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Analysis of the Earthquake Load Effects on the Cooling Tower Structure of the Ulumbu Geothermal Power Plant Using the Pushover Method

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Abstact. Earthquake loads pose a critical threat to the structural integrity of infrastructure in geothermal power plants, particularly cooling towers, which are essential for thermal regulation. This study aims to evaluate the seismic performance of the cooling tower structure at the Ulumbu Geothermal Power Plant through a nonlinear static pushover analysis. The analysis was performed using structural modeling software and applied the ATC-40 guidelines to assess performance levels under lateral seismic loads. The capacity spectrum method was utilized to transform the pushover curve into an equivalent single degree of freedom (SDOF) system, allowing the identification of the performance point. Results indicate a proportional relationship between base shear and displacement, with the structure capable of resisting a maximum lateral load of 730.383 kN. According to ATC-40 criteria, the structure meets the Immediate Occupancy (IO) performance level, demonstrating sufficient seismic resilience and indicating that the cooling tower remains safe and operational following a moderate earthquake. This research contributes to the understanding of seismic vulnerability in geothermal infrastructure and supports improved structural design and risk mitigation strategies.

Keywords: *pushover analysis, sap2000, ulumbu, performance level, plastic hinge*

1 Introduction

Indonesia, located on the Pacific Ring of Fire, is one of the most seismically active countries in the world due to its position at the convergence of three major tectonic plates: the Indo-Australian, Eurasian, and Pacific plates. This complex geotectonic setting leads to frequent and often destructive earthquakes, which pose significant risks to critical infrastructure, including energy facilities such as geothermal power plants. Consequently, incorporating earthquake-resistant design is essential in the development and maintenance of infrastructure within this high-risk region. Geothermal energy holds strategic importance for Indonesia's renewable energy future, as the country possesses approximately 40% of the world's total geothermal potential. According to the Geological Agency of Indonesia (2020), the nation's geothermal reserves are estimated at around 23.7 GW. In support of sustainable development, the Indonesian government has designated several Geothermal Working Areas (Wilayah Kerja Panas Bumi, WKP) for exploration and utilization. However, the siting of many geothermal facilities in seismically active areas necessitates robust structural resilience, particularly for essential components such as cooling towers, which are critical for the thermodynamic efficiency of geothermal power generation systems.

In recent years, performance-based seismic evaluation methods have gained prominence over conventional force-based approaches. One widely accepted technique is nonlinear static pushover analysis, which enables engineers to simulate structural behavior beyond the elastic limit and estimate the potential for inelastic deformation or collapse under earthquake loading scenarios. The ATC-40 guidelines, alongside national regulations such as SNI 1726:2019, provide comprehensive frameworks for assessing seismic performance based on defined performance levels, namely Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

Despite the increasing application of these methodologies in high-rise buildings and bridges, limited studies have addressed their use in the structural evaluation of geothermal cooling towers, particularly in the Indonesian context. Most existing literature focuses on mechanical or thermal efficiency, leaving a gap in understanding the seismic vulnerability of such vertical structures composed of reinforced concrete.

Therefore, this study aims to evaluate the seismic performance of a reinforced concrete cooling tower structure at the Ulumbu Geothermal Power Plant using nonlinear pushover analysis in accordance with ATC-40 guidelines. The key objective is to identify the structural response under lateral seismic loading and determine whether it satisfies safety criteria for continued operation post-earthquake. The findings of this study are expected to contribute to the development of more resilient geothermal infrastructure and to provide reference data for future seismic assessments in similar facilities.

2 Research Methodology

This study employed a nonlinear static pushover analysis to evaluate the structural performance of the cooling tower at the Ulumbu Geothermal Power Plant under seismic loading conditions. Pushover analysis is a method used to determine the capacity of a structure by incrementally applying lateral loads until the structure reaches a target displacement or collapse mechanism. This method provides insights into how a structure behaves beyond its elastic range, making it particularly useful for seismic assessment.

The analysis was conducted using SAP2000 structural analysis software, which allows for detailed modeling of structural behavior under nonlinear conditions. The cooling tower model included appropriate assumptions for material properties, cross-sectional dimensions, and boundary conditions, based on the as-built drawings and field inspection data.

