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Article

Analysis of Fill Dam Using Finite Element Method and Comparison with Monitoring Results

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Abstract: Nowadays, a detailed safety policy is applied for dams. These policies cover structural safety, monitoring, inspection, safe operation, and emergency plans. For high-risk dams, all these policy elements need to be included in dam safety programs. Deficiencies in embankment dams, which suffer the most damage, can be detected by visual inspection and programmed monitoring of dams. In dams, horizontal and vertical deformation, leakage, pressure, stress, loads acting on structural elements, and environmental factors are generally measured. These behaviors can be numerically modeled to determine the dam behavior. Numerical analysis methods are important for monitoring the safety of the dam. Models created with software such as Plaxis provide information about dam behavior. Although numerical analysis is very important for dams, obtaining the material parameters used in the construction of the dam needed for modeling, recording the construction stages of the dam, not taking the water level change in the dam reservoir instantaneously, and not taking the measurement records of the dam measurement instruments correctly for different reasons constitute problems and difficulties for the analyses. Within the scope of this study, İkizdere Dam in Turkey was modeled with the Plaxis finite element program; the survey and piezometer measurement data taken from the dam were evaluated by comparing with the analysis results; the difficulties and problems encountered in the modeling and analysis phase were stated, and recommendations were made on dam safety and numerical analysis. Thus, in addition to other studies, it was emphasized that it is important for dam engineers to monitor the use of numerical analysis models throughout the entire process, not only in the planning phase but also from the planning phase to the life of the dam, and to keep records of all recording intervals that will be needed in digital analysis models.

Keywords: dam safety; rock fill dam; finite element method; numerical analysis; dam failure

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1. Introduction

Many dams have been constructed for different purposes, such as flood protection, energy generation, water supply for drinking, irrigation, and utilization purposes. The fact that the dams built so far within the borders of Turkey have been constructed in the most technically and economically favorable locations has led to the necessity of constructing the dams to be built in less favorable locations compared to the existing dams, and therefore, more technical problems have started to be faced during the construction and operation of new dams. As a result of inadequacies that may arise due to technical problems, the dam may face the risk of collapse. After the dam collapse, the large volume of water mass in the dam reservoir moves uncontrollably in a very short time and causes material and moral damage in the region downstream of the dam.

According to the General Directorate of State Hydraulic Works (DSI) data, there are 1018 dams in Turkey that were completed between 1936 and 2022 [1]. Approximately 90 per cent of these dams were constructed as embankment dams [2].

According to statistics, earthfill dams are the most damaged dam type, followed by gravity dams, rockfill dams, and arch dams [3].

Dam collapse results in great loss of life and property. In 1963, 2600 people died as a result of the collapse of the Vajont dam in Italy; in 1976, 100 people died as a result of the collapse of the Teton dam in the USA, and an economic loss of approximately 1 billion dollars occurred; and 300 people died as a result of the collapse of the Gouhou dam in China in 1993 [4].

In the 20th century, approximately 200 dams collapsed, killing more than 8000 people [5]. Due to excessive rainfall on 8 August 1975 in the People's Republic of China, 62 large- and small-scale dams, including Banqiao and Shimantan dams, collapsed; a total of 171,000 people lost their lives; many people were injured; and 5.96 million buildings were destroyed. This tragic event was recorded as the biggest dam disaster in history [6].

Some of the dam collapses that resulted in more than 100 deaths in different countries and the causes of collapse are given in Table 1.

Table 1. Some dam collapses resulting in more than 100 deaths and causes of collapse [7].

Dam	Year	Country	Death	Collapse Reason
Derna dam	2023	Libya	18,000–20,000	Body collapse
Brumadinho dam	2019	Brazil	270	Weak regulatory structures and regulatory gaps
Koshi	2008	Nepal	250	Extreme rainfall
Kantale	1986	Siri Lanka	180	Faulty operation
Val di Stava	1985	Italy	268	Faulty design and construction
Machchu 2	1979	India	5000	Water exceeding the dam
Banqiao/Shimantan	1975	China	171,000	Extreme rainfall
Canyon Lake	1972	USA	238	Flooding
Buffalo Creek	1972	USA	125	Extreme rainfall
Sempor	1967	Indonesia	>2000	Water exceeding the dam
Vratsa	1966	Bulgaria	107	Mud and water flooding
Vaiont	1963	İtaly	2000	Water exceeding the dam
Panshet	1961	India	1000	Body collapse
Malpesset	1959	France	423	Under construction
Vega de Tera	1959	Spain	144	Body collapse
Sella Zerbino	1935	İtaly	111	Geological instability/flood
St. Francis	1928	USA	600	Geological instability
Gleno	1923	İtaly	356	Faulty design and construction
Tigra	1917	India	1000	Water seepage from the foundation
South Fork	1889	USA	2209	Extreme rainfall
Mill Nehri	1874	USA	139	Faulty design
Dale Dike	1864	England	244	Faulty construction
Puentes	1802	Spain	608	Soft soil

As can be seen in Table 1, many dam collapses have occurred for many different reasons so far, and as a result of dam collapses, many people have lost their lives and serious financial losses have occurred.

When the deficiencies occurring in 534 dams from 43 countries before 1974 were examined, it was seen that earth-rock dams were the most deficient dam types, and 49% were due to water overflow over the dam, 28% were due to leakage in the dam body, and 29% were due to leakage in the foundation [4].

After a long period of evaluations in the risk assessment of dams, it is increasingly accepted that there are significant uncertainties in dam risk assessment and that these uncertainties often cannot be eliminated by a reasonable investigation. Uncertainties are the source of dam risk. Hydrological, hydraulic, geotechnical, seismic, structural, and operational uncertainties have persisted in dam risk assessment to this day. Analyses must be made with limited or incomplete information. Additionally, the nature and range of uncertainties depend on, among other factors, the environment and history of a particular dam. Therefore, although deterministic studies are often conducted to assess dam risk, it is now recognized that the results of such studies have limitations in taking into account the influence of uncertain factors. More detailed studies within a probabilistic framework are often appropriate and desirable. For risk studies, such analyzes are necessary so that significant uncertainties can be identified and their effects on reliability can be systematically examined [8].

In order to detect inadequacies that may cause dam failure in advance and take the necessary precautions in a timely manner, it is necessary to constantly monitor and monitor whether the dams are working as planned, starting from the construction phase, throughout the dam's operating life. In this way, the collapse of dams can be prevented, and even if the dams collapse, loss of life and property can be minimized with timely interventions.

Numerical analyses are frequently preferred by engineers for fast and safe solutions to geotechnical problems. Commercial finite element software systems are available to solve geotechnical problems, including all versions of PLAXIS, ZSOIL, and FLAC [9].

Shahzadi and Soulaïmani modeled the Romaine-2 dam in Canada with Plaxis software, compared the displacements calculated from inclinometers placed on the dam with measurements, and stated that computational modeling plays an important role in the design of rockfill dams [10].

Aydın modeled the Sakarya Akçay Dam in Turkey using the finite element method, made evaluations by comparing the measurements taken from the dam with the model results, and emphasized the importance of using numerical analyses for dam safety investigations [11].

As can be understood from the literature, numerical analysis methods have an important place in terms of monitoring dam safety from the planning stage of the dam to the completion of the dam life. By using models created with software such as Plaxis, which performs analysis with the finite element method, information about the behavior of the dam can be obtained from the planning stage. In the natural case, it can be determined with the help of these programs whether a geotechnical ground collapse will occur after the construction of the dam, whether the settlements will exceed the limits, and whether ground improvement is required. In addition, the safety of the dam can be constantly questioned by comparing the deformations that may occur in the dam body and the water pressure changes in the impermeable clay core with real-time measurements during the operational life of the dam. However, the absence of the data needed for modeling the dam or the inaccuracy of the data may cause problems in reflecting the real situation to the model.

2. Monitoring and Inspection of Fill Dams

Identifying the failure modes and causes in high dams is critical for better guiding high dam designs and implementing safety prevention and control measures [12].

One of the challenges facing dams is that dams built to different standards and conditions grow old and are used for longer periods than planned. Any long-term behavior that causes changes in dam properties over time and thus may affect dam safety is defined as dam aging. ICOLD (International Commission On Large Dams) defines dam aging as structural deteriorations that occur more than 5 years after the dam is put into operation. Monitoring dams is one of the most important issues in terms of dam safety. Monitoring of dams includes installation of monitoring equipment, visual inspections, monitoring of dam performance, data management, and diagnostics. Monitoring of dams is important to detect emerging problems in advance and to provide information about the long-term behavior of dams [13].

Today, a detailed dam safety policy is implemented for dams at risk of damage. This policy includes the elements of structural safety of the dam, monitoring and inspection of dams, safe operation of dams, and preparation of emergency plans. Engineers are primarily concerned with the structural safety of the dam. The structural safety of the dam is ensured by designing and constructing the dam according to design guidelines such as flood and earthquake, taking into account local site conditions. However, in dams with high risk of damage, all mentioned safety elements must be included [14].

Some of the deficiencies in embankment dams can be detected by visual inspection at the dam top, dam slope, and the points where the dam body meets the dam ground surface. In embankment dams, the state of the linear form of the crest, settlements, the state of cracks, the presence of excessive and deep-rooted plants, the cavities created by animals, and whether the measuring systems and mechanical equipment are in working order or whether their locations have been changed should be examined [15].

