Internal Settlement Monitoring of Pre-Embedded Flexible Pipes for Disaster Prevention: a Case Study of the Upper Reservoir Panel Rockfill Dam of Tianchi Pumped Storage Power Plant

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Abstract. This paper discusses the challenges of monitoring internal settlement in high rockfill dams in China, specifically the Tianchi dam. Traditional sensors like water pipe settlement meters face challenges such as long equilibration times and accuracy loss due to longer piping in tall dams. To overcome these issues, this study introduces a monitoring method using pre-buried flexible pipes and a robotic system. The findings demonstrate that robotic monitoring yields highly consistent settlement trends, validating its effectiveness as a novel technology for enhancing dam safety and disaster prevention. This innovative approach significantly improves monitoring accuracy and early warning capabilities for structural safety.

Keywords: Rockfill dam, Geotechnical engineering, Disaster preparedness, Pipeline, Settlement

1 Introduction

Concrete panel rockfill dams, constructed with stone and supplemented with impermeable panels, are prevalent in China due to their economic advantages and adaptability to various geological conditions. [1] With advancements in geotechnical technology, several 200-meter-high face rockfill dams have been constructed, and there are efforts to develop 300-meter-high dams. [2-3] However, these high dams face deformations during construction and operation due to self-weight and impoundment pressure, including surface, internal deformations, and cracking. Continuous and accurate monitoring of these deformations is crucial for ensuring dam safety and operational

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reliability. Current research and development of safety monitoring technologies and new instruments for high rockfill dams are still lagging, mostly suitable for dams up to 100 meters in height. [4-5]

Currently, the development of instrumentation for monitoring internal deformation in high rockfill dams is significantly lagging behind dam construction techniques [4-5]. Conventional methods for internal deformation monitoring, such as extensometer-based horizontal displacement meters [6] and water pipe settlement meters, face challenges in 200-meter-high dams due to the excessive length of the monitoring pipes, which leads to an increase in the number of support points, self-weighting of the wires, and longer time for the equilibrium of the water level. These problems can lead to non-negligible measurement errors. In this regard, scholars such as Cai De [7], Liao Cheng [8], He Bin [9], and Sun Rujian [10] explored the use of a robotic system and specialized monitoring pipelines to measure the internal deformation of dams, but the high stiffness of these steel pipelines limited their ability to accurately reflect the settlement. Although pipe-measuring robots have been widely used in underground pipe inspection, [11-12] their accuracy is only centimeter-level in measurements over one hundred meters, which cannot meet the demand for high-precision monitoring. Therefore, there is an urgent need for further optimization in terms of pipe materials, robot design, sensor integration and data processing.

This paper combines existing research with the observed deformation patterns of the Tenchi CFRD to monitor internal settlement. It describes a method of using flexible monitoring pipes to periodically measure changes in pipe geometry and analyze internal deformation. In addition, it used water pipe settlement meters at various points within the dam and compared these results with flexible pipe data to validate the effectiveness of both monitoring methods. This comprehensive analysis enhances disaster prevention and dam safety monitoring and provides important technical support for the long-term safety of high CFRDs. This study has practical significance and broad prospects for improving safety management and disaster prevention in geotechnical engineering.

2 Monitoring Methodology and Rationale

2.1 Principles of Deformation Monitoring Inside Pre-Buried Flexible Pipes

This paper describes a method to monitor the internal deformation of high rockfill dams by measuring the pre-embedded flexible pipes using a pipe-measuring robot [15]. During dam construction, pre-embedded flexible pipes at critical locations act like nerve fibers to accurately reflect the internal deformation of the dam based on known deformation patterns [14]. As the dam is built and the rockfill is compacted, the monitoring pipes provide a path for the robot, which uses high-precision inertial navigation and multiple odometers. A multi-source data fusion algorithm then calculates the robot's trajectory and generates a high-precision 3D curve of the pipeline. By comparing the 3D curves over different time periods, the horizontal displacement and settlement within the dam can be determined. The measurement principle is shown in **Figs. 1, 2**.

