The Influence of Particle Size on the Elastic Modulus of Rock-Fill Materials Based on Consolidation Tests

M. Yushar Yahya Alfarobi
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
yuzniar@gmail.com

M. Bisri
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
mbisri@ub.ac.id

Lily Montarcih Limantara
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
lilymont@ub.ac.id (corresponding author)

Runi Asmaranto
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
runi_asmaranto@ub.ac.id

Received: 21 January 2026 | Revised: 1 March 2026 | Accepted: 15 March 2026

 DOI: https://doi.org/10.48084/etasr.17675

ABSTRACT

The elastic modulus is a key parameter influencing the deformation behavior of rockfill materials in Concrete Face Rockfill Dams (CFRDs), which is typically obtained from laboratory tests; however, these tests are limited by the maximum particle size, so specimen downscaling is required. This can result in a "size effect," leading to an apparent elastic modulus that does not accurately represent actual field conditions. This study analyzes the influence of maximum particle size (D_{max}) on the elastic modulus of Bener CFRD andesite rockfill using consolidation testing. Five samples ranging from 10 mm to 120 mm were tested under staged loading up to 2.5 MPa. The elastic moduli were determined as the oedometer modulus (E_{oed}) during initial loading and the unloading–reloading modulus (E_{ur}) during post-loading. After analyzing the results using an empirical approach, it was found that increasing D_{max} leads to higher strain and significantly reduces both E_{oed} and E_{ur}. E_{oed} values at a laboratory scale (D_{max} 10-120 mm) resulted in 78.77-156.45 MPa, while under field conditions (D_{max} 37.5-1000 mm) resulted in 44.71-107.35 MPa. Similarly, the E_{ur} values in the laboratory scale range from 510.70 - 6,181.75 MPa, while the field conditions range from 61.94 - 1,636.04 MPa. An empirical relationship was established between D_{max} and the elastic modulus, indicating that laboratory tests using smaller particle sizes tend to overestimate the elastic modulus compared to actual field conditions. Therefore, appropriate corrections or empirical adjustments are needed when applying the results to field conditions. This study confirmed that predicted laboratory elastic modulus values can be used as key parameters for deformation and deflection modeling of CFRD with andesite rockfill material.

Keywords-elastic modulus; CFRD; particle size effect; maximum particle size; consolidation testing; oedometer modulus; unloading–reloading modulus

I. INTRODUCTION

Concrete Face Rockfill Dams (CFRDs) are one of the most widely used types of rock fill dams for large projects in Indonesia, including the Bener Dam in Purworejo Regency, Central Java. In CFRDs, an inclined concrete slab on the upstream side of the dam provides impermeability, while the dam body's deformation response largely depends on the mechanical properties of the rock fill materials. Authors in [1] showed that structural variables such as dam height and reservoir size strongly influence the impact of dam failure. In the context of CFRDs, embankment deformation can contribute to concrete face slab failure and increase the risk of overall dam failure. According to [2], higher CFRDs tend to experience greater embankment deformation. Therefore, accurately understanding the rockfill deformation behavior is significant to evaluating the performance and safety of a CFRD. According to [3], the most dominant rockfill parameter in dam deformation analysis is the elastic modulus (E) of the embankment materials. The elastic modulus determines the deformation response under self-weight, hydrostatic pressure, and long-term effects such as creep. In this study, the elastic modulus of the rockfill material was determined using laboratory test results, particularly one-dimensional consolidation (oedometer) tests conducted on rockfill materials obtained from the Bener CFRD quarry. This testing method is preferred because it measures one-dimensional stress and strain conditions, which are consistent with the vertical deformation mechanism and more efficient than other testing methods. However, this test has a significant limitation related to the maximum particle size that can be tested. Rockfill materials are used in dam embankments, especially in rockfill zones characterized by very large, heterogeneous particle sizes. Due to constraints of the laboratory equipment, the maximum particle size tested must be reduced from actual field conditions. This leads to a phenomenon known as the "size effect," where mechanical behavior differs due to scale differences between laboratory- and field-scale specimens [4]. The rock fill material at the Bener CFRD is supplied from a local quarry and has relatively large particle sizes and varied gradation. Consolidation tests were conducted on these materials to determine the deformation parameter, particularly the vertical elastic modulus. This study aims to analyze how the size of the particles affects the elastic modulus values obtained from consolidation tests of rockfill materials from the quarry, proposing of an empirical relationship between the maximum particle size and elastic modulus of rockfill materials. This relationship can serve as a basis for analyzing the deformation of andesite rockfill embankments and evaluating the deflection of concrete face slabs in CFRDs. Elastic modulus values must be examined in order to consider size effects and ensure more accurate CFRD deformation and deflection analyses.