Geohazards such as bank collapses and landslides are usually triggered by reservoir filling and drawdown operations. Generally, analyzing the deformation mechanism of the slope through field monitoring and numerical simulation and then evaluating the stability is a crucial tool to ensure the safe operation of the reservoir, in which the determination of mechanical parameters is significant for safety evaluation. Due to the complex site conditions, the mechanical properties of the slope during impoundment are difficult to obtain through field testing. Therefore, parameter identification utilizing the back analysis approach based on field monitoring is a more appropriate strategy and now applied in engineering practice [16].

Dams are generally observed with measurements taken from the dam, photographs, on-site tests, and laboratory tests. Hydrological effects such as excessive rainfall, level and temperature of water in the reservoir, air temperature, internal temperature, and wind impulse, and structural movements such as buoyancy force applied by water to the dam, leakage amounts in the body and foundation, pressures on the body, seismic forces, and the measurements taken during the dam's ability to resist these effects. Measurements, examinations, and observations made at the dam site facilitate the detection of functional deficiencies and abnormal situations that have occurred in the dam. The data obtained as a result of measurements, examinations, and observations are transferred to the database and protected [17].

Observations, inspections, and measurements at dams should be carried out within a certain program. The measurements to be made vary depending on the dam type and characteristics. In dams, measurements such as horizontal and vertical deformation, leakage, pressure and stress, loads affecting structural elements, and environmental factors (water level, temperature, precipitation, seismic movement) are generally taken.

The minimum criteria for measuring devices that must be used in dams to be built in Turkey are specified in the Dam Measuring Devices Technical Specification published by DSI in 2014. The main instruments used in the observation of earth fill and rock fill dams and the locations of these instruments are given in Figure 1.

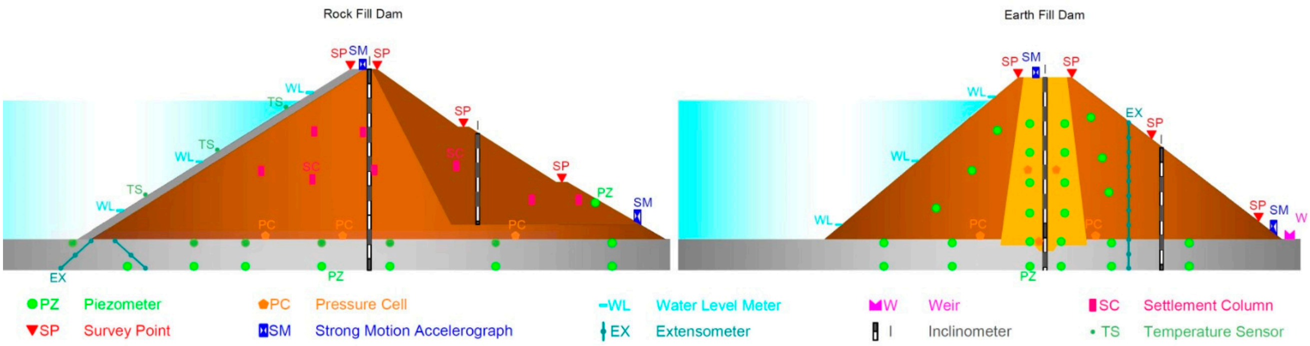

Figure 1. Measuring devices in earth and rock fill dams. Adapted from Baykan et al. [18].

2.1. Piezometers

Piezometers are used to observe the water pressure caused by leakage and compression in the dam body and foundation, to determine the efficiency of the drainage zones during the dam's water retention, and to determine the pore water pressures that occur during the construction of the dam. Piezometers are placed at the most critical points in the horizontal and vertical directions, which will allow creating the pressure model resulting from excessive pore water pressure and leakage. Fill-type piezometers are placed at critical points within the impermeable clay core to measure the pore water pressures occurring in the impermeable clay core. Foundation-type piezometers placed under the foundation are used to control the seepage in the dam foundation, the effectiveness of the injection curtain, if any, and the groundwater level.

2.2. Survey Points

These are measurement systems placed on the crest and downstream slope of the dam to monitor the horizontal and vertical displacements that will occur in the embankment. As soon as the dam filling is completed, the anchors should be placed in their places in the project, and their initial values should be determined.

2.3. Extensometers

Extensometers measure displacements on the ground at certain heights. They are used to observe vertical movements (collapse, swell, etc.) occurring at the base of the dam body or the base of the foundation ground.

2.4. Water Pressure Meters

Water pressure meters are placed at the bottom of the filter zone on the downstream side of the dam and function similar to observation wells in embankment dams. Unlike the piezometer, there are no filter units.

2.5. Inclinometers

Inclinometers are used to measure horizontal movements (displacements) in mm in dams at the relevant cross-section and depth. They are placed in boreholes drilled during the construction phase and usually in the body, foundation, and piers.

2.6. Settlement Meters

Settlement meters are used to determine the amount and rate of settlement that will occur at different depths.

3. Method and Application

Plaxis is a powerful finite element computer program used for analyzing stresses and deformations in geotechnical engineering problems. The program includes advanced features such as higher-order elements for improved accuracy, automatic mesh generation, tension-only structural elements for simulating geosynthetics, joint elements for interface behavior between materials, multiple soil models for different characteristics, and more. Plaxis also offers features like updated Lagrangian analysis for large deformations, staged-construction algorithms for sequential operations, and a post-processor for interpreting various relationships and diagrams related to load, stress, strain, and time settlements [19].

When defining initial and boundary conditions in the Plaxis program, it is very important to choose initial and boundary conditions in a way that does not affect the results. Otherwise, incorrect values may be obtained as a result of the analysis.

Plaxis software is able to model the natural conditions before dam construction, dam construction, and dam operation in detail and in stages at every stage, and analyses can be performed with the desired precision, so that the behavior of the dam can be obtained accurately.

Also, in the Plaxis program, different soil models such as linear elastic, Mohr–Coulomb, soft soil, and hardening soil are used to model the behavior of soils.

The hardening soil (HS) model in Plaxis is an elastoplastic soil model developed by Schanz et al. [20]. It calculates deformation using elastic and plastic strain but does not account for hysteretic or cyclic mobility in soils. The model consists of mathematical equations to define soil behavior and is detailed in the Plaxis Material Models Manual [21]. Users have found the HS model accurate in simulating complex soil behavior under various stress conditions. Model parameters can be determined through conventional triaxial compression tests on the soil (Figure 2). Overall, the hardening soil model is a valuable tool for accurately predicting soil behavior in geotechnical engineering applications [19]. Therefore, in this study, the zones were modeled using the hardening soil model in order to model the behavior of the dam more realistically.

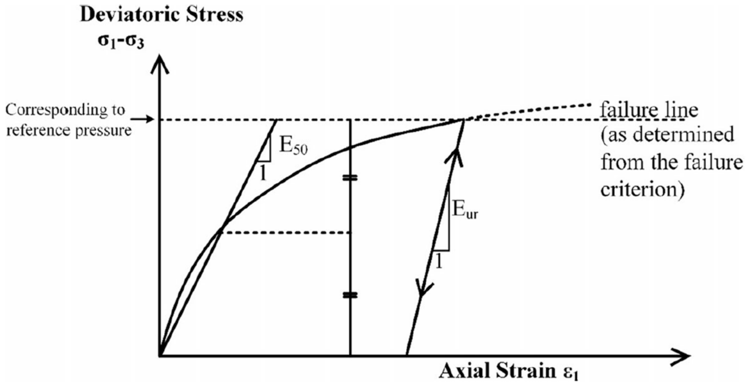

Figure 2. Determination of soil model parameters E50 and Eur from triaxial compression test results [17].

Ikizdere Dam is located on the Ikizdere Stream in the Aydin province of Turkey. The dam was built by DSI as a central clay core, upstream sand–gravel, and downstream rock fill dam for the purpose of supplying drinking and irrigation water. The height of the dam from the thalweg is 101 m, and the height from the foundation is 108 m (Figure 3).

Figure 3. View of Ikizdere dam.

Analyses were carried out with the Plaxis 2D finite element program under two-dimensional plane deformation conditions. B3, B4, and B5 sections, where both piezometer and surveyor measurements were taken, were used in the modeling. The results obtained from the analyses were compared with the measurement data taken from the dam, and evaluations and recommendations were made. The visual of the model of the B3 section used in the analysis is given in Figure 4.

In order to model the dam in detail and realistically, sections and zones were taken from as-built projects. Triangular elements with 15 nodes were used to provide more precise results in the finite element mesh of the section. The test and experimental results of the dam body filling materials used during the construction of the dam, which are necessary to model the realistic behavior of the dam, could not be obtained because laboratory test results obtained during the planning phase and material parameters in the literature were used in the dam model. In the analysis, the "very fine" mesh option offered by the program was selected in order to make the results more precise while creating the finite element mesh, and the mesh was tightened manually in the entire model, being the densest in the impermeable clay core zone. Figure 5 shows images of the model and finite element network created for sections B3, B4, and B5.

