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Research Article

A Flexible Network Structure for Temperature Monitoring of a Super High Arch Dam

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The aim of the study presented in this paper is to develop a flexible network structure for temperature monitoring of a super high arch dam under construction period. The multiple channel temperature acquisition method collects and analyzes system including flexible and stable field bus for the sensors, communication between intelligent module and control unit is proposed. In this temperature monitoring system, a total of 3 kinds of networks which independently marked by *(1), *(2), and *(3) were proposed, with *(1) being the lowest priority and *(3) being the highest priority. The lowest priority is field bus (ITU Bus) which connects all the grouped sensors into different channels of different intelligent acquisition modules. The ITU network protocol is a star type, and the network structure is independent on the sensors. The bus can connect different types of sensors such as strainmeter, stressmeter, jointmeter, rock-deformeter, piezometer et al., the measurement scope could be extended wider. This study provides a measuring technique has been successfully implemented in monitoring of the Xiluodu arch dam construction, and ultimately solved the shortcoming of manual measurement technique.

1. Introduction

In recent times, sensory technologies have been utilized in monitoring health of structural engineering [1–5]. The sensors utilized in a super arch dam structural health monitoring system (DSHMS) are required to monitor not only the dam structural status including stress, displacement, and acceleration but also the affecting environmental parameters, such as wind speed, temperature, and seepage properties of foundation, especially in dam construction [2, 5, 6]. The DSHMS is a large sensory network that is deployed on a spatially extended structure so that the data acquired from the selected locations will result in the most optimal identification of the dam's structural characteristic changes.

A super high arch dam is divided into many blocks by contraction joints in the construction period. Heat of hydration develops in fresh concrete, associated with the exothermic chemical reactions of the cement [7]. Due to the poor conductivity of concrete, high temperature gradients may occur between the interior and the surface of the structural elements or between parts of an element with sequential concreting phases [8]. The temperature gradients may lead to tensile stresses and excessive tensile strength will result in the young concrete to crack [9]. A preemptive action can be taken to maintain the concrete temperature at the preferred design temperature, which in turn satisfies construction procedures and quality long-lasting lifetime. The other factors that play a major role are the heat of hydration temperature as a function of the construction plan and the quality of the materials used. Up to now, the proper curing methods are essentially empirical and rely on the experience of the contractor who usually considers the precooling (warming) of the materials and the use of cooling tubes, covering the insulation material or low-heat cements. For example, the 186 m high Kurobe Dam, a dome-type arch dam located at the Kurobe River, Japan, was completed in June 1963 [10]. Temperature evaluation requires not only thermometer readings but also theoretical calculations. The temperature data was collected by using vibrating cord thermometers and electrical resistance thermometers, which lacked in durability and precision. The Ertan arch dam is 240 m and is located in the Yalong River of China. The temperature of the concrete was measured by means of 3 sets of dial readouts using sufficient

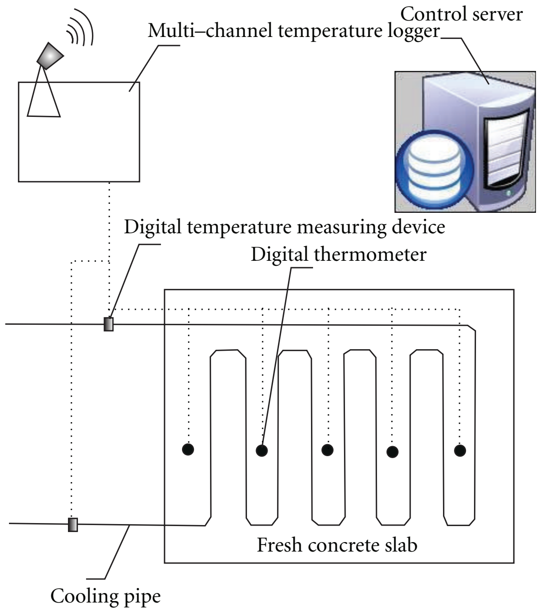


Figure 1: The schematic of temperature acquisition, and collecting, analyzing system.

portable resistance thermometers, and maximum-minimum thermometers embedded in concrete [11]. The contractor provided all necessary assistance in obtaining weekly reports of the placing temperature of the concrete, direction of flow, pressure, and the temperature of the cooling water at the inlet and outlet of each individual cooling coil. Final average temperature checks were obtained by stopping the circulating water in an individual cooling coil for 96 hours and then measuring the water temperature. The 292.5 m Xiaowan arch dam was constructed in 2010 at the Lancang River of China [12]. For measuring internal-concrete temperature, the contractor buried infrared thermometers, and read data manually, since the existence of some errors in the concrete temperature leads to the occurrence of cracks in the dam body [13].

Above all, the current temperature data collection methods and control of manual records are very rudimentary due to thier poor accuracy and lack of data reliability. The main factors of accurate temperature control are real-time measurement, accurate collection of the real dam internal temperature data, inlet and outlet water temperature of the cooling pipe, and weather temperature data. Thus, development of a wall-mounted multisite environment temperature monitoring system for the super high arch dam has an important significance. In this paper, the methodology of temperature measurement based on the flexible network structure for temperature monitoring of super high arch dam is discussed in detail. The method entails collecting multiple channel temperature, analyzing system including flexible and stable field bus for the sensors, and communicating between intelligent module and control unit. An application case of temperature monitoring for the Xiluodu arch dam under construction period is discussed in detail.

