial modes is subject to minor changes when the distance between sensors and the acquisition apparatus changes from 300 m to 1,020 m. However, the apparatus can no longer work normally when the distance of separation in the serial mode exceeds 300 m. Our research findings show that the acquisition accuracy of the parallel-serial and parallel modes is very high when the distance of separation between sensors and the acquisition apparatus reaches 1,020 m, but the serial mode could no longer work properly when the distance of separation between the sensor and the acquisition apparatus is kept at 300 m.

B. VERIFICATION OF ACQUISITION EFFICIENCY

We have assessed the acquisition efficiency of the parallel-serial mode by using the contrast methods (Fig. 8). Fig. 8(a) shows that less time is needed for the signal acquisition of the parallel mode, which does not vary with the number of the connected sensors when there is only one acquisition unit. By contrast, it takes longer time for the serial and parallel-serial modes to collect signals, and the needed time increases with the increasing number of connected sensors. When the number and type of sensors connected to each acquisition unit are kept as the same, the acquisition time of the serial mode is proportional to the number of the connected sensors. Fig. 8(b) and Fig. 8(c) show that the relative time of the signal acquisition of the parallel mode is less than the serial, parallel-serial modes when there are two acquisition units, and does not change with the number of sensors. In addition, the acquisition time of the serial and parallel-serial modes is longer than that of the parallel mode, and the acquisition time increases with the increasing number of the connected sensors. The acquisition time of the parallel-serial mode falls in the range between the serial mode and the parallel mode. Fig. 8(d) shows that the acquisition time of the serial mode increases with the increasing number of the acquisition units when each acquisition unit is connected to 12 sensors, and under such circumstance, the acquisition time of the parallel and parallel-serial modes is basically unchanged, which is not affected by the number of connected acquisition units. The acquisition time of the parallel mode is less than that