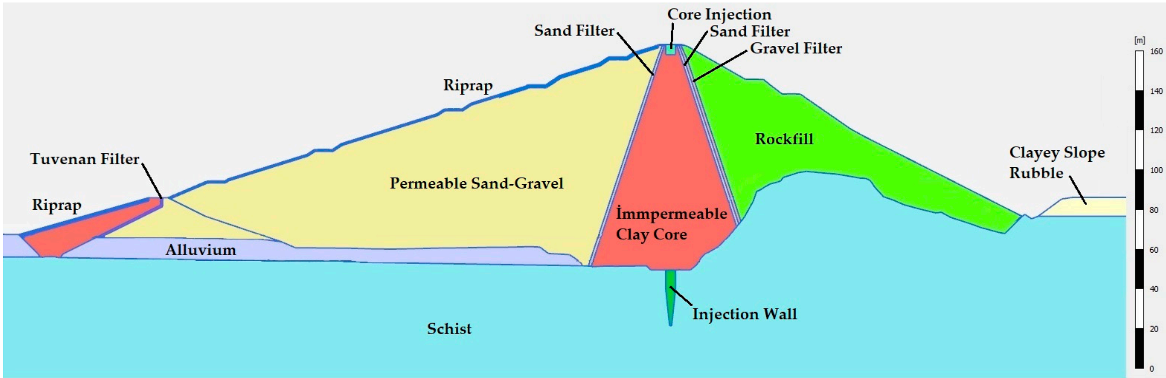

Figure 4. Model of section B3.

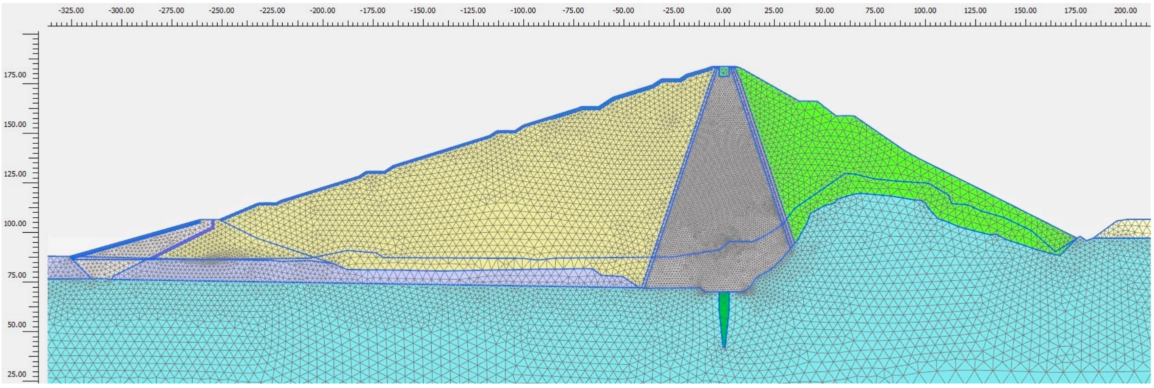

Figure 5. Finite element mesh of section B3.

In order to obtain realistic behavior of the dam under different conditions and water levels, the injection curtain and cover injection were modeled using the linear elastic soil model, and all soils in the dam foundation and zones were modeled using the hardening soil model. In soils modeled using the hardening soil model, p_{ref} = 100 kN/m^2, υ_{ur} = 0.2, and $E_{oed}{}^{ref}$ = $E_{50}{}^{ref}$ and $E_{ur}{}^{ref}$ = 3 × $E_{50}{}^{ref}$ values recommended to be used by the Plaxis program are defined in the program. The parameters of the materials used in the analysis model are given in Table 2.

In order to measure the water pressures that will occur in the dam, 44 fill-type piezometers, 6 foundation-type piezometers, and 3 water pressure meters were placed at different elevations and coordinates during the construction phase. In addition, 29 reference points were placed at different elevations and coordinates during the construction phase in order to measure the displacements that will occur in the dam body. Visuals showing the locations of piezometers and guides on the dam are given in Figure 6.

Table 2. Parameters of the materials used in the analysis model.

Material	Material Model	Drainage Type	γ_{unsat} γ_{sat} (kN/m^3)	$E_{50}{}^{ref}$ (kN/m^2)	$k_x - k_y$ (m/day)	c'_{ref} (kN/m^2)	φ' (°)	ψ' (°)
Injection Wall—cover Injection	L.E. [1]	Non-porous	24.00	20,000	-	-	-	-
Alluvium	H.S. [2]	Drained	19.00 20.00	5000	3.024	5	30	0
Schist	H.S.	Drained	27.00 28.00	50,000,000	30.24	20,000	30	0
Clayey slope rubble	H.S.	Drained	19.00 20.00	20,000	0.0864	10	35	5

Table 2. *Cont.*

Material	Material Model	Drainage Type	γ_{unsat} γ_{sat} (kN/m^3)	E_{50}^{ref} (kN/m^2)	$k_x - k_y$ (m/day)	c'_{ref} (kN/m^2)	φ' (°)	ψ' (°)
Impermeable Clay core	H.S.	Undrained-A	18.60 19.60	25,000	0.007957	120.6	20	0
Permeable Sand–gravel	H.S.	Drained	16.90 17.90	30,000	8.64	0	36	6
Sand filter	H.S.	Drained	16.70 17.70	25,000	86.4	0	37	7
Gravel filter	H.S.	Drained	17.10 18.10	32,000	864	0	38	8
Tuvenan filter	H.S.	Drained	16.90 17.90	30,000	8.64	0	37	7
Rockfill	H.S.	Drained	26.50 27.50	200,000	864	0	42	12
Riprap	H.S.	Drained	26.50 27.50	200,000	8640	0	42	12

Notes: [1] L.E.: linear elastic. [2] H.S.: hardening soil.

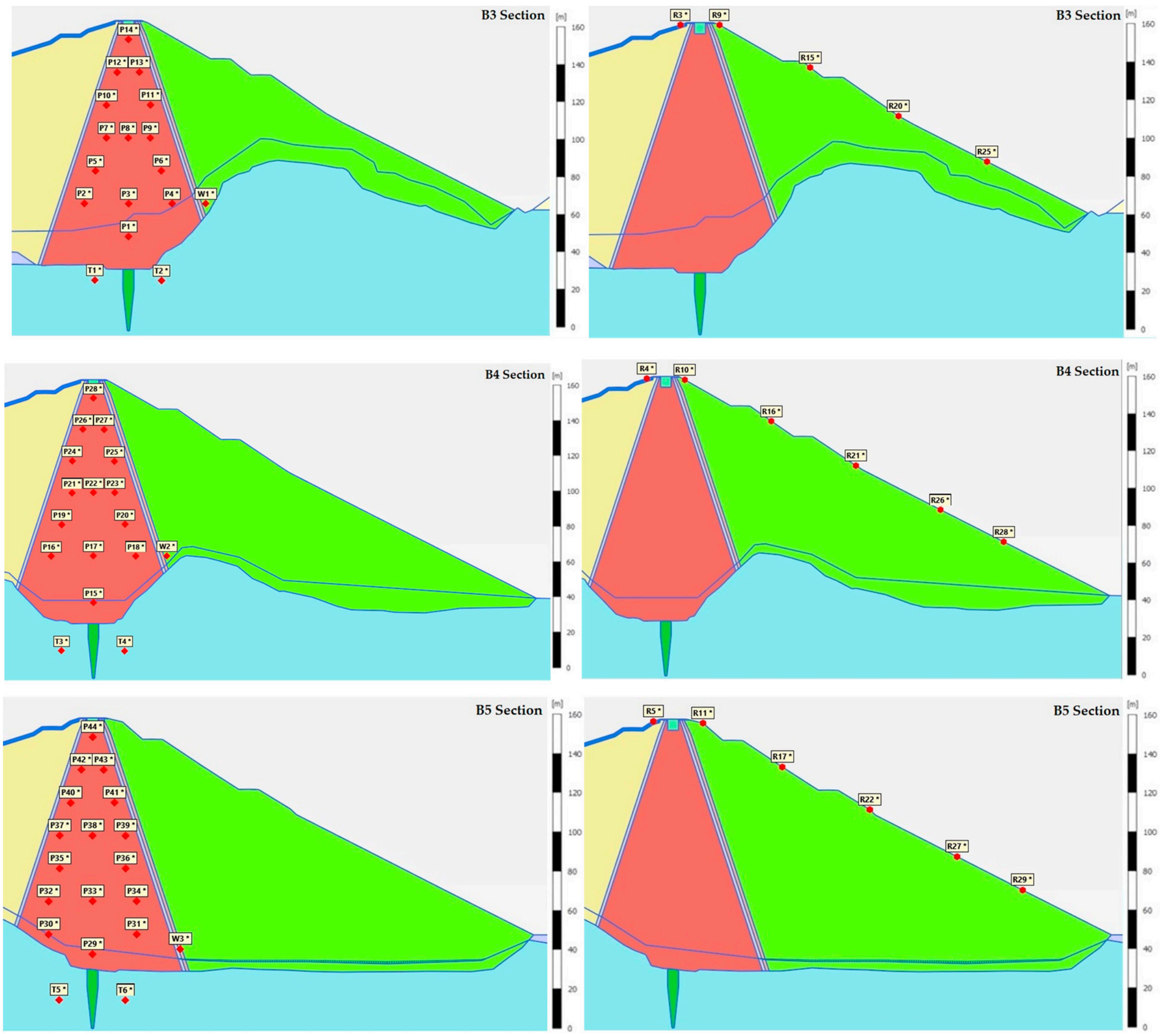

Figure 6. Piezometer and survey points of B3, B4 and B5 sections. (R: survey point, P: fill-type piezometer, T: foundation-type piezometer, W: water pressure meter).