2. Methodology and Technology

2.1. Overview of Instrumentation System. This system focuses mainly on providing a real-time, multipoint temperature logger that can automatically capture, transfer, and analyze the internal temperature distribution characters of water in the cooling pipe and mass concrete. Figure 1 shows a schematic of temperature acquiring, collecting, and analyzing system, including. (1) Digital temperature measurement devices installed in each inlet and outlet of the cooling pipe; see Figure 2(a); (2) digital thermometers embedded into the concrete block were used to detect internal temperature distribution of fresh concrete elements; the sensor is designed for underwater use and has a coaxial cable armored by stainless steel wires, so that it can be directly embedded in concrete blocks; see Figure 2(b). The temperature range of this sensor is approximately -10°C–60°C, working within an accuracy of $\pm 0.3^\circ$C. (3) Multichannel temperature logger for data acquisition was collected based on flexible network structure, shown in Figure 3. (4) Control server, the receiver temperature logger data.

2.2. Flexible Network Structure. It is very important to read the values from the several hundred sensors covering all pouring blocks and analyze them via computer temperature model system. A detailed solution method for the acquiring, collecting, and analyzing system of the temperature sensors on the dam site is detailed in the following.

In this temperature monitoring system, a total of 3 kinds of networks which are independently marked by *(1), *(2), and *(3) were proposed, with *(1) being the lowest priority and *(3) being the highest priority. The lowest priority is field bus (ITU bus) which connects all the grouped sensors into different channels of different intelligent acquisition modules. The intelligent modules are the interface between sensors and the PLC (Programmable Logic Controller) control system, which communicate with PLC via standard RS485 network (the medium network level marked by *(2)). The PLC polls all the modules in a certain time interval and gets updated temperature values circularly; the protocol is a standard RS485 ASCII. Using industrial Ethernet network (marked by *(3)) and monitoring PC, the data is collected from the PLC and stored in PLC data storage database, which in turn can be accessed by a remote PC via internet connection. For dam temperature control through internet or intranet router, the authorized engineer could make the right analysis or conclusion in real time.

2.3. Flexible and Stable Field Bus for the Sensors. The basic requirement for monitoring the dam temperature is to continuously collect and record values of the temperature measured by the sensors using a stable, fault tolerated field bus that must be used on site. The ITU bus is developed on the basis of 1-wire protocol (trade mark of Dallas Semiconductor) and the purpose is to communicate over one single twisted-pair cable. This network is defined with an open-drain master/slave multidrop architecture with resistor pullup to a nominal 5 V supply at the master. It is built up


(a) Digital internal temperature measurement devices of cooling pipe


(b) Digital thermometer for internal temperature measurement of mass concrete

FIGURE 2: Digital temperature measurement devices and digital thermometers.