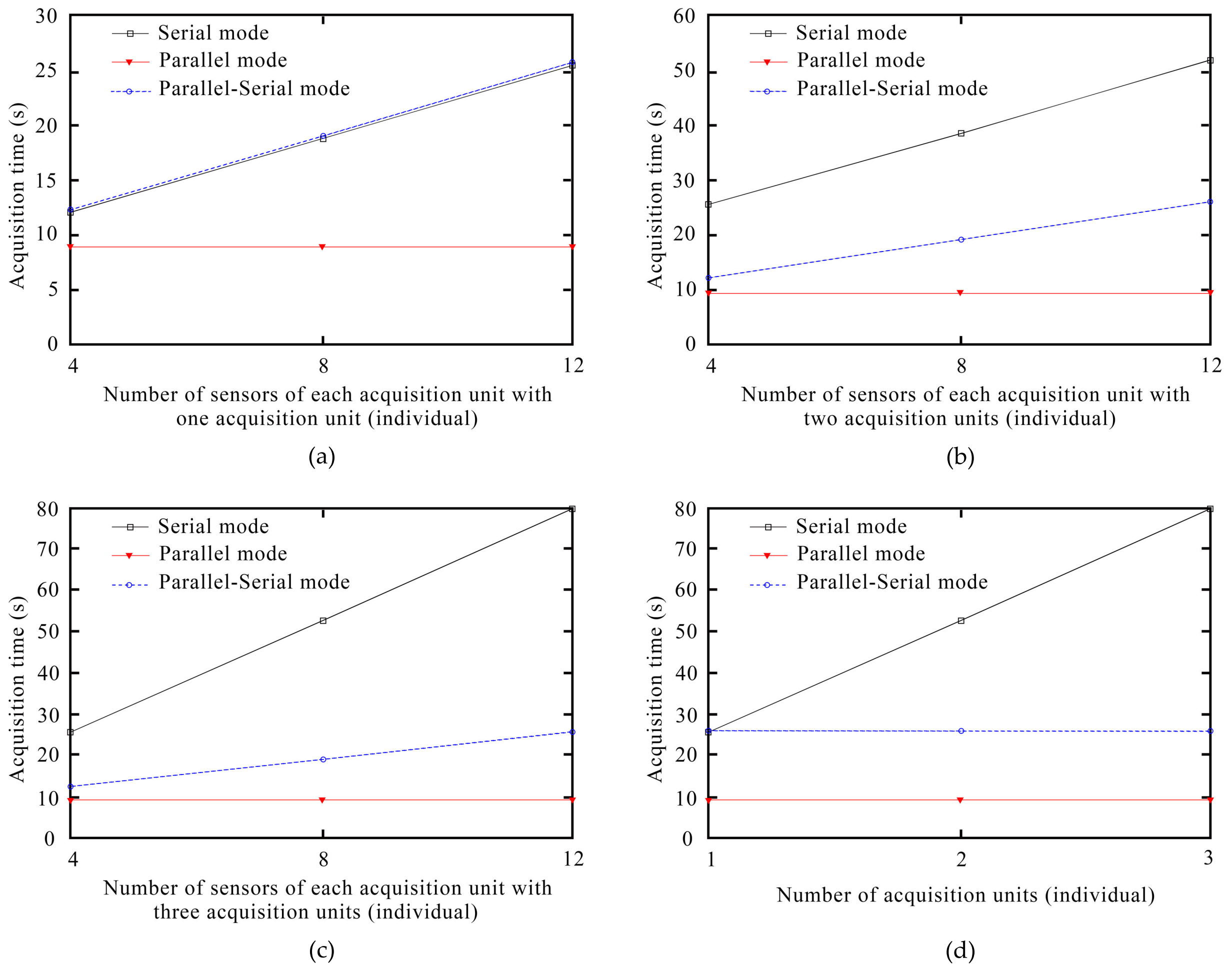


FIGURE 8. (a) Influence of the number of sensors on the acquisition time with one acquisition unit. (b) Influence of the number of sensors on the acquisition time with two acquisition units. (c) Influence of the number of sensors on the acquisition time with three acquisition units. (d) Influence of the number of the acquisition units on the acquisition time with each acquisition unit connected to twelve sensors.

of the parallel-serial mode under the same conditions. If the number of the acquisition units is m, then the acquisition time of the parallel-serial mode is $1/m$ of that of the serial mode. Our research findings suggest that the acquisition time of the parallel-serial mode is $1/m$ of the serial mode, higher than that of the parallel mode when the number and type of sensors connected to each acquisition unit are kept as the same, but the mode could also meet the time response requirement of dike monitoring [44]. Therefore, the parallel-serial mode could address the problems of lengthy time and low acquisition efficiency typical in the serial mode.

C. VERIFICATION OF REAL-TIME PERFORMANCE

We have assessed the real-time performance of the parallel-serial mode by comparing the time interval between the acquisition unit and the acquisition apparatus (Table 2).

Table 2 shows that the display time interval between the acquisition apparatus and the acquisition unit is not more than 12 s when the distance is not more than 1,000 m between the acquisition apparatus and the acquisition unit. It can be seen that the parallel-serial mode of signal measurement has a perfect real-time performance, which can meet the technical requirements of real-time monitoring of dikes (the data acquisition process is generally required to be completed within 30 min [44]. Table 2 shows that the time interval

TABLE 2. Results of the real-time monitoring performance of an osmometer.

Distance between the acquisition and the acquisition unit (m)	Results of the display time of the acquisition unit (hour : min : s)	Results of the display time of the acquisition apparatus (hour : min : s)	Interval of display time shown between the acquisition apparatus and the acquisition unit (s)
20	09:00:00	09:00:10	10
200	10:10:00	10:10:12	11
400	11:17:00	11:17:10	10
600	15:00:00	15:00:12	12
800	16:25:00	16:25:11	11
1000	17:30:10	17:30:12	12

TABLE 3. Results of the two-way communication function of the parallel-serial mode.

Set sampling interval of the acquisition apparatus (min/times)	Actual sampling interval of the acquisition unit (min/times)	Comparison of the sampling interval between the acquisition apparatus and the acquisition unit
10	10	equivalent
30	30	equivalent
60	60	equivalent
120	120	equivalent
720	720	equivalent
1440	1440	equivalent

between the acquisition apparatus and the acquisition unit of the monitoring results of the osmometer changes when the distance increases between the acquisition apparatus and the acquisition unit and does not exceed 1,000 m, but the change is small without a strong regularity. The range of fluctuation is not related to the distance between the acquisition apparatus and the acquisition unit. Our research findings show that the real-time performance of the parallel-serial mode is not more than 12 s when the distance is not more than 1,000 m between the acquisition instrument and the acquisition unit, which could meet the technical requirements of the real-time monitoring of dikes.

D. VERIFICATION OF THE TWO-WAY COMMUNICATION FUNCTION

We have assessed the two-way communication function of the parallel-serial mode by adjusting the sampling frequency of the acquisition unit through the acquisition apparatus (Table 3). When the sampling frequency of the acquisition apparatus changes from 10 min/times to 1440 min/times, Table 3 shows that the actual sampling frequency of the acquisition unit changes with the change of the sampling frequency of the acquisition apparatus, and the sampling interval of the two are equivalent with each other. The sampling frequency of the acquisition unit can be dynamically adjusted by the acquisition apparatus. Our research findings suggest that the two-way communication function can be realized between the acquisition apparatus and the acquisition unit, in which parameters of the acquisition interval could be set in the acquisition unit, and the acquisition data of the sensors from the acquisition unit can be transmitted to the acquisition apparatus.