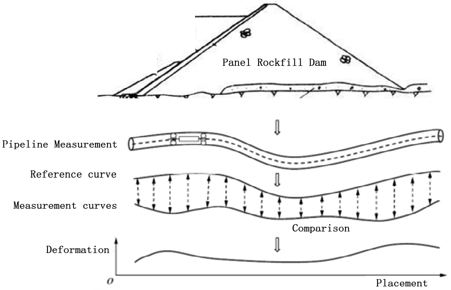


Fig. 1. Principle of internal settlement measurement of rockfilldam based on pipeline measuring robot

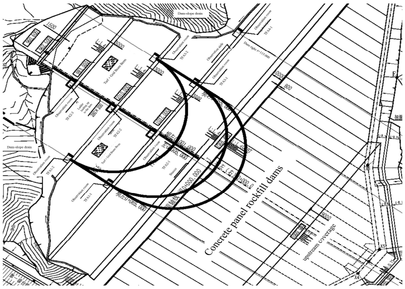


Fig. 2. Deformed pipeline layout diagram of Tianchi Reservoir

The technical process for monitoring internal deformation of a rockfill dam using pre-buried flexible piping consists of pre-buried flexible piping at key locations during dam construction to conform to expected deformation patterns. Periodic measurements are then taken using a pipe surveying robot to collect data on relative elevations and internal settlements. This data is then processed and analyzed to determine settlement at specific points and to understand the overall settlement trend of the dam.

2.2 Monitoring System for Internal Deformation of Pre-Buried Flexible Pipes.

The rockfill dam of Tianshan Pumped Storage Power Station has a minimum elevation of 1005 meters and a crest elevation of 1068 meters. According to the Technical Specification for Safety Monitoring of Earth and Rock Dams (SL551-2012), the design results and the topography and geomorphology of the dam site area, and in combination with the original safety monitoring design, cross-validation with the original safety monitoring design is considered. Make full use of the existing facilities such as observation room. The layout of the pipeline robot is set between the observation rooms of the original design. As shown in **Fig. 3** , two pipelines are located at 1010 meters above sea level and one pipeline is located at 1037 meters above sea level. The black lines in the figure indicate the pipeline layout.

(a) Pipeline robots **(b) Flexible monitoring pipeline**

Fig. 3. Pipeline Robotics and Flexible Piping

The settlement measurement system for the rockfill dam utilizes a precision robot developed by Shenzhen University as shown in **Fig. 3.** (a), which can navigate through flexible HDPE pipes that deform with the dam as shown in **Fig. 3.** (b) [17-19]. These pipes, chosen for their flexibility and strength, are key to accurately monitoring the settlement of the dam. The pipes are laid in a "U" shape, with a slope of 1% at different sections of the dam, and the pipes are connected by electrofusion joints to form a continuous channel for the robot to make measurements. The design and installation of these pipes, including protective excavation and backfilling practices, is critical to ensure that comprehensive and reliable data are collected for the dam safety assessment.

2.3 Data Acquisition and Processing

The angle of mounting deviation has a large impact on the accuracy of the pipe measurement robot. [19] The robot is calibrated on the bench to remove these deviations prior to data acquisition. After calibration, the robot was inserted into the pipe for data acquisition, and the one-measurement back flow is shown in **Fig. 4**. [15] The speed of the robot was maintained at 1 m/s to prevent slippage and ensure accuracy. Multiple runs and observations improve accuracy and the internal consistency of the robot. External control points are verified with a total station and a level at the pipe opening.

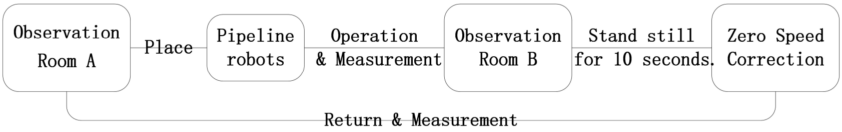


Fig. 4. Pipeline Measuring Robot one round of measuring process

Data processing for pipeline measurements in rockfill dams uses a Kalman filter to refine inertial measurements and uses the orifice coordinates as absolute control points to improve accuracy and control noise. This approach helps to dynamically track and predict changes in the state of the pipe. In addition, the RTS (Rauch-Tung-Striebel) smoothing algorithm optimizes the trajectory of the pipeline measurement robot, improves the estimation of the 3D shape of the pipeline, and increases the data accuracy. the relative elevation profile of the monitored pipeline is derived recursively based on the pitch angle and distance traveled by the robot. This approach allows for more accurate and smoother trajectory estimation in dynamic environments [16]. The data processing framework for pipeline robotics is shown in **Fig. 5**.

