

Finite Element Analysis of Radial Gate Arm Buckling under Hydrostatic Loading Using One-Way FSI

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Abstract: Radial gates are critical hydraulic structures used in spillway systems to regulate water discharge under various operational conditions. The radial arm functions as the primary compression member responsible for transferring hydrostatic loads from the gate leaf toward the trunnion support. Due to its slender structural configuration, the radial arm is vulnerable to instability failure in the form of buckling. This study investigates the buckling behavior and structural response of the Karangnongko Dam radial gate arm under hydrostatic loading using a one-way Fluid-Structure Interaction (FSI) method combined with Finite Element Analysis (FEA). Computational Fluid Dynamics (CFD) simulation was conducted to obtain the hydrostatic pressure distribution acting on the gate surface, which was subsequently transferred into Static Structural and Eigenvalue Buckling analyses in ANSYS Workbench. The structural material used in the simulation was SM490B steel based on JIS G3106 standard. The CFD simulation produced a maximum hydrostatic pressure of 105,591.2 Pa. Structural analysis resulted in a maximum von Mises stress of 106.56 MPa and a maximum total deformation of 14.899 mm. The Eigenvalue Buckling analysis generated a critical load multiplier of 18.153, indicating that the structure maintains a high resistance against buckling instability under maximum operational loading conditions. The calculated safety factor reached 3.05, exceeding the minimum requirement specified by USACE EM 1110-2-2702. The results demonstrate that the radial gate arm possesses sufficient stiffness and structural stability to safely withstand hydrostatic loading during operation.

Keywords: Finite Element Analysis, Radial Gate, Buckling, Hydrostatic Loading, One-Way FSI, SM490B Steel, ANSYS.

I. INTRODUCTION

Transportation is a fundamental element Radial gates are widely used in spillway systems because of their ability to efficiently resist hydrostatic loading while minimizing operational torque requirements [1]. The curved geometry of radial gates allows hydrostatic forces to pass through the trunnion center, reducing bending moments acting on the gate leaf [2]. This configuration makes radial gates suitable for large-scale hydraulic structures such as dams and flood control systems.

The Karangnongko Dam is one of Indonesia's strategic water infrastructure projects designed to support flood mitigation, irrigation systems, and regional water management [3]. The operational safety of the spillway system strongly depends on the structural integrity of the radial gate assembly. Among all structural components, the radial arm acts as the primary load-carrying member responsible for transferring hydrostatic forces from the skin plate toward the trunnion

support [4].

Because the radial arm primarily experiences compressive loading, instability failure in the form of buckling becomes a critical design consideration [5]. Buckling failure may occur suddenly before the material reaches its yield strength, making it more dangerous than conventional yielding failure [6]. Structural imperfections, eccentric loading, and secondary bending moments can significantly reduce buckling resistance in hydraulic steel structures [7].

Several historical radial gate failures have demonstrated the importance of accurate buckling evaluation. Failures caused by excessive trunnion friction and instability have highlighted the limitations of conventional analytical approaches for predicting structural behavior under realistic loading conditions [8]. Therefore, advanced numerical simulation techniques are required to investigate the interaction between hydrostatic loading and structural response.

Finite Element Analysis (FEA) has become an effective

numerical method for evaluating stress distribution, deformation, and buckling behavior in hydraulic steel structures [9]. Furthermore, the implementation of Fluid-Structure Interaction (FSI) methods enables realistic transfer of hydrostatic pressure obtained from Computational Fluid Dynamics (CFD) simulations into structural analysis environments [10]. One-way FSI approaches are computationally efficient for structures with relatively small deformation because the structural response does not significantly alter fluid flow behavior [11].

This study aims to evaluate the buckling stability and structural response of the Karangnongko Dam radial gate arm under hydrostatic loading using a one-way CFD-FEA coupling approach implemented in ANSYS Workbench.

II. RESEARCH METHODOLOGY

2.1 Geometry Modeling

The three-dimensional geometry of the radial gate system was developed using SolidWorks software based on engineering drawings [12]. The assembly model consisted of several major structural components, including the skin plate, horizontal girders, radial arms, and trunnion system.

