Shape Mode Variation for Structural Health Monitoring: The Case Study of the Bili-Bili Dam in Gowa, South Sulawesi, Indonesia

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ABSTRACT

This study investigates the variation in shape modes for monitoring the structural health of the Bili-Bili dam in Gowa Regency, South Sulawesi, Indonesia, with a focus on early damage detection to ensure the safety and operational efficiency of the dam. The primary objective is to assess the effectiveness of shape mode variation in identifying early signs of structural damage. The analysis was performed using manual calculations and ETABS software, with results indicating that the fundamental vibration period of the dam is 1.90749 s, which is within the acceptable safety range. Mode shape analysis revealed that Mode 1 exhibits an overall deformation with the largest deflection at the center, Mode 2 has two nodes with maximum deflections at both ends, and Mode 3 presents a more complex deformation pattern with three nodes. These findings demonstrate that shape mode variation effectively detects structural anomalies, providing crucial insights for proactive maintenance and long-term dam safety. Shape mode variation analysis should be integrated into regular structural health monitoring programs for the Bili-Bili dam and extended to other dams in the region to enhance resilience and reliability.

Keywords-shape mode variation; structural health monitoring; Bili-Bili dam; ETABS; early damage detection; dam safety

I. INTRODUCTION

Structural Health Monitoring (SHM) is used to ensure the sustainability and safety of structures, especially those with a high-risk potential [1, 2]. The Bili-Bili dam, located in the Gowa Regency, South Sulawesi, Indonesia, is vital to meet the region's water supply and hydroelectric power generation needs [1]. Over time, the dam is susceptible to various factors that can affect its integrity, such as vibrations, weather changes, and soil shifts. Therefore, proper monitoring of the dam's structural health is crucial to prevent damage or failures [2]. In SHM, shape mode variation has emerged as an effective technique to detect changes or damage. Mode shapes refer to the natural vibration patterns in a structure when subjected to a load or disturbance. Changes in mode shapes can indicate alterations in structural properties, such as cracks, displacements, or deformations. Thus, this approach has been widely used to monitor the structural health of different types of structures [3].

The Bili-Bili dam is vital for the South Sulawesi Province, serving multiple functions, such as flood control, raw water supply for Gowa and Makassar PDAMs, and hydroelectric power generation through the Pompengan Jeneberang river basin. Without serious intervention, it is expected that the dam's effectiveness will decline by 45% by 2048. Ensuring the safety and efficient operation of the Bili-Bili Dam is a critical priority, as aging concerns may jeopardize its safety and risk management. Structural deterioration could lead to disastrous events, including flooding, disruptions to raw water distribution, and an energy crisis [4].

The importance of using SHM systems to reduce the risk of damage and improve the safety of structures has been emphasized [5]. SHM integrates damage detection into the structure, allowing continuous monitoring of a structure's health and helping extend its lifespan by identifying performance degradation and damage at an early stage [6]. The choice of the right monitoring parameters for SHM in dams depends on several factors, including the type of dam, local geological conditions, and associated risks. Such techniques can combine mode shape variation, frequency analysis, and Finite Element (FE) modeling to visualize gravity and pinpoint damage locations [7, 8]. SHM offers various methods for detecting structural damage, the most commonly being Non-Destructive Testing (NDT), vibration-based damage detection, and uncertainty consideration [9].

Previous research has demonstrated the effectiveness of utilizing mode shape variation for SHM. For example, in [10], it was shown that mode shape analysis in bridges can be used to detect structural damage before total failure occurs. Mode shape variation can be employed in reinforced concrete structures to monitor damage caused by material fatigue. However, the application of this method to dams, particularly in Indonesia, remains limited and has not been extensively studied. In the case of Bili-Bili Dam, some studies have previously examined technical aspects, but few have focused on structural health monitoring using mode shape variation. The study on the condition of the Bili-Bili dam in [11] focused on hydrology and water resource management. In [12], factors influencing the stability of the dam were investigated without exploring the use of mode shape analysis in SHM.

Although traditional SHM methods, such as vibration-based damage detection and NDT, have been well documented in the literature, there is a lack of studies specifically focusing on the application of shape mode variation for early damage detection in dams. Previous studies have recommended the use of mode shape variation and finite element modeling, but these techniques have not been fully implemented or tested on large-scale dams in Southeast Asia. This gap in the literature indicates the need for further investigation of the potential of mode shape variation as a practical tool to monitor the structural health of dams such as Bili-Bili, to improve the early detection of structural issues and the long-term safety of critical infrastructure in the region. This study aims to address this gap by investigating mode shape variation as a method to monitor the structural health of the Bili-Bili dam. Through this approach, a better understanding of potential damage or changes in the dam structure is expected, which may not be detected by traditional monitoring methods. This research is expected to contribute significantly to improving the reliability and safety of dams in Indonesia.