II. MATERIALS AND METHODS

A. Rockfill Material

This study uses materials derived from a local quarry in Wadas Village, Bener District, Purworejo Regency, Central Java Province, Indonesia, the primary source of rockfill material for the Bener Dam. Therefore, these materials are assumed to represent the actual conditions of the dam embankment. Based on early geological identification during Bener CFRD planning, the rocks from this quarry were classified as andesite [5]. Andesite is a volcanic igneous rock that generally exhibits high compressive strength, relatively high stiffness, and good weather resistance. These properties make andesite a popular choice for rock-fill material in CFRDs due to its ability to provide stability and an adequate deformation response under long-term loading. Generally, andesite used for rockfill, exhibits angular to subangular fragment shapes, a rough surface texture, and a heterogeneous particle size distribution, as shown in Figure 1. According to [6], the angular shape and rough surface of andesite fragments contribute to strong interlocking between particles, thereby enhancing the stiffness and deformation resistance of embankment materials. Authors in [7] showed that the average Unconfined Compressive Strength (UCS) of andesite rock test specimens is 115 MPa, the dry density is 2.4 g/cm³, the specific gravity is 2.5 g/cm³, and the shear stress is 490. However, the deformation behavior of andesite rock fill is influenced by the particle size, degree of compaction, and applied stress conditions.

Fig. 1. Andesite from Bener quarry.

B. Particle Size Distribution and Size Reduction Scheme

The Particle Size Distribution (PSD) of the rockfill material was determined using a combination of sieve analysis and field observations of large particles. Due to limitations of the laboratory apparatus in testing materials with large particle sizes, the maximum particle size (D_{max}) needed to be reduced. According to [8], laboratory gradation test results indicate particle size distribution, which significantly influences embankment deformation behavior. Well-graded rock-fill material has a more stable internal structure because smaller particles fill the voids between larger particles, which enhances interlocking and increases the elastic modulus. The particle size reduction was performed while maintaining the general shape of the original gradation curve to ensure that changes in mechanical behavior were primarily attributed to the scale effect on the rockfill material. Several gradation variations with different maximum particle sizes were prepared to evaluate the influence of size on the elastic modulus of embankment rockfill material. Authors in [9], using Discrete Element Method (DEM), showed that small-scale results cannot be directly applied to field-scale analysis without scale correction. Rockfill materials with larger particle sizes tend to experience higher degrees of particle crushing under certain stress conditions, which can significantly affect their elastic response [10].

C. Laboratory Testing

This study focuses on one-dimensional consolidation tests to determine the relationship between the vertical stress and strain of andesite rockfill material from the quarry. The stress-strain relationship was then used to determine the elastic modulus for each variation in maximum particle size, enabling the evaluation of the effect of size on the elastic parameter. The consolidation tests were conducted using an oedometer apparatus with a specimen tube that was 19.2 cm in diameter and 20 cm in height, as displayed in Figure 2. These dimensions limit the maximum particle size that can undergo testing; therefore, the maximum particle size of the specimen needs to be adjusted while maintaining the actual gradation characteristics. The rock specimens consisted of three variations based on maximum particle sizes (D_{max}) of 10 mm, 20 mm, 32 mm, 80 mm, and 120 mm. The selection of D_{max} values was primarily affected by the limitations of specimen size inherent to oedometer testing. To minimize boundary effects and ensure representative stress transmission, the maximum particle size was selected according to established experimental practice. The chosen particle sizes provide systematic variation, allowing for evaluating the effects of particle size on stiffness behavior. Additionally, the selected D_{max} range enables identifying scaling trends relevant to modulus interpretation.

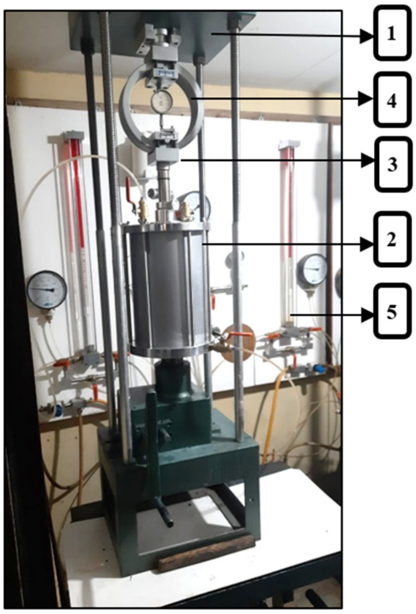

Fig. 2. Oedometer consolidation test apparatus: 1 = loading frame (15 t); 2 = oedometer tube (d = 20 cm, h =20 cm); 3 = hydraulic cylinder (10 t); 4 = prov ring (10 t); 5 = back pressure unit (for saturation).

Loading was applied gradually in 30-min intervals at each stage. The vertical stress increased gradually from 0.05 MPa to 0.1 MPa, 0.2 MPa, and 0.3 MPa, continuing up to a maximum of 1.6 MPa during the loading stage. After reaching the maximum stress, the stress was gradually reduced back to 0.05 MPa through unloading. The oedometer test procedure, including load selection and load time, followed ASTM D 2435-03 [11]. Vertical settlement data were obtained during the loading and unloading stages and were used to calculate the vertical strain. This strain was then correlated with vertical stress to determine the elastic modulus values for each size variation. This approach enables a quantitative evaluation of the size effects resulting from specimen downscaling.