The radial arm was modeled as the primary structural member because it represents the most critical compression component associated with buckling failure. The built-up box configuration of the radial arm was modeled in detail to accurately capture stress distribution and instability behavior.

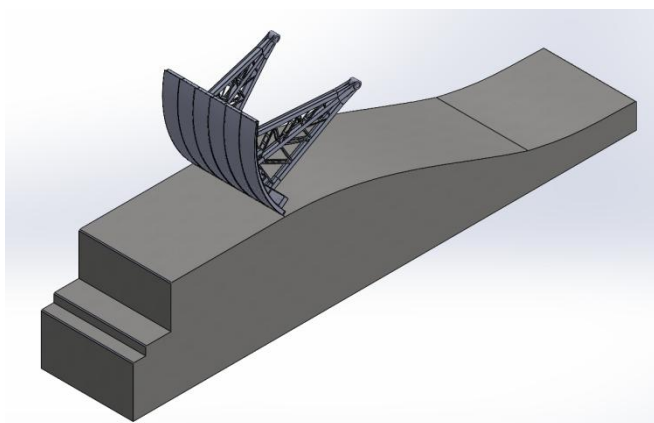


Figure 1: Three-dimensional assembly model of the radial gate system developed in SolidWorks

2.2 Material Properties

The radial gate structure utilized SM490B steel according to JIS

G3106 standards. This material was selected due to its high strength, ductility, and suitability for hydraulic steel structures subjected to fluctuating loading conditions [13].

The mechanical properties applied in the finite element simulation are presented in Table 1.

Table 1: Mechanical Properties of SM490B Steel

Property	Value
Yield Strength	325 MPa
Tensile Strength	490–610 MPa
Young's Modulus	200 GPa
Poisson Ratio	0.3
Density	7850 kg/m ³

2.3 One-Way Fluid-Structure Interaction

This study employed a one-way Fluid-Structure Interaction (FSI) method to transfer hydrostatic pressure from the fluid simulation into the structural domain [14]. In this approach, fluid pressure affects the structure, while structural deformation is assumed insufficient to significantly alter the fluid flow characteristics.

The hydrostatic pressure distribution generated from the CFD simulation in ANSYS Fluent was imported into the Static Structural and Eigenvalue Buckling modules in ANSYS Workbench.

2.4 CFD Simulation Setup

The Computational Fluid Dynamics simulation was conducted using ANSYS Fluent 2023 R1. The fluid domain represented the upstream water volume interacting directly with the radial gate surface [15].

Water-liquid properties were assigned to the fluid region, while gravitational acceleration was activated to generate hydrostatic pressure effects. Boundary conditions were defined using pressure inlet and pressure outlet configurations.

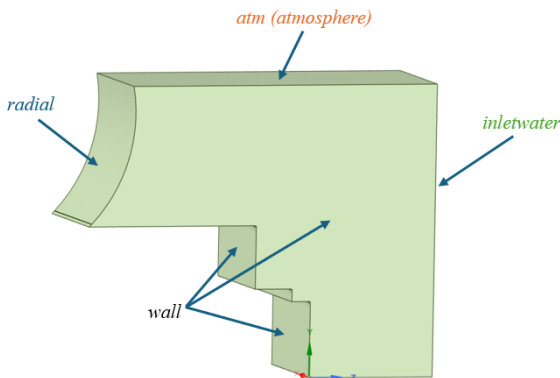


Figure 2: Fluid domain used in CFD simulation

The hydrostatic pressure acting on the gate surface is expressed as:

$$P = \rho \cdot g \cdot h$$

where (ρ) is fluid density, (g) is gravitational acceleration, and (h) is water depth [16].

2.4.1 Grid Independent Meshing

A grid independent meshing study was conducted to ensure that the numerical solution was not significantly influenced by mesh density [17]. In finite element and CFD simulations, excessively coarse meshes may fail to capture local stress and pressure gradients accurately, whereas excessively fine meshes substantially increase computational cost without providing meaningful improvements in result accuracy [18].

Three different mesh configurations were evaluated during the mesh convergence study. The element sizes were gradually refined from coarse to fine mesh configurations while monitoring the variation of maximum hydrostatic pressure and von Mises stress values obtained from the simulation.

