International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 05 | May - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Analysis of Hyperbolic Cooling Tower Across Varying Earthquake Zones

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Abstract

This project uses STAAD to present the seismic analysis of a hyperbolic natural draft cooling tower located in Krishnapatnam Nellore district, Andhra Pradesh. As a vital component in industrial and power plant infrastructure, the structural stability of cooling towers under seismic loading is essential—particularly in regions like Krishnapatnam, which lies in Seismic Zone III as per IS 1893:2002. A tower model with realistic dimensions and material properties was analyzed under seismic forces corresponding to Zones II, III, IV, and V. The comparative study highlights the tower's behaviour under varying seismic intensities and evaluates the effect of zone-wise seismic forces on displacement, internal stresses, and support reactions. The findings support the need for zone-specific design modifications to improve seismic resilience. The study underscores the role of STAAD.Pro is an effective tool for evaluating tall, shell-type structures in earthquake-prone areas.

Keywords: Hyperbolic Cooling Tower, Seismic Analysis, Equivalent Static Method, Shell structures, Displacement, Base shear, Principal stress, Plate moments, Plate stresses.

1. Introduction

Cooling towers are an integral feature of many chemical plants. A cooling tower's primary function is to release heat into the atmosphere. A cooling tower is a direct contact heat exchanger that cools warm water by combining it with air that moves quickly. It is primarily used in power plants and process industries to remove heat from warm cooling water from condensers, compressor cooling jackets, pumps and internal combustion engines. They offer a consistent and reasonably priced way to extract inferior heat from cooling water. Cooling towers use evaporation, in which a portion of the water evaporates into a stream of moving air before being released into the atmosphere. This causes the rest of the water to cool considerably.

This project aims to perform a zone-wise seismic analysis of a cooling tower structure using STAAD.Pro is a leading structural analysis and design software. The tower is taken from a thermal plant in Krishnapatnam, which is located in the Nellore district of Andhra Pradesh, and is a major coastal industrial zone under Seismic Zone III as per the Indian standard IS 1893:2016. The analysis is carried out for four different earthquake zones, Zone II, III, IV, and V, to evaluate how varying seismic intensities affect the structural behaviour of the cooling tower.

By comparing the structural performance under different seismic zones, the project provides valuable insights for safe and economical design practices by comparing the structural performance under different seismic zones. It also emphasizes the importance of earthquake-resistant design in industrial projects, especially in coastal and seismically active regions like Krishnapatnam.

2. Objectives:

i. To understand the structural behaviour of hyperbolic cooling towers under seismic loading conditions
ii. Evaluate the seismic response of the cooling tower across a range of earthquake zones, representing different seismic hazard levels.
iii. To compare seismic responses, such as base shear, displacement across different seismic zones.
iv. Identify critical structural elements and potential failure modes under seismic loading.

3. Need for the Study

The detailed study of the analysis of cooling towers across varying Earthquake zones is vital for ensuring structural integrity and operational safety, especially in regions prone to seismic activity. Cooling towers, being tall, and slender structures, are particularly susceptible to lateral forces generated during earthquakes. In the Indian context, such structures seismic design and analysis are governed primarily by IS 1893 (Part 4) : Criteria for Earthquake Resistant Design of Structures – Industrial Structures, which provides specific guidelines for designing cooling towers and similar critical infrastructure. This standard considers various factors such as the seismic zone factor, importance factor, soil type, and dynamic characteristics of the structure. Since India is divided into four seismic zones (II to V), each with varying levels of seismic risk, a zone-wise analysis ensures that the design of the cooling tower is customized to withstand the expected intensity of ground motion in that region.

The scope of the study includes:

- Modeling a Reinforced concrete cooling tower with specified geometric and material properties.
- Performing linear elastic seismic analysis using STAAD.Pro connect edition 2024.
- Multiple earthquake zones should be considered based on a relevant seismic code (e.g., IS 1893).
- Analyzing key structural response parameters, including displacements, base shear, overturning moments, and stresses.
- Evaluating the applicability of STAAD.Pro for seismic analysis of cooling towers.

4. Cooling Tower Elements

Basin- The area at the bottom of the tower for collecting cold water cross flow towers has a hot water distribution basin at the top and, in some cases, a water basin between the top and bottom basin.