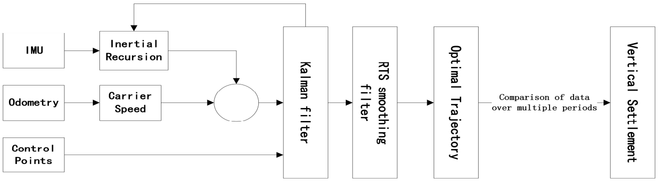


Fig. 5. Framework of data processing of pipeline measuring robot

3 Monitoring Results and Analysis

We conducted 12 linear measurements using an inertial navigation robot at Shenzhen University on three pre-built pipes at Tianchi Dam: 1010s (short), 1010l (long) and 1037, with measurement lengths of 258.9 m, 371 m and 218.9 m, respectively. Settlements were calculated by comparing the differences between the two measurement periods and these results were validated against a conventional water main settlement instrument. This comparison confirms the validity and scientific validity of using pre-embedded flexible pipes to measure deformation within rockfill dams, as detailed in Table 1.

3.1 Pipeline Line Measurement Results and Analysis.

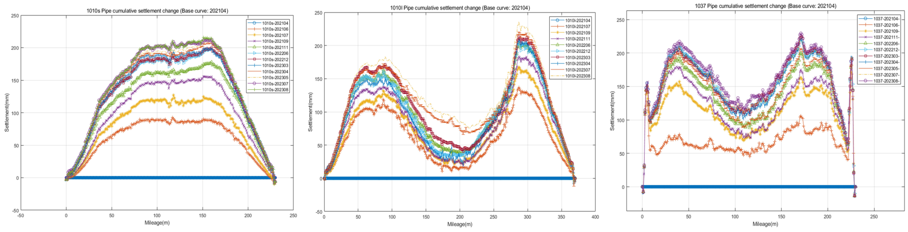
Multiple measurements were taken at each observation period to assess repeatability and data quality. The calculated "pipeline relative elevation" represents the average elevation curve and is used as a reference for calculating the "elevation residual" for each curve. The standard deviation of this average represents the repeatability and is a key measure of the accuracy of the pipeline line measurements. Repeatability in terms of total pipe length quantifies relative repeatability accuracy. After 12 measurement cycles, accuracy results were obtained for the three observed flexible pipelines. Based on the observed results, the average elevation repeatability was calculated to be 4.17 mm, 5.93 mm, and 4.25 mm for Pipeline 1010s, Pipeline 1010l, and Pipeline 1037, respectively, with an average relative repeatability of 17.18 ppm over multiple measurement cycles, as shown in Table 1. These results meet the accuracy criteria required for deformation monitoring of rockfill dams. [13]

Table 1. Pipeline Average Observation Accuracy

Pipeline ID	Mean Elevation Repeatability	Mean Relative Repeatability
1010s	4.17mm	16.10ppm
1010l	5.93mm	16.00ppm
1037	4.25mm	19.43ppm

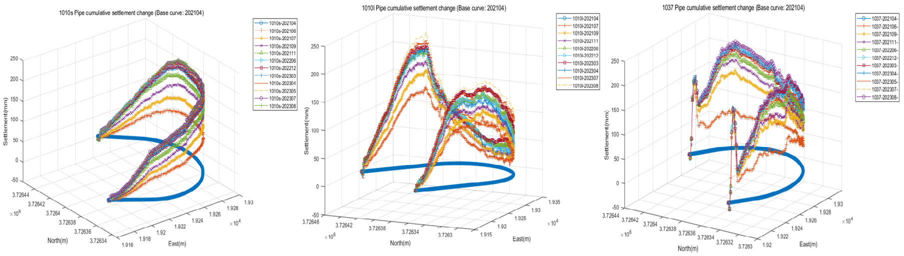
Settlement calculations for the dam monitoring pipeline were based on April 2021 measurements. Subsequent data were compared to this baseline to calculate cumulative relative settlements. **Fig. 6** and **Fig. 7** depict the ongoing cumulative settlement for each of the three pipelines, where vertical subsidence is considered positive.