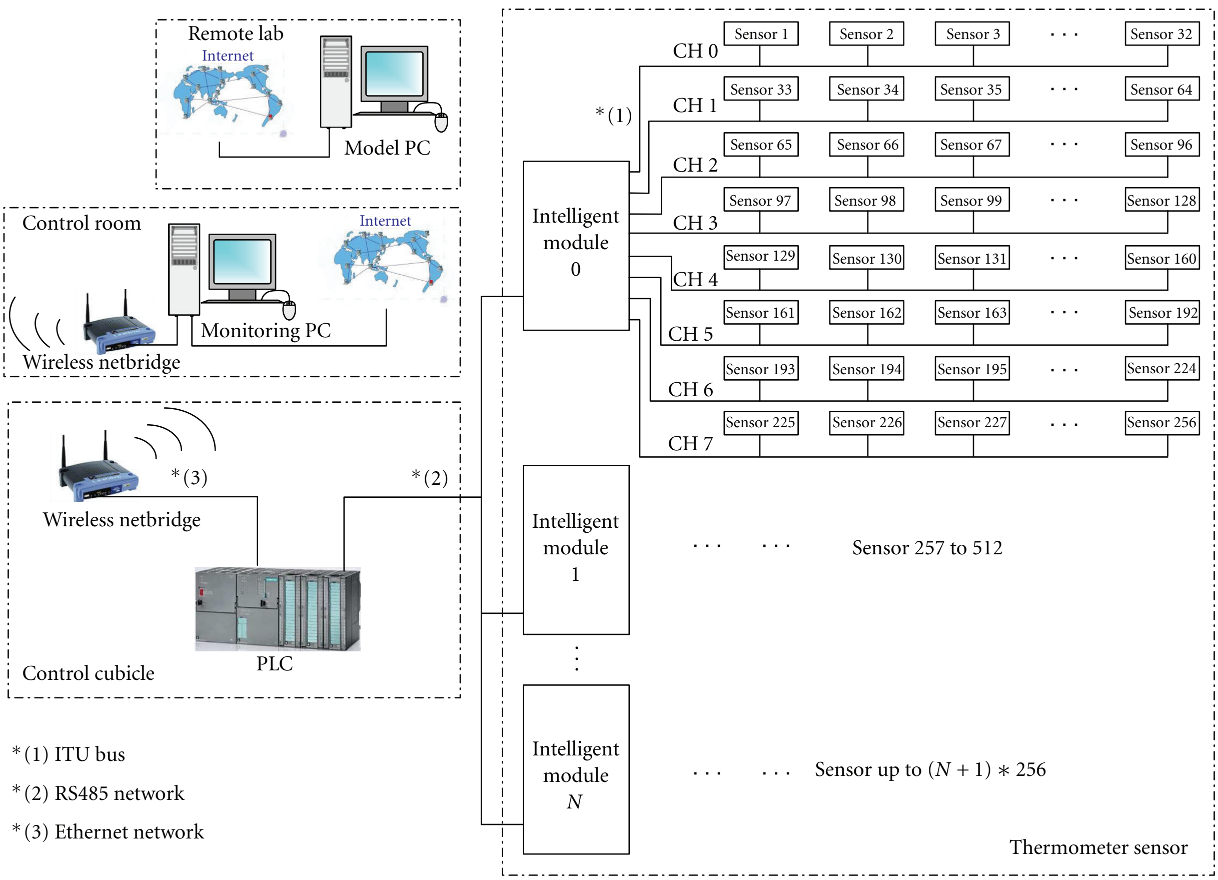


FIGURE 3: Network structure for the temperature control system.

of 3 components: bus master, cable, and multiple slaves. The protocol can be described as follows.

(1) Using conventional CMOS/TTL logic levels (maximum 0.8 V for logic "zero" and a minimum 2.2 V for logic "one") with operation specified over a supply voltage range of 2.8 V to 6 V. (2) Both master and slaves are configured as transceivers permitting bit sequential data to flow in either directions, but only one direction at a time (half duplex); master initiates and controls all devices. (3) Data is byte sequential and bit sequential. Reading and writing least significant bit (LSB), first signal is transferred in time slots. (4) System clock is not required; each slave is self-clocked by an internal oscillator synchronized to the falling edge of the master. (5) Each 1-wire slave has stored in ROM a unique 64-bit serial number that acts as its node address, so the devices can be individually selected from among many that are connected to the same bus wire.

Data inquiring sequence and operations shown in Figure 4 include the following. (1) When the master polling sequence is triggered, the master first sends an inquiring command whose header contains the unique ID of slave 1; (2) the 1st slave is activated when the ID is called in the network, which will send the actual data to the master; (3) if the master finishes reading the data successfully, the 1st slave will stop the data transmitting at the falling edge of the master's reading action; (4) the master resets the slave devices and the slaves are ready for the next command.

The ITU bus is a key component utilized in this system and the most important flexible features are the following.

(1) The usual control cable acts as the communication carrier. The sensors (type: DS18B20) are adhered on the bus which supply the power to the sensors and fetch the signals from the sensors at the same time. The cable length can be extended as long as 200 meters. Briefly one single cable carries power and signals together; each cable is named as one channel, and each intelligent module can deal with 8 channels.

(2) The maximum sensors on one single cable is 64 (so one intelligent module is able to handle $8 \times 64 = 256$ sensors), and the sensors are distinguished from each other using a sensors coding system. Each sensor has its own unique ID which is read by the intelligent module. The module will sort the temperature values according to the IDs on the bus before it is sent to PLC. The main advantage of this architecture is that there are no drawbacks if some sensors are out of service (fault or removed).

(3) The bus can also connect other types of sensors such as strainmeter for measuring the strain the dam is under, stress meter for measuring the compressive stress the dam is under, jointmeter for detecting the opening of joints, rock deformeter, and piezometer. Moreover, the measurement scope of the contacts designed for this network specification could be extended wider. Figure 5 shows how the sensors connect with the ITU bus.

(4) The ITU network protocol is a star type. The master can access each slave directly. With global unique ID, each slave joins or quits the network freely taking into account the users' demand. One master can manage from 1 to 256 slaves including pressure transducers, stress meters, and flow. Since the unique ID is recognized by the master, it is possible that the program sorts the various values from filed sensors.

(5) The network structure is independent from the sensors. If one or several previously linked sensors failed, the master can still read data from other sensors. After replacement, the sensors can be accessed again, as the master collects the data on the whole network repeatedly.

2.4. Communication between the Intelligent Module and Control Unit. Using the standard industrial protocol, the intelligent module can easily interchange data with different control units such as PLC, MCU (Microcontrol Unit), or even PCs. Figure 6 illustrates how one intelligent module communicates with Simatic S7-300 CPU, the communicating processor on PLC side is CP 341-RS 422/485, and the protocol is ASCII driver which has a baud rate of 9600 bp, and a half duplex (RS485) two-wire mode interface.

PLC recognizes up to 128 modules which in turn connects many (maximum 256 for each module) sensors and captures them cycle by cycle. The PLC side is to poll all the modules/channels/sensors in predetermined order, identify all the modules/channels/sensors by unique IDs, and target each module/channel to get a response; this architecture can service 256 different temperature values in one module (32 sensors $\times$ 8 channels) in 12 seconds using an inquire/answer method.

Figure 7 shows the PLC's polling sequence, where there are 2 circularly actions: the inner cycle is for the 1st to 8th channels inside one single intelligent module and the outer cycle is for the 1st to maximum number 128 intelligent modules which are connected in one RS485 network. Theoretically, one Simatic CP341 module can access $32 \times 8 \times 128 = 32768$ sensors, which exceeds the requirement for temperature measurement of a super high arch dam.