D. Determination of Elastic Modulus

Authors in [12] defined the elastic modulus as the ratio of stress to strain in a material. In CFRD, the elastic modulus of the rock fill material is a significant mechanical parameter because it directly controls the embankment's deformation response and significantly influences the performance and integrity of the concrete face slab. Authors in [13, 14] stated that the elastic modulus can be defined as either the secant or the tangent modulus, depending on the loading conditions being analyzed. The secant modulus is obtained from the ratio of stress and strain change during loading, while the tangent modulus is obtained during the unloading-reloading stages. In this study, the secant modulus under loading is denoted E_{oed}, and the tangent modulus under unloading-reloading is denoted E_{ur}:

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

The elastic modulus is considered a stress-dependent parameter. Therefore, the elastic modulus was determined as a function of vertical stress for each maximum particle size variation (D_{max}):

$$E = f(\sigma_v) \tag{2}$$

Elastic modulus values were obtained at various vertical stress levels and analyzed for each Dmax variation. To evaluate the size effect resulting from specimen downscaling, the relationship between the elastic modulus and maximum particle size, was analyzed at specific stress levels using empirical approaches like logarithmic regression and power-law relationships:

$$E = c \times \sigma^d \tag{3}$$

where c and d are material constants determined through the logarithmic regression analysis of laboratory test data which represent the relationship between the elastic modulus and the vertical stress across the different particle size distributions, both during the loading and unloading–reloading stages. The relationship between the elastic modulus and maximum particle size was analyzed using logarithmic regression and power-law models. These models are widely employed in rockfill materials to describe scale effects and nonlinear, stress-dependent behavior [15-16].

III. RESULTS AND DISCUSSION

A. Gradation Analysis of Andesite Rockfill Tests

A gradation analysis was conducted on andesite rockfill materials with several variations in maximum particle size to evaluate the effect of the maximum grain size on the elastic modulus. As shown in Tables I and II and Figure 3, the post-consolidation PSD analysis indicates systematic particle breakage across all D_{max} variations.

The increase in percent passing values at smaller sieve sizes confirms the generation of finer particles due to mechanical crushing. Additionally, the degree of particle breakage increases with D_{max}, suggesting that larger particles experience greater stress concentration and are more susceptible to crushing. This behavior is consistent with the observed increase in permanent strain and reduction in stiffness. Figure 4 illustrates images of the test specimen sample before and after testing for D_{max} of 20 mm and 80 mm.

TABLE I. THE RESULTS OF GRADATION ANALYSIS BEFORE AND AFTER TESTIING (DMAX = 10 MM, 20 MM, AND 32 MM)

Hole Diameter (mm)	Percent Passing (%)					
	10 mm		20 mm		32 mm	
	Before	After	Before	After	Before	After
38.1	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
25.4	100.0%	100.0%	100.0%	100.0%	88.8%	91.9%
19	100.0%	100.0%	86.0%	88.3%	74.8%	78.3%
12.5	100.0%	100.0%	75.7%	79.5%	67.5%	70.5%
9.5	78.4%	84.3%	59.8%	62.2%	54.5%	58.5%
4.75	58.4%	62.2%	46.5%	47.9%	40.5%	42.8%
2.36	41.1%	43.1%	34.5%	35.6%	29.5%	30.8%
1.18	28.8%	31.5%	24.5%	26.7%	20.5%	22.8%
0.6	20.1%	21.7%	16.5%	18.3%	13.5%	14.7%
0.3	12.4%	15.1%	10.9%	13.2%	8.9%	10.2%
0.15	6.9%	8.6%	6.2%	8.2%	5.2%	7.7%
0.075	2.2%	3.5%	2.2%	3.6%	2.2%	4.5%
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

TABLE II. THE RESULTS OF GRADATION ANALYSIS BEFORE AND AFTER TESTIING (DMAX = 80 AND 120 MM)

Hole Diameter (mm)	Percent Passing (%)			
	80 mm		120 mm	
	Before	After	Before	After
160	100.0%	100.0%	100.0%	100.0%
102	100.0%	100.0%	73.5%	78.9%
76	100.0%	100.0%	63.8%	68.7%
38	53.7%	55.9%	46.7%	49.5%
19	34.5%	36.5%	34.5%	36.2%
10	21.2%	23.2%	21.2%	23.9%
5	7.4%	9.0%	7.4%	9.1%
0	0.0%	0.0%	0.0%	0.0%

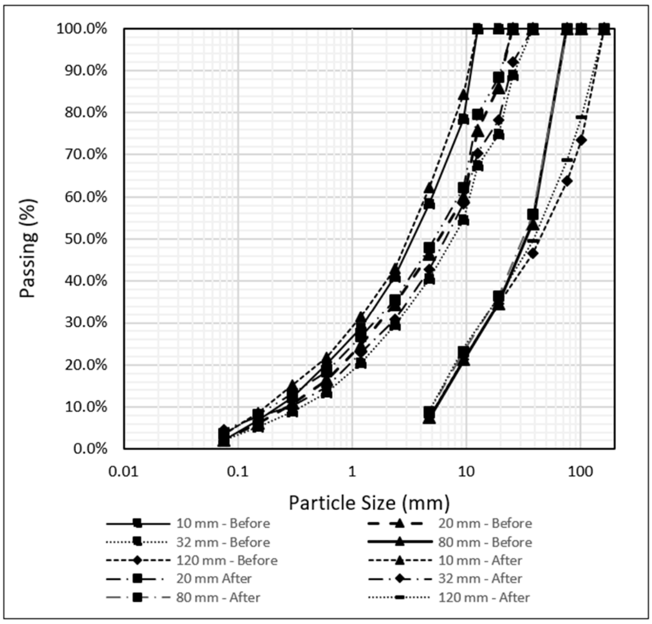

Fig. 3. Distribution curve of andesite rockfill before and after testing.

