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Geological Investigation and Treatment of the Cabean Dam Foundation

Muhammad Perwira Rachman[1], Sri Sangkawati[1], Ignatius Sriyana[1], Yudi Kurniawan[2]

[1]*Civil Engineering, Diponegoro University, Semarang, Indonesia*
[2]*Balai Besar Wilayah Sungai Pemali Juana, Kementerian PU, Semarang, Indonesia*

**Corresponding Author: Muhammad Perwira Rachman*
Email: perwira.rachman@gmail.com

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Abstract

Embankment dams are critical infrastructure requiring comprehensive geological and geotechnical investigation to ensure long-term structural integrity and prevent catastrophic failure. This study presents the results of two-stage Multichannel Analysis of Surface Waves (MASW) investigations conducted at Cabean Dam core zone to characterize shear wave velocity (Vs) profiles and identify weak zones susceptible to seepage and slope instability. The first stage (2022) involved 17 survey lines while the second stage (2025) comprised 11 additional lines targeting critical areas. Shear wave velocity values ranged from 78–756 m/s, indicating significant material heterogeneity. Low Vs anomalies (78–200 m/s) were identified in the upper 0–7 meter depth at survey lines L-01, L-07, L-08, and L-09, correlating with residual soil having high permeability values up to 3.06×10^{-4} m/s and Lugeon values reaching 25.34 Lu. Integration of MASW data with borehole logs confirmed material classifications ranging from Site Class E (soft soil) at shallow depths to Site Class B (stiff soil) at greater depths. The identified weak zones pose significant risks for seepage, internal erosion (piping), and slope instability, requiring remedial measures including recompaction, optimized internal drainage design, and enhanced instrumentation monitoring. This research contributes methodological advancement in applying MASW as an integral component of staged investigation protocols for embankment dam projects, particularly for monitoring and refining geological-geotechnical conditions during construction phase. Results serve as a reference for practitioners and researchers in geotechnical dam engineering for improving safety and reliability of embankment dam infrastructure in Indonesia.

Introduction

Dams are strategic infrastructure with vital functions in water supply, irrigation, hydroelectric power generation, and flood control. The safety and stability of dams depend heavily on the geological and geotechnical conditions of their foundations. Comprehensive engineering geological investigation is a fundamental prerequisite at every stage of dam construction, from planning, design, construction, to operation, to ensure long-term structural integrity and prevent potential failures that could have catastrophic impacts (Fekadu et al., 2025; Moradi et al., 2022; Saberi Mehr & Field, 2021).

Embankment dams, as one of the most common dam types, are structures constructed from compacted soil or rock material in layers (Salehi, D., & Heidari, A. (2022; Wang et al., 2023; EL-Molla & Kilit, 2025) . This structure consists of several main zones with specific

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functions, including the impervious core, transition zone, shell/support zone, and filter and drainage zones. The dam core is the most critical component as it serves as the main barrier to prevent water seepage from the reservoir to the downstream section (ICOLD, 2020). Dam failures are often caused by inadequate understanding of subsurface geological conditions, particularly in critical zones such as the dam core and spillway (Asthana & Khare, D. (2022; Lee et al., 2022; Połomski et al., 2025). Dam safety mechanisms face various threats, including seepage and internal erosion (Gordan et al., 2022; Monteiro et al., 2025). Seepage is the phenomenon of water flow through porous media forming the dam body and foundation. Uncontrolled seepage can cause internal erosion, which is the process of soil particle transportation due to hydraulic forces (Kumar, Kumar, et al., 2022). Piping is the most dangerous form of internal erosion, characterized by the formation of continuous channels within the dam body or foundation due to progressive erosion, and is one of the leading causes of embankment dam failure worldwide, contributing approximately 30–50% of total dam failures (Jafarian et al., 2024).

Slope instability in dams can occur on upstream or downstream slopes. Landslides are generally caused by a combination of factors including material with low shear strength, high groundwater table or rapid fluctuations, seismic loading, toe erosion, and the presence of weak zones in the foundation (Kramer, 1996). In the dam core zone, landslides can damage the integrity of the waterproofing system and create new seepage paths that potentially cause catastrophic failure (Liu et al., 2022). Therefore, continuous and multi-stage engineering geological investigation is essential to identify, characterize, and mitigate these risks (Fekadu et al., 2025; Moradi et al., 2022; Saberi Mehr & Field, 2021).