The intelligent module has some powerful ASCII interface. For example, when PLC sends the command "−000CR" (Hex codes are 2A 30 30 30 0D), PLC inquires all the sensors' values of channel 0, module 0; subsequently the intelligent module will respond ">0032, *** . . . ***" (Hex codes are likely 3E 30 30 33 32 *** . . . ***); here the symbol "*" means the different values read out from the sensors: ">" means the inquiry is valid, "00" is the module address, and "32" means a total of there is 32 sensors in the channel. The PLC will acquire all the wanted valid values.

3. Case Analysis

3.1. Outline of the Xiluodu Super High Arch Dam. The Xiluodu hydroelectric power station [14, 15] is the second largest power generation outputting 13.86 million kW which is close to the Three Gorges hydroelectric power station in

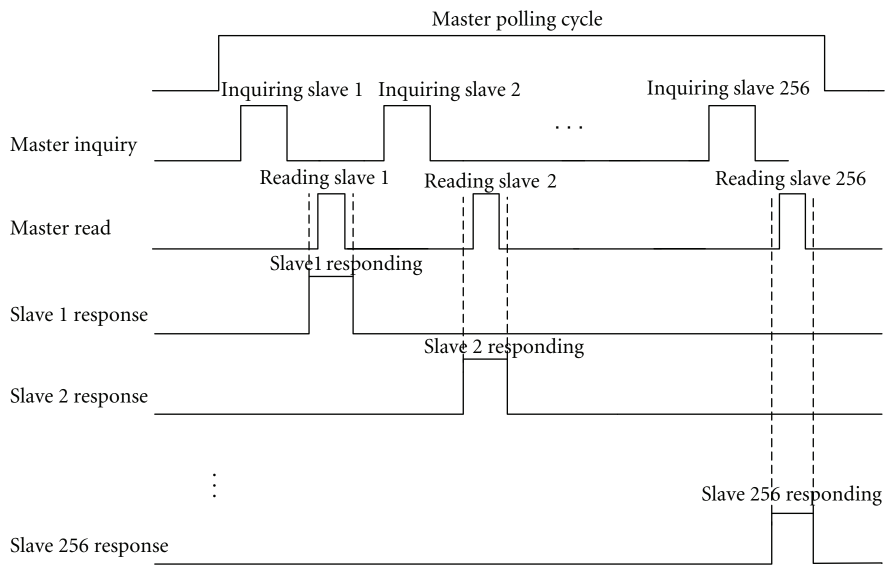


Figure 4: The protocol schematic of ITU bus.