Table 2: Grid Independent Meshing Results

Meshing Parameters	Coarse Mesh	Medium Mesh	Fine Mesh
Element Size (mm)	55	50	45
Number of Elements	710,640	828,036	998,205
Average Skewness	0.12855	0.12154	0.11585

Maximum Pressure (Pa)	105,499.26	105,591.20	105,796.87
Difference (%)	-	0.087%	0.194%

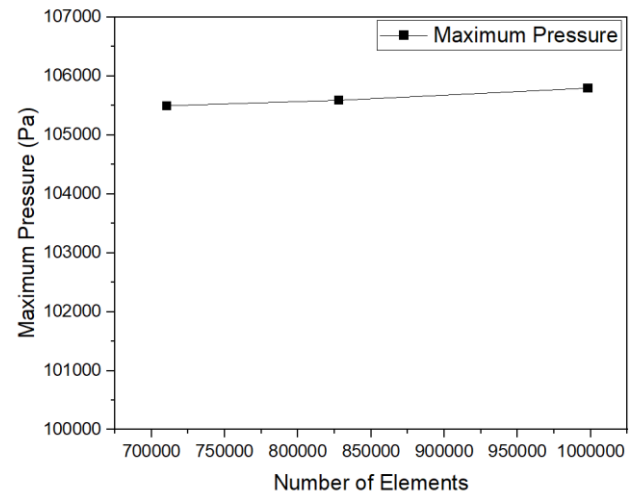


Figure 3: Convergence of Maximum Pressure with Increasing Number of Elements

The comparison results showed that the variation between the medium mesh and fine mesh configurations was less than 2%, indicating that the numerical solution had reached convergence. Therefore, the medium mesh configuration was selected as the optimal mesh because it provided a balance between computational efficiency and numerical accuracy.

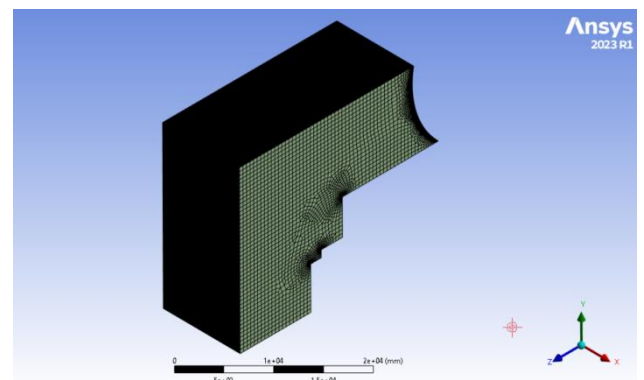


Figure 4: Medium-sized mesh used in studies of mesh independence

The implementation of grid independent meshing is essential in ensuring that the simulation results represent the actual physical behavior of the fluid domain rather than

numerical artifacts caused by inappropriate mesh density.

2.5 Structural Simulation Setup

The pressure distribution obtained from the CFD simulation was transferred into the Static Structural module for stress and deformation analysis. Fixed support boundary conditions were applied at the trunnion region to represent rigid attachment to the dam structure.

Meshing refinement was concentrated around stress concentration regions, particularly near the radial arm and trunnion connection.

The von Mises equivalent stress criterion used in the structural analysis is expressed by:

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where (σ_1) , (σ_2) , and (σ_3) are the principal stresses [18].

2.6 Eigenvalue Buckling Analysis

Eigenvalue Buckling analysis was conducted to determine the critical load multiplier and buckling mode shapes of the radial arm structure [19]. The pre-stress condition generated from Static Structural analysis was imported into the buckling solver.

The Euler critical buckling load equation is expressed as:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

where (E) is Young's modulus, (I) is moment of inertia, and (KL) is the effective length of the compression member [20].

III. RESULTS AND DISCUSSIONS

3.1 Hydrostatic Pressure Distribution

The CFD simulation successfully generated hydrostatic pressure contours acting on the radial gate surface. The maximum hydrostatic pressure reached 105,591.2 Pa and occurred near the lower section of the gate due to increasing water depth.