B. Stress-Strain Response from Consolidation Tests

The stress-strain ratio is the primary basis for evaluating the elastic modulus and analyzing the deformation behavior of rock fill materials. Through oedometer consolidation testing, the strain response of materials to incremental and released vertical stress can be systematically examined, providing insights into elastic and permanent deformation characteristics. Therefore, analyzing the stress–strain relationship is essential to understand the deformation mechanisms of rock fill materials, particularly in relation to the particle size effects and loading conditions. This study presents the results of oedometer consolidation tests in the form of stress-strain curves for each variation in maximum particle size. These curves are used to evaluate strain during the loading and unloading-reloading stages, which are caused by the maximum particle size effect.

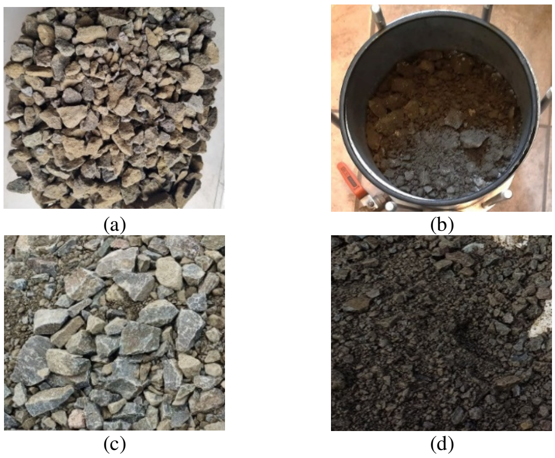

Fig. 4. The test specimen: (a) before test D_{max} 20 mm, (b) after test D_{max} 20 mm, (c) before test D_{max} 80 mm, (d) after test D_{max} 80 mm.

Figure 5 shows the stress-strain relationships obtained from the one-dimensional (vertical) oedometer consolidation tests. During the loading stage, specimens with D_{max} = 10 mm exhibited a strain of 1.58% at a maximum stress of 1.6 MPa. Specimens with D_{max} = 20 mm had a strain of 2.42% at the same stress level, while specimens with D_{max} = 32 mm had a strain of 2.94% at the same stress level, which increased to 3.93% at a maximum stress of 2.5 MPa. Specimens with D_{max} = 80 mm showed a strain of 4.16% at a maximum stress of 2.1 MPa, while specimens with D_{max} = 120 mm showed a strain of 5.53% at the same stress level. These results suggest that larger maximum particle sizes in andesite rock fill materials led to greater strain under identical stress conditions. The strain values gradually decreased during the unloading stage.

At an initial unloading stress of 0.05 MPa, the residual strain decreased as the D_{max} increased. Specifically, it decreased from 1.36% for D_{max} = 10 mm to 2.27% for D_{max} = 20 mm, to 3.16% for D_{max} = 32 mm, to 2.9% for D_{max} = 80 mm, and to 4.38% for D_{max} = 120 mm. This behavior indicates that the andesite rock fill material does not exhibit perfectly elastic behavior but rather nonlinear elastoplastic characteristics. This means that a portion of the strain induced during loading is not fully recovered upon unloading. Residual strain after unloading indicates permanent deformation due to inter-particle rearrangement, particle sliding, and potential particle crushing during loading.

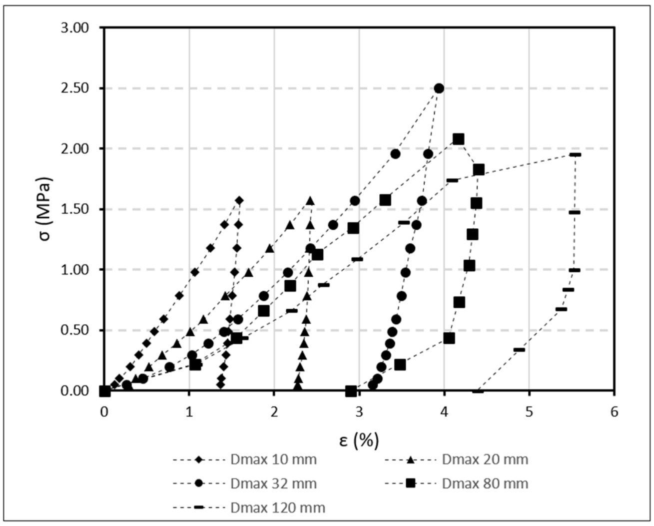

Fig. 5. The stress-strain ratio under various D_{max} conditions.

C. Elastic Modulus on Laboratory Scale

The elastic modulus is a primary mechanical parameter that describes the stiffness of rock fill materials when subjected to loading. Based on oedometer consolidation test results, elastic modulus values can be derived from stress-strain relationships under each loading and unloading condition. Analyzing the elastic modulus evaluates the influence of maximum particle size and serves as a basis for developing predictive models for the in situ elastic modulus. Elastic modulus analysis (E_{oed} and E_{ur}) was conducted using logarithmic regression of the stress-strain relationship. Elastic modulus values were calculated using a power-law formulation (3), where the constants *c* and *d* were determined from the regression results presented in Table III.