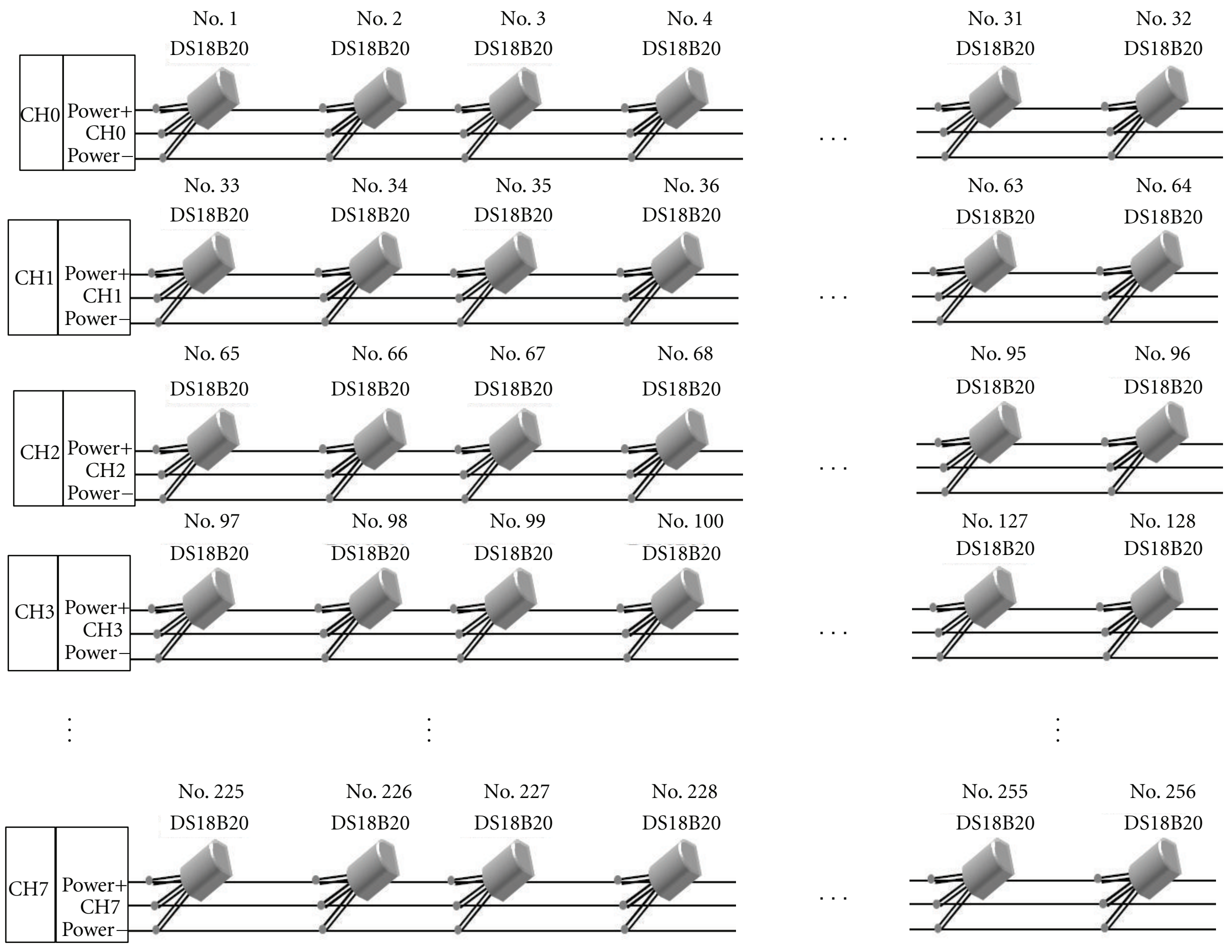


Figure 5: The link method for a maximum of 265 sensors in one intelligent module.

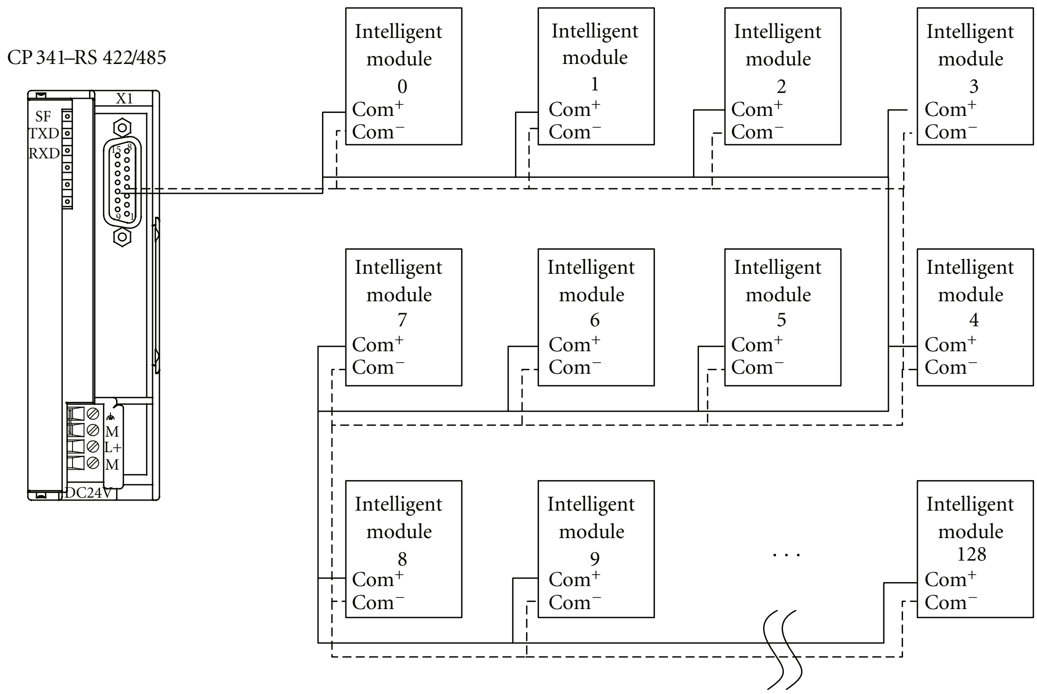


Figure 6: RS485 network for Simatic CP341 and 128 intelligent modules.

China. The project is located at the Jinshajiang River, in Leibo Country of Sichuan province. The principal structures consist of a double-curvature arch dam with a height of 285.5 meters, crest length of about 700 meters, spillway, underground powerhouse, and logway. Both sides of the arch dam are very steep with a good slope surface. Figure 8 illustrates a downstream view of the Xiluodu arch dam under construction.

3.2. Requirement of Concrete Temperature Control. Considering the arch structure of the stress and construction control difficulties, the basic control principle is ultimately small temperature difference, slow cooling, and early cooling [15]. The temperature control of pouring and cooling should satisfy the following requirements.

The original temperature of concrete for the Xiluodu arch dam was maintained at 7°C in hot seasons (from May to September) and 9°C in cold seasons (from October to April). The temperature of concrete upon entry into the silo was capped at 11°C in cold seasons and 9°C in hot seasons. The placement temperature was capped at 12°C all year round. The maximum concrete temperature was capped at 27°C with a tolerance of 1∼2°C, which is to take in to consideration the abnormal hot summer days. After the concrete was detached from the foundation constraint zone, the concrete temperature in the foundation constraint zones on the sections of the dam on both banks was capped at 25°C.

The cooling process for controlling the temperature of concrete at Xiluodu was carried out in three stages including the first stage being the medium phase and the second phase. Considering temperature changes due to body of the dam exposed to water, the two cooling supply systems were running at 8∼10°C and 14∼16°C, respectively. In the first stage, cooling was supplied for about 21 days at a stretch, where the maximum temperature of concrete was less than 27°C. The temperature reduction and cooling process lasted more than 45 days, 90 days and 120 days at a stretch for the medium phase, the second phase, and joint grouting phase, respectively. Table 1 lists the target temperature of dam concrete during medium-term cooling period. During the temperature control stage, concrete temperature in all phases was dropped down as close to the target temperature as possible, and temperature rebound was to be minimized.