Casing – Exterior enclosing wall of a tower, exclusive of the louvers.

Drift – Water droplets from the cooling tower with the exhaust air. Drift droplets have the same concentration of impurities as the water entering the tower.

Drift eliminators – an assembly constructed of plastic, cement board, wood, or other material minimize the entrained water moisture from the discharged air.

Fill – That portion of a cooling tower constitutes its primary heat transfer surface.

Louvers – Blade or passage-type assemblies installed at the air inlet face of a cooling tower to control water splash out and/or promote uniform airflow through the fill. In the case of film-type cross-flow fill, they may be integrally moulded to the fill sheets.

Module – A preassembled portion or section of a cooling tower cell. On larger factory-assembled towers, two or more shipping modules may require joining to make a cell.

Nozzle – A device used to control water distribution in a cooling tower. Nozzles are designed to deliver water in a spray pattern either by pressure or gravity flow.

Psychrometer – An instrument incorporating both a dry-bulb and a wet-bulb thermometer by which simultaneous dry-bulb and wet-bulb temperature readings can be taken.

Riser – Piping which connects the circulating water supply line, from the level of the base of the tower or the supply header, to the tower's distribution system.

Shell – The chimney-like structure, usually hyperbolic in cross-section, induces air flow through a natural draft tower.

Wet-bulb thermometer – A thermometer whose bulb is encased within a wetted wick.

Air inlet - This is the entry point for the air entering a tower. The inlet may take up an entire side of a tower–cross flow design– or be located low on the side or the bottom of counter-flow designs.

Fans - Both axial (propeller type) and centrifugal fans are used in towers. Generally, propeller fans are used in induced draft towers, and both propeller and centrifugal fans are found in forced draft towers. Propeller fans can have fixed or variable pitches, depending on their size. A fan with non-automatic adjustable pitch blades permits the same fan to be used over a wide range of kW, with the fan adjusted to deliver the desired airflow at the lowest power consumption. Automatic variable pitch blades can vary airflow in response to changing load conditions.

5. Classification

A. <u>Classification by build</u>
- a) Packed Type
- b) Field Erected Type

B. <u>Classification based on the heat transfer method</u>
- a) Wet Cooling Tower
- b) Dry Cooling Tower

C. <u>Classification based on air draft</u>
- a) Atmosphere Tower
- b) Natural Draft
- c) Mechanical Draft
  - i) Forced draft
  - ii) Induced draft

D. <u>Classification based on airflow Pattern</u>
- a) Cross Flow
- b) Counter Flow

Natural and mechanical draft cooling towers are the two most frequently utilized cooling towers mentioned above.

Natural draft:

A natural draft cooling tower is a heat exchanger that cools water by direct contact with air. It is used in power plants, oil refineries, petrochemical industries, and natural gas plants to remove heat from the circulating water system. A natural draft cooling tower uses convective flow to circulate air without fans or other mechanical equipment. The density difference between the warm and wet air inside the tower and the cooler and drier ambient air outside causes the airflow.

Due to the tower's layout, no fan is required, and there is almost no circulation of hot air, which could affect the performance. However, a few fans are installed at the bottom in some cases to enhance the air flowrate.

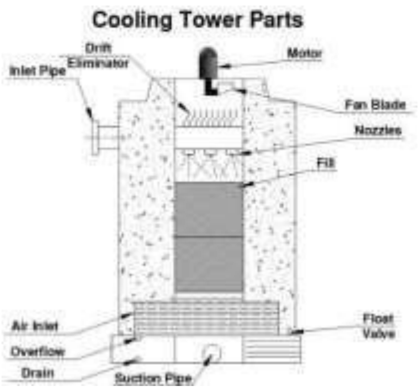

Fig: Components of Cooling Tower

Mechanical draft

Mechanical draft towers have replaced natural draft towers in several places due to their large size building challenges, and high cost. Mechanical draft towers use enormous fans to suck air through circulating water. Water pours downwards over fill surfaces, increasing contact time with air. Mechanical draft tower cooling rates vary based on fan diameter, rpm, and system resistance. There are two different classes of mechanical draft cooling towers:

a. Forced draft.