TABLE III. CONSTANTS C AND D AS A RESULT OF LOGARITHMIC REGRESSION OF THE STRESS-STRAIN RATIO

Dmax (mm)	Loading		Unloading	
	c	*d*	*c*	*d*
10	717.891	0.240	1,642.651	0.956
20	413.799	0.354	2,125.116	0.979
32	323.574	0.319	575.048	0.945
80	267.532	0.415	292.573	0.897
120	243.984	0.310	252.675	0.911

Tables IV and V display the elastic modulus values obtained from consolidation tests for each variation of maximum particle size (D_{max}).

TABLE IV. E_{OED} AND E_{UR} ANALYSIS ON DMAX = 10 MM, 20 MM, 32 MM

Laboratory data		D_{max} 10 mm				D_{max} 20 mm				D_{max} 32 mm			
		ε (%)	log ε	Logarithmic linear regression prediction		ε (%)	log ε	Logarithmic linear regression prediction		ε(%)	log ε	Logarithmic linear regression prediction	
σ (MPa)	log σ			E_{oed} (MPa)	E_{ur} (MPa)			E_{oed} (MPa)	E_{ur} (MPa)			E_{oed} (MPa)	E_{ur} (MPa)
0.00	-	0.00	-	-	-	0.00	-	-	-	0.00	-	-	-
0.05	-0.30	0.12	-0.93	59.61	83.05	0.28	-0.55	31.74	105.70	0.26	-0.59	25.44	29.29
0.1	0.00	0.18	-0.75	70.40	161.09	0.37	-0.43	40.58	208.40	0.45	-0.35	31.73	56.39
0.2	0.30	0.31	-0.52	83.14	312.46	0.53	-0.28	51.88	410.90	0.77	-0.12	39.58	108.57
0.3	0.48	0.40	-0.39	91.64	460.36	0.68	-0.17	59.89	611.23	1.03	0.01	45.04	159.28
0.4	0.60	0.49	-0.30	98.19	606.06	0.85	-0.07	66.32	810.16	1.22	0.09	49.37	209.04
0.5	0.69	0.59	-0.23	103.59	750.14	1.01	0.00	71.77	1008.06	1.40	0.15	53.01	258.12
0.6	0.78	0.69	-0.16	108.22	892.94	1.17	0.07	76.56	1205.13	1.57	0.20	56.19	306.66
0.8	0.90	0.88	-0.05	115.95	1175.55	1.42	0.15	84.78	1597.36	1.88	0.27	61.58	402.47
1.0	1.00	1.07	0.03	122.33	1455.01	1.69	0.23	91.75	1987.55	2.16	0.33	66.12	496.96
1.2	1.08	1.25	0.10	127.80	1731.99	1.95	0.29	97.87	2376.12	2.43	0.39	70.08	590.41
1.4	1.15	1.42	0.15	132.62	2006.94	2.19	0.34	103.37	2763.36	2.69	0.43	73.61	683.00
1.6	1.20	1.58	0.20	136.94	2280.15	2.42	0.38	108.37	3149.45	2.94	0.47	76.82	774.87
2.0	1.30	-	-	-	-	-	-	-	-	3.42	0.53	82.48	956.79
2.5	1.39	-	-	-	-	-	-	-	-	3.93	0.60	88.56	1181.43
2.5	1.39	-	-	-	-	-	-	-	-	3.93	0.560	88.56	1181.43
2.0	1.30	-	-	-	-	-	-	-	-	3.81	0.58	82.48	956.79
1.6	1.20	-	-	-	-	-	-	-	-	3.73	0.57	76.82	774.87
1.4	1.15	1.58	0.20	132.62	2006.94	2.42	0.38	103.37	2763.36	3.70	0.57	73.61	683.00
1.2	1.08	1.56	0.19	127.80	1731.99	2.41	0.38	97.87	2376.12	3.59	0.56	70.08	590.41
1.0	1.00	1.54	0.19	122.33	1455.01	2.40	0.38	91.75	1987.55	3.54	0.55	66.13	496.96
0.8	0.90	1.51	0.18	115.95	1175.54	2.39	0.38	84.78	1597.36	3.49	0.54	61.58	402.47
0.6	0.78	1.48	0.17	108.22	892.94	2.37	0.38	76.56	1205.13	3.43	0.54	56.19	306.66
0.5	0.69	1.46	0.17	103.59	750.14	2.36	0.37	71.77	1008.06	3.38	0.53	53.01	258.12
0.4	0.60	1.45	0.16	98.19	606.06	2.34	0.37	66.32	810.16	3.36	0.53	49.37	209.04
0.3	0.48	1.43	0.16	91.64	460.36	2.33	0.37	59.89	611.23	3.31	0.52	45.04	159.28
0.2	0.30	1.41	0.15	83.14	312.46	2.30	0.36	51.88	410.90	3.26	0.51	39.58	108.57
0.1	0.00	1.38	0.14	70.40	161.08	2.28	0.36	40.58	208.40	3.21	0.51	31.73	56.39
0.05	-0.30	1.36	0.14	59.61	83.05	2.27	0.36	31.74	105.70	3.16	0.50	25.44	29.29