The cumulative settlement plots for the 1010s monitoring pipeline show an "A" shaped pattern with settlement increasing from 0 to 200 meters, peaking between 150 and 200 meters, and then decreasing to 250 meters. This pattern is typical of panel rockfill dams and may be due to deformation of the panels under water pressure and other loads, especially along the axis of the dam. The stability of these dams depends on the interlocking and support of the rock and panels, and the rock along the dam axis is more susceptible to erosion and other forces, resulting in greater settlement in this region.



(a)Monitoring pipeline 1010s cumulative settlement (b)Monitoring pipeline 1010l cumulative settlement (c)Monitoring pipeline 1037 cumulative settlement

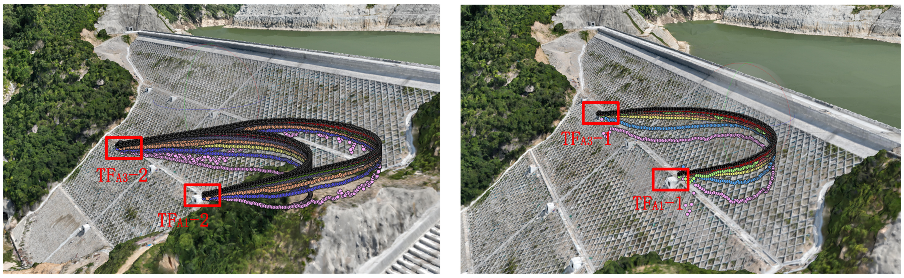
Fig. 6. Cumulative settlement curves for three pipelines



(a)Three-dimensional map of cumulative settlement of 1010s in the monitoring tube (b)Three-dimensional map of cumulative settlement of 1010l in the monitoring tube (c)Three-dimensional map of cumulative settlement of 1037 in the monitoring tube

Fig. 7. Three-dimensional maps of cumulative settlement in the three monitoring tubes

The cumulative settlement plots for Pipes 1010l and 1037 have an "M" shape, with maximum settlement along the dam at 150 m and 175 m, and lesser settlement from approximately 75 m to 150 m. This pattern of settlement can be attributed to the fact that the panels are not connected to each other, but rather to the fact that the panels are connected to each other. This pattern for panel rockfill dams can be attributed to the connections between the panels, which stabilize the edges of the dam initially and thus reduce settlement. Meanwhile, the intermediate portion, which is more susceptible to horizontal forces, experiences greater settlement. In addition, heterogeneous foundation conditions such as heterogeneous soil compositions in the intermediate areas or changes in the water table can further exacerbate this settlement.



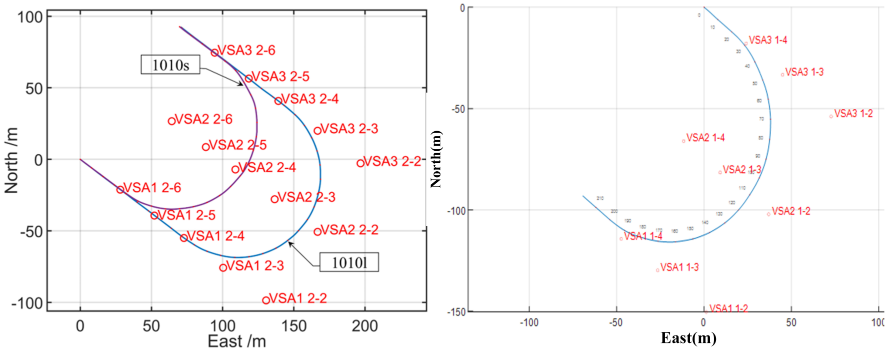
(a) Settlement of pipeline at 1010m elevation of the dam (b) Settlement of pipeline at 1037m elevation of the dam