The performance evaluation followed the ATC-40 (Applied Technology Council) guidelines. ATC-40 is a well-established framework for seismic evaluation of existing buildings using nonlinear procedures. It provides criteria to determine structural performance levels, including Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). These levels indicate how a structure is expected to perform during and after an earthquake, with IO signifying minimal damage and continued usability.

To interpret the pushover results, the Capacity Spectrum Method (CSM) was applied. This method transforms the pushover curve into an equivalent Single Degree of Freedom (SDOF) system by using a process called modal transformation. The resulting capacity curve is then superimposed with a demand spectrum (based on site-specific seismicity) to find the performance point—a key intersection that indicates the expected displacement response under the design earthquake.

2.1 Data Collection

The data used in this study include:

- Architectural and structural layout of the cooling tower
- Material properties and structural dimensions
- Seismic hazard parameters based on SNI 1726:2019
- Load data including dead loads, live loads, and earthquake loads

2.2 Structural Modelling

The cooling tower is modelled using SAP2000 software. The model includes critical components such as beams, columns, and shear walls. The structural configuration and boundary conditions follow the actual design data.

2.3 Earthquake Load Calculations

Earthquake loads are calculated using the Equivalent Static Force Procedure as per SNI 1726:2019. The resulting base shear is distributed vertically according to the mass and height of each floor level.

2.4 Pushover Analysis

Nonlinear static pushover analysis is conducted to evaluate the structural performance under lateral loads:

- A monotonic lateral load is applied incrementally until the structure reaches target displacement.
- The resulting pushover curve (base shear vs. displacement) is used to derive a capacity spectrum.
- The performance point is identified by the intersection of the capacity curve and the demand spectrum.

2.5 Performance Evaluation

The performance point is interpreted using ATC-40 criteria to determine the building's expected behaviour under seismic conditions. This includes identifying whether the structure remains within acceptable performance levels such as IO, LS, or CP.

3 Result and Discussion

3.1 Dead Load

Dead load is defined as the load caused by the structural elements of a building, including beams, columns, and floor slabs. This type of load is automatically calculated by the SAP2000 software. Additional dead load refers to the permanent weight of non-structural components or architectural finishes. In the case of the Cooling Tower Building in Ulumbu Geothermal Power Plant, the additional dead loads consist of:

- Sand layer (1 cm thick): 0.01×16 kN/m^3 = 0.16 kN/m
- Mortar layer (4 cm thick): 0.04×22 kN/m^3 = 0.88 kN/m
- Ceiling and hangers: 0.20 kN/m
- Mechanical and electrical installations: 0.25 kN/m
- Waterproofing (asphalt, 2 cm thick): 0.28 kN/m
- Wall load (uniform load): 2.5 kN/m^2

Table 1 Dead Loads for Each Floor

No	Floors	Structural Dead Load (kN)	Additional Dead Load (kN)	Dead Load Total (kN)
1	1st Floor	3043.793	2297.323	5341.116
2	2nd Floor	3048.056	2226.189	5274.245
3	3rd Floor	3098.037	2202.212	5300.249
4	4th Floor	3063.843	2284.551	5348.394
5	5th Floor	3044.195	2249.651	5293.846
6	6th Floor	3078.641	2276.647	5355.288
7	7th Floor	3032.312	2198.674	5230.986
8	8th Floor	3051.891	2284.367	5336.258
9	Roof Floor	2959.213	1648.375	4607.588
		Dead Load Total		47087.97

3.2 Live Load

Live load is defined as a non-permanent load acting on a structure, such as the load caused by building occupants. The Indonesian Loading Regulation of 1987 recommends the following live loads:

- Live load on room floors: 1.92 kN/m²
- Live load on roof floors: 0.96 kN/m²

The calculated live loads for each floor level are presented in Table 2.