The cooling process should be based on the temperature measurement results taking into consideration the concrete partition, pouring temperature, water pipes, density, and ambient temperature. The flow is adjusted in a timely manner to meet the targeted temperature requirements.

3.3. Discussion on Temperature-Related Measurements. During the construction period, digital thermometers were embedded in the dam to monitor temperature change of concrete blocks. Figure 9 is an illustration of 3D maximum temperature distribution of the Xiluodu arch dam under construction. The grey section represents the concrete blocks which will be poured later; meanwhile the color blocks means the temperature distribution across the dam. The results show that the maximum temperature of about 3.5 percent concrete blocks is greater than 27 degree which is the designed temperature extreme value.

The results of dam section 25–32, at EL.483 m, were discussed as a case. Nine thermometers were embedded

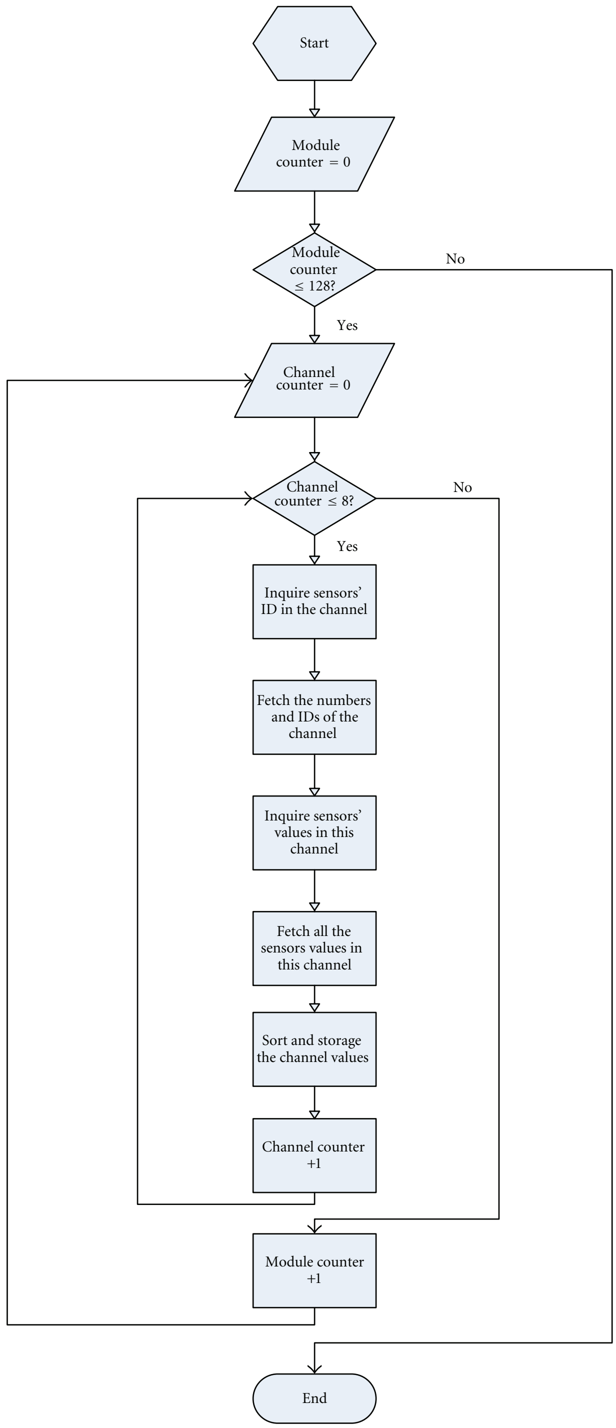


FIGURE 7: The PLC sequence of polling temperature values in various modules.

in spindle mode as seen in Figure 10 in dam section 25–32 (the x axis points to the downstream direction). Internal temperature of dam concrete and entrance or exit temperature of cooling pipes were measured in real time with data collected two seconds apart.

Temperature fluctuation curves of cooling water were shown in Figure 11. The block's (dam section 25–32) average temperature change with time is shown in Figure 12. Figure 13 shows real temperature distribution field of dam section 25–32 with respect to different ages of concrete. These figures identify the following characteristics.

(1) In different temperature control phases, cooling water of different temperatures flows through concrete, absorbing heat generated by hydration in fresh

Table 1: The target temperature of dam concrete during medium phase of cooling.

Position	Month	Joint grouting temperature	Dam section: Approximately 7–22	Dam section: Approximately 1–6, approximately 23–31
Constraints zone	Approximately January–December	12°C, 13°C	16°C	16°C
		14°C, 16°C		18°C
Free zone	Approximately January–March, November–December	12°C, 13°C	16°C	
		14°C, 16°C	18°C	
	Approximately April–October	12°C, 13°C	16°C	
		14°C, 16°C	18°C	

Figure 8: The downstream view of the Xiluodu arch dam under construction.

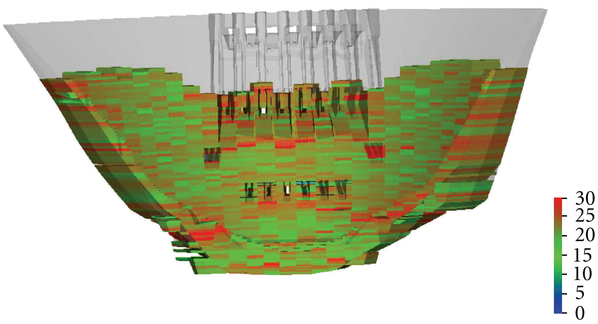


Figure 9: The maximum temperature distribution of the Xiluodu arch dam under construction.