4. Analysis Results

B3, B4, and B5 sections of the dam, where both piezometer and surveyor readings were found, were modeled and analyzed in two dimensions. The values obtained as a result of the analysis and the measurement results were evaluated under separate headings for reference points and piezometer points.

The examples given in Figure 7 are based on the fact that sudden increases and decreases in the vertical displacement and dam breaking distance measurement values made on certain dates in the reference measurement charts will create major problems for the performance and safety of the dam, and on these dates, such shape behavior and safety problems have not been observed in the dam so far. Therefore, the readings on these days are thought to be operator-induced reading errors. These significant changes in distance and water level have resulted in significantly revised measurement graphs based on the previous and next readings, making the measurement graphs more accurate.

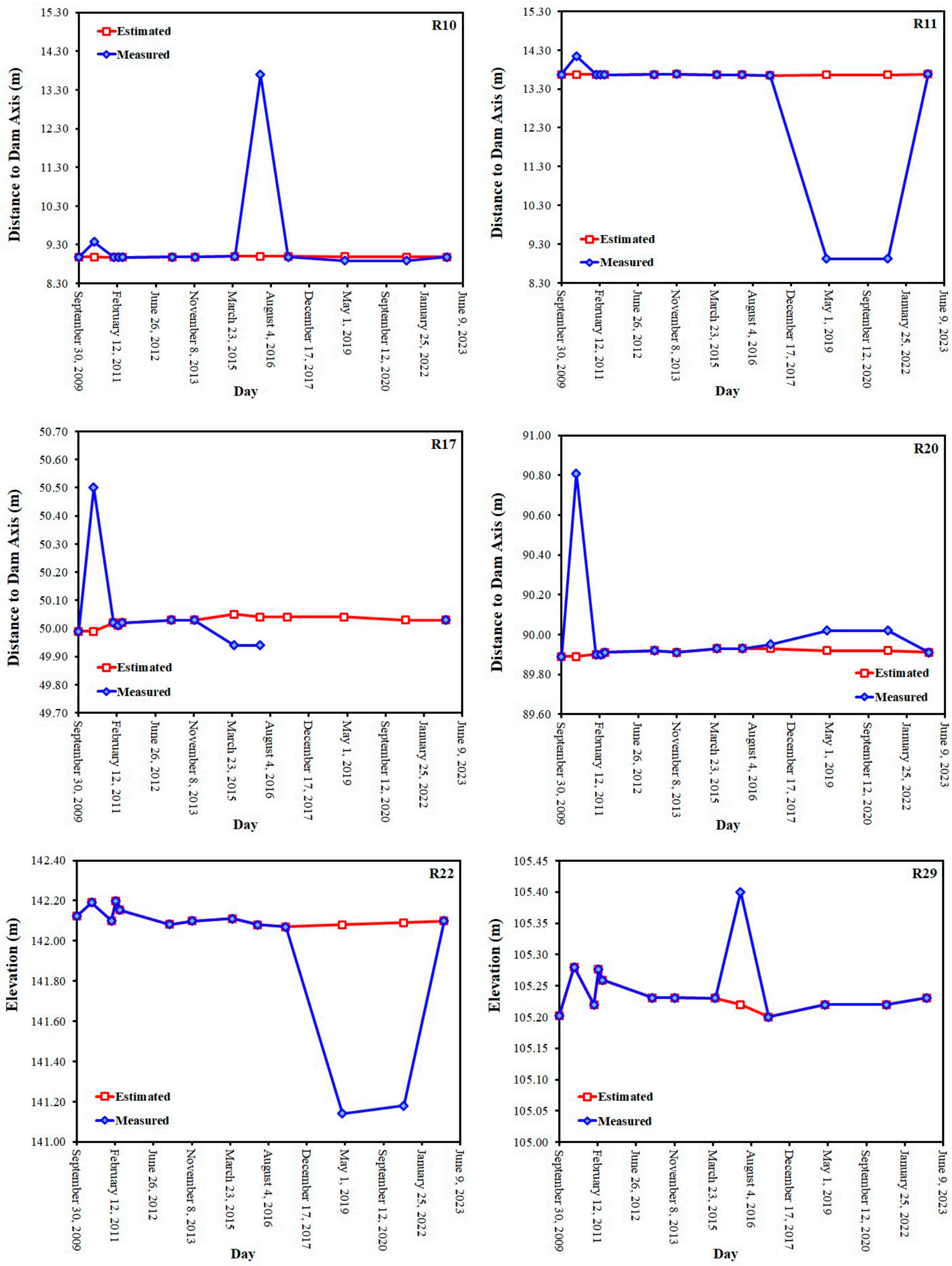

Figure 7. Graphs of measurement values and regulated values of the survey points.

4.1. Comparison and Evaluation of Analysis Results of Survey Points and Measurement Results

Deformations occurring at survey points provide important information about the behavior of the dam. In the light of this information, comments can be made about dam safety, and the possible behavior of the dam can be predicted. At İkizdere Dam, reference measurements were taken at 13 different times between 30 September 2009 and 9 November 2022. Some examples of the total deformation outputs obtained for these measurement dates as a result of the two-dimensional analysis of the B3, B4, and B5 sections with the finite element model are given in Figures 8 and 9.

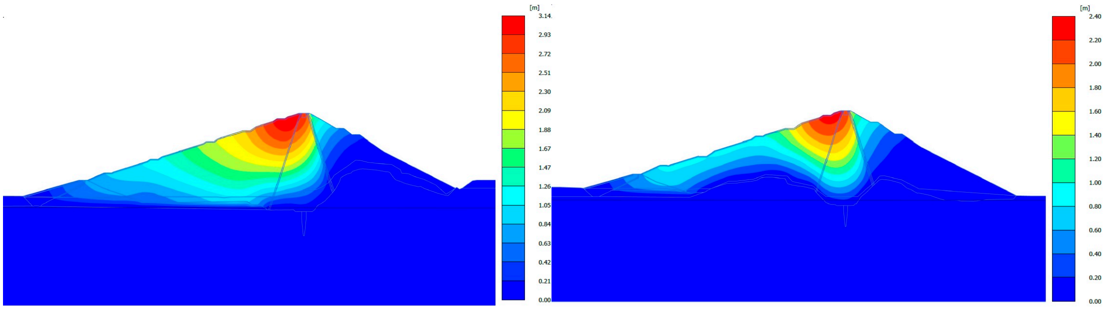

Figure 8. Total deformation analysis output of B3 and B4 sections dated 30 September 2009.

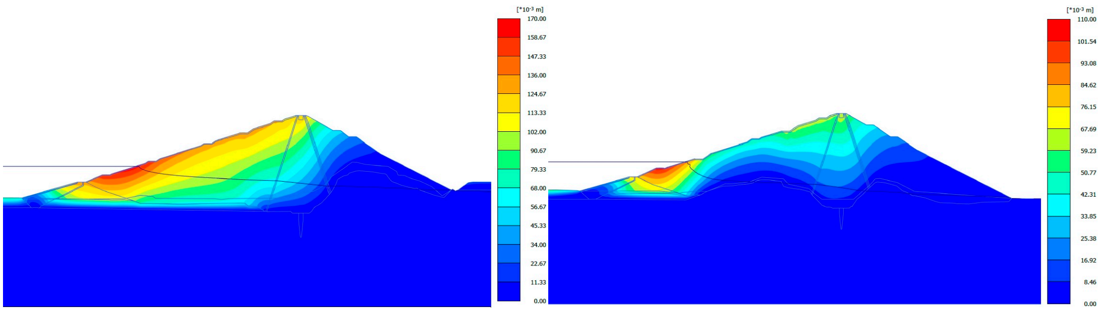

Figure 9. Total deformation analysis output of sections B3 and B4 dated 9 November 2022.

Vertical displacement values of measured and computed values of R3, R4, and R5 survey points are given in Table 3.

Table 3. Vertical displacement values of measured and computed values of R3, R4, and R5 survey points.

Day	Water Level (m)	R3		R4		R5	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
30 September 2009	0.00	182.572	182.572	182.632	182.632	182.592	182.592
13 April 2010	0.00	182.630	182.571	182.660	182.632	182.633	182.593
27 December 2010	108.53	182.540	182.650	182.570	182.679	182.550	182.629
22 February 2011	120.55	182.638	182.684	182.633	182.693	182.629	182.640
18 April 2011	125.55	182.639	182.689	182.660	182.700	182.653	182.648
24 January 2013	154.36	182.518	182.752	182.529	182.741	182.518	182.711
15 November 2013	158.70	182.490	182.763	182.506	182.744	182.501	182.726
21 April 2015	167.01	182.470	182.785	182.480	182.758	182.450	182.755
18 March 2016	162.00	182.430	182.772	182.440	182.749	182.410	182.739
16 March 2017	145.90	182.420	182.756	182.420	182.722	182.380	182.684
25 March 2019	152.80	182.430	182.783	182.430	182.732	182.400	182.702
1 June 2021	134.29	182.410	182.743	182.390	182.706	182.400	182.656
9 November 2022	124.81	182.490	182.685	182.506	182.694	182.501	182.641

Vertical displacement graphs of measured and computed values of R3, R4, and R5 survey points are given in Figure 10.