It has one or more fans at the tower's bottom that force air into it. The fan moves air at low velocity horizontally through the packing and vertically against the downward flow of water on each side. Drift eliminators at the top of the tower eliminate airborne water. The rotating equipment's sturdy foundation ensures slight vibration and noise. The fans handle largely dry air, minimizing erosion and water condensation issues.

b. Induced draft

Induced draft towers use a fan at the discharge to pull air through the tower. The fan forces hot, damp air out of the discharge. This reduces the chance of recirculation, which occurs when discharged air flows back into the air intake.

6. Literature Review

6.1. International Journal of Creative Research Thoughts (IJCRT)

Volume 06, Issue: 01 March 2018

ANALYSIS AND DESIGN OF COOLING TOWER BY USING STAAD.PRO

AUTHORS: P. Balaji, V.S. Sateesh, Suresh Babu

This study analyzes the structural behaviour of a hyperbolic natural draught cooling tower under seismic and thermal loads using STAAD.Pro. The tower model, with a height of 84 m, top diameter of 45 m, and base diameter of 66 m, is evaluated under dead, live, temperature, and seismic loads per IS 875 and IS 1893:2002. To assess its impact on structural performance, shell thickness varies from 60 mm to 300 mm. Results show thinner shells increase vulnerability, with failure occurring at 60 mm under a 5 kN/m load. Force and moment variations help identify optimal design parameters for stability

6.2. International Journal of Scientific Engineering and Technology Research

Volume 05, Issue: 12 May 2016

SEISMIC ANALYSIS AND DESIGN OF A HYPERBOLIC COOLING TOWER

AUTHORS: Puja Venkataiah, P. Prakash

This study analyses the structural behaviour of hyperbolic cooling towers under wind and seismic loads using STAAD.Pro v8i. Models with varying heights (150 m to 300 m) and plate thicknesses (200 mm to 300 mm) were examined through equivalent static and response spectrum analyses. Key parameters assessed include nodal displacement, support reactions, mode shapes, base shear, and plate stress. Results show that taller towers exhibit greater displacement, while thicker plates improve stability. The optimal design is identified as a 250 m tall tower with 300 mm plate thickness and a 60 m throat diameter, balancing strength and cost-efficiency.

6.3. International Journal of Creative Research Thoughts (IJCRT)

Volume 06, Issue: 01 March 2018

ANALYSIS AND DESIGN OF COOLING TOWER BY USING STAAD.Pro

AUTHORS: P. Balaji, V.S. Sateesh, Suresh Babu

This study presents a comparative analysis of RCC cooling towers with varying heights and locations across different seismic zones, using STAAD.Pro v8i for modeling and structural analysis. To assess their impact on displacement and stress, ten models were developed, varying in height (10 m, 15 m, 20 m) and seismic zones (II to V). Results show that both parameters increase with tower height and seismic intensity. The optimal design (Model 4) was identified based on minimal displacement and stress. The findings highlight the importance of height and seismic zone considerations in cooling tower design.

7. Study Area

This project involves the structural analysis of a hyperboloid cooling tower under varying seismic conditions. In order to ensure the study reflects real-world structural behaviour, the design parameters and geometric proportions of the cooling tower model were inspired by an actual cooling tower. The details of the tower are given below.

Location:Krishnapatnam, Nellore, Andhra Pradesh
Seismic Zone: Zone III (as per IS 1893)
Soil Type: Medium Soil
Tower Height: 172.5 m (typical natural draft cooling tower)
Tower Base Diameter: ~132 m
Tower Top Diameter: 77.4 m
Material: Reinforced Concrete (M40, Fe550D assumed)
Foundation Type: Raft/Foundation on piles (assumed)

Key geometrical parameters such as total height (172.5 meters), base diameter, throat diameter, and top diameter were taken from the publicly available design data of this tower, ensuring realism in modeling and analysis. The values still needed for the analysis are assumed and then modelled.

8. Methodology

8.1 Tower Geometry and Modeling Approach

The cooling tower is modeled as a hyperbolic shell structure with a total height of 172.5 meters. The geometry is defined using key parameters such as top, base, and throat diameters.

