U Karst
Volume 08 Number 02 Year 2024

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

Tersedia Secara Online di
https://ojs.unik-kediri.ac.id/index.php/ukarst/index

https://dx.doi.org/10.30737/ukarst.v8i2.6191

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Non-Destructive Test and Numerical Approach for Tailrace Safety Evaluation of Ir. H. Djuanda Dam

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ARTICLE INFO

Article History :
Article entry : 01 – 11 – 2024
Article revised : 11 – 11 – 2024
Article received : 28 – 11 – 2024

Keywords **:**
Non-Destructive Test (NDT), Plaxis 2D, Safety Factor, Schmidt Hammer, Tailrace.

IEEE Style in citing this article:

V. A. Damayanti, and F. Mulyawati, "Non-Destructive Test and Numerical Approach for Tailrace Safety Evaluation of Ir. H. Djuanda Dam," U Karst, vol 8, no. 2, pp 109 – 121, 2024, doi: 10.30737/ukarst.v8i2.6191

A B S T R A C T

Dam Ir. H. Djuanda is one of the important infrastructures in managing water resources in Indonesia, with strategic functions such as flood control, irrigation, hydroelectric power plants (PLTA), and raw water supply. The lower channel (tailrace) plays a crucial role in supporting the efficiency of the dam's hydraulic system. However, previous inspections revealed erosion and exposed aggregate in the tailrace concrete layer which could threaten the stability of the structure. This research aims to evaluate the condition of the tailrace structure of Dam Ir. H. Djuanda. An evaluation was carried out by integrating the NDT method using Schmidt Hammer and numerical simulation via Plaxis 2D software. The Schmidt Hammer test data gives an average concrete quality value of 37.47 MPa, while the Plaxis 2D simulation shows that the Cartesian stress (σ_{xx}, σ_{yy} and σ_{zz}) on the structure is still within safe limits. The simulation results also show a safety factor value of 1.795, which meets the structural safety criteria. These findings indicate that the tailrace concrete was designed with a high safety factor, so that it can withstand hydrostatic loads and ground pressure even though it has been in operation for more than five decades. This research shows that the combination of NDT and numerical simulation is an effective method for evaluating structural conditions without damaging the material. This approach can be adopted to inspect and maintain similar infrastructure to ensure long-term operational stability and sustainability.

1. Introduction

Dam Ir. H. Djuanda, located in Purwakarta, West Java, is one of the important infrastructures in managing water resources in Indonesia [1]. This dam has a strategic role, such as controlling floods, providing water for irrigation, generating hydroelectric power (PLTA), and supplying raw water for domestic and industrial needs [2]. In operation, the tailrace plays a crucial role by channeling water from the turbines back into the river, ensuring the efficiency

ISSN (*Online*) 2581-2157
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and sustainability of the dam's hydraulic system [3]. However, previous inspections of the right tailrace of the Ir. H. Djuanda have revealed that there is erosion of the concrete layer and exposed aggregate in several areas. This problem was identified since the initial inspection in 1981 and continues to be discovered in subsequent inspections, such as in 2008 and 2021. This condition raises concerns regarding the potential for deterioration in the quality of the dam structure. If left unchecked, this could threaten the stability and safety of the dam as a whole. Therefore, an in-depth evaluation of the condition of the tailrace concrete is essential to ensure that the structure remains safe and operational.

To overcome this problem, evaluation can be carried out using a combination approach of Non-Destructive Test (NDT) with Schmidt Hammer and numerical simulation using Plaxis 2D software. NDT is a method of evaluating material quality without damaging structural elements [4]. This method is quite effective for getting a quick picture of the quality of concrete, especially in structures that are difficult to reach [5], [6]. In addition, Plaxis 2D software can be used as a numerical simulation tool for finite element modeling in the geotechnical field. By utilizing concrete parameters, such as compressive strength, modulus of elasticity, and soil properties, Plaxis can analyze the stress distribution, bending moment, and axial force in structures[7]–[9]. This simulation can provide a detailed picture of how the tailrace structure reacts to water pressure, soil weight, and other forces acting simultaneously.