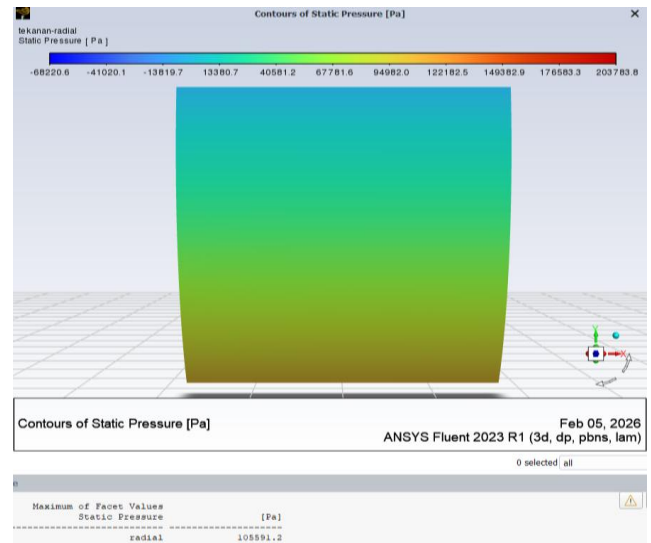


Figure 5: Hydrostatic pressure contour obtained from CFD simulation

The pressure distribution pattern increased linearly with depth, consistent with hydrostatic loading theory. The simulation results confirmed that the boundary conditions and fluid domain configuration accurately represented operational conditions of the radial gate.

3.2 Stress Distribution of Radial Arm

The hydrostatic loading generated compressive stress within the radial arm structure. The maximum von Mises stress reached 106.56 MPa and was concentrated near the connection region between the radial arm and trunnion assembly.

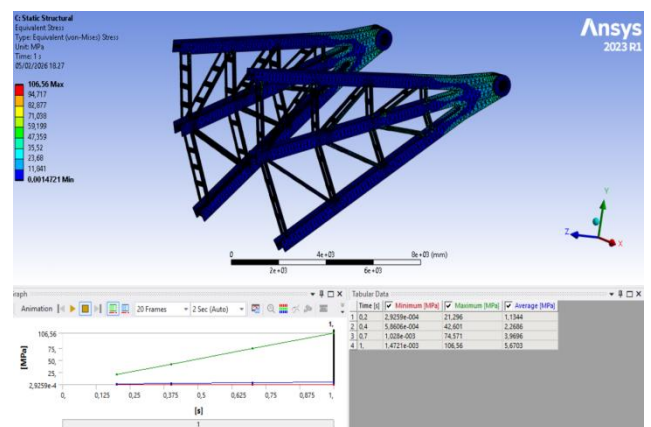


Figure 6: Von Mises stress distribution of the radial arm structure

The stress concentration occurred because of geometric discontinuities and load transfer interactions between structural members. However, the resulting stress remained significantly

below the SM490B yield strength of 325 MPa, indicating that yielding failure did not occur under operational loading conditions.

3.3 Structural Deformation

The total deformation analysis produced a maximum displacement of 14.899 mm at the outer region of the radial gate structure.

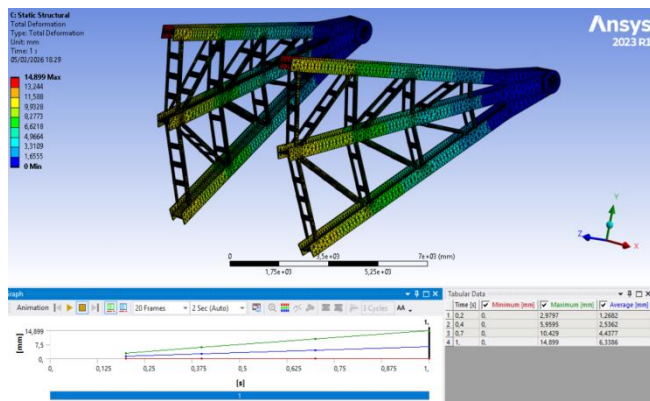


Figure 7: Total deformation contour of the radial gate structure

The deformation pattern demonstrated elastic structural behavior under hydrostatic pressure loading. The relatively small displacement magnitude indicates that the radial arm maintains sufficient stiffness during operation.