Engineering geological investigation in dam projects is conducted in stages following the planning, design, construction, and operation cycle (Adiyanto et al., 2020). Conventional investigation methods include surface geological mapping, core drilling, standard penetration testing, and laboratory testing. However, given the complexity of subsurface geological conditions and the limitations of conventional point-based investigation methods, non-destructive geophysical methods such as Multichannel Analysis of Surface Waves (MASW) are increasingly used to complement conventional investigations due to their capability to provide continuous information and extensive spatial coverage with more efficient costs and time (Foti et al., 2018; Majer & Lüschen, 2007; Thompson & Zupan, 2024).

MASW is a non-destructive seismic geophysical method that utilizes the dispersive property of surface waves, particularly Rayleigh waves, to determine subsurface shear wave velocity profiles. Rayleigh waves propagate along the earth's surface with energy comprising approximately 67% of the total seismic energy generated (Consortium, 2024). The dispersive property of Rayleigh waves refers to the phenomenon where phase velocity depends on frequency. In a layered medium, low-frequency components penetrate deeper and are influenced by deeper layer properties, while high-frequency components are more sensitive to shallow layer properties. Analysis of the relationship between phase velocity and frequency produces a dispersion curve that serves as the basis for Vs profile inversion (Shinoda et al., 2023).

The MASW method consists of three main stages: data acquisition, dispersion curve analysis, and inversion (Thompson & Zupan, 2024). Data acquisition typically uses a multi-channel configuration with 12–48 geophones placed linearly with consistent spacing between them. Seismic sources can be hammers, weight drops, or vibroseis. Recording data in time-distance domain is transformed into frequency-phase velocity domain using various transformation techniques to produce a dispersion spectrum. From the dispersion spectrum, the dispersion curve is extracted by selecting energy peaks at each frequency (Adiyanto et al., 2020;

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Thompson & Zupan, 2024). Inversion is a mathematical process to estimate the Vs profile that best fits the observed dispersion curve. MASW inversion uses an iterative approach where an initial Vs model is assumed, theoretical dispersion curve is calculated, and the Vs model is updated iteratively until convergence (Zhang et al., 2023). In the context of dam investigation, the MASW method has been widely applied for dam foundation characterization, identification of weak zones, evaluation of embankment material compaction quality, detection of zones with high permeability, structure integrity monitoring, and seismic site classification for dynamic response analysis.

Shear wave velocity is a direct indicator of stiffness and mechanical properties of soil and rock. Vs values are influenced by material type, compaction level, porosity, water saturation level, effective overburden pressure, and the presence of fractures or discontinuities (Phoon & Kulhawy, 1999; Uchida et al., 2020). Various international standards use Vs for seismic site classification. NEHRP classifies sites as follows: Site Class A (hard rock, Vs > 1500 m/s), Site Class B (rock, 760 < Vs ≤ 1500 m/s), Site Class C (hard soil to soft rock, 360 < Vs ≤ 760 m/s), Site Class D (stiff soil, 180 < Vs ≤ 360 m/s), and Site Class E (soft soil, Vs < 180 m/s) (Kramer, 1996). Maximum dynamic shear modulus can be calculated using the equation:

$$G_{max} = \rho . V_s^2 \quad (1)$$

where ρ is the material density. Dynamic Young's modulus and Poisson's ratio can be estimated from the combination of Vs and compressional wave velocity through elasticity theory. These elastic parameters are important for stress-strain and deformation analysis of dam structures (Kramer, 1996). Comprehensive investigation of dams requires integration of data from various methods to reduce uncertainty and increase interpretation confidence. A multi-stage and multi-method approach allows for cross-validation of results among methods, improved spatial resolution, characterization of parameters that cannot be measured by a single method alone, and identification of anomalies with high confidence levels.

Initial engineering geological investigation at Cabean Dam site was conducted in 2021 and 2022 through Identification Study (SID) and Detailed Engineering Design (DED) activities. Investigation stages included surface geological mapping, core drilling, laboratory testing of soil and rock parameters, and hydrogeological analysis. The data obtained provided fundamental information regarding lithology, geological structures, physical and mechanical properties of materials, and hydrogeological characteristics (Petrone et al., 2023; Gabrielsen & Olesen, 2024; Cao et al., 2024). Additional investigation using the MASW method was then conducted in two stages. The first stage in 2022 involved 17 survey lines to characterize shear wave velocity profiles and elastic properties of materials at dam foundation and embankment. The second stage in 2025 was conducted with 11 additional lines strategically placed in critical zones, particularly in the dam core area and around the spillway, to provide higher spatial resolution and deeper understanding of local geotechnical conditions (Bucci et al., 2022; Hasan et al., 2022; Liu et al., 2022).