Various previous studies have shown the importance of combining NDT and numerical simulation in evaluating the condition of existing structures. NDT is quite effective in identifying concrete quality quickly and with high accuracy [10]. Other studies emphasize the importance of validation through numerical simulations to ensure a more in-depth evaluation of structural stability, especially for buildings that have been operating for a long time [11]. Utilizing finite element software can provide a comprehensive picture of the stresses that occur, so that you can evaluate soil and structure interactions in more detail [12]. In addition, the use of a combination of NDT and numerical simulations in evaluating structural stability in extreme environments is important [13]. Combining field test data with numerical simulations can better assess real conditions in the field and increase user safety [14]. Previous research has shown that the combination of NDT methods and numerical simulation can comprehensively evaluate the condition of existing structures. However, research on combining these methods in evaluating tailraces of long-operating dams has not been widely explored. This is important to ensure that the tailrace structure remains safe and operationally viable even after operating for decades.

https://dx.doi.org/10.30737/ukarst.v8i2.6191

 ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

This research aims to evaluate the condition of the tailrace structure of Dam Ir. H. Djuanda. An evaluation was carried out by integrating the NDT method using Schmidt Hammer and numerical simulation via Plaxis 2D software. This research contributes to developing an approach based on a combination of NDT and numerical simulation as a reliable method for evaluating structural stability. In addition, the research results are expected to provide a scientific basis to support inspection and maintenance planning for the Ir Dam tailrace. H. Djuanda to ensure its operational feasibility. The approach used in this research can be used as a reference for evaluating similar infrastructure such as irrigation canals, tunnels and other dams to improve the safety and sustainability of their use.

2. Research Method

This research began with collecting secondary data in the form of Schmidt Hammer test results on the right tailrace wall of the Ir Dam. H. Djuanda as well as soil and water parameter data. Concrete quality data from Schmidt Hammer test results was integrated into a numerical model using Plaxis 2D software. This model simulates the Cartesian stress distribution (σ_{xx}, σ_{yy}, and σ_{zz}) around the tailrace. The simulation generated maximum and minimum stress distributions, which were analyzed to assess the structure's performance in resisting hydrostatic pressure and soil loads. The analysis involved comparing the simulated stress results with the concrete's compressive strength capacity obtained from the Schmidt Hammer test. Additionally, the safety factor derived from the simulation results was evaluated to ensure the structural stability of the tailrace. This comprehensive assessment aimed to confirm that the tailrace structure operates within safe limits.

2.1 Data Collection

The secondary data used in this study includes Schmidt Hammer test results provided by Perum Jasa Tirta II [15]. The Schmidt Hammer tests were conducted on the right tailrace wall of the Ir. H. Djuanda Dam at multiple points and varying heights, covering both the right and left sides of the tailrace. The resulting data consists of concrete compressive strength values (in MPa), representing the quality of the concrete across different locations. The average concrete strength from all test points was calculated and used as a key parameter in the analysis. Additionally, soil and water parameter data, also provided by Perum Jasa Tirta II, were used as input values for the numerical model. The data is summarized in **Table 1.**

https://dx.doi.org/10.30737/ukarst.v8i2.6191

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Table 1. Material Properties

Description	Symbol	Unit	Material		
			General Rockfill	Foundation Rock	Water
Unit Weight	γ	Kg/m3	2090	2560	1000
Angle Of Internal Friction	ϕ	Degrees	42	26	-
Modulus Of Elasticity/Bulk	E/K	N/m2	3.0×10^9	1.0×10^9	1.3×10^6
Poisson's Ratio	υ		0.30	0.30	0.50

Source: Perum Jasa Tirta II

Table 2. Soil Parameter

No	Soil Type	Depth (m)	Model	Type	Soil Properties			kx/ky (m/days)
					c' (kPa)	φ'	E (kPa)	
1	Embankment	0 - 4	Mohr–Coulomb	Undrained A	15	15	15000	8.64×10^{-3}
2	Clay or Silty Clay	4 - 80	Mohr–Coulomb	Undrained A	35	20	25000	8.64×10^{-3}

Source: Perum Jasa Tirta II

In addition, other technical data such as structural geometry, environmental conditions, and hydrostatic and soil loads are also collected to ensure the simulation reflects actual tailrace conditions.