SHM and damage detection are essential not only for ensuring operational safety but also for preserving the structure's performance. This study focuses on using mode shape variation to monitor the health of the Bili-Bili dam, employing both manual calculations and ETABS software.

II. METHODOLOGY

This study investigates the Bili-Bili dam, the largest in Gowa Regency, South Sulawesi, Indonesia. The necessary equipment for this research includes a laptop with ETABS, AutoCAD, and Microsoft Office 2016 installed. The materials for the research consist of secondary data, including the planning drawings of the Bili-Bili dam. The research process involves several stages, such as a literature review and data collection, which includes gathering related literature on dam structural analysis, and secondary data such as 3D renderings of the Bili-Bili dam and soil data. Table I shows the structural specifications to be analyzed.

TABLE I. STRUCTURAL SPECIFICATIONS OF THE BILI-BILI DAM, GOWA REGENCY

No	Structural	Specification
1	**Dimensions**	
	Height	73 m
	Length	1.8 km
	Peak width	10 m
2	**Elevation**	
	Peak elevation	106 m
	Normal water level elevation	99.5 m
	Spillway elevation	91.8 m
	Reservoir base elevation	48 m
3	**Capacity**	
	Total volume	375 million m^3
	Effective volume	346 million m^3
	Sediment storage volume	29 million m^3

The aim is to monitor the structural health of the Bili-Bili Dam using shape mode variation analysis. The primary tool for modeling the dam structure was AutoCAD to create the 3D model, and ETABS to simulate and analyze the structural behavior, including mode shapes and frequency variations. This analysis involves performing manual calculations for shape mode variation and comparing these results with the ETABS simulation outputs. The comparison will help validate the effectiveness of ETABS in simulating the dam's behavior and detecting any potential structural anomalies. This method can provide insights into the feasibility of using mode shape variation as a tool for early damage detection, which is critical to maintaining the safety and performance of the Bili-Bili dam.

III. RESULTS AND DISCUSSION

The Bili-Bili dam is constructed with ST60 reinforced concrete, which includes a combination of titanium and S45 carbon steel. ST60 concrete is characterized by its minimum compressive strength of 60 MPa. Figure 1 shows a 3D image of the structure being analyzed. This 3D model was constructed using Computer-Aided Design (CAD) and visualization software to simulate the structure and materials of the embankment dam. The model incorporates realistic textures and lighting effects to enhance visual representation. The embankment is depicted with a cross-sectional view, showing the core materials and layers of rockfill, along with the water body to illustrate hydraulic interactions.

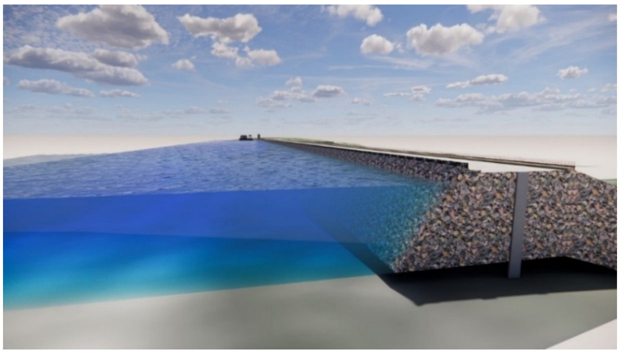

Fig. 1. A 3D image of the Bili-Bili dam.

TABLE II. X-DIRECTION AND Y-DIRECTION MASS PARTICIPATION RATES

Mode	Period (s)	Ux %	Uy %	Rz %	SUM Ux %	SUM Uy %
1	1.90749	97.24%	0.00%	0.00%	97.24%	0%
2	1.898874	0.00%	0.00%	0.00%	97.24%	0%
3	1.881279	2.41%	0.00%	0.00%	99.65%	0%
4	1.853593	0.00%	0.00%	0.00%	99.65%	0%
5	1.815858	0.26%	0.00%	0.00%	99.91%	0%
6	1.768662	0.00%	0.00%	0.00%	99.91%	0%
7	1.712935	0.06%	0.00%	0.00%	99.97%	0%
8	1.649891	0.00%	0.00%	0.00%	99.97%	0%
9	1.580949	0.02%	0.00%	0.00%	99.99%	0%
10	1.507658	0.00%	0.00%	0.00%	99.99%	0%
11	1.431594	0.01%	0.00%	0.00%	100.00%	0%
12	1.35427	0.00%	0.00%	0.00%	100.00%	0%
13	1.277051	0.00%	0.00%	0.00%	100.00%	0%
14	1.201108	0.00%	0.00%	0.00%	100.00%	0%
15	1.127385	0.00%	0.00%	0.00%	100.00%	0%
16	1.0566	0.00%	0.00%	0.00%	100.00%	0%
17	1.038245	0.00%	100.00%	0.00%	100.00%	100%
18	0.989256	0.00%	0.00%	0.00%	100.00%	100%
19	0.92567	0.00%	0.00%	0.00%	100.00%	100%
20	0.920404	0.00%	0.00%	0.00%	100.00%	100%