TABLE V. E_{OED} AND E_{UR} ANALYSIS ON DMAX = 80 MM, 120 MM

Laboratory data		D_{max} **80 mm**				D_{max} **120 mm**			
		ε (%)	log ε	Logarithmic linear regression prediction		ε (%)	log ε	Logarithmic linear regression prediction	
σ (MPa)	log σ			E_{oed} (MPa)	E_{ur} (MPa)			E_{oed} (MPa)	E_{ur} (MPa)
0.05									
0.2	0.35	1.06	0.03	36.48	58.55	1.09	0.04	30.60	51.12
0.4	0.65	1.55	0.19	48.63	109.05	1.63	0.21	37.92	96.12
0.7	0.83	1.88	0.27	57.84	158.77	2.20	0.34	43.17	140.75
0.9	0.95	2.19	0.34	64.82	203.11	2.58	0.41	47.14	182.38
1.1	1.06	2.50	0.40	72.26	257.02	2.98	0.47	50.36	221.48
1.3	1.14	2.93	0.47	77.73	300.96	3.53	0.55	54.36	277.33
1.6	1.21	3.30	0.52	83.09	347.61	4.09	0.61	58.24	339.85
2.1	1.33	4.16	0.62	93.19	445.56	5.54	0.74	60.41	378.34
1.8	1.27	4.40	0.64	88.30	396.50	-	-	-	-
1.6	1.20	4.38	0.64	82.42	341.60	5.53	0.74	55.39	293.08
1.3	1.12	4.33	0.64	76.47	290.48	5.53	0.74	49.07	205.28
1.0	1.02	4.29	0.63	69.78	238.30	-	-	-	-
0.7	0.88	4.17	0.62	60.52	175.08	5.45	0.74	46.44	174.55
0.4	0.65	4.05	0.61	48.63	109.05	5.38	0.73	43.43	143.28
0.2	0.35	3.48	0.54	36.48	58.55	4.88	0.69	35.05	76.20
0.05		2.90	0.46	-	-	4.39	-	-	-

For D_{max} = 10 mm, E_{oed} at the maximum applied stress (1.6 MPa) was 136.94 MPa, and E_{ur} was 2,280.15 MPa. For D_{max} = 20 mm, E_{oed} at the maximum applied stress (1.6 MPa) was 108.37 MPa, and E_{ur} increased to 3,149.45 MPa. For D_{max} = 32 mm, E_{oed} at the maximum stress (2.5 MPa) was 88.56 MPa, and E_{ur} was 1,181.43 MPa. For D_{max} = 80 mm, E_{oed} at the maximum stress (2.1 MPa) was 93.19 MPa, and E_{ur} was 445.56 MPa. Lastly, for D_{max} = 120 mm, E_{oed} at the maximum stress (2.1 MPa) was 60.41 MPa and E_{ur} was 378.34 MPa. Overall, these results suggest that the elastic modulus obtained from the unloading-reloading condition is notably higher than the oedometer modulus derived from the initial loading stage.

This difference suggests that deformation during the initial loading phase is dominated by non-elastic mechanisms, resulting in low E_{oed} values. In contrast, the unloading–reloading modulus E_{ur} measures the material's elastic response after its internal structure has stabilized, providing a more accurate representation of its deformation behavior under dam operational conditions.

D. Prediction of In-Situ Elastic Modulus

Values of elastic modulus resulting from laboratory testing generally do not fully represent the mechanical behavior of rock fill embankments under actual field conditions. This discrepancy is primarily due to differences in scale and maximum particle size of the rock fill material. Therefore, an approach is needed to predict the in-situ elastic modulus based on laboratory test results. This would allow the mechanical parameters used in deformation analysis to more accurately reflect the real conditions of rock fill embankments in dams. The in-situ elastic modulus was measured by considering the empirical relationships among the elastic modulus, stress, and maximum particle size of the material, as derived from the laboratory consolidation test results. This approach is expected to more accurately represent field conditions for andesite rockfill embankment deformation analysis and concrete face slab deflection evaluation in CFRDs. The prediction constants c and d obtained from the logarithmic linear regression analysis of the laboratory-scale modulus test results are presented in Table VI, whereas the predicted values of E_{oed} and E_{ur} are summarized in Table VII. The stress value used to predict the elastic modulus was set at 3.1 MPa, which represents the maximum vertical stress induced by the self-weight of the rock fill embankment. This stress value was determined using calculations based on the Bener Dam's maximum height of 159 m and the dry unit weight of the rock fill material of 2.0 kN/m³. The elastic modulus values obtained at this stress level were subsequently used as fundamental parameters in empirical calculations and numerical modeling to analyze and evaluate embankment deformation and concrete face slab deflection.

