Statistical Evaluation and Performance Assessment of Instrumentation in an Earth–Rockfill Dam: Shahid Madani Dam, Tabriz, Iran

Ramin Vafaei Poursorkhabi [*1,2], Rasoul Farajniya[3]

[1] Associate Professor, Department of Civil Engineering, Ta. C., Islamic Azad University, Tabriz, Iran
[2]Robotics & Soft Technologies Research Center, Ta. C., Islamic Azad University, Tabriz, Iran[1] Department of
[3] Department of Civil Engineering, Va.C., Islamic Azad University, Varzeghan, Iran

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ABSTRACT

Long-term monitoring is essential for assessing the safety of earth–rockfill dams, particularly before the first reservoir impoundment. This study evaluates the condition and performance of the instrumentation installed in Shahid Madani Dam near Tabriz, Iran, approximately ten years after construction was completed. The reservoir had not yet been impounded, making it important to establish the dam's current condition and to provide a reliable basis for monitoring during initial filling. Instrumentation records from more than 500 installed devices were reviewed, with particular attention to settlement, total stress, and pore-water pressure. The largest cross-section (Section C) was also modelled in MIDAS using a two-dimensional finite-element approach and the Mohr–Coulomb elastoplastic model. Monitoring measurements were compared with numerical predictions to assess consistency. The maximum measured vertical settlement was 1.90 m, compared with 1.79 m from numerical analysis. The maximum total stress measured by pressure cells was 1,205 kPa, while the model predicted 1,440 kPa. The maximum pore-water pressure measured by piezometers was 420 kPa, compared with a numerical value of 450 kPa. The study reports that numerical results were approximately 94%, 83%, and 93% of the instrument-derived values for settlement, total stress, and pore-water pressure, respectively. Most instruments remained operational and readable after a decade. The agreement between measured and modelled responses supports the continued use of the monitoring system, while readings during reservoir filling should be assessed continuously before decisions are made about safe impoundment.

KEYWORDS

Earth–rockfill dam; instrumentation; settlement; pore-water pressure; numerical modelling

1. Introduction

Earth–rockfill dams are large geotechnical structures whose safety depends on the performance of the embankment, foundation, drainage zones, and core. Because soil behaviour is heterogeneous and changes with stress, pore-water pressure, consolidation, and seismic loading, the actual response must be checked against design assumptions. Instrumentation provides measurements of settlement, deformation, total stress, pore-water pressure, seepage, and water levels. These observations can help identify unusual behaviour and support decisions during construction and operation [1–12]. Shahid Madani Dam is a 93-m-high rockfill dam with a clay core, a crest length of 277 m, and a location about 5 km from Tabriz. The study is unusual because roughly ten years had elapsed after completion of the dam body while the reservoir had not yet been impounded. More than 500 instruments were installed across five principal sections (A–E), including pressure cells, electric and Casagrande piezometers, settlement gauges, inclinometers, seepage instruments, and seismic instruments. The study's main contribution is to combine long-term instrument readings with two-dimensional finite-element analysis to evaluate the monitoring system and establish a technical basis for monitoring before and during first filling [13–30].

2. Methodology

The study reviewed instrument locations, installation records, operating condition, and readings from the five instrumented cross-sections. The main response variables were vertical settlement, total stress in the dam core, and pore-water pressure. Total stress and pore-water pressure were considered together because effective stress, which is important for assessing hydraulic-fracture risk, is obtained

[1] Corresponding Author: Email: vaafei@iau.ac.ir raminvafaei@yahoo.com

from their difference. The paper reports 120 total-pressure cells, 62 electric piezometers, 27 Casagrande piezometers, 17 inclinometers, and 275 settlement gauges among the principal instruments described in the monitoring inventory. The strength parameters for the dam body and foundation materials were determined based on laboratory test results derived from borrow area investigations, regional geological studies, and laboratory tests conducted on materials from various zones of the dam body.

For numerical verification, the largest dam section (Section C) was modelled in MIDAS using a two-dimensional finite-element mesh. The Mohr–Coulomb elastoplastic model was adopted, and material parameters were taken from laboratory tests and the dam's geotechnical investigations. The model geometry, boundary distances, and mesh were selected with reference to sensitivity checks; the base was restrained in both horizontal and vertical directions, while the side boundaries were restrained horizontally. The calculated settlement, total stress, and pore-water pressure were then compared with instrument-derived values. This comparison is a consistency check rather than a substitute for continued field monitoring.