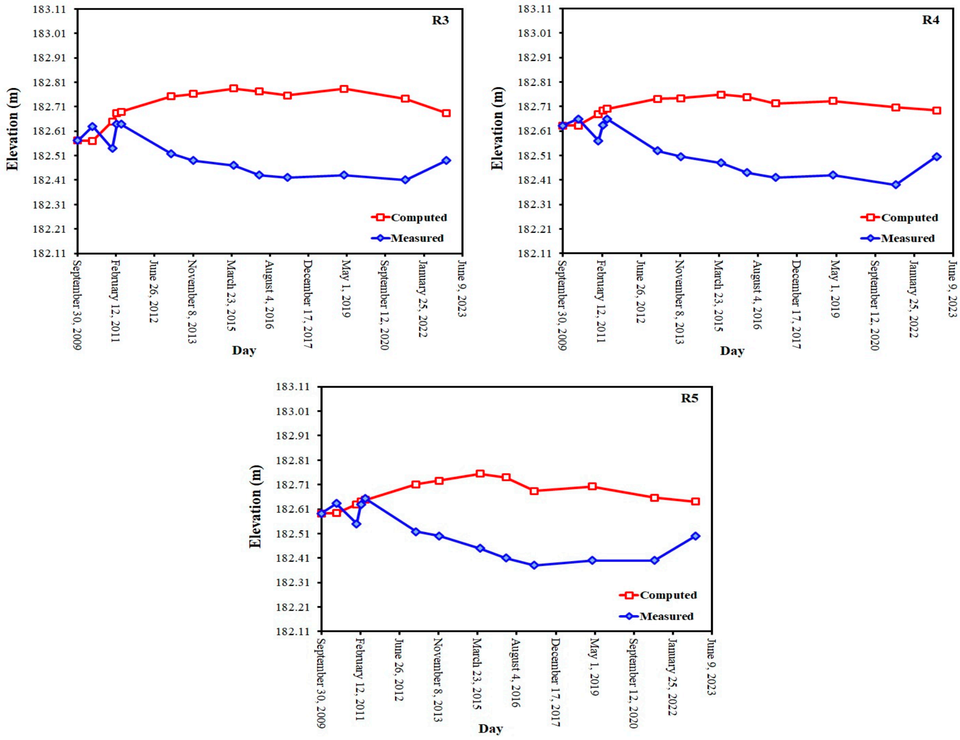

Figure 10. Vertical displacement graphs of measured and computed values of R3, R4, and R5 survey points.

Vertical displacement values of measured and computed values of R20, R21, and R22 survey points are given in Table 4.

Table 4. Vertical displacement values of measured and computed values of R20, R21, and R22 survey points.

Day	Water Level (m)	R20		R21		R22	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
30 September 2009	0.00	141.202	141.202	141.442	141.442	142.122	142.122
13 April 2010	0.00	141.245	141.202	141.494	141.442	142.190	142.122
27 December 2010	108.53	141.190	141.200	141.420	141.439	142.100	142.125
22 February 2011	120.55	141.232	141.199	141.516	141.439	142.199	142.125
18 April 2011	125.55	141.249	141.199	141.501	141.438	142.153	142.125
24 January 2013	154.36	141.154	141.197	141.424	141.435	142.082	142.124
15 November 2013	158.70	141.157	141.196	141.434	141.435	142.099	142.123
21 April 2015	167.01	141.160	141.195	141.430	141.434	142.110	142.121
18 March 2016	162.00	141.120	141.196	141.360	141.434	142.080	142.122
16 March 2017	145.90	141.120	141.197	141.370	141.436	142.070	142.122
25 March 2019	152.80	141.120	141.196	141.370	141.435	142.080	142.122
1 June 2021	134.29	141.120	141.197	141.370	141.436	142.090	142.122
9 November 2022	124.81	141.157	141.198	141.434	141.437	142.099	142.121

Vertical displacement graphs of measured and computed values of R20, R21, and R22 survey points are given in Figure 11.

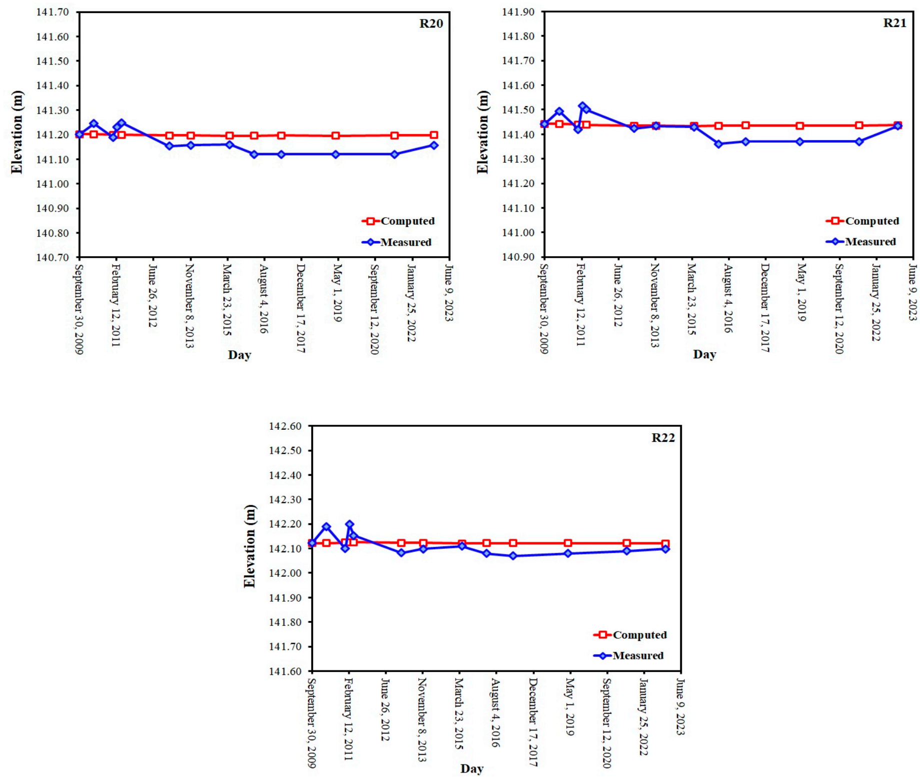

Figure 11. Vertical displacement graphs of measured and computed values of R20, R21, and R22 survey points.

Vertical displacement values of measured and computed values of R28 and R29 survey points are given in Table 5.

Table 5. Vertical displacement values of measured and computed values of R28 and R29 survey points.

Day	Water Level (m)	R28 Measured Values (m)	R28 Computed Values (m)	R29 Measured Values (m)	R29 Computed Values (m)
30 September 2009	0.00	141.202	141.202	141.442	141.442
13 April 2010	0.00	141.245	141.202	141.494	141.442
27 December 2010	108.53	141.190	141.200	141.420	141.439
22 February 2011	120.55	141.232	141.199	141.516	141.439
18 April 2011	125.55	141.249	141.199	141.501	141.438
24 January 2013	154.36	141.154	141.197	141.424	141.435
15 November 2013	158.70	141.157	141.196	141.434	141.435
21 April 2015	167.01	141.160	141.195	141.430	141.434
18 March 2016	162.00	141.120	141.196	141.360	141.434
16 March 2017	145.90	141.120	141.197	141.370	141.436
25 March 2019	152.80	141.120	141.196	141.370	141.435
1 June 2021	134.29	141.120	141.197	141.370	141.436
9 November 2022	124.81	141.157	141.198	141.434	141.437

Vertical displacement graphs of measured and computed values of R28 and R29 survey points are given in Figure 12.

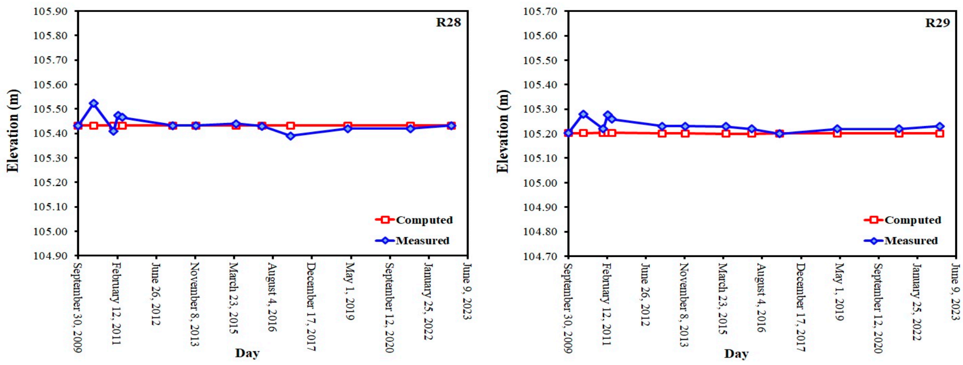

Figure 12. Vertical displacement graphs of measured and computed values of R28 and R29 survey points.

According to the measurement results, it was observed that the vertical displacements of the survey points at the upper elevations decreased between the first reference reading date of 30 September 2009 and 9 November 2022. For this reason, it is thought that settlements in the upper elevations continue. The relationship between the measurement values and the water level was not clearly understood due to the continuing settlement of the dam, and the analysis values showed dynamic changes depending on the water level. Since the vertical elevation measurement values until 14 January 2013 changed independently of the water level and dam behavior, it is thought that the readings until this date are incorrect. The sudden increase in the measurements dated 9 November 2022, regardless of the water level, led to the conclusion that these dated measurements were incorrect. In addition, the vertical elevation measurements and analysis results of the survey points located at the lower elevations showed similar values.