Table 2 Live Loads

No	Floors	Live Load on Each Floor (kN)	Area	Earthquake Reduction Coefficient (kN)	Live Load Total (kN)
1	1st Floor	1.92	551.602	30%	317.723
2	2nd Floor	1.92	551.602	30%	317.723
3	3rd Floor	1.92	551.602	30%	317.723
4	4th Floor	1.92	551.602	30%	317.723
5	5th Floor	1.92	551.602	30%	317.723
6	6th Floor	1.92	551.602	30%	317.723
7	7th Floor	1.92	551.602	30%	317.723

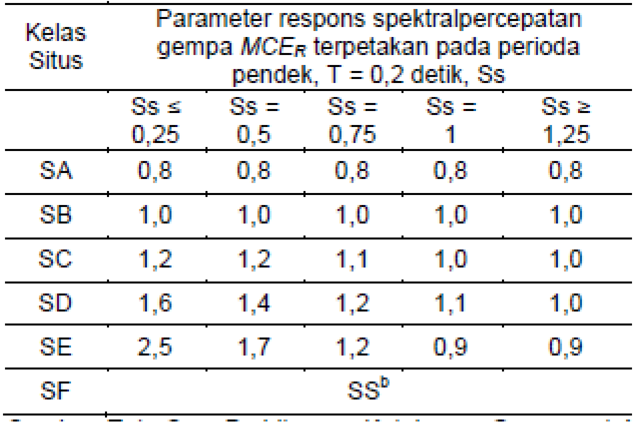
8	8th Floor	1.92	551.602	30%	317.723
9	Roof Floor	0.96	551.602	30%	158.861
		Live Load Total			2700.643

3.3 Earthquake Load

The seismic design parameters for the building and structural system are determined based on the following criteria:

- Seismic Zone = Zone 4
- Structural System = Special Moment Resisting Frame (SMRF)
- Building Occupancy Type = Category II
- Importance Factor = (Ie) = 1
- Soil Type = SD (Medium Soil)
- Classification Status = Vs = 175 – 350 m/s
  N = 15 – 50
  Su = 50 – 100 kPa
- Seismic amplification factor on period:
  T = 0,2 s
  Ss = 0,7 – 0,8 g
  = 0,774 g
- Seismic amplification factor on period:
  T = 1 s
  Ss = 0,3 – 0,4 g
  = 0,325 g

Table 3 Site Coefficient, *Fa*



Kelas Situs	Parameter respons spektralpercepatan gempa MCE_R terpetakan pada perioda pendek, T = 0,2 detik, Ss				
	Ss ≤ 0,25	Ss = 0,5	Ss = 0,75	Ss = 1	Ss ≥ 1,25
SA	0,8	0,8	0,8	0,8	0,8
SB	1,0	1,0	1,0	1,0	1,0
SC	1,2	1,2	1,1	1,0	1,0
SD	1,6	1,4	1,2	1,1	1,0
SE	2,5	1,7	1,2	0,9	0,9
SF	SS[b]				

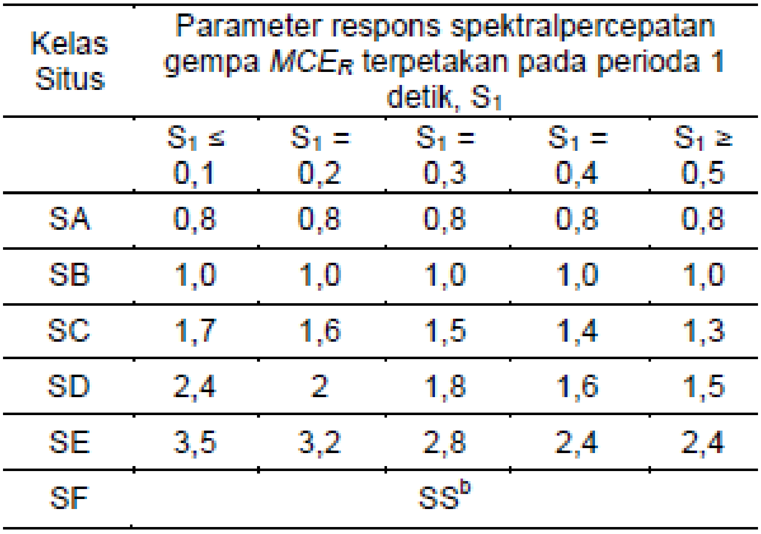
Source: (SNI 1726:2019)

Ss = 0,774 g

Linear interpolation is performed because the value of Ss falls between tabulated Ss values.