2.2 Schmidt Hammer Test

The Schmidt Hammer Test was carried out to assess the quality of the Ir Dam tailrace concrete. H. Djuanda through non-destructive testing. Tests were carried out at several points with varying heights on the right and left walls to obtain an overall distribution of concrete quality values. There are 14 test points on each right and left wall with different heights and a 20-30 cm distance from each point. Data processing starts from recording the initial value (rebound number, R), which is then corrected based on the test angle to obtain the correction value (R'). This correction uses a reference table considering the test angle according to the Schmidt Hammer measurement standard. The correction process ensures that the influence of the test position on the rebound value is minimized. After correction, the data were further analyzed to calculate the statistical parameters mean ($\bar{R}'$) and standard deviation. Corrected test value data (R') that exceeds the tolerance ($\bar{R}' \pm 6$) will be discarded. The filtered data is then averaged to generalize the quality of concrete in that area.

2.3 Modeling in Plaxis 2D

Modeling was carried out using Plaxis 2D software to analyze the Cartesian stress distribution (σ_{xx}, σ_{yy}, and σ_{zz}) around the Ir Dam tailrace structure. H. Djuanda and safety factor values. The modeling process begins with creating structural geometry using AutoCAD software, which is then imported into Plaxis. Material data and soil parameters are input into

https://dx.doi.org/10.30737/ukarst.v8i2.6191

ISSN (*Online*) 2581-2157
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the model. Modeling is carried out in stages using the Staged Construction feature to describe a realistic construction sequence. This stage includes simulating existing conditions, initial construction, channel installation, application of hydrostatic loads and soil pressure, as well as consolidation analysis. Each stage is designed to reflect gradual changes in structural and environmental conditions. In the final stage, the Cartesian stress distribution and safety factor are calculated to evaluate the stability of the tailrace structure.

3. Results and Discussions

3.1 Schmidt Hammer Test Results

This test was carried out at several heights of the right tailrace, both on the right and left walls, to obtain the distribution of concrete quality values at various inspection points. Test result data are summarized in **Table 3**.

Table 3. Hammer Test Result on Right Tailrace

No.	Wall	Depth (m)	Concrete Quality Value		
			Kgf/cm^2	Mpa	psi
1	Right	0.5	370.01	36.285	5262.7
2	Left	0.5	383.68	37.626	5457.1
3	Right	10.4	389.13	38.161	5534.7
4	Left	10.4	387.78	38.028	5515.5
5	Right	18	379.64	37.230	5399.8
Average Concrete Quality Value			382,05	37.47	5435,0

Source: Perum Jasa Tirta II [16]

From the data in the Table 1, the concrete quality value on the right wall at a height of 0.5 m has a value of 36.285 MPa, while on the left wall at the same height it is 37.626 MPa. This small difference shows the uniformity of concrete quality between the right and left walls at a height of 0.5 m. At a height of 10.4 m, the right wall shows a concrete quality value of 38.161 MPa, slightly higher than the left wall which has a value of 38.028 MPa. At a height of 18 m, the concrete quality value on the right wall was recorded at 37,230 MPa. The overall concrete quality value ranges from 36,285 MPa to 38,161 MPa, with an average concrete quality value of 37.47 MPa.

These results indicate that Tailrace concrete shows uniform concrete quality at various test points, both on the right and left walls. Differences in concrete quality values at various heights, although present, are minimal and insignificant in influencing the structure's overall stability. Concrete on the Tailrace Dam Ir. H. Djuanda, which has been operating for more than 50 years, showed that the choice of concrete materials and construction techniques at that time had succeeded in meeting long-term durability standards. However, this success cannot be