Fig. 8. Settlement of the dam pipeline

Fig. 8 depicts the pipeline layouts and corresponding settlements at elevations of 1010 and 1037 meters. We color-coded the settlement data for each measurement point at different time intervals and connected the data for the three pipelines at these two elevations to a three-dimensional model of the dam (marked with a red box in the figure). This visualization method helps to determine the exact location of the pipes within the dam and to track the trend of pipe settlement over time.

3.2 Comparison of Settlement Measurement Results.

A number of pipe settlement gauges were deployed at the 1010 m and 1037 m elevation planes of the Tianchi Upper Reservoir rockfill dam. **Fig. 9** shows the planimetric alignment of the three pipelines and the planimetric coordinates of the measured points of the deployed water main settlement gauges.

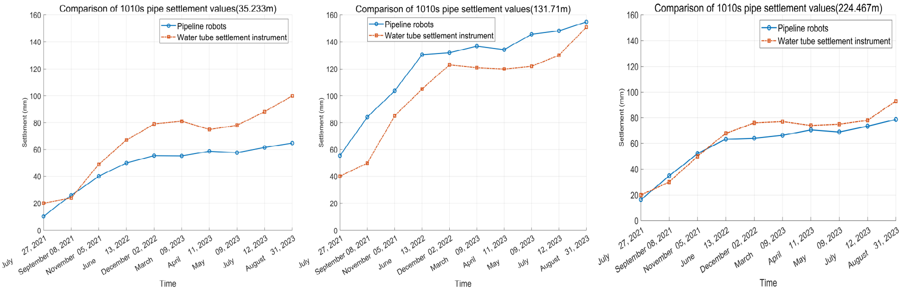


(a) Layout plan of water pipe settling meter at 1010m elevation surface

(b) Layout plan of water pipe settling meter at 1037m elevation surface

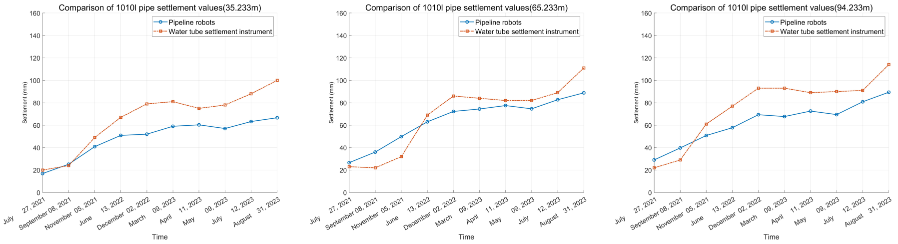
Fig. 9. Measuring point of water pipe settlement instrument

A water pipe settlement gauge works on the principle that the liquid levels in the connected water pipes are equal. By measuring the liquid level at one end of the observation chamber, the elevation at the other end can be inferred. The difference in successive readings indicates the settlement at that measurement point. For pipelines 1010s and 1010l, control points were set up along their lengths with June 2021 as the reference baseline. The difference between the pipe elevation curves and the reference baseline for different periods was calculated and adjusted according to the settlement of the observation room. The settlement values derived from the pipe measurements were then compared with the settlement values derived from the water pipe settlers at the same points. **Fig. 10** and **Fig. 11** show the results for the two pipes measured using the two measurement methods.