Fa = 1,192

Table 4 Site Coefficient, Fv



Kelas Situs	Parameter respons spektralpercepatan gempa *MCE$_R$* terpetakan pada perioda 1 detik, S_1				
	$S_1 \leq$ 0,1	$S_1 =$ 0,2	$S_1 =$ 0,3	$S_1 =$ 0,4	$S_1 \geq$ 0,5
SA	0,8	0,8	0,8	0,8	0,8
SB	1,0	1,0	1,0	1,0	1,0
SC	1,7	1,6	1,5	1,4	1,3
SD	2,4	2	1,8	1,6	1,5
SE	3,5	3,2	2,8	2,4	2,4
SF			SS^b		

Source: (SNI 1726:2019)

S_1 = 0,774 g

Linear interpolation is performed because the value of S_1 falls between tabulated S_1 values.

Fv = 1,74

Maka,

SMS = 0,923 g

SM1 = 0,556 g

Acceleration spectral design parameter

SDS = 0,62 g

SD1 = 0,38 g

3.4 Structural Modelling

The 3D structural modelling of the Cooling Tower building at the Ulumbu Geothermal Power Plant was developed based on data and information obtained from the shop drawings and loading calculations. Using this data, a 3D model was created to analyse the structural strength under earthquake forces through nonlinear static analysis (pushover analysis). The analysis in this study was carried out using the SAP2000 software.

3.5 Capacity Curve

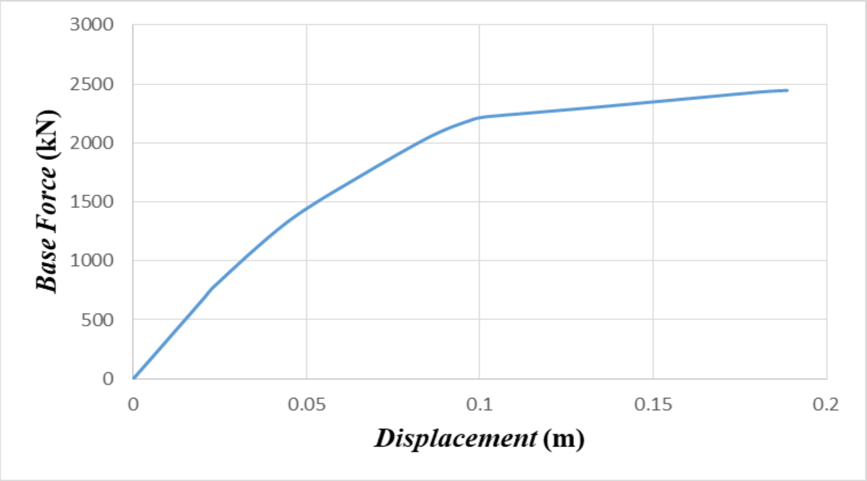


Figure 1. Capacity Curve of Cooling Tower

The curve indicates that when the displacement reaches 0.023608 meters, the structural condition remains elastic, after which it exhibits inelastic behavior up to a displacement of 0.15729 meters.

3.6 Plastic Hinge Distribution

The plastic hinges were designed to follow the intended failure mechanism, namely the beam-sway mechanism (strong column–weak beam). In this mechanism, plastic hinges are expected to form primarily in the beam elements and at the base columns of the structure. The analysis results indicate the locations where plastic hinges occur within the structure.