The shell is discretized using plate elements. For modeling simplification, a uniform shell thickness of 0.4 m was assigned throughout the height of the cooling tower. This value approximates the average of the variable shell thickness used in real structures, ranging from 180 mm at the top to 400 mm at the base. It ensures safe and realistic performance under applied loading. Inclined RCC raker columns are modeled using beam elements to support the base. Pinned supports were assigned at the base of the inclined raker columns to simulate the behavior of hinged or flexible foundation connections realistically. This also simplifies moment transfer and reflects practical construction scenarios for cooling tower supports.

8.2 Material Properties

For structural design, M40 grade concrete and Fe550 grade reinforcement have been used based on IS 456:2000 recommendations for durability and strength requirements of large concrete shells.

Concrete: M40 grade (fc = 40 N/mm² or 40000 KN/m²)

Steel reinforcement: Fe550 (fy = 550 N/mm² or 550000 KN/m²)

8.3 Load Cases Considered

The following load cases were defined:

- Dead Load (DL): Self-weight of the structure
- Wind Load (WL): Applied as a pressure on plate elements
- Seismic Load (EQ): As per IS 1893:2002 for Zones II to V
- Temperature Load (TL): Simulated using uniform and gradient temperature inputs.

8.4 Load Combinations

Load combinations were manually created following IS 875(part 5): 1987 and IS 1893:2002 guidelines. These included:

- DL + EQ
- DL + WL
- DL + TL
- DL + EQ + TL
- DL + WL + TL

Each combination was assigned appropriate load factors to reflect realistic loading scenarios.

8.5 Seismic Zone Variants

Four separate STAAD models were created to represent each seismic zone (II, III, IV, and V) by changing the zone factor (Z) and keeping all other parameters constant.

8.6 Analysis Type

This project involves seismic analysis of a cooling tower using the Equivalent Static Method (ESM) as per IS 1893:2002. ESM is a simplified approach suitable for regular, low-to-medium-rise structures, assuming response in the fundamental mode. Design base shear is calculated based on seismic zone, importance factor, response reduction factor, and natural period, then distributed as lateral forces along the structure's height. STAAD.Pro was used to apply these forces across Zones II to V, and the resulting displacements, bending moments, and shear forces were analysed for comparison.

9. Analysis in STAAD.Pro

This chapter presents the detailed procedure of modelling a hyperboloid natural draft cooling tower in STAAD.Pro software. The model was developed to analyse the structural behaviour under seismic loading conditions corresponding to different seismic zones of India.

9.1 Design Parameters

Height of the tower = 172.5 m

Diameter at the top = 77.4 m

Throat diameter = 76.4 m

Throat height from top = 17.8 m

Diameter at the base = 132.11 m

Inclined support columns were modeled at the base using the Add Beam tool and were later converted into circular column elements.

9.2 Support Conditions

Pinned supports were assigned at the base of the inclined columns to simulate realistic boundary conditions, allowing rotation but restraining translation.

9.3 Material Properties and Specifications

Material Used: Concrete (M40)

Modulus of Elasticity: 34,700 MPa

Poisson's Ratio: 0.2

Density: 25 kN/m³

Plate Thickness: 0.5 m uniformly assigned

For inclined support columns:

Material assumed: Concrete

Cross-sectional shape: Circular of dia 1.0m

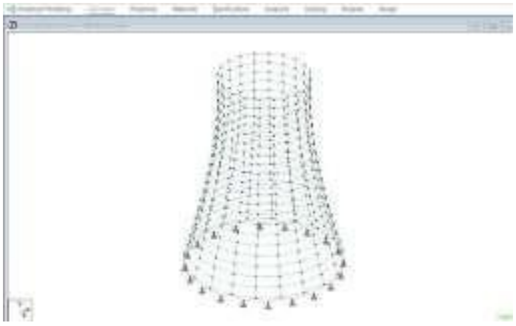

Fig. 2: Analytical model of a Cooling tower

9.4 Load Case Details

1. Seismic load cases

Seismic load X+ 1893 load X 1

Seismic load X- 1893 load X -1

Seismic load Z+ 1893 load Z 1

Seismic load Z- 1893 load Z -1

2. Wind load cases

Wind load X+ PR GX 2.5 kN/m^2

Wind load X- PR GZ 2.5 kN/m^2

3. Temperature cases

Temp 30^0 10^0

4. Dead load case

DL - self weight Y – 1

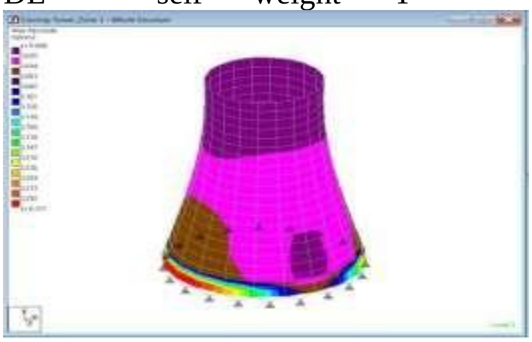

Fig. 3: Plate Stresses on EQ-X

10. Graphs

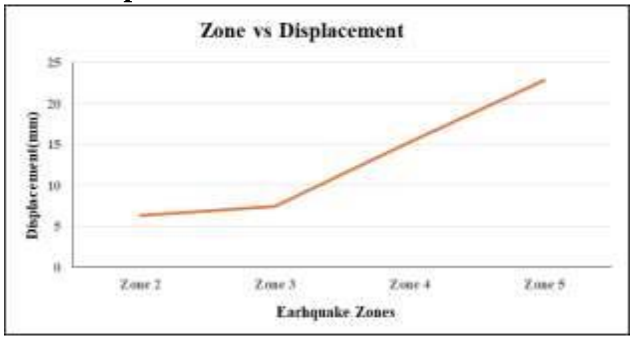

Fig. 10.1 Displacement across varying Earthquake Zones

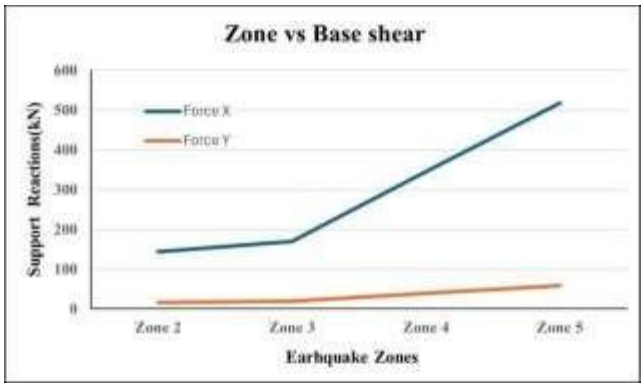

Fig. 10.2: Base Shear across varying Earthquake Zones

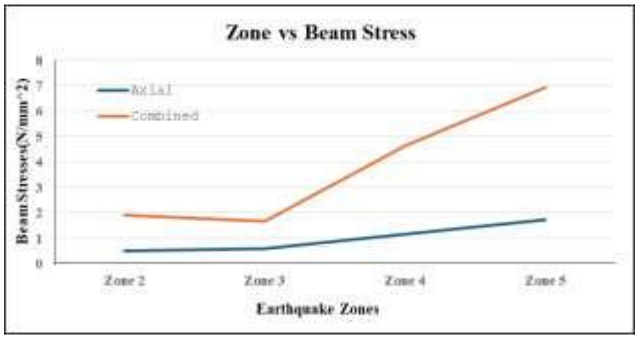

Fig. 10.3: Beam Stress across varying Earthquake Zones

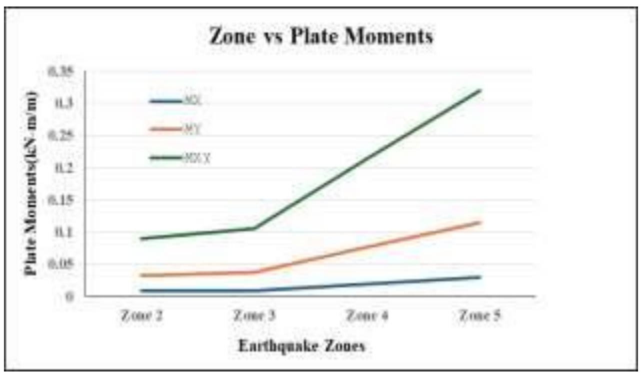

Fig. 10.4: Plate Moments across varying Earthquake Zones

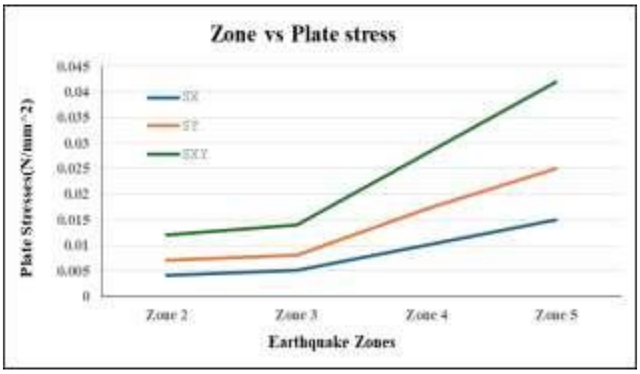

Fig. 10.5: Plate stress across varying Earthquake Zones

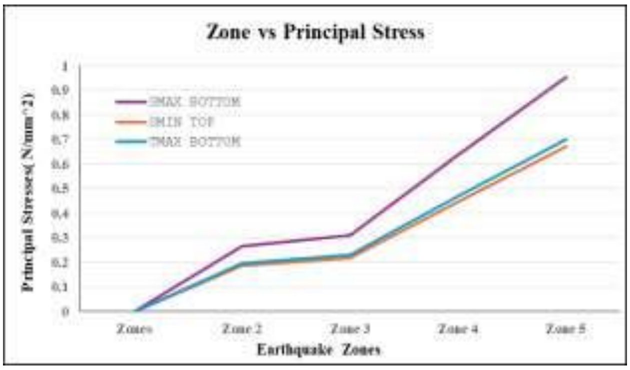

Fig. 10.6: Principal stress across varying Earthquake Zones

11. Results and Discussions:

- Fig. 10.1 shows that displacement increases significantly from Seismic Zone II to Zone V.
- Fig. 10.2 indicates that Base shear, especially in the X-direction, increases sharply with higher seismic zones, indicating rising lateral loads. Stronger foundations are essential in high-risk areas to resist these forces.
- Fig. 10.3 shows that Axial and combined stresses in support beams increase with seismic intensity, with combined stress rising more sharply. This indicates the need for careful reinforcement detailing and stronger sections in higher seismic zones to ensure safety.