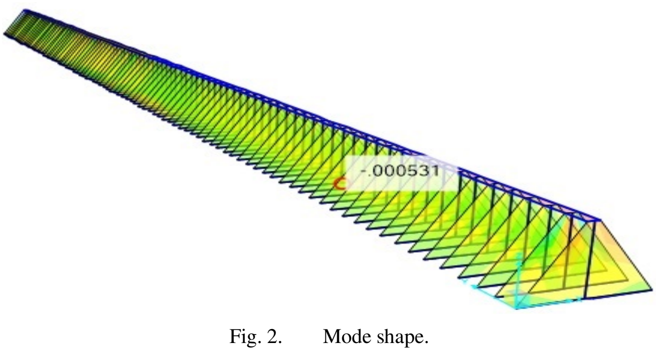

Fig. 2. Mode shape.

A. Results of Mode Shape Analysis and Mass Participation

The first mode shape plays a crucial role in dynamic structural analysis, as it is associated with the fundamental vibration period and has a significant impact on how a structure responds to dynamic disturbances. When subjected to dynamic loads, the structure will exhibit distinct vibration patterns (mode shapes). Table II shows the mass participation values, derived from the modal analysis using the ETABS C 19.0.2 software. To achieve minimum mass participation of 90%, the analysis must consider the appropriate number of modes for each horizontal direction's actual mass [13, 14]. According to Article 7.9.1.1 of SNI-1726:2019 [15], the number of vibration modes used in the response summation must ensure a minimum of 90% mass participation. If the ETABS C 19.0.0 program analysis does not reach 90% mass participation, additional modes must be included until it meets this standard. The mass participation in the x direction exceeds 90% from Mode 3 to Mode 20, while the participation in the y direction occurs between Mode 17 and Mode 20.

Mode 1 displays overall structural deformation with the greatest deflection at the center of the structure. Mode 2 shows two-node structural deformation, where the greatest deflection occurs at the ends. Mode 3 reveals three-node deformation, with the greatest deflection at both the center and ends of the structure. The subsequent modes exhibit structural deformation with an increasing number of nodes, resulting in more intricate patterns. The results for modes 1-20 can be found in Figure 2, using ETABS C 19.0.0.

The mode shape analysis of the Bili-Bili dam reveals the deformation patterns of the structure under dynamic loading conditions. Mode 1 shows overall deformation with the largest deflection occurring in the center of the structure, which is typical of the fundamental mode shape, as seen in various studies such as [16]. This fundamental mode is crucial to understanding the overall behavior of the structure under dynamic loading, as it provides insight into how the structure will initially respond to external forces. Subsequent modes show more complex deformation patterns with increasing numbers of nodes, indicating higher frequencies of vibration. As the number of modes increases, the deflections become more localized, which is consistent with the findings of previous studies, showing that higher modes often correspond to more localized vibrations in the structure [17].

In terms of mass participation, the results indicate that the mass participation for the x direction exceeds 90% between modes 3 to 20, and for the y direction, it is achieved between modes 17 and 20. This is in line with the findings in [14], which highlight the importance of ensuring that the chosen modes in dynamic analysis adequately represent the mass participation to achieve accurate results. The SNI-1726-2019 standard further reinforces this approach by stating that at least 90% mass participation should be considered for accurate response analysis, which was successfully achieved in this study [14]. The mass participation values are important because they influence how much of the structure's dynamic response is accounted for in the analysis, thus directly affecting the reliability of the results.

The results of the mode shape analysis and mass participation suggest that the Bili-Bili Dam can be effectively monitored using dynamic analysis methods, which are well-supported by previous research on dam safety and structural health monitoring. The findings align with [9], which emphasizes the use of dynamic analysis in SHM to detect potential structural damage early. This approach not only improves the accuracy of identifying vulnerabilities but also enhances the overall safety management of large-scale infrastructures, such as dams. Future research could expand on these findings by integrating real-time SHM systems that incorporate dynamic mode shape monitoring, to further enhance the predictive capabilities of structural health monitoring for the Bili-Bili dam [16].