https://dx.doi.org/10.30737/ukarst.v8i2.6191

ISSN (*Online*) 2581-2157
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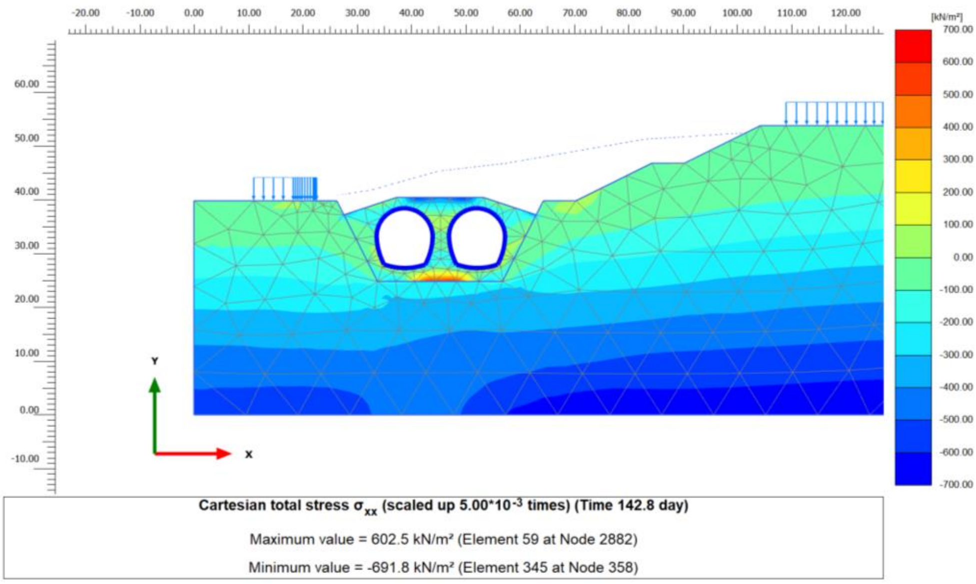
separated from the challenges of Tailrace's concrete environment, which is always inundated with water and is exposed to hydrostatic pressure from the flow of water coming out through the turbine. This condition can cause erosion of the concrete surface, exposed aggregate, and the risk of water penetration which can affect the quality of the concrete over time. This is in line with the theory that concrete in a wet and dynamic environment is susceptible to damage due to erosion, chemical attack from minerals contained in water, and wet-dry cycles if channel emptying occurs.

However, based on these findings, high quality concrete can survive in wet and dynamic environments. This is in line with previous research where high quality concrete can withstand erosion and degradation for decades [17]–[19]. Additionally, other studies confirmed that high-strength concrete has superior resistance to wet conditions and wetting-drying cycles [20], [21]. Even though the tailrace concrete is always saturated, the structure can still maintain its integrity.

3.2 Plaxis Simulation Results

To verify whether the quality of Tailrace Dam concrete Ir. H. Djuanda is suitable and able to withstand the workload and pressure due to the surrounding environment, a simulation was carried out using Plaxis 2D software by knowing the Cartesian total stress in various directions.



Source: Author's Analysis Result (2024).

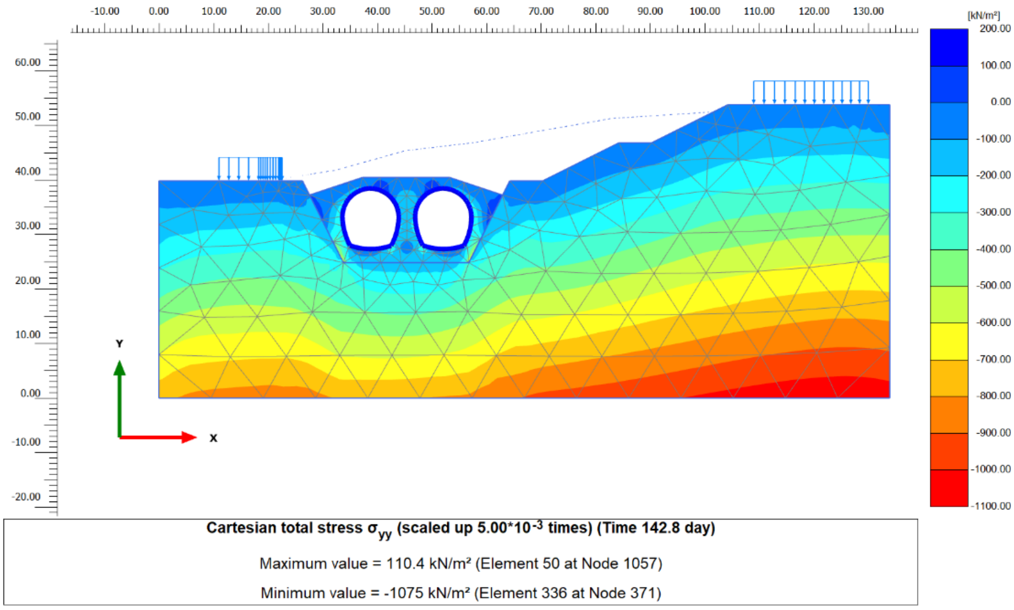
Figure 1. Cartesian Total Stress σ_{xx}

Figure 1 shows the Cartesian total stress distribution σ_{xx} around the Ir Dam tailrace structure. H. Djuanda after 142.8 days of simulation time. The simulation results show the

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

maximum stress value is 602.5 kN/m², while the minimum stress is -691.8 kN/m². These stress values are distributed over the tailrace structural elements with a color gradient pattern that reflects the stress distribution. The maximum stress occurs in the area approaching the tailrace wall, this is because this area receives the highest hydrostatic pressure from the flow of water which is always stagnant. In contrast, minimum stresses are found at the bottom of the structure, which experiences tensile conditions due to the pressure distribution of the surrounding soil and water.