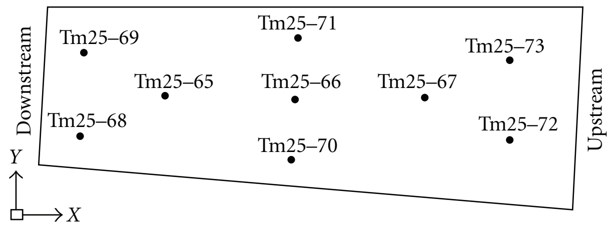


Figure 10: Schematic of thermometers distribution in dam section 25–32.

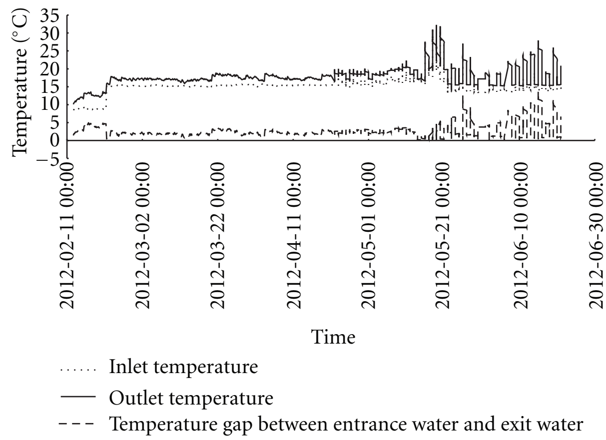


Figure 11: The entrance/exit of cooling pipe temperature curve of cooling pipe of dam section 25–32.

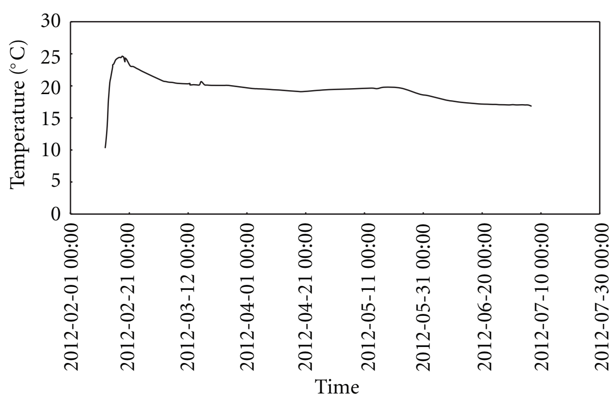
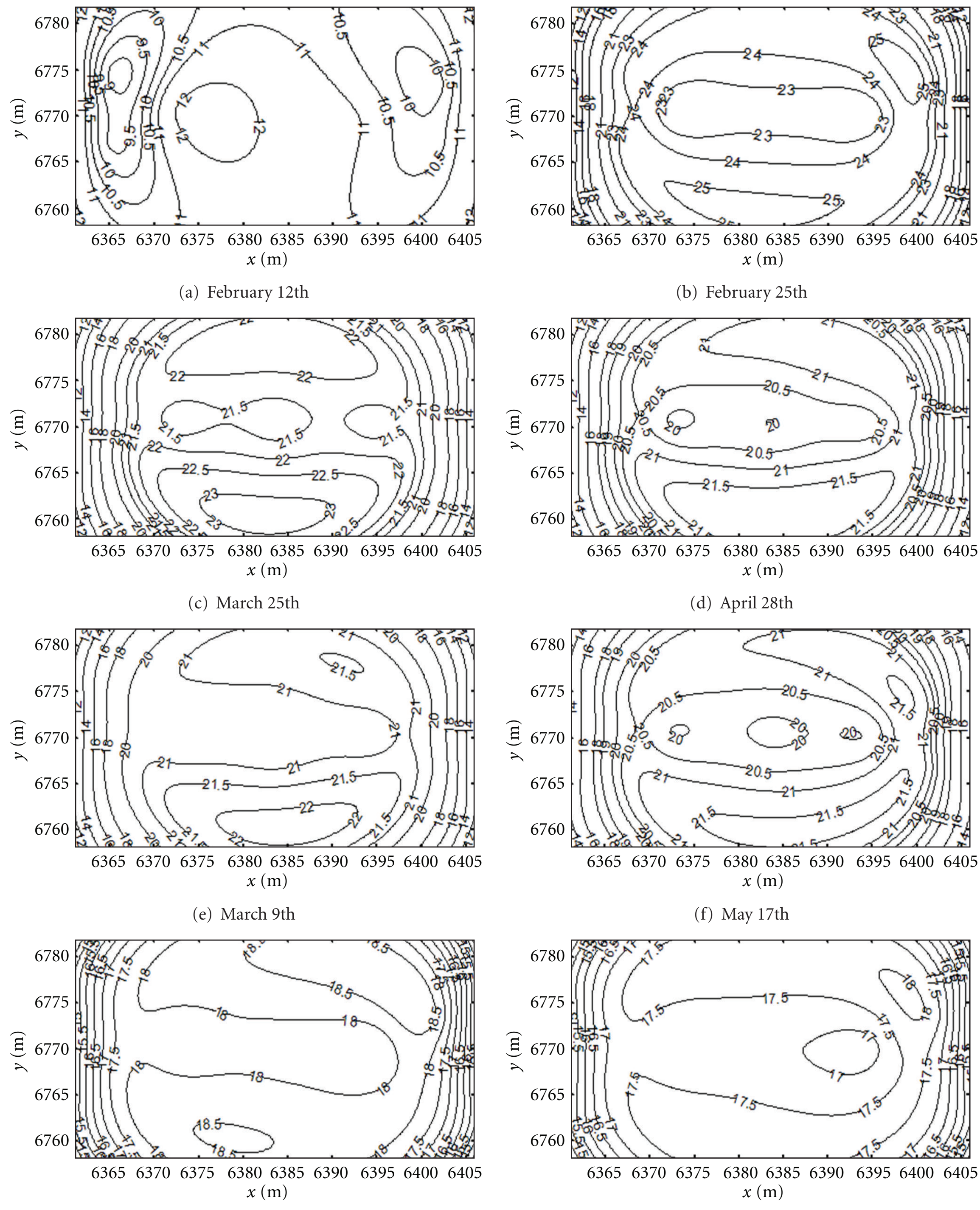