3. Results and Discussion

The monitoring records indicate that most installed instruments remained functional and readable after about a decade. The maximum vertical settlement was recorded in Section C and reached 1.90 m. The authors suggest that consolidation of the embankment materials and regional earthquakes during the intervening period may have contributed to this settlement. The numerical model predicted 1.79 m, a reasonably close value that supports the model's use for interpreting the observed response, while the settlement itself should continue to be tracked. The maximum total stress recorded by pressure cells near the core–foundation interface was 1,205 kPa. The numerical analysis predicted 1,440 kPa. Although the model result is higher than the measured value, both results indicate the high stress concentration at the lower part of the core. The paper attributes the measured response partly to consolidation over time and reports consistency with the original design assessment. Since pressure-cell readings can be affected by installation and calibration, the measurements should be interpreted alongside the wider instrumentation network. The maximum pore-water pressure measured in the clay core was 420 kPa near its lowest elevation, compared with 450 kPa in the numerical model. The maximum reported pore-pressure ratio, Ru, was 0.47, close to the design estimate of 0.5. The authors interpret these values as acceptable with respect to hydraulic-fracturing resistance. They also calculate a maximum effective stress of 785 kPa. These findings are encouraging, but the reservoir has not undergone first impoundment; therefore, the pre-impoundment condition cannot by itself demonstrate performance under the changing hydraulic loads of filling. Table 1 provides a comparison of the key monitoring measurements against the corresponding numerical predictions.

Table 1. Comparison of key monitoring measurements and numerical predictions

Parameter	Instrument	MIDAS
Maximum settlement (m)	1.90	1.79
Maximum total stress (kPa)	1,205	1,440
Maximum pore pressure (kPa)	420	450

The article reports that numerical results were approximately 94%, 83%, and 93% of the instrument-derived values for settlement, total stress, and pore-water pressure, respectively. The comparison supports the general consistency of the instrumentation data and numerical model, although the different direction and size of the discrepancy for total stress underline the need to interpret each parameter separately. For practical dam safety, readings should be checked for trends and anomalies rather than relying only on a single comparison of maximum values. Figure 1 presents a comparison of five data series (A–E) plotted against a horizontal axis ranging from approximately 0.25 to 2.05 and a vertical axis ranging from 1410 to 1510. Series A (blue squares) is clustered on the far left, showing relatively high y-values (approximately 1475–1505) at low x-values; Series B (orange squares) starts at lower y-values on the left-central part of the plot and generally increases toward higher x-values; Series C (grey triangles) begins at the lowest y-values among the series and exhibits a steady upward trend with increasing x; Series D (yellow crosses) and Series E (dark-blue crosses) both start at high y-values on the left-central region and display a general downward trend as x increases, with Series D showing more pronounced stepwise variations.

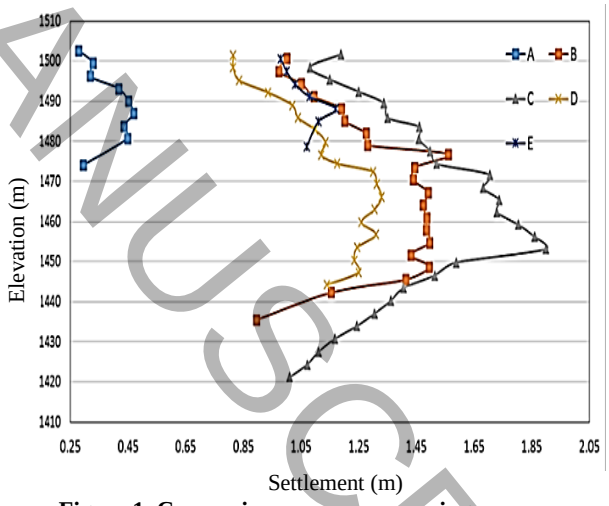

Figure 1. Comparison of key monitoring measurements and numerical predictions for cases A–E.

4. Conclusion

In the present study, the performance of conventional monitoring systems for the body of earth-rockfill dams was statistically evaluated, with Shahid Madani Dam in Tabriz serving as a case study one decade after the completion of construction. Field readings from settlement gauges, pressure cells, and piezometers were compared with the results of numerical analyses, revealing good overall agreement. The maximum vertical settlement reached 1.90

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m (versus 1.79 m predicted numerically), the maximum total stress was 1205 kPa (versus 1440 kPa), and the maximum pore-water pressure was 420 kPa (versus 450 kPa). The corresponding maximum pore-pressure coefficient (Ru) of 0.47 indicates an acceptable level of safety against hydraulic fracturing. The number and spatial distribution of the installed instruments across different sections and elevations of the dam body were also found to be adequate. Nearly all instruments remain functional and readable, and critical zones are satisfactorily covered. The close correspondence between the monitoring data and the numerical predictions not only confirms the reliability of the installed instrumentation but also demonstrates the satisfactory long-term stability of the dam body after ten years of service.

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