The MASW method was selected for its capability to map lateral and vertical variations in mechanical properties of soil and rock continuously, identify weak zones, estimate shear modulus, and detect variations in material saturation levels that directly relate to permeability and dam stability. Shear wave velocity data obtained are used to estimate material elastic modulus and foundation quality classification, which are important parameters in dam stability and deformation analysis (Dou et al., 2024; Foti et al., 2018; Pérez-Ruiz et al., 2007; Strobbia & Cassiani, 2007). This research aims to analyze geotechnical characteristics based on shear wave velocity profiles, identify critical zones, and provide recommendations for dam construction and operational management. The significance of this research includes

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methodological contributions in applying MASW as an integral part of staged investigation protocols in dam projects and improved understanding of geotechnical conditions during the construction phase.

Methods

Location and Technical Data of Cabean Dam

Cabean Dam is located in Karanganyar Village and Tondanan Village, Tondanan District, Blora Regency, Central Java Province as shown in *Figure 1*. The planned dam axis location is at coordinates 6°55'15.1"S and 111°9'33.1"E. This dam is strategic infrastructure with functions including irrigation of 80 hectares, raw water supply of 0.127 m³/second, micro-hydro power generation of 84 kW, and flood control up to 25-year design discharge with retention of 86.04%. The dam is a zoned embankment type with vertical core, 25.00 meter height, 339.00 meter length, 7.00 meter crest width. Effective storage volume reaches 2.58 million m³.

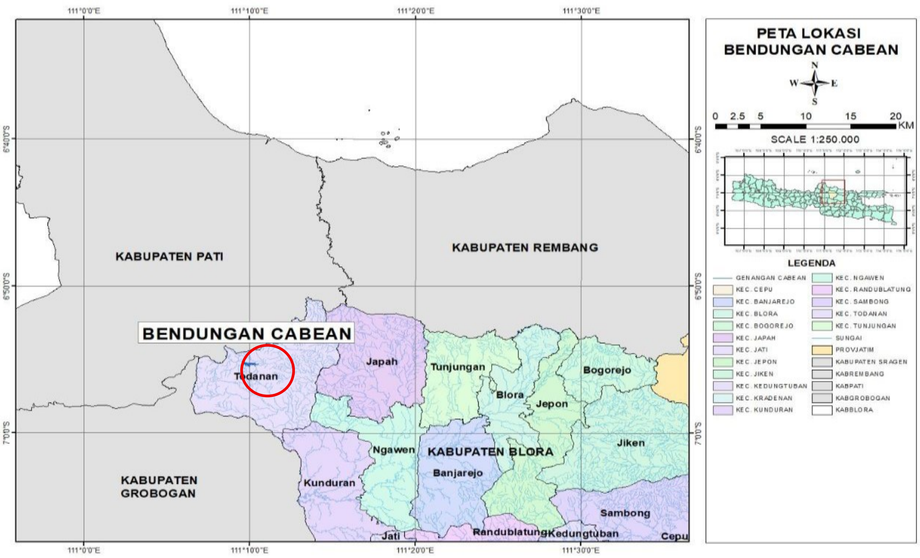

Figure 1. Cabean Dam Location

Investigation Data and Testing Equipment

Data used include results of initial engineering geological investigation from SID and DED (2021–2022) consisting of borehole log data from 10 drilling points with depths of 15–35 meters in the dam core zone. Data include lithological classification, rock conditions (completely weathered to fresh), hardness level, rock classification according to engineering geology standards, as well as permeability values and Lugeon test results from various depths.

MASW (Multichannel Analysis of Surface Waves) is a non-invasive geophysical method to determine shear wave velocity of soil at various depths. This method works by utilizing Rayleigh surface waves that propagate through soil layers; the wave velocity differs depending on frequency (dispersion), so it can be analyzed to calculate shear wave velocity profiles at different depths. The test procedure consists of three stages: first, data acquisition by placing a series of geophones (sensors) on the ground surface at equal intervals (typically 1 meter apart), then generating waves by striking a ground and recording the arrival time of waves at each geophone using a seismograph; second, data processing by converting raw data to the frequency domain and creating a dispersion curve that shows the relationship between phase velocity and frequency; third, inversion where a computer compares the measured

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dispersion curve with theoretical models iteratively until producing a shear wave velocity profile versus depth. To obtain a 2D map, the entire geophone array is moved to a new position and the process is repeated until all 1D profiles are combined to form a 2D cross-section.