E. RESULTS OF ENGINEERING APPLICATION

1) VERIFICATION OF THE ACQUISITION ACCURACY OF ENGINEERING APPLICATION

We have assessed the acquisition accuracy of the parallel-serial mode in engineering projects by direct measurement. The results of the inclinometers of the dike in 2018 are shown in Fig. 9. The measurement accuracy of the parallel-serial mode is 99.05%, and 71.65%, respectively when the length of wires between the acquisition apparatus and the acquisition units is set as 1,000 m and 1,500 m, The measurement accuracy of the parallel-serial mode is high when the distance is not more than 1,000 m between the acquisition unit and the acquisition apparatus, and the length of wires does not affect the measurement accuracy. In addition, the acquisition unit can be separated from the acquisition apparatus. The data acquisition error increases significantly when the wire length exceeds 1,500 m between the acquisition apparatus and the acquisition units. Our research findings suggest that the acquisition unit could be separated from the acquisition apparatus so as to realize the separable layout when the distance exceeds 1,500 m between the acquisition apparatus and the acquisition unit.

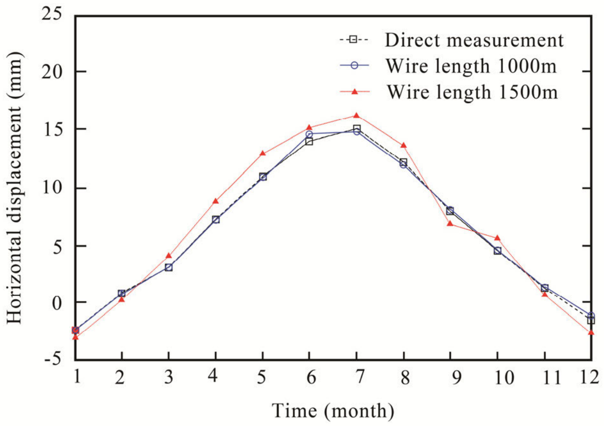


FIGURE 9. Influence of the testing accuracy on wire length (Year: 2018).

2) VERIFICATION OF THE ACQUISITION EFFICIENCY OF ENGINEERING APPLICATION

We have assessed the acquisition efficiency of the parallel-serial mode in engineering projects by means of comparing the number of accessed acquisition units. Tests show that the acquisition time of one and two signal acquisition units lasts for 21.5 s, whereas the acquisition time of one acquisition unit is the same as that of the two acquisition units. The acquisition time of the acquisition apparatus is almost unchanged with the increasing number of the acquisition units connected to the acquisition apparatus. Our research findings suggest that we could significantly enhance the acquisition efficiency of dike monitoring by using the parallel-serial mode of signal acquisition.

V. DISCUSSION

In this study, we have demonstrated that the serial mode of signal measurement of dikes features massive amount of wiring, severe attenuation and signal interference of sensors, limited accuracy, and low efficiency. To clarify the feasibility of the parallel-serial mode for dike monitoring, we have conducted comparative tests of the parallel, serial, and parallel-serial modes to analyze the accuracy and efficiency of the three signal measurement modes. Our research findings show the parallel-serial mode of signal measurement features less wiring and high level of accuracy and efficiency, which is suitable for the engineering monitoring of linear dikes.

As shown in Table 1, we have found that the acquisition accuracy of the parallel-serial mode is similar to that of the parallel mode, but much higher than that of the serial mode when the distance reaches 1,020 m between the collector apparatus and the sensors. As shown in Fig. 8, we have found that the acquisition time of the parallel-serial mode is only $1/m$ of the serial mode (m refers to the number of acquisition units) under the same conditions. As shown in Table 2, we have found that the real-time performance of the parallel-serial mode is not more than 12 s, which could meet the technical requirements of real-time monitoring of dikes [44]. Therefore, the parallel-serial mode has a higher level of accuracy and efficiency than that of the serial mode with optimal real-time performance, thus the parallel-serial mode could be used instead of the serial mode in dike monitoring.