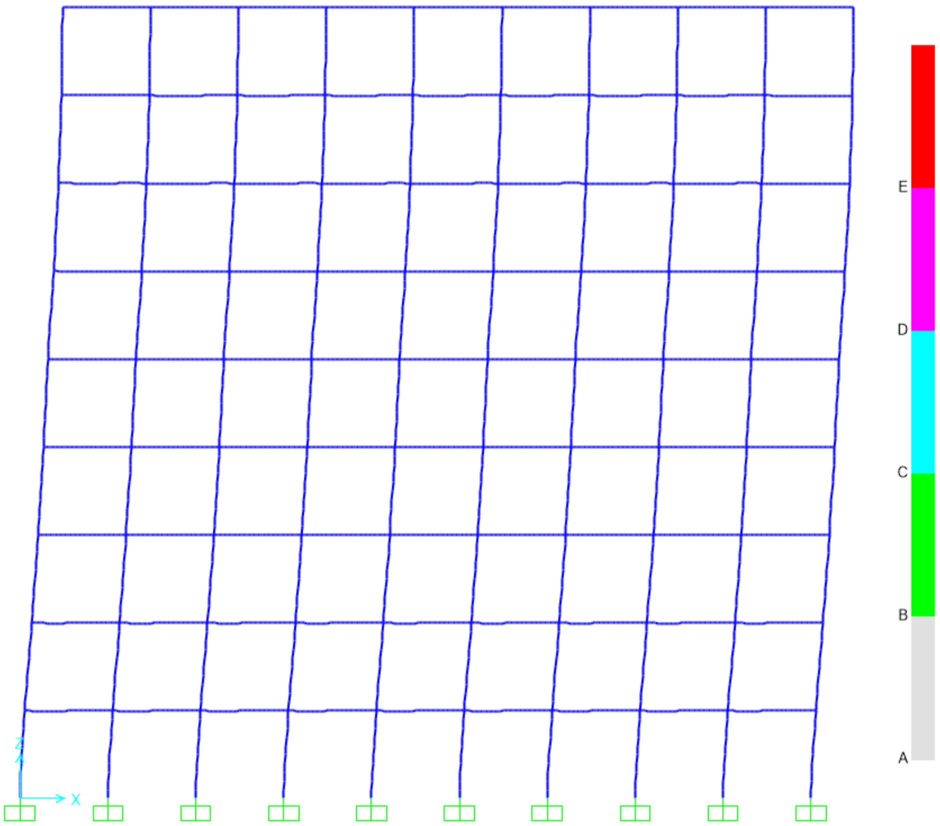


Figure 2. Step 1

At step 1, when the displacement reached 0.020141 meters, no plastic hinges were observed to form in the structural elements of the building.

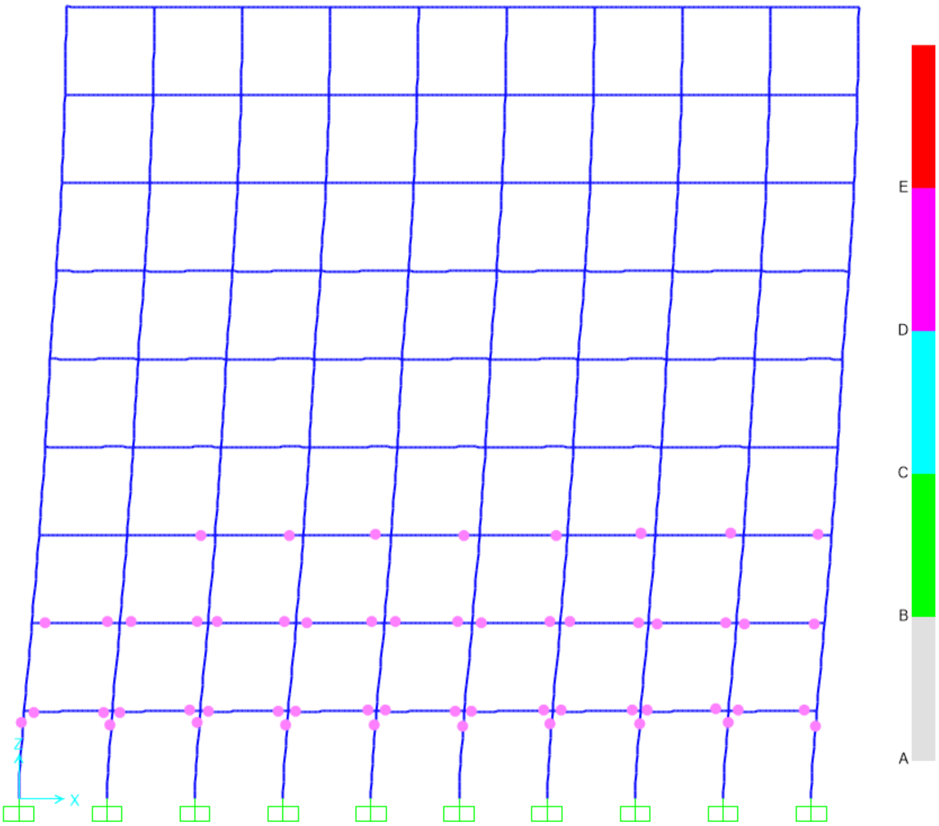


Figure 3. Step 6

At step 6, when the displacement reached 0.098029 meters, a greater number of plastic hinges began to form in the structure. The plastic hinges at this stage were categorized at the B to IO level, indicating that the beam elements remained in the elastic range, as represented by the purple color.