MASW testing was conducted in two stages using standard equipment including 24–48 channel multi-channel seismograph for digital data acquisition, 4.5 Hz geophones, sledgehammer seismic source of 8 lb with aluminum strike plate, multi-channel seismic cables, power system (batteries), laptop for control and real-time visualization, and GPS for location determination. Acquisition parameters include 24 geophones, 2-meter spacing between geophones, 2-meter offset, and 10-second recording duration per strike for investigation depth up to 30 meters.

Research Stages

The research was conducted through the following stages:

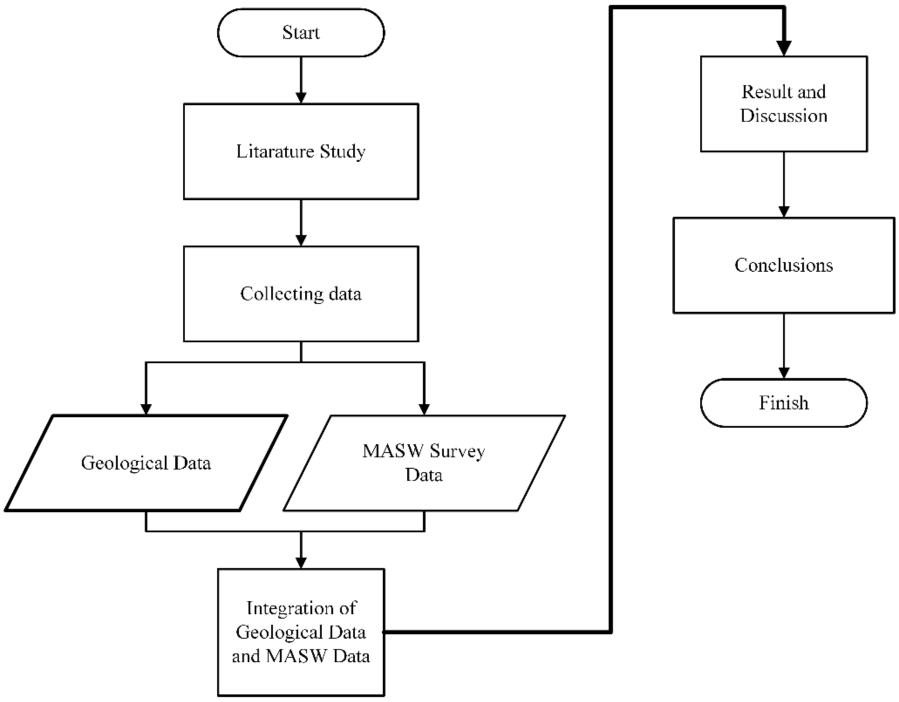

Figure 2. Research Flowchart

Results and Discussion

MASW Testing Results and Material Characteristics

MASW testing on 28 survey lines showed Vs values ranging 78–756 m/s, indicating significant heterogeneity. In 2022, Vs values ranged 87–750 m/s with lines BC-03, BC-07, BC-13, and BC-14 showing minimum values of 87–98 m/s at depths 0–7 m. In 2025, Vs ranged 78–756 m/s with line L-01 recording 78 m/s minimum, L-04 (93 m/s), L-09 (94 m/s), L-07 (112 m/s). Lines L-03 and L-11 showed higher values (220–267 m/s minimum) without significant low anomalies.

NEHRP classification showed core zone at depths 0–7 m predominantly in Site Class E (Vs < 180 m/s), indicating low density and stiffness. Material stratification shows: uppermost layer (0–5 m) of residual soil with complete weathering, soft consistency, and permeability 2.60×10^{-5} to 3.06×10^{-4} m/s (Lugeon 25.34 Lu); middle layer (5–15 m) of interlayered sandstone-siltstone-mudstone with Vs 200–400 m/s and permeability 1.61×10^{-4} to 9.95×10^{-6}

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m/s; lower layer (>15 m) of fresh rock with Vs 300–700 m/s and very low permeability (1.10×10^{-6} to 3.51×10^{-5} m/s).