Based on the simulation results, the stress that occurs in the tailrace concrete is still within safe limits because it does not exceed the average characteristic compressive strength value of concrete of 37.47 MPa obtained from the Schmidt Hammer test. The maximum stress of 602.5 kN/m² (equivalent to 0.6025 MPa) only utilizes a small portion of the design capacity of the tailrace concrete, indicating that the tailrace concrete structure has an adequate safety factor. This indicates that the tailrace concrete design successfully accommodates internal and external loads, such as water pressure from inside the channel and soil pressure from outside.



Source: Author's Analysis Result (2024).

Figure 2. Cartesian Total Stress σ_{yy}

Figure 2 shows the Cartesian total stress distribution σ_{yy} around the Ir Dam tailrace structure. H. Djuanda based on simulation results after 142.8 days. The maximum stress of 110.4 kN/m² (0.1104 MPa) was found in the light yellow to orange colored area, located around the top of the tailrace wall. Meanwhile, a minimum stress of -1075 kN/m² (-1.075 MPa) was identified in the dark red area, which is at the bottom of the tailrace structure. The area around

https://dx.doi.org/10.30737/ukarst.v8i2.6191

ISSN (*Online*) 2581-2157
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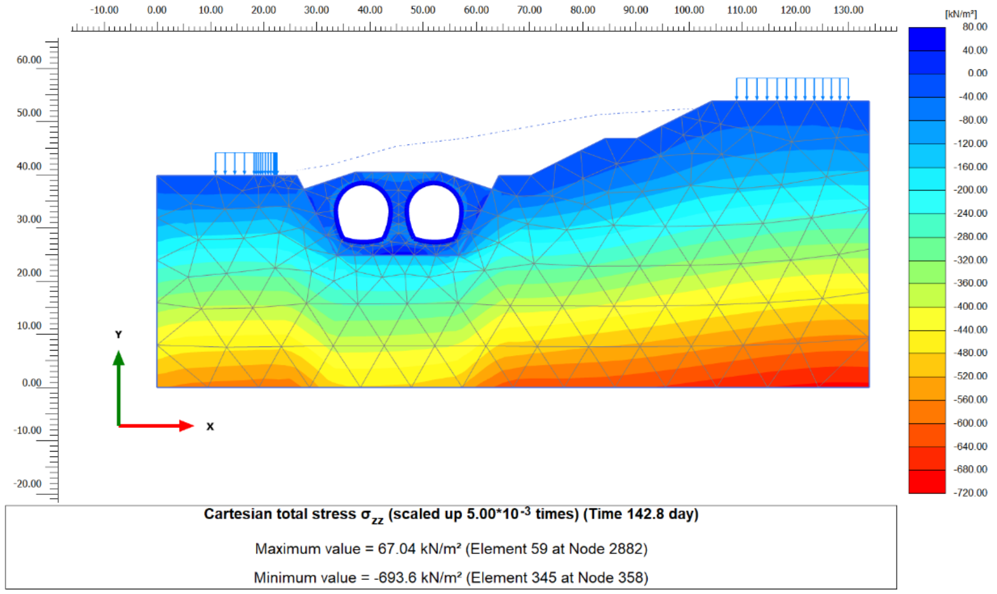
the tailrace mostly shows a stress distribution with values ranging from -600 to 100 kN/m², reflecting vertical stress variations due to the combination of hydrostatic pressure from the water inside the channel and soil pressure on the outside.

The identified stress around the tailrace is still far below the average concrete quality of 37.47 MPa, obtained from Schmidt Hammer testing. The maximum stress of 0.1104 MPa indicates that the tailrace concrete has only received a fraction of its compressive strength capacity, while the minimum tensile stress of -1.075 MPa remains within the design tolerance limits for high strength concrete. These results indicate that the tailrace structure is well designed to accommodate vertical stresses without experiencing the risk of material failure. The identified stress distribution is accordingly focused around the top wall of the tailrace which is the result of direct pressure from the water in the channel, while the tensile stress area at the bottom of the tailrace shows the response of the structure to the combined pressure of soil and water [22]–[24]. Overall, the tailrace concrete structure has proven to be able to maintain its stability and safety for operation.