Figure 12: Concrete average temperature curve line of dam section 25–32.

concrete. Temperature gap between inlet and outlet of cooling pipe ranges from 0 to 3 centigrade.

(2) In order to ensure that concrete can be cooled evenly, the direction of flow is changed once daily, which could lead to periodic fluctuation of entrance and exit temperature of water as illustrated in Figure 11. Amplitude of the fluctuation can reach 2 centigrade.

(3) Block temperature of dam section 25–32 run in accordance with the designed cooling process. Temperature monitoring result shows that data is being obtained accurately and consistently. The temperature field distribution results, see Figure 13, show that, under concrete temperature increasing stage, the highest temperature mainly concentrates close upstream and downstream surface; see Figure 13(a).



(a) February 12th

(b) February 25th

(c) March 25th

(d) April 28th

(e) March 9th

(f) May 17th

(g) June 9th

(h) June 22nd

Figure 13: Temperature distribution field of dam section 25–32 in different cooling periods. (a) Temperature control stage in the first phase of concrete cooling; (b) temperature dropping stage of the first phase of concrete cooling; (c)∼(h) temperature control stage in the middle phase of concrete cooling.

Large temperature gradient exists in arch axis zone and near upstream/downstream zone. As the concrete ages, cooling water technique takes away only some heat from accumulated hydration heat. Internal temperature field in the concrete also changes gradually. Internal temperature field of block transits gradually from the earlier spindle distribution to uniform distribution.

(4) After the concrete placement, the highest temperature in the section occurred about approximately 6–10 days later and is controlled below 27 centigrades

generally as shown in Figure 12. Concrete consists of different materials poured in different positions and different seasons, which require different times to win the highest temperature. Boundary temperature of the upstream and downstream faces approximately exhibits a constant value. The concrete surface warm-protection layer functions as a good thermal insulation. During summer and winter, temperature of the upstream and downstream surface can be 15 and 12 centigrades, respectively.

The monitoring results display that the flexible network structure was proven to be very useful for temperature monitoring of high arch dam under construction.

4. Conclusions

A flexible network structure for field temperature monitoring of a super high arch dam under construction period was developed based on the state-of-the-art intelligence control technology.

By employing flexible network structural architecture, the bus can also connect other types of sensors such as strainmeter for strain of dam, stress meter for compressive stress of dam, jointmeter for opening of joints, rock deformeter, and piezometer for seepage flow, or even contacts, which are designed for this network specification. Thus, the measurement scope can be utilized in a wider spectrum and in turn suffice temperature measurement requirement of a super high arch dam.

In this temperature monitoring system, a total of 3 kinds of networks which are independently marked by *(1), *(2), and *(3) were proposed, with *(1) being the lowest priority and *(3) being the highest priority. The lowest priority is field bus (ITU bus) which connects all the grouped sensors into different channels of different intelligent acquisition modules. The ITU network protocol is a star type, and the network structure is independent from the sensors.

A flexible network structure for temperature control system overcomes the shortcoming of manual measuring, recording, analyzing, and controlling, and, in turn, saves time, acquires high quality and accurate measurement, and responds with adjustment settings in a timely manner. The other benefits of utilizing real-time temperature precision control are mitigation of concrete cracking, upholding quality of mass concrete, and, as a result, progressing construction smoothly.

In conclusion, the flexible network structural architecture was proven to be very useful for the temperature control of high arch dam under construction. The proposed temperature monitoring method will be beneficial for the design and construction of controlling thermal stress of mass concrete in similar projects.

Acknowledgments

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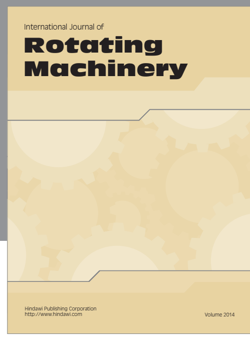

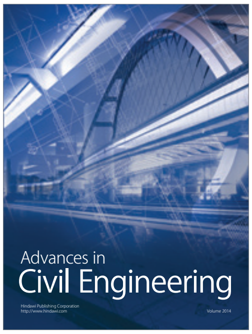

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