Identification of Weak Zones

Analysis identified zones with low Vs anomalies. Lines L-01, L-07, L-08, L-09 from 2025 showed most significant anomalies: L-01 (78–200 m/s, depths 0–3 m), L-07 (112–200 m/s, 0–6 m), L-08 (78–200 m/s, 0–3 m), L-09 (94–200 m/s, 0–4 m). From 2022, lines BC-01 to BC-14 showed low Vs anomalies at 0–5 m depth; BC-07 and BC-14 recorded minimum 87 m/s. all the weak zone can be seen at Table 1.

Table 1. Identification of weak zone

Survey Line	Year	Location	Low Shear Wave Velocity Depth (m)	Shear Wave Velocity Range (m/s)	Lithology from Detailed Engineering Design	Permeability /Lugeon Values	Site Class	Key Findings
L-01	2025	Diversion outlet	0–3	78–200	Residual soil and Wonocolo Formation	Permeability: $2.60–3.06\times10^{-4}$ m/s; Lugeon: ≈25	E–D	Highly weathered residual soil; high seepage risk at diversion outlet
L-02	2025	Main dam toe downstream	0–3	161–200	Residual soil, colluvium, and Wonocolo Formation	Permeability: $10^{-5}–10^{-4}$ m/s; Lugeon: moderate	E–D	Soft layer at downstream toe; localized slope stability concerns
L-03	2025	Stilling basin spillway	Not significant	220–670	Fresh to compact Wonocolo Formation rock	Permeability: $10^{-6}–10^{-5}$ m/s; Lugeon: 5–10	C–B	Competent fresh rock; good bearing capacity; low internal erosion risk
L-04	2025	Main dam downstream slope	0–2	93–200	Embankment fill and soil cover over Wonocolo Formation	Permeability: $10^{-5}–10^{-4}$ m/s	E–D	Soft embankment layer; potential deformation risk during rapid drawdown
L-05	2025	Main dam downstream slope	0–2	147–200	Residual soil and embankment fill over Wonocolo Formation	Permeability: $10^{-5}–10^{-4}$ m/s; Lugeon: moderate	E–D	Shallow soft zone; potential surface cracking and seepage pathways
L-06	2025	Main dam downstream slope	3–6	142–200	Thick residual soil over Wonocolo Formation	Permeability: $10^{-5}–10^{-4}$ m/s	E–D	Weak layer at 3–6 m depth; potential failure plane and seepage pathway
BC-01	2022	Main dam axis left abutment	0–5	135–200	Residual soil and Wonocolo Formation	Permeability: 2.57×10^{-4} m/s; Lugeon: 21.7	E–D	Highly permeable residual soil; primary seepage pathway in core

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BC-03, BC-07, BC-13, BC-14	2022	Main dam axis and spillway	0–7	87–200	Residual soil, weathered rock, and fresh Wonocolo Formation	Permeability: 10^{-5}–10^{-4} m/s; Lugeon: >20	E–D to D–C	Lateral heterogeneity well-mapped by surface wave method; variable shear wave velocity distribution
BC-17	2022	Spillway	0–5	118–200	Thin residual soil over compact Wonocolo Formation rock	Permeability: 10^{-5}–10^{-5} m/s; Lugeon: 5–15	E–D to C–B	Shallow limited weak zone; spillway foundation quality adequate

Source : BBWS Pemali Juana

Correlation and Geotechnical Implications

MASW-borehole log integration shows strong correlation: low Vs zones correspond with residual soil and highly weathered material. For example, BC-01 borehole at 0–5 m with residual soil (permeability 2.57×10^{-4} m/s) corresponded with MASW Vs of 135–200 m/s. Weak zones with low Vs at shallow depths pose serious safety implications. At critical positions with significant dam weight and reservoir pressure stresses but minimal material strength, multiple failure modes threaten. First, seepage and internal erosion risks are very high; high permeability material becomes preferential water flow paths. Progressive erosion transporting fine particles forms channels or pipes. High Lugeon values confirm significant water transmission capability (Kumar, Kumar, et al., 2022).

Second, slope instability can occur during upstream rapid drawdown or downstream saturation, as material with low Vs has low shear strength. Third, seismic loading amplification is heightened in low Vs materials. These findings demand comprehensive remedial strategies.