Source: Author's Analysis Result (2024).

Figure 3. Cartesian Total Stress σ_{zz}

Figure 3 shows the Cartesian total stress distribution σ_zz around the Ir Dam tailrace. H. Djuanda based on simulation results after 142.8 days. The maximum stress of 67.04 kN/m² (0.06704 MPa) occurs at the top of the tailrace shown in light blue, which reflects an area of low z-direction stress. In contrast, a minimum stress of -693.6 kN/m² (-0.6936 MPa) was found at the bottom of the tailrace, marked in dark red. Most stresses around the tailrace structure are

https://dx.doi.org/10.30737/ukarst.v8i2.6191

 ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

in the -400 to 0 kN/m² range, with distribution patterns reflecting the structure's response to z-direction stresses from water flow and surrounding soil.

This stress is much smaller than the average concrete quality of 37.47 MPa, indicating that the tailrace structure works within safety limits. The stress distribution σ_{zz} tends to be lower than the vertical σ_{yy} and horizontal σ_{xx} stresses. The area with the highest z-direction pressure is at the top of the tailrace wall, which receives pressure due to water flow in the channel. The stress value σ_{zz} that occurs in the tailrace structure remains within safe limits and does not pose a significant risk to the concrete.

Plaxis simulation results show that the Cartesian stress distribution (σ_{xx}, σ_{yy}, and σ_{zz}) around the Ir Dam tailrace structure. H. Djuanda is within safe limits compared to the average concrete quality of 37.47 MPa obtained from the hammer test. Overall, these stresses utilize only a small portion of the design capacity of the concrete, indicating that the tailrace has an adequate safety factor to withstand internal and external loads. This is reinforced by the safety factor value from the simulation of 1.795, which shows that the structure is still safe. A safety factor value greater than 1.5 is considered sufficient to ensure the structure's safety against the risk of failure due to internal and external loads [25], [26].

The results of this research align with previous studies showing that a combination of non-destructive testing (NDT) methods such as Schmidt Hammer and numerical modeling using software such as Plaxis can provide a comprehensive evaluation of the condition of structures that have been built. Previous research shows that the combination of NDT and simulation using software can evaluate structures efficiently [27]. The use of NDT can provide direct and accurate material quality data [28], while a numerical simulation can map the stress distribution that occurs so that it can assess the capacity of the structure to accept the load [29]. This research confirms that an approach based on a combination of NDT and numerical modeling is a reliable method for evaluating the condition of structures that have been built or are in operation.

The combination of NDT methods and numerical simulations used in this research was proven to be effective for assessing the overall condition of structures without damaging the material. This approach allows early identification of potential structural failures by utilizing direct data from Schmidt Hammer testing and stress distribution analysis via Plaxis software. This combination-based approach can be adopted as a standard method in inspecting and maintaining similar infrastructure, such as dams, irrigation canals and tunnels, to ensure long-term stability without the need for destructive inspections. In addition, these findings reinforce

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the importance of using high-strength concrete in the initial design of structures in extreme environments, such as tailraces that are constantly exposed to water pressure. So the structure's service life can be longer, the risk of failure can be minimized, and maintenance costs can be reduced, thus supporting the future sustainability and operational efficiency of infrastructure.

4. Conclusion

Based on the results of Schmidt Hammer testing and simulations using Plaxis 2D, the tailrace structure of the Ir. H. Djuanda has excellent performance with an average concrete quality of 37.47 MPa. The Cartesian stresses (σ_{xx}, σ_{yy}, and σ_{zz}) distributed around the tailrace indicate that the structure is working within safe limits, where the Cartesian stress value is not greater than the quality of the concrete. Apart from that, the safety factor value of 1.795 indicates that the structure is safe. These findings indicate that the tailrace concrete was designed with a high safety factor, so that it can withstand hydrostatic loads and ground pressure even though it has been in operation for more than five decades. The combination of non-destructive methods (NDT) with the Schmidt Hammer and numerical modeling using Plaxis proved effective for evaluating the structure's overall condition. NDT is able to provide concrete quality data directly during inspection and stress distribution analysis using Plaxis can determine the stress value that must be received by the tailrace so that it can identify potential early structural failure without damaging the material. This approach is relevant not only for the tailrace evaluation of the Ir Dam. H. Djuanda, but also as a standard method in other infrastructure inspections.