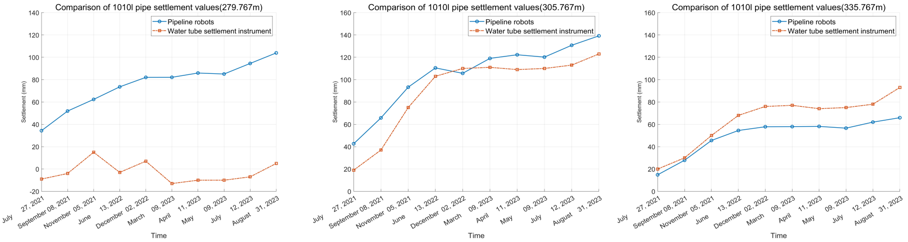


(a) **Comparison of settlement values at 35.233m of 1010s pipe** **(b)** **Comparison of settlement values at 131.71m of 1010s pipe** **(c)** **Comparison of settlement values at 224.467m of 1010s pipe**

Fig. 10. Comparison of 1010s pipe settlement values



(a) **Comparison of settlement values at 35.233m of 1010s pipe** **(b)** **Comparison of settlement values at 65.233m of 1010s pipe** **(c)** **Comparison of settlement values at 94.233m of 1010s pipe**



(d) **Comparison of settlement values at 279.767m of 1010s pipe** **(e)** **Comparison of settlement values at 305.767m of 1010s pipe** **(f)** **Comparison of settlement values at 335.767m of 1010s pipe**

Fig. 11. Comparison of 1010l pipe settlement values

In order to assess the difference between the settlement values measured by the water pipe settlement meter (S_W) and the pipe survey (S_P), the formula $S_W - S_P$ was used for each pipe point. By calculating these differences for all observed points, the mean and standard deviation were calculated as a measure of variability. In addition, the ratio of the difference D of the pipe to the length L of the pipe can be used to measure relative accuracy. These statistics (mean $\overline{D}$, standard deviation σ_D, and ratio $\overline{D}/L$) can be used as benchmarks to verify the accuracy of the measured data. These calculations are usually summarized in a table, such as Table 2, to clearly illustrate the comparative analysis between the two measurement methods.

Table 2. Comparison of Pipeline Settlement Values (Relative to June 2021)

Pipe Number	$\bar{D}$	σ_D	$\bar{D}/L$
1010s	**1.858mm**	**14.881mm**	**1/139343**
1010l	**-7.475mm**	**33.371mm**	**1/10298**
1010l*	**6.72122mm**	**11.273mm**	**1/55198**

Analysis of the data showed a strong correlation, albeit with some discrepancies, between the settlement trends monitored by the pipeline gauging robot and those measured by the watermain settlement gauge. In the 1010s pipeline area, the robot's data showed settlements that were generally about 10 mm lower than those measured by the water main. In contrast, in the 1010l pipeline area, the robots reported settlements that were about 10 mm higher. The main reason for these differences is the limitations of the water pipe gauge in measuring large panel rockfill dams, which have complex shapes and variable geologic conditions that make it difficult to accurately reflect overall settlement trends.

Specifically, the measurement taken at the 279.767 m location of the 1010l pipeline was found to be in apparent contradiction to the neighboring trend, and was therefore excluded from the analysis and noted as 1010l* in Table 2. Excluding this data point reduces the difference between the two measurements to 6.72 mm, which is closer to the actual settlement pattern of the dam and improves the reliability of the monitoring results.

4 Conclusion

This study validates the effectiveness of using a flexible pipe measuring robot for internal settlement monitoring of high rockfill dams with improved accuracy and reliability compared to traditional methods such as water pipe settlers. The robot provides detailed internal deformation data through a distributed measurement approach, is less affected by dam elevation, and simplifies upgrades and maintenance. The design of the robot ensures precise alignment with the pipe and improves the repeatability of the measurements compared to conventional methods. In addition, the use of flexible piping better accommodates internal deformations and contributes to the effectiveness of the system for long-term monitoring.

Despite the successes, this study also identified areas for improvement, particularly in terms of improving measurement stability under extreme conditions and improving data processing techniques to handle outliers more efficiently. Future research should focus on developing advanced data processing algorithms and integrating other sensing technologies, such as fiber optics, to further improve monitoring accuracy. The application of robotics to various types of dams, including earth and concrete dams, could also expand the application of these innovative monitoring techniques. This advancement in geotechnical structural monitoring is critical for disaster preparedness, providing real-time data that can be used as an early warning system to improve the safety and operational reliability of dams.

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