Technical Recommendations for Handling Weak Zones

Remedial strategy combines multiple complementary approaches. Soil Improvement: Recompaction or soil improvement targets lines L-01, L-07, L-08, L-09. Dynamic compaction, proven for residual materials, increases Vs by 30–50% from Site Class E toward D ((Adiyanto et al., 2020). Chemical grouting with cement or stabilizing agents reduces permeability 1–3 orders of magnitude (Kumar, Singh, et al., 2022). Material replacement with high-quality compacted clay is alternative, though more costly (Liu et al., 2022).

Instrumentation Monitoring: Multi-parameter stations in weak zones include: piezometers for pore pressure and phreatic surface (ICOLD, 2020); settlement plates for vertical displacement; inclinometers for lateral movement; calibrated weirs for seepage discharge. Real-time automated systems enable early warning when thresholds exceed baseline (Thompson & Zupan, 2024). Periodic MASW re-surveys (2–3 year intervals) assess temporal Vs changes and validate improvement effectiveness.

Internal Drainage Optimization: Filter and transition zones require strict Terzaghi-Sherard gradation criteria preventing piping while maintaining hydraulic conductivity (Foti et al., 2018). Chimney and toe drains reduce phreatic surface and pore pressure. Geotextile filters supplement granular filters in fine-grained zones (Dou et al., 2024).

Numerical Stability Analysis: GeoStudio SLOPE/W or FLAC 3D models incorporating MASW-derived stiffness ($G = \rho Vs^2$) and validated shear strength parameters assess stress-

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deformation. Analyses include rapid drawdown, steady seepage, and seismic scenarios. Probabilistic risk analysis incorporating spatial variability provides realistic failure probability estimates; sensitivity analysis prioritizes monitoring and remediation efforts (Jafarian et al., 2024).

Construction Quality Control: During construction, in-situ density and periodic MASW surveys verify target Vs values. Core minimum target is Site Class C (Vs > 360 m/s); Class E materials (Vs < 200 m/s) should be avoided or substantially improved. Adaptive management based on monitoring results allows construction procedure modifications if performance deviates from design.

Conclusion

Results of the second-stage MASW investigation in Cabean Dam core zone yielded several important conclusions. Geotechnical characteristics of the core zone show significant material heterogeneity with the upper layer dominated by soft residual soil (Vs 78–200 m/s, Site Class E), the middle layer consisting of interlayered sandstone–siltstone–mudstone more compact (Vs 200–400 m/s, Site Class D), and the lower layer of fresh rock with high strength and waterproofing (Vs >300–700 m/s, Site Class C–A).

Weak zones were identified on lines L-01, L-07, L-08, L-09 with low Vs anomalies (78–200 m/s) at depths 0–6 meters, confirmed by borehole log data showing high permeability up to 3.06×10^{-4} m/s and Lugeon values reaching 25.34 Lu. These zones potentially become preferential seepage paths and areas prone to slope instability and internal erosion.

Integration of second-stage MASW data (11 lines, 2025) with previous investigations (first-stage MASW 17 lines 2022, SID and DED 2021–2022, borehole logs) shows high consistency in identifying geotechnical conditions. Data comparison shows that low Vs zones correlate strongly with completely weathered material, residual soil, and high permeability. Significant lateral variability in material quality (example lines BC-15/L-11 with higher Vs) confirms core zone heterogeneity requiring special attention in design and construction.

Comprehensive investigation using MASW method as part of a staged investigation protocol has increased confidence level in the geotechnical engineering model and provided a strong basis for specific handling recommendations including recompaction of weak zones, optimization of drainage systems, strengthening of instrumentation monitoring, and numerical stability analysis with parameters characterized from multi-method investigation. This research provides important methodological contributions in applying modern geophysical technology to improve safety of embankment dam infrastructure in Indonesia.

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References

Adiyanto, B., Soemitro, R. A. A., & Sumardi, S. (2020). Comparison of MASW and seismic refraction for embankment dam foundation characterization. *Geotechnical and Geological Engineering*, *38*(5), 5081–5093. https://doi.org/10.1007/s10064-020-01769-z

ISSN: 2716-3865 (Print), 2721-1290 (Online)

Asthana, B. N., & Khare, D. (2022). Embankment Dams. In *Recent Advances in Dam Engineering* (pp. 89-123). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-32278-6_5

Bucci, F., Santangelo, M., Fongo, L., Alvioli, M., Cardinali, M., Melelli, L., & Marchesini, I. (2022). A new digital lithological map of Italy at the 1: 100 000 scale for geomechanical modelling. *Earth System Science Data*, *14*(9), 4129-4151.