Distance change values from the dam axis of the measured and computed values of R3, R4, and R5 survey points are given in Table 6.

Table 6. Distance change values from the dam axis of the measured and computed values of R3, R4, and R5 survey points.

Day	Water Level (m)	R3		R4		R5	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
30 September 2009	0.00	8.94	8.940	9.05	9.050	9.06	9.060
13 April 2010	0.00	8.94	8.940	9.05	9.050	9.05	9.059
27 December 2010	108.53	8.93	8.908	9.04	9.033	9.04	9.022
22 February 2011	120.55	8.92	8.891	9.04	9.027	9.04	9.009
18 April 2011	125.55	8.92	8.888	9.03	9.025	9.03	8.999
24 January 2013	154.36	8.92	8.848	9.02	9.004	9.02	8.919
15 November 2013	158.70	8.91	8.842	9.01	9.006	9.01	8.900
21 April 2015	167.01	8.90	8.828	8.99	8.996	9.00	8.861
18 March 2016	162.00	8.91	8.839	9.01	9.005	9.00	8.883
16 March 2017	145.90	8.91	8.858	9.00	9.027	9.00	8.953
25 March 2019	152.80	8.90	8.840	8.99	9.020	9.01	8.930
1 June 2021	134.29	8.90	8.868	9.00	9.035	9.01	8.988
9 November 2022	124.81	8.91	8.901	9.01	9.041	9.01	9.006

Distance change graphs from the dam axis of the measured and computed values of R3, R4, and R5 survey points are given in Figure 13.

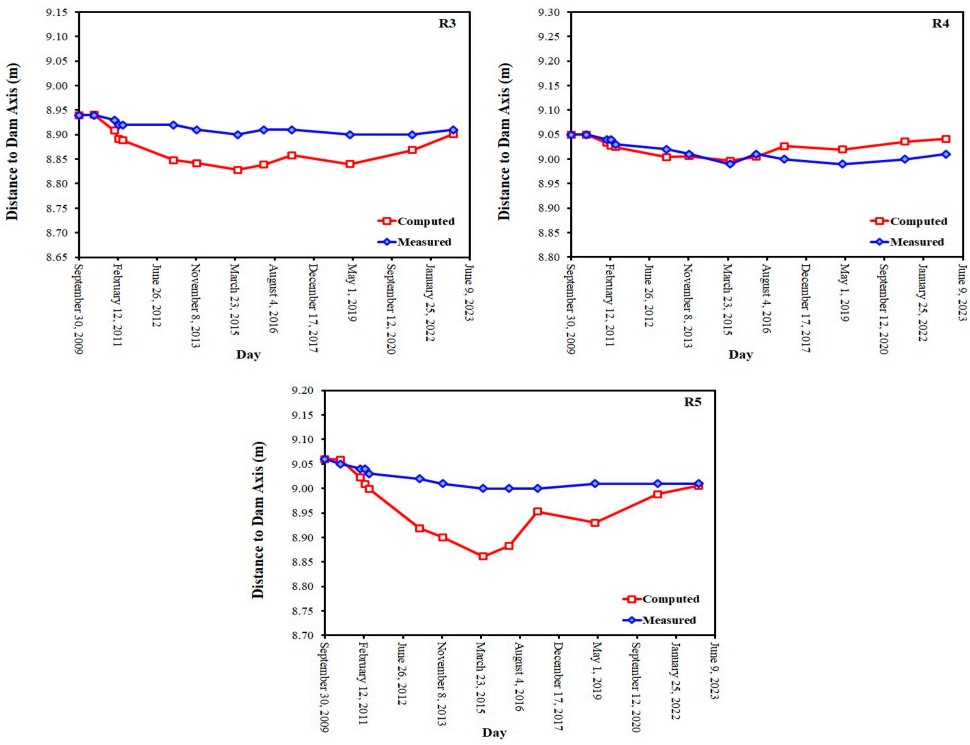

Figure 13. Distance change graphs from the dam axis of the measured and computed values of R3, R4, and R5 survey points.

Distance change values from the dam axis of the measured and computed values of R20, R21, and R22 survey points are given in Table 7.

Table 7. Distance change values from the dam axis of the measured and computed values of R20, R21, and R22 survey points.

Day	Water Level (m)	R20		R21		R22	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
30 September 2009	0.00	89.89	89.890	89.91	89.910	90.00	90.000
13 April 2010	0.00	89.89	89.890	89.93	89.910	90.00	90.000
27 December 2010	108.53	89.9	89.897	89.95	89.918	90.01	90.016
22 February 2011	120.55	89.9	89.900	89.95	89.921	90.00	90.022
18 April 2011	125.55	89.91	89.900	89.95	89.922	90.00	90.026
24 January 2013	154.36	89.92	89.907	89.96	89.931	90.01	90.059
15 November 2013	158.70	89.91	89.908	89.96	89.931	90.01	90.067
21 April 2015	167.01	89.93	89.910	89.96	89.935	90.03	90.083
18 March 2016	162.00	89.93	89.909	89.96	89.933	89.99	90.076
16 March 2017	145.90	89.93	89.906	89.98	89.927	90.02	90.050
25 March 2019	152.80	89.92	89.909	89.97	89.929	89.95	90.059
1 June 2021	134.29	89.92	89.905	89.97	89.924	89.99	90.036
9 November 2022	124.81	89.91	89.899	89.96	89.922	90.01	90.029

Distance change graphs from the dam axis of the measured and computed values of R20, R21, and R22 survey points are given in Figure 14.

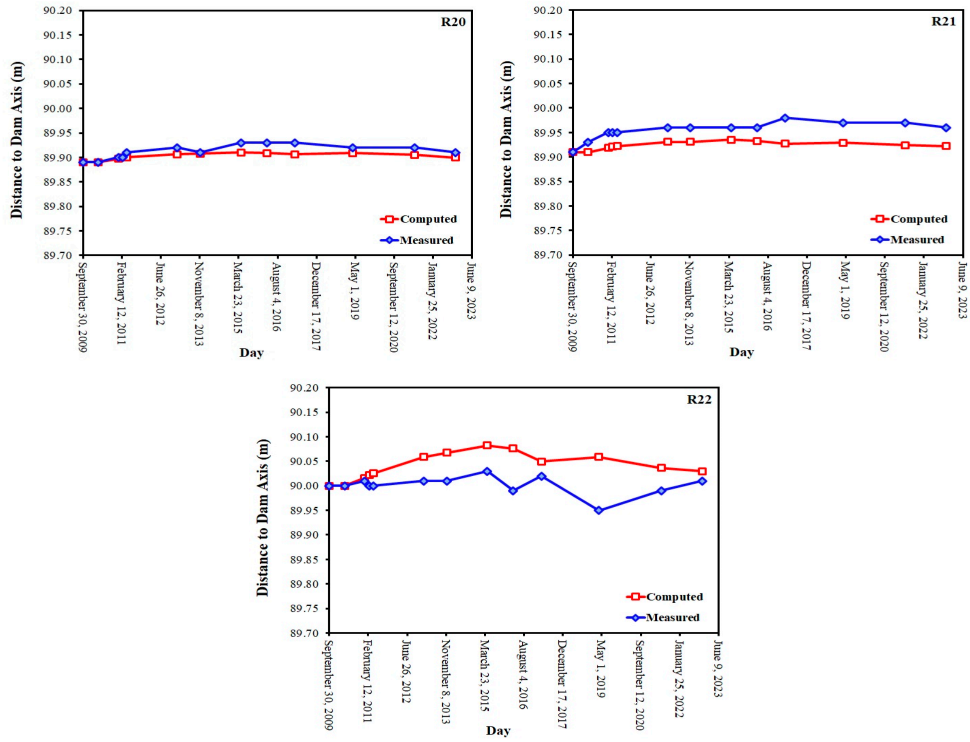

Figure 14. Distance change graphs from the dam axis of the measured and computed values of R20, R21, and R22 survey points.

Distance change values from the dam axis of the measured and computed values of R28 and R29 survey points are given in Table 8.

Table 8. Distance change values from the dam axis of the measured and computed values of R28 and R29 survey points.

Day	Water Level (m)	R28		R29	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
30 September 2009	0.00	159.83	159.830	159.97	159.970
13 April 2010	0.00	159.83	159.830	159.97	159.970
27 December 2010	108.53	159.86	159.831	160.00	159.973
22 February 2011	120.55	159.85	159.831	159.99	159.973
18 April 2011	125.55	159.86	159.831	159.98	159.974
24 January 2013	154.36	159.86	159.832	159.99	159.979
15 November 2013	158.70	159.86	159.833	159.99	159.980
21 April 2015	167.01	159.88	159.833	160.00	159.983
18 March 2016	162.00	159.88	159.833	160.00	159.982
16 March 2017	145.90	159.88	159.832	160.00	159.978
25 March 2019	152.80	159.87	159.832	160.00	159.979
1 June 2021	134.29	159.87	159.832	160.00	159.975
9 November 2022	124.81	159.86	159.831	159.99	159.974

Distance change graphs from the dam axis of the measurement and analysis values of R28 and R29 survey points are given in Figure 15.