3.4 Buckling Behavior Analysis

The Eigenvalue Buckling analysis generated several instability mode shapes for the radial arm structure. Among the evaluated modes, mode 3 represented the critical buckling condition with a load multiplier of 18.153.

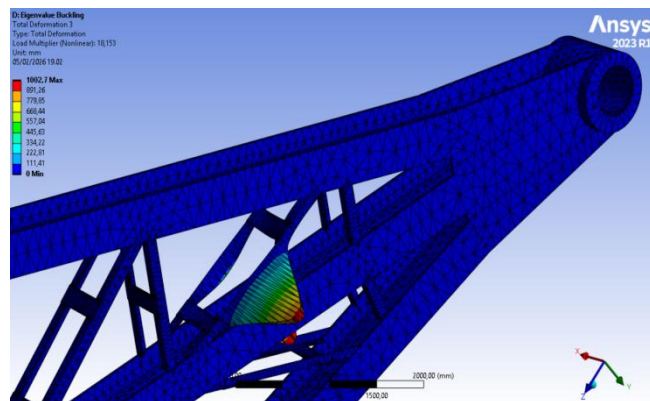


Figure 8: Critical buckling mode shape of the radial arm

The critical load multiplier indicates that the applied hydrostatic load must be amplified more than eighteen times before theoretical buckling occurs. This result demonstrates that the radial arm possesses substantial resistance against instability failure.

The buckling deformation pattern showed lateral displacement concentrated in the mid-span region of the radial arm, which is consistent with classical compression member instability behavior.

3.5 Safety Factor Evaluation

The structural safety factor was calculated by comparing the material yield strength with the maximum von Mises stress obtained from the finite element simulation.

The resulting safety factor reached 3.05, exceeding the minimum allowable value specified in USACE EM 1110-2-2702 design standards [20].

Table 3: Summary of Numerical Simulation Results

Parameters	Results
Maximum Hydrostatic Pressure	105,591.2 Pa
Maximum von Mises Stress	106.56 MPa
Maximum Total Deformation	14.899 mm
Safety Factor	3.05
Critical Load Multiplier	18.153

These results indicate that the radial gate arm structure satisfies both strength and buckling stability requirements under maximum hydrostatic loading conditions.

IV. CONCLUSION

This study investigated the buckling behavior and structural response of the Karangnongko Dam radial gate arm under hydrostatic loading using a one-way Fluid-Structure Interaction (FSI) approach combined with Finite Element Analysis (FEA). The CFD simulation successfully generated the hydrostatic pressure distribution acting on the gate surface, with a maximum pressure of 105,591.2 Pa occurring at the lower section of the radial gate due to increasing water depth.

The Static Structural analysis showed that the maximum von Mises stress reached 106.56 MPa, while the maximum total deformation was 14.899 mm. The highest stress concentration occurred near the connection between the radial arm and

trunnion assembly due to load transfer interactions and geometric discontinuities. However, the resulting stress remained well below the yield strength of SM490B steel, indicating that the structure operated safely within the elastic region under maximum hydrostatic loading conditions.

The Eigenvalue Buckling analysis demonstrated that the radial arm structure possesses high resistance against instability failure. The critical buckling condition occurred in mode 3 with a load multiplier of 18.153, indicating that the applied hydrostatic load would need to increase more than eighteen times before theoretical buckling occurs. In addition, the calculated safety factor reached 3.05, which exceeds the minimum allowable value specified in the USACE EM 1110-2-2702 standard.

The grid independent meshing study also confirmed the numerical reliability of the simulation results. The variation between medium and fine mesh configurations was below 2%, indicating that the selected mesh configuration produced stable and converged numerical solutions. Overall, the one-way CFD-FEA coupling method proved effective in evaluating hydrostatic loading effects and buckling behavior, and the Karangnongko Dam radial gate arm can be classified as structurally safe and stable under maximum operating conditions.

Future studies are recommended to investigate nonlinear buckling behavior and transient Fluid-Structure Interaction effects to obtain more comprehensive insight into the dynamic response of radial gate structures during operation.

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