TABLE VI. CONSTANTS C AND D AS A RESULT OF LOGARITHMIC REGRESSION OF ELASTIC MODULUS

Zone	D_{max} **(mm)**	**Loading (**E_{oed}**)**		**Unloading (**E_{ur}**)**	
		c	*d*	*c*	*d*
2A	37.5	357.173	0.324	660.255	0.934
2B	75	269.586	0.351	355.828	0.911
3A	300	153.580	0.412	103.346	0.869
3B	400	136.655	0.427	79.959	0.860
3C	600	115.919	0.447	55.696	0.848
3D	1000	94.213	0.475	35.316	0.834

TABLE VII. E_{OED} AND E_{UR} VALUE PREDICTION WITH THE VERTICAL STRESS VALUE OF 3.1 MPA

Zone	D_{max} **(mm)**	E_{oed} **(MPa)**	E_{ur} **(MPa)**
Laboratory scale	10	156.45	6,181.75
	20	128.02	3,076.00
	32	97.58	1918.29
2A	37.5	107.35	1,636.04
2B	75	89.03	816.98
Laboratory scale	80	87.52	765.90
	120	78.77	510.70
3A	300	62.74	204.82
3B	400	58.61	153.84
3C	600	53.39	102.82
3D	1000	47.71	61.94

Based on Table VII and Figure 6, the relationship between D_{max} and E_{oed} can be described as: Downscaled particle sizes with D_{max} ranging from 10 mm to 32 mm show a sharp decrease in E_(oed) values despite relatively small increases in D_{max}. This implies that E_{oed} values obtained from small-scale laboratory tests are misleading and tend to overestimate material stiffness due to the large number of interparticle contacts and relatively low contact stresses. Therefore, elastic modulus values derived from small-scale laboratory specimens may not directly represent field-scale rockfill stiffness. Overestimation of stiffness can lead to underprediction of deformation and stress redistribution in empirical and numerical modeling. Consequently, laboratory-derived modulus parameters should be interpreted as scale-dependent apparent values that require appropriate correction or empirical adjustment when applied to field conditions. For particle sizes in zones 3A-3D, the oedometer modulus remains relatively constant within the range of 47.71-62.74 MPa. This indicates that, for larger particle sizes, E_{oed} reaches a stable condition and is no longer sensitive to D_{max} increments. At D_{max} 10, 20, and 32 mm, the elastic modulus (E_{oed}) is strongly influenced by changes in particle size (size effect) in the laboratory scale (downscaled). Under actual field conditions, E_{oed} represents the average stiffness during the initial loading stage, but not the dam operational conditions.

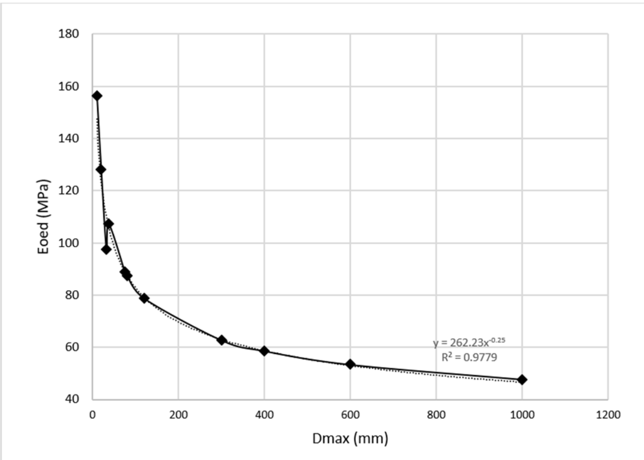

Fig. 6. Relationship between D_{max} and E_{oed}.

Based on Table VII and Figure 7, the relationship between D_{max} and E_{ur} can be described as: The E_{ur} value decreases sharply as D_{max} increases from laboratory-scale to field-scale particle sizes (zones 2A–3D), dropping drastically from 6,181.75 to 61.94 MPa.

This indicates that the elastic response of rock fill embankments decreases significantly as D_{max} increases, due to a reduction in particle contact and increased local inter-particle deformation. The E_{ur} value is consistently greater than the Eoed value. However, the difference between E_{ur} and E_{oed} decreases as D_{max} reaches actual field-scale sizes. This confirms that deformation during the initial loading stage is dominated by nonelastic mechanisms, resulting in relatively low E_{oed} values. Under postloading (unloading) conditions, however, deformation becomes relatively stable, with modulus values being more strongly influenced by a mature interparticle contact configuration. Therefore, the unloading–reloading elastic modulus (E_{ur}) is proposed for analyzing and evaluating the deformation of andesite rockfill embankments and the deflection of concrete face slabs in CFRD because E_{ur} more accurately represents actual dam operational conditions in the field. Further research can continue to model andesite rockfill embankment deformation and concrete face slab deflection using empirical and numerical approaches.

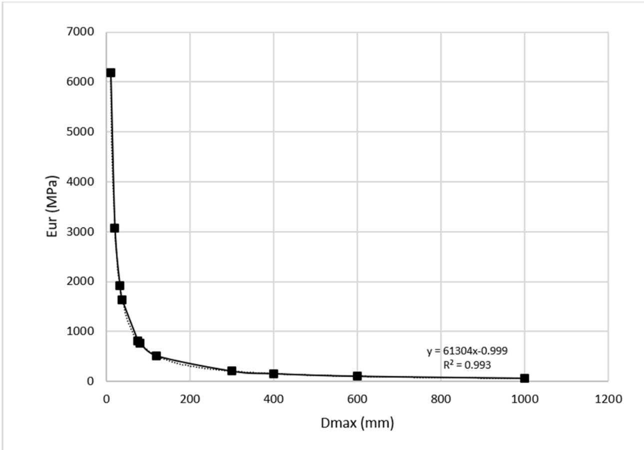

Fig. 7. Relationship between D_{max} - E_{ur}.