Cao, X., Liu, Z., Hu, C., Song, X., Quaye, J. A., & Lu, N. (2024). Three-dimensional geological modelling in earth science research: an in-depth review and perspective analysis. *Minerals*, *14*(7), 686. https://doi.org/10.3390/min14070686

Consortium, E. (2024). Near-surface Rayleigh wave dispersion curve inversion algorithms: A comprehensive comparison. *Surveys in Geophysics*, *45*(3), 941–967. https://doi.org/10.1007/s10712-024-09826-y

Dou, Z., Tang, Q., Liu, H., & Chen, Z. (2024). Application of MASW method in dam foundation investigation. *Open Journal of Geology and Mining*. https://doi.org/10.1007/s44290-024-00124-5

EL-Molla, D. A., & Kilit, M. (2025). Seepage Control, Detection, and Treatment in Embankment Dams: A State-of-the-Art Review. *Arabian Journal for Science and Engineering*, 1-27. https://doi.org/10.1007/s13369-025-10185-y

Fekadu, A., Chemeda, Y. C., Karuppannan, S., & Chala, E. T. (2025). Engineering geological evaluation of Bowa Dayole dam site, North Shewa Zone, Oromia, Ethiopia. *Heliyon*, *11*(1), e41385. https://doi.org/10.1016/j.heliyon.2024.e41385

Foti, S., Lai, C. G., Rix, G. J., & Strobbia, C. (2018). *Surface wave methods for near-surface site characterization*. CRC Press.

Gabrielsen, R. H., & Olesen, O. (2024). The concept of lineaments in geological structural analysis; principles and methods: a review based on examples from Norway. *Geomatics*, *4*(2), 189-212. https://doi.org/10.3390/geomatics4020011

Gordan, B., Raja, M. A., Armaghani, D. J., & Adnan, A. (2022). Review on dynamic behaviour of earth dam and embankment during an earthquake. *Geotechnical and Geological Engineering*, *40*(1), 3-33. https://doi.org/10.1007/s10706-021-01919-4

Hasan, M., Shang, Y., Shao, P., Yi, X., & Meng, H. (2022). Evaluation of engineering rock mass quality via integration between geophysical and rock mechanical parameters. *Rock Mechanics and Rock Engineering*, *55*(4), 2183-2203. https://doi.org/10.1007/s00603-021-02766-8

ICOLD. (2020). *Internal erosion of dams and their foundations* (Vol. 3). International Commission on Large Dams.

Jafarian, Y., Javaheri, B., & Behnam, B. (2024). Reliability analysis of backward erosion piping in an embankment dam considering the spatial variability of soil properties. *Scientific Reports*, *15*, 9175. https://doi.org/10.1038/s41598-025-09175-9

Kramer, S. L. (1996). *Geotechnical earthquake engineering*. Prentice-Hall, Inc.

Kumar, V., Kumar, A., & Rana, N. (2022). A numerical analysis of the leakage characteristics of an embankment dam slope with internal erosion. *Frontiers in Earth Science*, *10*, 866238. https://doi.org/10.3389/feart.2022.866238

ISSN: 2716-3865 (Print), 2721-1290 (Online)

Kumar, V., Singh, P., & Rao, K. (2022). Real-time monitoring of embankment dams using integrated sensor networks and geophysical methods. *Sensors*, *22*(7), 2482. https://doi.org/10.3390/s22072482

Lee, Y. H., Ryu, J. H., Heo, J., Shim, J. W., & Lee, D. W. (2022). Stability improvement method for embankment dam with respect to conduit cracks. *Applied Sciences*, *12*(2), 567. https://doi.org/10.3390/app12020567

Liu, D., Liu, H., Wu, Y., Zhang, W., Wang, Y., & Santosh, M. (2022). Characterization of geo-material parameters: Gene concept and big data approach in geotechnical engineering. *Geosystems and Geoenvironment*, *1*(1), 100003.