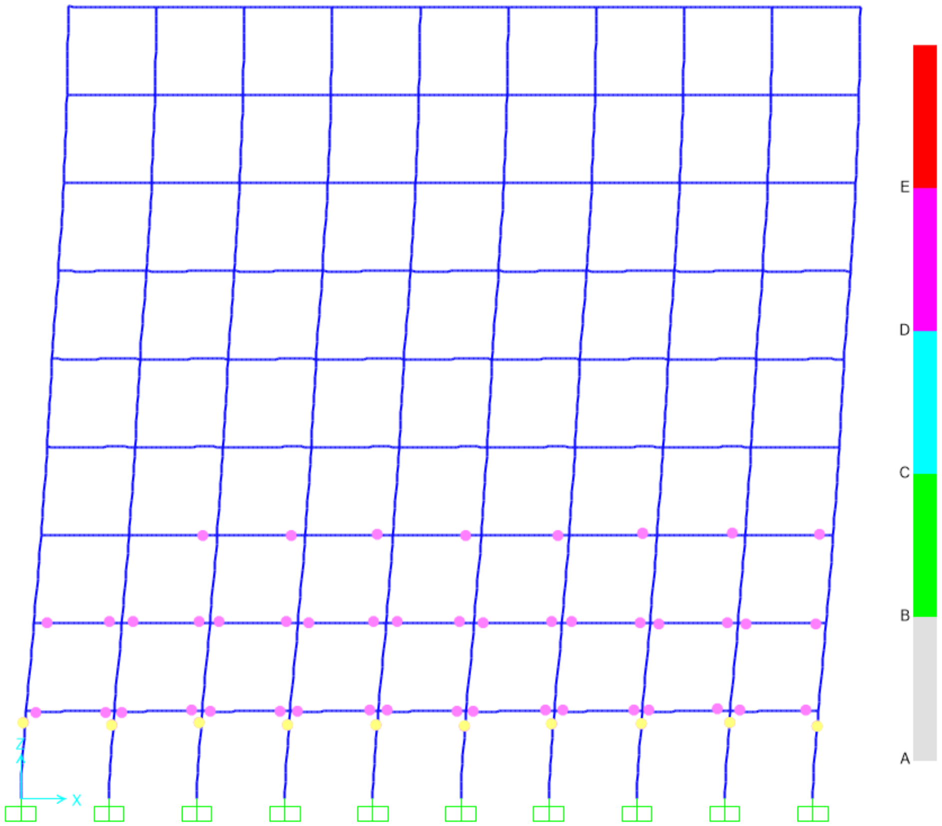


Figure 4. Step 14

At step 14, when the displacement reached 0.188651 meters, the number of plastic hinges in the structure increased significantly, with some hinges progressing to the C to D performance level. At this stage, plastic hinges were observed at both the B to IO level (indicated in purple) and the C to D level (indicated in yellow), signifying that several column elements had reached their yield point and were exhibiting nonlinear behavior.

4 Conclusion

Based on the nonlinear static (pushover) analysis conducted on the Cooling Tower building of the Ulumbu Geothermal Power Plant using SAP2000 software, the following conclusions are drawn:

1. The capacity curve indicates that when lateral force (base force) is applied to the structure, displacement occurs. The greater the applied force, the greater the resulting displacement in the structure.

2. The maximum earthquake load that the Cooling Tower structure is capable of withstanding is 730.383 kN.
3. The distribution of plastic hinges occurs over 14 steps. Plastic hinges begin to form at step 3, and by step 14, they have reached the yielding stage.
4. The performance level of the Cooling Tower building is classified as **Immediate Occupancy (IO)**, indicating that the structure remains safe for occupancy during an earthquake event.

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