IV. CONCLUSIONS

Based on the elastic modulus analysis of the rock fill material, the following conclusions can be drawn:

- Maximum particle size (D_{max}) is a key parameter in evaluating the elastic modulus of rockfill dams. E_{oed} and E_{ur} values obtained from laboratory tests with a small D_{max} tend to overestimate material stiffness compared to actual field conditions for rockfill. Therefore, predicting the in-situ elastic modulus requires considering scale effects and the empirical relationship between D_{max} and elastic modulus.
- The coefficients of determination (R^2) for the relationships between D_{max} and elastic modulus indicate that maximum particle size variations can explain 97% of the variability in oedometer modulus (E_{oed}) and 99% of the variability in unloading–reloading modulus (E_{ur}). This suggests that maximum particle size is the main parameter that controls the elastic stiffness of rockfill materials, particularly under unloading–reloading conditions.
- The elastic modulus obtained under initial loading conditions (E_{oed}) primarily represents the deformation response during the initial loading stage. Values range from 47.71 to 107.35 MPa under actual field conditions. In contrast, the unloading–reloading modulus (E_{ur}) more accurately represents the elastic response of the material under operational conditions. Field-scale E_{ur} values range from 61.94 to 1,636.04 MPa. Thus, E_{ur} is proposed for analyzing and evaluating the deformation of andesite

rockfill embankments and the deflection of concrete face slabs in CFRD applications.

This study establishes empirical relationships between maximum particle size and elastic modulus that can be used to predict in situ elastic modulus values from laboratory test results. Furthermore, these relationships can be used to analyze deformation and deflection in Concrete Face Rockfill Dams (CFRDs) using empirical and numerical approaches.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

ACKNOWLEDGMENT

Not applicable to this work.

DATA AVAILABILITY

The acquired data are described within the paper.

REFERENCES

[1] R. Asmaranto, P. T. Juwono, and R. N. A. Rastanto, "Linking the Reservoir Volume to the Flood Inundation Extent: A Multi-Dam Empirical Model for Indonesian Dam Safety," *Engineering, Technology & Applied Science Research*, vol. 15, no. 5, pp. 27006–27016, Oct. 2025, https://doi.org/10.48084/etasr.12018.

[2] Z. Xu, "Discussions on the technical issues of the construction of 300 m high CFRD," presented at the 78th International Commission on Large Dams Annual Meeting, Hanoi, Vietnam, 2010.

[3] *Bulletin 141: Concrete Face Rockfill Dams – Concepts for Design and Construction*. Paris, France: ICOLD, 2010.

[4] Y. Xiao, M. Meguid, A. Daouadji, Q. Chen, Z. Wu, and X. Jiang, "Effect of particle size on crushing and deformation behaviors of rockfill materials," *Geoscience Frontiers*, vol. 11, no. 2, pp. 375–388, 2020, https://doi.org/10.1016/j.gsf.2018.10.010.

[5] *Dokumen Spesifikasi Teknis Pembangunan Bendungan Bener*. Jakarta, Indonesia: BBWS Serayu Opak, 2015.

[6] P. Kurniawan and M. B. Hadimuljono, *Applied Geotechnics for Engineers*. Yogyakarta, Indonesia, 2021.

[7] Indra Karya Geotechnic Laboratory (Persero), *Laboratory Test Result Report*. Malang, Indonesia, 2024.

[8] G. Hunter and R. Fell, *The Deformation Behaviour of Rockfill*. Sydney, Australia: The University of New South Wales, 2002.

[9] H. Wu, X. Gu, J. Hu, G. Deng, and F. Liu, "Investigation of compressibility of rockfill materials using DEM: Role of sample size and boundary condition," *Computers and Geotechnics*, vol. 176, 2024, Art. no. 106768, https://doi.org/10.1016/j.compgeo.2024.106768.

[10] N. P. Honkanadavar and K. G. Sharma, "Modeling the triaxial behavior of riverbed and rockfill materials," *International Journal of Geomechanics*, vol. 16, no. 6, 2016, Art. no. 04016026, https://doi.org/10.1061/(ASCE)GM.1943-5622.0000701.

[11] *D2435 Standard Test Method for One-Dimensional Consolidation Properties of Soils*. West Conshohocken, PA, USA: ASTM International, 2003.

[12] F. P. Beer, E. R. Johnston, J. T. DeWolf, and D. F. Mazurek, *Mechanics of Materials*, 7th ed. New York, NY, USA, 2015.

[13] M. A. Rai, S. Karamadibrata, and R. K. Wattimena, *Mekanika Batuan*. Bandung, Indonesia: Institut Teknologi Bandung, 2014.

[14] T. Schanz, P. A. Vermeer, and P. G. Bonnier, "The hardening soil model: Formulation and verification," in *Beyond 2000 in Computational Geotechnics*, Rotterdam, The Netherlands, 2000.

[15] B. Indraratnain, "Implications of non-linear strength criteria in the stability assessment of rockfill dams," presented at the International conference on soil mechanics and foundation engineering, 1994, pp. 935–938.

[16] T. Zhao and G. Hu, "Study on size effect of elastic modulus of rock considering the joint spacing," *Frontiers in Materials*, vol. 10, 2023, https://doi.org/10.3389/fmats.2023.1142683.