The analysis values of the distance to the dam axis of survey points located at the upper elevations were below the measurement values, and large differences were observed between the analysis results and measurement values. It is thought that the reason for this is that the material parameters used in the application are different from the material parameters used in the analysis, and the settlement behavior of the dam continues. The analysis values of the distance to the dam axis of survey points located at the lower elevations were close to the measured values, and the measurement values remained above the analysis values.

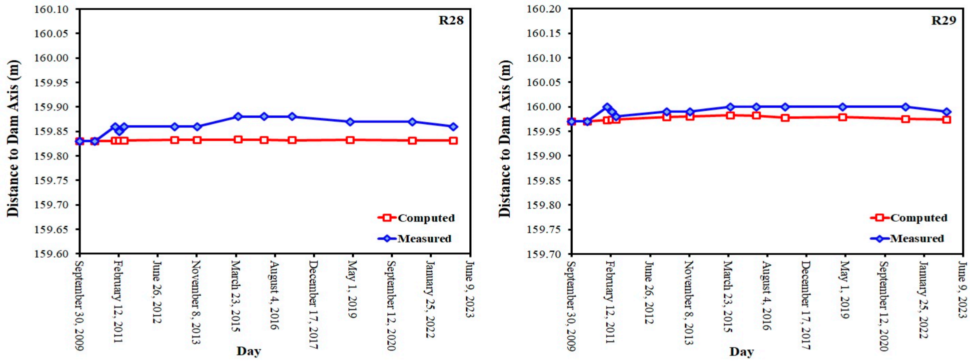

Figure 15. Distance change graphs from the dam axis of the measured and computed values of R28 and R29 survey points.

4.2. Comparison and Evaluation of Analysis Results of Piezometers and Dam Measurement Results

Measuring water pressures in dams is an important step in monitoring the stability and security of embankment dams. Water pressure measurements were taken at İkizdere Dam at different times between 7 January 2010 and 1 March 2023. Some examples of the water pressure outputs obtained for these measurement dates as a result of the two-dimensional analysis of sections B3, B4, and B5 with the finite element model are given in Figures 16 and 17.

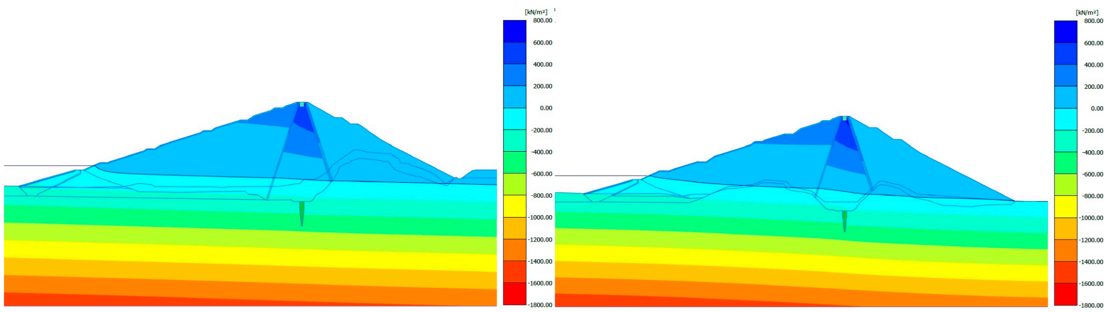

Figure 16. Water pressure analysis output of B3 and B4 sections dated 6 November 2011.

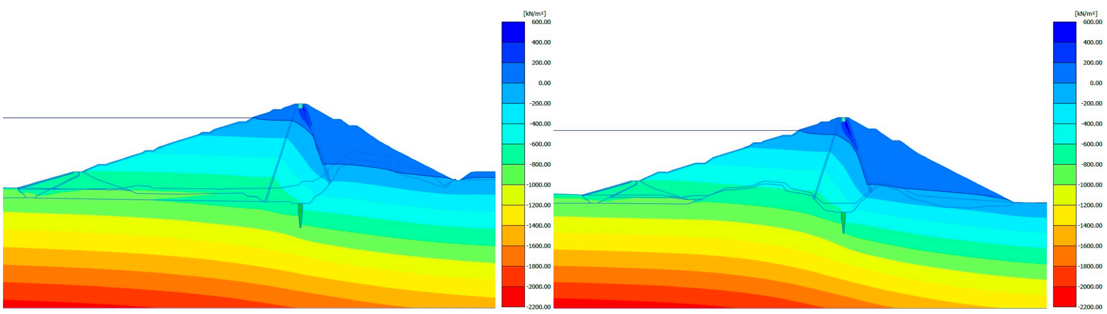

Figure 17. Water pressure analysis output of B3 and B4 sections dated 15 May 2015.

Measured and computed values of P29, P15, and P1 piezometers are given in Table 9.

Change graphs of measured and computed values of P29, P15, and P1 piezometers are given in Figure 18.

Measured and computed values of P37, T4, and T6 piezometers are given in Table 10.

Change graphs of measured and computed values of P37, T4, and T6 piezometers are given in Figure 19.

Table 9. Change values of measured and computed values of P29, P15, and P1 piezometers.

Day	Water Level (m)	P29 Elevation: 76 m Dam Axis		P15 Elevation: 78 m Dam Axis		P1 Elevation: 85 m Dam Axis	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
15 April 2010	0.00	269.182	−13.305	1.898	−30.882	279.317	−85.684
15 June 2010	100.00	270.014	103.581	2.462	88.753	281.410	49.766
21 December 2010	107.38	272.719	159.598	2.872	116.783	284.130	103.104
6 January 2011	111.24	276.777	176.210	2.821	135.142	289.936	104.156
12 April 2011	125.23	322.749	252.550	3.693	214.872	346.694	177.576
9 September 2011	117.50	319.629	204.360	2.103	170.209	333.982	139.146
8 February 2012	139.80	372.591	346.335	4.513	310.458	401.526	317.345
26 September 2012	150.00	448.004	421.692	7.080	379.844	477.268	379.853
3 July 2014	160.50	545.806	493.654	7.539	448.420	561.823	443.309
2 September 2014	155.16	533.838	458.551	6.528	414.810	544.012	413.201
15 May 2015	167.53	591.464	533.020	8.052	488.802	611.004	481.203
22 July 2015	165.55	589.205	526.480	7.539	480.783	606.805	472.757
27 October 2015	160.16	572.870	494.964	7.539	447.806	586.407	442.076
30 December 2015	158.24	567.477	479.013	8.549	435.622	580.119	430.801
9 February 2016	160.22	607.424	495.562	9.062	446.896	589.561	440.346
31 May 2017	147.07	525.297	400.908	5.548	361.028	531.468	363.396
22 November 2018	136.06	483.387	319.815	6.498	286.176	484.905	296.374
19 February 2020	145.63	526.612	388.919	9.062	351.114	534.098	354.265
31 October 2020	126.98	451.747	263.510	8.052	226.605	440.934	185.594
2 May 2021	132.70	464.832	297.030	9.575	265.265	470.306	204.387
21 May 2022	135.01	467.310	312.023	10.088	246.550	481.879	211.358
13 August 2022	129.51	465.788	278.289	9.108	246.785	461.843	194.200
8 November 2022	124.83	446.179	251.096	9.062	213.317	438.304	177.121
1 March 2023	128.04	451.157	269.291	10.103	235.862	439.928	188.843

The analysis values of P29 and P1 piezometers remained below the measurement values, and the measurement values and analysis values showed dynamic changes depending on the water level. The measurement values on the P15 piezometer are below the required values. Therefore, it is thought that the P15 filler-type axis piezometer is defective. The analysis values of the P37 piezometer remained below the measurement values at certain times and above the measurement values at other times. While measurement values generally changed depending on the water level, analysis values showed dynamic changes depending on the water level. Measurement values increased significantly, especially after 8 February 2012. While the analysis values of the T4 piezometer remained above the measurement values, the analysis values of the T6 piezometer remained below the measurement values at certain times and above the measurement values at certain times. Measurement values and analysis values showed dynamic changes depending on the water level. While the piezometer values obtained as a result of the analysis in all piezometers changed dynamically depending on the water level, the measurement values generally changed independently of the modeled water levels. It is thought that the reason for this is that the measurement values give results according to the actual water level change, while the analysis water levels give results according to the modeled water levels. It was concluded that piezometer readings and model results would give similar results as a result of creating a real scenario by instantly monitoring the water level change in the field and reflecting the real permeability values of the materials used in the application to the model. While there is generally no negative pressure value in the reading values, negative pressure values were obtained in the model results depending on the water level.