References

[1] purwakartakab.go.id, "Sejarah Bendunga Jatiluhur," *purwakartakab.go.id*, 2018. .

[2] Sinbad.sda.pu.go.id, "Waduk Jatiluhur," *SINBADSISTEM*, 2019. .

[3] A. Guryev, N. Khanov, O. Mareeva, V. Fartukov, A. Zhuravleva, and A. Verkhoglyadova, "New way to dampen the energy of medium- And high-pressure flows," in *E3S Web of Conferences*, 2021, vol. 264, doi: 10.1051/e3sconf/202126403046.

[4] S. G. Saremi, D. G. Goulias, and A. A. Akhter, "Non-Destructive Testing in Quality Assurance of Concrete for Assessing Production Uniformity," in *Transportation Research Record*, vol. 2677, no. 1, 2023, pp. 1259–1275.

[5] H. Naderpour, M. Abbasi, D. P. N. Kontoni, M. Mirrashid, N. Ezami, and A. A. Savvides, "Integrating Image Processing and Machine Learning for the Non-Destructive

https://dx.doi.org/10.30737/ukarst.v8i2.6191

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

Assessment of RC Beams Damage," *Buildings*, vol. 14, no. 1, 2024, doi: 10.3390/buildings14010214.

[6] S. Leonovich, N. Budrevich, P. Lyu, and J. Miao, "Pile quality assessment by vibroacoustic method," vol. 212, pp. 1–8, 2020, doi: 10.1051/e3sconf/202021202010.

[7] M. S. Al-Tememy, M. A. Al-Neami, and M. F. Asswad, "A Numerical Analysis on the Behavior of Single Battered Pile under Pullout Loading," *E3S Web Conf.*, vol. 318, pp. 1–8, 2021, doi: 10.1051/e3sconf/202131801010.

[8] Q. Fang, T. Chen, and C. Zhang, "Compression-bending behavior of grouted connections considering axial load ratio," in *fib Symposium*, 2020, pp. 1070–1076.

[9] P. F. Chen and X. N. Gong, "The influence of the parameters of the diaphragm wall on the deformation of the excavation," *E3S Web Conf.*, vol. 198, pp. 1–6, 2020, doi: 10.1051/e3sconf/202019802013.

[10] A. Masdar, Z. N. Wati, U. Khatab, and A. D. Masdar, "Asesmen Gedung Serba Guna Sekolah Tinggi Teknologi Payakumbuh (Assessment of the Multipurpose Building of Sekolah Tinggi Teknologi Payakumbuh)," *J. Civ. Eng. Plan. J.*, vol. 4, pp. 72–81, 2023, doi: 10.37253/jcep.v4i1.7825.

[11] M. Z. Syahdana and D. Safitri, "Perkiraan Kekuatan (Mutu) Beton Tanpa Merusak Beton (Pengujian Kuat Tekan Beton dengan Hammer Test)," *J. Ilmu Tek.*, vol. 1, no. 3, pp. 1–9, 2021.

[12] M. Md Nujid, D. A. Tholibon, and M. Mukhlisin, "Geotechnical and structural assessment on estimated bearing capacity of strip footing resting on silty sand incorporating moisture content effect," *Case Stud. Constr. Mater.*, vol. 20, no. March, p. e03106, 2024, doi: 10.1016/j.cscm.2024.e03106.

[13] N. N. Imam Robit, M. M. Nujid, N. S. Md Nor, D. A. Tholibon, and M. Mukhlisin, "Investigation Moisture Content Effect on Bearing Capacity Failure of Strip Footing Rested on Silty Sand Soil Based on Crack Characteristics Assessment Using Non-Destructive Test," *Procedia Struct. Integr.*, vol. 47, no. 2022, pp. 597–601, 2023, doi: 10.1016/j.prostr.2023.07.064.

[14] M. Aghayarzadeh, H. Khabbaz, and B. Fatahi, "Numerical analysis of concrete piles driving in saturated dense and loose sand deposits," in *Numerical methods in geotechnical engineering IX*, 2018, vol. 2, pp. 1031–1038.

[15] Perum Jasa Tirta II, "Laporan Akhir Pekerjaan Inspeksi Dan Pengujian Beton Dengan Schmidt Hammer Pada Kegiatan Inspeksi Tailrace Kanan Bendungan IR. H. Djuanda

ISSN (*Online*) 2581-2157
V. A. Damayanti/ U Karst Vol 08 No. 02 Year 2024 ISSN (*Print*) 2502-9304
Tahun 2021," 2021.