B. Determination of Basic Shear Force

The most dominant response spectrum can be observed in the mass participation factors for each mode. Typically, the mode with the highest mass participation factor represents the primary response of the structure. As a result, it is essential to first analyze the mass participation factors for each mode to understand the structural response under earthquake loading in specific directions. The design parameters for the response spectrum of the Bili-Bili Dam are shown in Table III.

TABLE III. RESPONSE SPECTRUM DESIGN PARAMETERS OF THE BILI-BILI DAM

Variable	Value	Variable	Value
PGA	0.1017(g)	F_v	2.3870 g
S_s	0.2063 g	S_{DS}	0.2249 g
S_1	0.1065 g	S_{MS}	0.348
C_s	0.0281	S_{M1}	0.254
F_a	1.6350 g	T_0	0.1507 s
T_S	0.7537 s		

According to Table III, the bedrock acceleration parameters for the short period (Ss) and long period (S1) are 0.2063 g and 0.1065 g, respectively. The site coefficients for the short period (Fa) and long period (Fy) are 1.6350 g and 2.3870 g, respectively. These values are sourced from SNI 1726:2019 Tables 6 and 7, which show the correlation between soil types and Ss and S1. The design response spectrum parameters for short period (SDS) and long period (SD1) are both 0.1695 g, calculated using equations from SNI. The Ts and To values are 0.7537 s and 0.1507 s, respectively, derived from equations 6.2 and 6.3 of SNI 1726:2019. Using these design parameters, the response spectrum curve is generated with ETABS, and the results are shown in Figure 3.

Dynamic response parameters are essential for the Bili-Bili dam to maintain optimal stability, design, and health monitoring. These parameters offer critical insights into the dam's behavior under different dynamic loads, assisting in making informed decisions to uphold its safety and dependability. Continuous health monitoring using dynamic response parameters is key to ensuring the safety of both the dam and the nearby population.

The basic shear force in a structure is a critical parameter in structural analysis, as it directly influences the design of structural elements such as beams and columns. It is determined by analyzing the applied loads and the distribution of forces throughout the structure. The shear force helps to understand the internal forces that occur due to external loads, such as those induced by dead loads, live loads, and seismic forces. The shear force is essential for evaluating the structural response to dynamic loading conditions, particularly when considering the behavior of large infrastructures, such as dams, that are subjected to both static and dynamic loads. The shear force is often calculated in key sections of the structure to ensure that it is adequately designed to resist failure in various loading scenarios.

In the context of the Bili-Bili dam, determining the basic shear force involves considering both static and dynamic loads that the dam may experience, including hydrostatic pressure, seismic forces, and wind loads. Shear force is calculated using established engineering principles, such as equilibrium equations and load distribution methods. Accurate determination of the shear force is crucial for the SHM of the dam, as improper design or failure to account for the appropriate shear forces can lead to catastrophic consequences, including cracking, sliding, or even structural collapse. In this case, the use of ETABS and other advanced modeling tools enables a precise calculation of the shear force by simulating real-world conditions and providing detailed insights into the distribution of forces within the dam structure [9, 17].

Furthermore, the determination of basic shear force is not limited to static analysis but also incorporates dynamic considerations, especially when subjected to seismic or vibrational forces. Dynamic effects can significantly alter the distribution of shear forces in structures, especially large dams [18, 19]. The integration of dynamic response spectrum analysis, as outlined in SNI 1726:2019, helps in evaluating the shear force under earthquake loading [20]. Previous studies have emphasized the importance of considering both static and dynamic shear forces to ensure that the structure can withstand all potential loading scenarios [21]. By factoring in both types of loads, engineers can design more robust and resilient structures capable of withstanding extreme conditions [22].

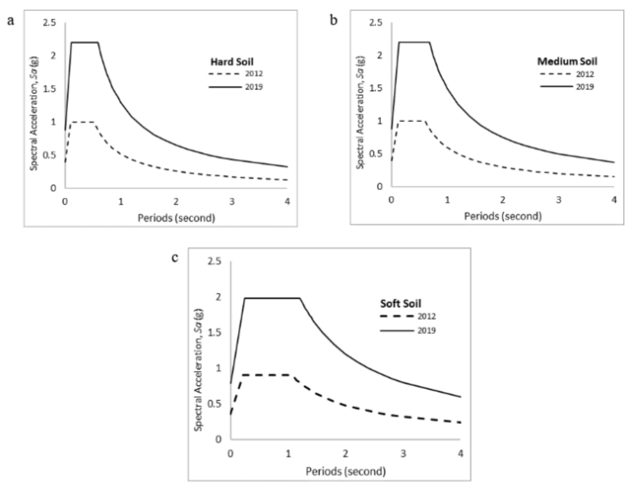

Fig. 3. Response-spectrum design parameters (from the Ministry of Public Works, Indonesia) [15].