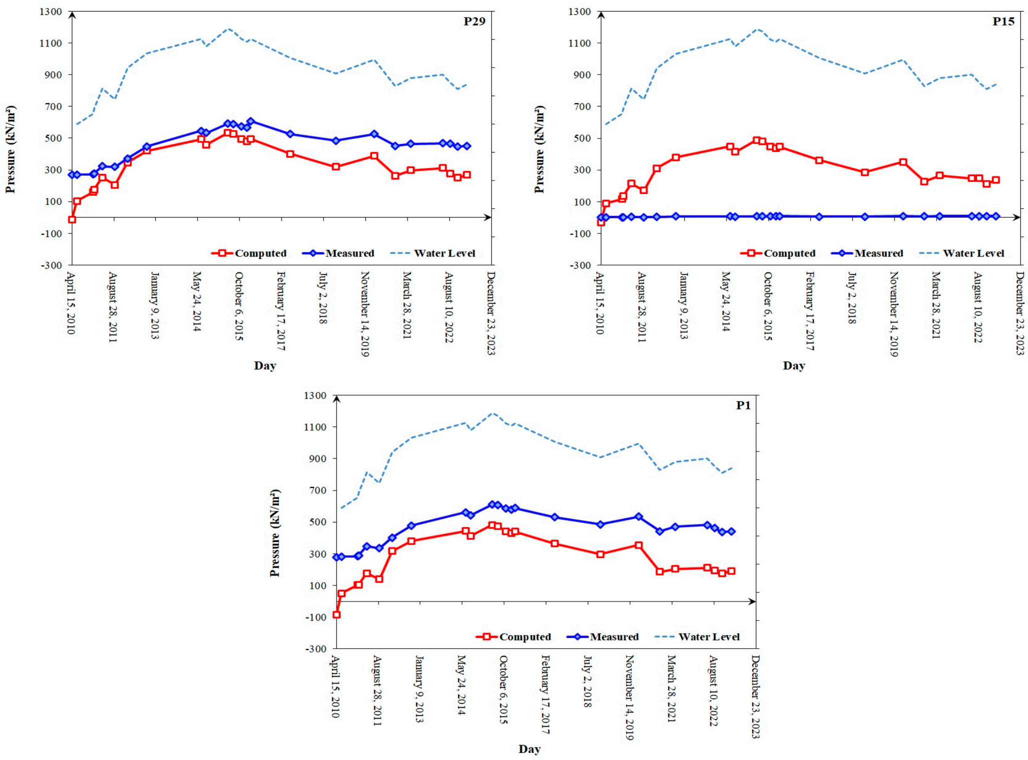

Figure 18. Change graphs of measured and computed values of P29, P15, and P1 piezometers.

Table 10. Change values of measured and computed values of P37, T4, and T6 piezometers.

Day	Water Level (m)	P37 Elevation: 130 m Upstream-15 m		T4 Elevation: 55 m Downstream-15 m		T6 Elevation: 55 m Downstream-15 m	
		Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)	Measured Values (m)	Computed Values (m)
15 April 2010	0.00	−340.182	−398.412	255.037	193.924	270.504	194.954
15 June 2010	100.00	−340.678	−309.076	293.736	302.963	273.226	305.511
21 December 2010	107.38	−339.630	−252.429	300.992	328.845	276.274	345.165
6 January 2011	111.24	−339.465	−235.634	303.949	343.642	281.662	356.251
12 April 2011	125.23	−338.638	−158.898	335.075	404.019	336.308	404.952
9 September 2011	117.50	−340.458	−208.173	334.053	370.141	327.055	374.049
8 February 2012	139.80	−337.315	−48.661	372.011	472.167	392.637	461.352
26 September 2012	150.00	−45.963	83.246	419.441	519.294	469.695	503.996
3 July 2014	160.50	361.518	227.228	473.872	563.973	565.466	547.773
2 September 2014	155.16	297.789	153.018	463.652	542.458	548.598	525.075
15 May 2015	167.53	497.690	298.287	501.308	590.410	612.803	571.340
22 July 2015	165.55	500.984	286.034	498.080	583.574	607.362	564.801
27 October 2015	160.16	401.612	228.508	487.859	562.655	590.495	546.608
30 December 2015	158.24	369.757	192.389	484.631	555.230	583.421	537.288
9 February 2016	160.22	378.545	228.407	488.935	562.857	593.759	546.806
31 May 2017	147.07	100.418	46.275	455.584	506.354	533.362	492.410
22 November 2018	136.06	−10.733	−86.326	432.456	454.653	485.476	445.189
19 February 2020	145.63	70.161	25.702	457.735	499.708	533.362	486.318
31 October 2020	126.98	−4.678	−148.114	422.237	411.916	444.663	411.149
2 May 2021	132.70	−116.444	−112.863	426.002	440.003	465.886	431.796
21 May 2022	135.01	−183.096	−95.802	429.767	449.890	472.961	440.697
13 August 2022	129.51	−173.179	−133.008	421.162	426.466	453.370	420.205
8 November 2022	124.83	−183.096	−160.672	410.406	402.246	429.425	403.546
1 March 2023	128.04	−201.829	−142.093	417.397	418.898	437.044	414.958

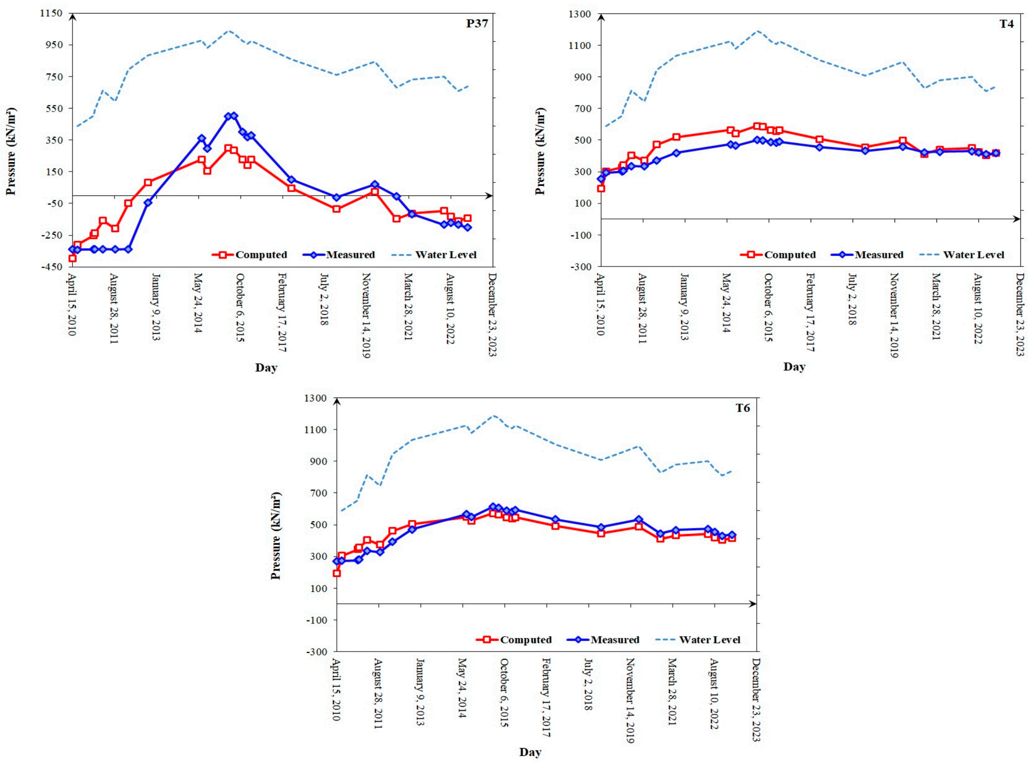

Figure 19. Change graphs of measured and computed values of P37, T4, and T6 piezometers.

5. Results and Discussion

As stated in the studies conducted in the literature, performing safety analyses by modeling dams with numerical analysis and obtaining the data needed in the analyses completely and accurately directly affects the analysis results and may cause problems in terms of dam safety.

It is thought that the reason for the difference between the piezometer and survey point measurements taken and the results obtained by analysis is that the real soil parameters in the dam zone and foundation cannot be obtained and the water level change in the dam is not measured instantly.

Considering the analysis results and the real-time behavior of the dam, it is thought that survey point measurement values taken at certain times are incorrect.

Since the dam under investigation did not have settlement measurements during the construction phase, real-time deformation behavior of the dam could not be obtained.

The data obtained as a result of the analysis show that the behavior of the dam changes depending on the change in water level and the values of the parameters (elasticity modules, permeability, etc.) entered in the ground model. For this reason, it is important to determine the material parameters used in the application and correctly introduce them into the analysis programs in order to analyze the dam behavior in the most real way.

In order to model the pore water pressures in dams realistically, it is important to monitor the water pressures and water levels at the time of measurement and reflect them in the analysis model. The water level defined in the analysis model occurs at certain time intervals, and the water level change between these time intervals is assumed to be linear. However, in reality, the water level change between these dates may not show a linear change. In this case, the pore water pressure data obtained as a result of the analysis and the measured pore water pressure data do not match each other, and the realistic behavior of the dam cannot be obtained.

It is recommended that the ground models to be used in the modeling of the dams planned to be built are decided at the planning stage, and the necessary tests and experiments for the parameters needed in the ground structure model for which this decision is made during the planning and construction stages are also carried out and reported and recorded.

It is important for dam safety that dam monitoring plans are created for each dam at the planning stage and that periodic inspections, observations, and measurements begin from the first day of the dam's construction and continue throughout the operating life of the dam.

Inspections, observations, and measurements at dams should be carried out periodically by expert personnel. The data obtained based on the audit, observation, and measurement results should be analyzed, evaluated by expert personnel, and archived carefully.

It is recommended to establish systems where critical measurements can be taken as automatically as possible and to carry out maintenance, calibration, and physical checks of measuring instruments and the systems they are connected to at specified periods. In this way, damage and malfunctions in measuring instruments and the systems they are connected to will be minimized, personal errors in measurement values will be prevented, and continuous data recording will be possible at specified periods.

In order for the measurement data to be taken from the dams to be more accurate and to obtain good performance from the devices, it is necessary to be very careful in choosing the measurement devices to be placed, determining the settlement areas, and taking the readings.

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Conflicts of Interest: The authors declare no conflicts of interest.

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