[16] Perum Jasa Tirta II, "Laporan Akhir Kajian Mutu Beton Dalam Rangka Inspeksi Tailrace Kanan Dan Access Gallery Bendungan IR. H. Djuanda," 2021.

[17] J. Kou, L. Li, and J. Shi, "Experimental Study on Durability and Mechanical Properties of High Ductile Concrete under Long-Term Sulfate Attack," *KSCE J. Civ. Eng.*, vol. 26, no. 4, pp. 1793–1802, 2022, doi: 10.1007/s12205-022-0445-2.

[18] Y. Qian, D. Yang, M. Liu, Z. Guo, Z. Xiao, and Z. Ma, "Performance recovery of high-temperature damaged ultra-high-performance concrete under different curing environments," *Dev. Built Environ.*, vol. 16, no. October, p. 100274, 2023, doi: 10.1016/j.dibe.2023.100274.

[19] H. Ma, W. Gong, H. Yu, and W. Sun, "Durability of concrete subjected to dry-wet cycles in various types of salt lake brines," *Constr. Build. Mater.*, vol. 193, pp. 286–294, 2018, doi: 10.1016/j.conbuildmat.2018.10.211.

[20] H. Shao, Z. Li, S. Xiao, X. Yao, and N. Zhang, "Mechanical Properties and Microstructure of Concrete under Drying-Wetting Cycles," *Bull. Chinese Ceram. Soc.*, vol. 40, no. 9, pp. 2948–2955, 2021.

[21] U. Marushchak, N. Sydor, S. Braichenko, and M. Hohol, "Effect of Dry–Wet Cycles on Properties of High Strength Fiber-Reinforced Concrete," in *Lecture Notes in Civil Engineering*, 2024, vol. 438, pp. 265–272, doi: 10.1007/978-3-031-44955-0_27.

[22] J. B. Yang, J. D. Yang, W. C. Guo, J. J. Luo, and G. F. Fu, "Investigation of water column separation induced by pressure pulsation based on critical cavitation rate model," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 774, no. 1, 2021, doi: 10.1088/1755-1315/774/1/012055.

[23] M. S. Won and C. P. Langcuyan, "A 3D numerical analysis of the compaction effects on the behavior of panel-type MSE walls," *Open Geosci.*, vol. 12, no. 1, pp. 1704–1724, 2020, doi: 10.1515/geo-2020-0192.

[24] L. S. Tang and Y. X. Wang, "Study on the Internal Mechanics and Energy Characteristics of Soil under Different Failure Modes," *Appl. Sci.*, vol. 13, no. 15, 2023, doi: 10.3390/app13158648.

[25] A. El Maguiri, S. Souabi, M. Z. Toro, and L. Idrissi, "Design of the Safe Model of Landfill Dikes for Developing Countries," *Civ. Environ. Eng.*, vol. 16, no. 1, pp. 11–20, 2020, doi: 10.2478/cee-2020-0002.

[26] C. A. Siregar, H. R. Nuggraha, G. A. Azhar, and D. Warlina, "Slope Stability Analysis Using Plaxis & Slope/W (Case Study: Bagbagan-Jampangkulon Road Section STA

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

8+400, STA 8+200, and STA 13+000)," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1321, no. 1, pp. 0–13, 2024, doi: 10.1088/1755-1315/1321/1/012031.

[27] N. Khalid, M. Darmon, and J.-F. Chaix, "Advanced Hohogenization Model For Ultrasonic Non-Destructive Testing Of Concrete and Its Validation," 2024, doi: 10.1115/QNDE2024-134694.

[28] X. Lai, Z. Kan, W. Sun, X. Song, B. Tian, and T. Yuan, "Digital twin-based non-destructive testing for structural health monitoring of bridges," *Nondestruct. Test. Eval.*, vol. 39, no. 1, pp. 57–74, 2024, doi: 10.1080/10589759.2023.2239434.

[29] A. Katunin, W. Danek, A. Wronkowicz, and K. Dragan, "Methodology of residual strength prediction of composite structures with low-velocity impact damage based on NDT inspections and numerical-experimental CAI testing," *Int. J. Impact Eng.*, vol. 181, no. April, p. 104762, 2023, doi: 10.1016/j.ijimpeng.2023.104762.