In our dike monitoring system, we have adopted the parallel-serial mode of signal measurement and used the RS485 digital signal to transmit the data between the acquisition apparatus and the acquisition unit. In addition, it was easy to operate the human-computer interface of the acquisition apparatus. In the system by Xavier *et al.* [5], the signal measurement mode is serial, whereas the signal of transmission is analog, and the serial mode can realize the data acquisition of dike monitoring. However, the parallel-serial mode in our system could overcome the inherent shortcomings of the serial mode, and improve the efficiency and accuracy of dike monitoring. In the system by Dong *et al.* [20], the signal measurement mode is parallel, and the parallel acquisition units are built into the acquisition apparatus, whereas there are fewer monitoring parameters. However, the acquisition units in our system could be separated from the acquisition apparatus and allow us to collect more monitoring parameters. In the monitoring system by Wenneker *et al.* [25], the data acquisition is carried out in the serial mode, and data transmission is carried out by coaxial protocol and RS485, the Qinsy online system is used for monitoring control. There are two types of signals during data transmission at the same time, and the system is more complex. However, in our system, we have only used RS485 for data transmission, and we have adopted the parallel-serial mode of signal measurement. Furthermore, we have used the human-computer interface to operate and monitor the acquisition apparatus, which helps to greatly improve the efficiency and accuracy of data acquisition and transmission with a relatively simple structure. In the slope monitoring system by Shen *et al.* [30], the acquisition apparatus is designed by leveraging the technology of human-computer interaction, which is more convenient for field operation. However, the acquisition apparatus is mainly suitable for slope monitoring, and the human-computer interface shall be developed based on the requirements of dike monitoring.

The error of the serial mode changes with the distance between the acquisition apparatus and the sensor, which is primarily due to the fact that the output voltage of the acquisition apparatus is not more than 32 V in general. When the cable is directly connected between the acquisition apparatus and the sensor, the voltage on the sensor is lower at a long distance of the connection line. The terminal voltage of the sensor is lower than the exciting voltage when the distance between the collector and sensors reaches a certain distance (e.g.: 300 m). Under such circumstances, the sensors could not work normally and output effective signals. Therefore, we could deduce that the measurement error of the sensor is huge in this case. The excitation voltage of different sensors varies from each other, whereas the maximal length of the connecting line is not equivalent, and the distance dividing point of the error change is not the same. The specific boundary points could be determined through tests.

We have mainly determined the real-time performance of the parallel-serial mode by assessing the acquisition apparatus and the acquisition unit themselves. The reason is that sensors collect signals in turn when the acquisition unit is working. The display results of a sensor on the acquisition unit are related to the order of the sensor and the response time of the acquisition unit. Due to the high velocity of data transmission, which is generally calculated for milliseconds, the influence of the speed of data transmission could not be considered in the results of the display time of the acquisition apparatus. Therefore, the time interval between the acquisition apparatus and the acquisition unit is mainly determined by the performance and response time of the acquisition apparatus and the acquisition unit themselves. Our results are shown in Table 2.

The analog signal is used between sensors and the acquisition unit as well as the acquisition apparatus in the traditional serial mode, and the signal of the acquisition unit is serially processed. Our research has a major advantage in that the digital signal is used between the acquisition unit and the acquisition apparatus in the parallel-serial mode, and the signal of the acquisition unit is processed concurrently. As a result, we have effectively enhanced the accuracy and efficiency of signal measurement compared with the traditional serial mode, and it is easier to operate and popularize the monitoring system equipped with the technology of human-computer interaction.

Our study scheme is not completely consistent with the actual situation of dike monitoring. It was assumed that the number and type of sensors connected to each unit were the same in the experimental design, yet they are not exactly the same in the actual situation of dike monitoring. In addition, the number of the acquisition units connected by the acquisition apparatus was up to 3, and the type and number of sensors connected by each acquisition unit were up to 4 and 12 respectively. However, there might be more acquisition units and sensors of various sorts in the monitoring system of engineering projects in practice. Therefore, it is still not known whether our results are applicable to the large-scale dike monitoring.

VI. CONCLUSION

In conclusion, we have explicitly demonstrated the accuracy and efficiency of the parallel-serial mode of signal measurement. In addition, we have developed a dike monitoring system based on the human-computer interactive interface, which can realize the remote online monitoring of dike engineering with a separable layout of the acquisition unit.

In the separable on-line system of dike monitoring that we developed, we have adopted the parallel-serial mode of signal measurement equipped with a human-computer interface, which is easy to use and has greatly improved the acquisition accuracy and efficiency of the traditional dike monitoring system. This mode is suitable for linear dike engineering, and may further contribute to the decentralized, linear, regional and wide-range engineering monitoring.

Our findings suggest issues left to be explored further on the working principles of the parallel-serial mode of the signal measurement applicable to the dike monitoring system. We shall discuss its operating mechanism from the working principles behind, deduce the expected outputs of the dike monitoring system, and conduct the corresponding mathematical formulas accordingly. In addition, we shall compare the experimental results with the expected outputs, thereby demonstrating the scientific and advanced nature of the parallel-serial mode both in theory and practice.

Future research can be conducted to study issues of the forecast and early warning of dike safety based on the monitoring system and the monitoring data. It is advocated to explore ways of integrating the monitoring data with the models of safety evaluation, and early warning and forecast, so as to realize the dike safety evaluation and early warning through the existing online monitoring data. This shall be an effective way to promote the practical and popularized application of the dike monitoring system, and can provide strong technical support for flood prevention and emergency rescue as well as engineering management.

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