Liu, H., Wang, X., & Sun, Y. (2022). Failure behavior attributed to internal erosion caused by conduit cracks in homogeneous embankment. *Applied Sciences*, *12*(13), 6305. https://doi.org/10.3390/app12136305

Majer, E. L., & Lüschen, E. (2007). Geophysics in dam engineering. In *Encyclopedia of Surface and Applied Geophysics*. Society of Exploration Geophysicists.

Monteiro-Alves, R., Moran, R., Toledo, M. Á., Jimenez-Rodriguez, R., Picault, C., & Courivaud, J. R. (2025). Overflow-Induced Breaching in Heterogeneous Coarse-Grained Embankment Dams and Levees A State of the Art Review. *Applied Sciences*, *15*(16), 8808. https://doi.org/10.3390/app15147811

Moradi, S., Vakili, A. H., & Ghalandarzadeh, A. (2022). Seismic characterization of embankment dams using MASW method. *Environmental Earth Sciences*, *81*(13), 1–18. https://doi.org/10.1007/s12665-022-10463-0

Pérez-Ruiz, J. A., Luzón, F., García-Jerez, A., & Navarro, M. (2007). Rayleigh wave mode velocities in sedimentary layers over bedrock. *Geophysical Journal International*, *170*(1), 219–230. https://doi.org/10.1111/j.1365-246X.2007.03395.x

Petrone, P., Allocca, V., Fusco, F., Incontri, P., & De Vita, P. (2023). Engineering geological 3D modeling and geotechnical characterization in the framework of technical rules for geotechnical design: the case study of the Nola's logistic plant (southern Italy). *Bulletin of Engineering Geology and the Environment*, *82*(1), 12. https://doi.org/10.1007/s10064-022-03017-y

Phoon, K. K., & Kulhawy, F. H. (1999). Characterization of geotechnical variability. *Canadian Geotechnical Journal*, *36*(4), 612–624. https://doi.org/10.1139/cgj-36-4-612

Połomski, M., Wiatkowski, M., & Ługowska, G. (2025). Comparative Analysis of Studies of Geological Conditions at the Planning and Construction Stage of Dam Reservoirs: A Case Study of New Facilities in South-Western Poland. *Applied Sciences*, *15*(14), 7811.

Saberi Mehr, S., & Field, M. S. (2021). Investigating seepage paths at Golfaraj earthen dam, northwest Iran. *Quarterly Journal of Engineering Geology and Hydrogeology*, *55*(2), 444–453. https://doi.org/10.1144/qjegh2021-053

Salehi, D., & Heidari, A. (2022). Embankment dam design with dispersive soil: solutions and challenges. *Geotechnical and Geological Engineering*, *40*(8), 4289-4299. https://doi.org/10.1007/s10706-022-02153-2

Shinoda, M., Kunii, S., & Inada, Y. (2023). Multiple inversions of Rayleigh wave dispersion curve for geotechnical site characterization using particle swarm optimization and

ISSN: 2716-3865 (Print), 2721-1290 (Online)

genetic algorithm. *Journal of Physics: Conference Series*, *2103*(1), 12007. https://doi.org/10.1088/1755-1315/2103/1/012007

Strobbia, C., & Cassiani, G. (2007). Multi-offset phase analysis of surface wave data (MOPSWA). *Journal of Applied Geophysics*, *63*(3–4), 159–169. https://doi.org/10.1016/j.jappgeo.2007.05.003

Thompson, E. M., & Zupan, K. S. (2024). Determination of seismic site class and potential geologic hazards using multi-channel analysis of surface waves (MASW) at the industrial city of Abu Dhabi, UAE. *Transportation Geotechnics*, *36*, 100877. https://doi.org/10.1080/20909977.2022.2055829

Uchida, A., Abe, K., & Uchikawa, Y. (2020). Dataset of computed N-value and factual N-value traced for soil subsurface profiling. *Data in Brief*, *30*, 105607. https://doi.org/10.1016/j.dib.2020.105607

Wang, Y., Zhao, Y., Liu, B., Wang, N., & Li, C. (2023). Key technologies and future development trends of intelligent earth-rock dam construction. *Journal of Intelligent Construction*, *1*(3), 1-18. https://doi.org/10.26599/JIC.2023.9180018

Zhang, G., Zhang, S., & Li, Y. (2023). Research on the Rayleigh surface wave inversion method based on the improved whale optimization algorithm. *Annals of Geophysics*, *66*(5), 9042. https://doi.org/10.4401/ag-9042

ISSN: 2716-3865 (Print), 2721-1290 (Online)