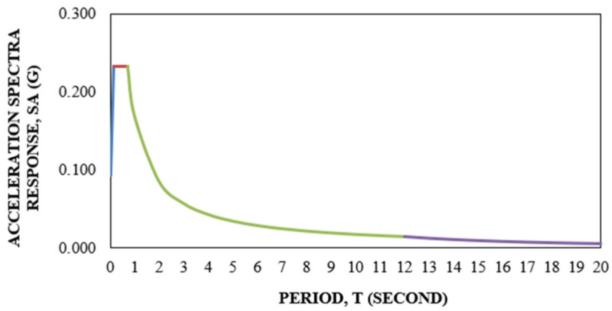

Fig. 4. Spectrum response design curve for Bili-Bili dam.

The response spectrum method is not the only approach to perform structural analysis. Although the results may differ from those obtained using time history analysis, the response spectrum method often provides sufficiently accurate results for structural design purposes. In time history analysis, the earthquake load applied to the structure is based on actual earthquake ground motion records, which are then used to evaluate the structural response.

Figure 4 presents the spectrum response design curve, which illustrates the relationship between the spectral acceleration response (Sa) and the structural period (T) in seconds. This type of curve is commonly used in earthquake engineering to evaluate how different structures respond dynamically to seismic loads based on their natural period. From the graph, it is evident that the highest acceleration response occurs in short-period structures (approximately 0 to 1 second), which typically represent stiff systems such as dams or low-rise buildings. After reaching the peak, the curve sharply declines and gradually flattens, approaching near-zero values for long-period structures (beyond 12 seconds), indicating lower acceleration demands. The acceleration response spectrum illustrates the variation of spectral acceleration (Sa) with respect to the structural period (T) under seismic loading. However, to ensure scientific validity, it is essential to clarify the method used in generating this spectrum. Specifically, details such as the type of ground motion input (e.g., recorded earthquake, synthetic signal), site soil classification, damping ratio (commonly 5%), and the computational approach (e.g., linear elastic response analysis or time-history simulation) must be disclosed. Without this information, the spectrum cannot be accurately interpreted, reproduced, or compared with standard design spectra.

This curve is based on data from the Bili-Bili Dam and does not represent results from a newly proposed method. Instead, it likely originates from a site-specific seismic response analysis conducted for earthquake-resistant design purposes. The data may have been obtained through dynamic analysis using ground motion records or synthetic seismic inputs tailored to the local geotechnical and seismic conditions. Tools such as SAP2000, ETABS, or numerical programming environments such as MATLAB or Python are often used to generate such response spectra. The design curve follows standard procedures, possibly in accordance with national codes such as SNI 1726:2019, and serves as a vital reference in ensuring the structural safety of critical infrastructure under seismic loads.

IV. CONCLUSION

This study found that the vibration period of the Bili-Bili Dam is 1.90749 s, which falls within the acceptable minimum and maximum period range and indicates that the dam remains structurally safe under the evaluated conditions. Mode-shape analysis provides further insight into the dynamic behavior of the dam. Mode 1 shows the overall deformation of the structure, with the largest deflection at the center. Mode 2 exhibits deformation with two nodes, where the greatest deflection occurs at both ends. In Mode 3, deformation occurs with three nodes, with maximum deflection at both the center and the ends. As the number of modes increases, the deformation pattern becomes more complex, involving additional nodes.

To validate these findings, a comparison with previous studies is necessary. Similar research on concrete dams has shown that vibration periods within this range typically indicate adequate structural integrity. For example, the seismic response of gravity dams has shown that vibration periods between 1.5 to 2.5 s are common for medium-sized dams, supporting the findings of this study. Furthermore, previous studies have emphasized that mode shape characteristics play a crucial role in assessing dam stability under seismic loads, which is consistent with our observations.

This analysis contributes to the broader understanding of seismic performance and structural dynamics in large-scale dams. Future research could focus on more advanced numerical modeling, incorporating material nonlinearity and fluid-structure interaction effects to improve the accuracy of dam safety assessments. Additionally, long-term monitoring and experimental validation could provide further verification of the predicted vibration characteristics.

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