- Fig. 10.4 shows that bending moments (MX, MY, MXY) increase with seismic intensity, with MXY showing the steepest rise due to torsional effects. This highlights the need for strong moment-resisting reinforcement, especially in high seismic zones.
- Fig. 10.5 shows plane stresses (SX, SY, SXY) rise with seismic intensity, with SXY increasing most due to shell curvature and combined loading. This underscores the need for proper shell thickness and reinforcement design in high seismic zones.
- Fig. 10.6 indicates Principal stresses (SMAX, SMIN, TMAX) increase with seismic intensity, with SMAX showing a sharp rise in Zones IV and V, indicating higher tensile risks

The discussion confirms that seismic zone severity significantly influences the structural performance of a cooling tower. All response parameters — displacement, base shear, internal forces, and stresses — increase notably from Zone II to Zone V. The findings underscore the necessity for location-specific design, shell optimization, and proper seismic detailing to ensure safety and performance of such tall industrial structures in earthquake-prone regions.

12. Conclusions

From the analysis of cooling towers in varying earthquake zones, the following conclusions are drawn:

- Base shear and displacements increase significantly with higher seismic zone factors, highlighting the need for enhanced design provisions in higher zones.
- The tower remains stable in Zone III (its actual location) but fails to meet displacement or reinforcement criteria in Zone V without design modifications.
- Thicker plate sections are necessary to manage stress and ensure stability in higher seismic zones.
- Towers in Zone V should adopt enhanced seismic detailing such as ductile reinforcement, increased base thickness, and high-grade concrete.
- The study indirectly confirms that increasing plate thickness can mitigate displacement and stress, while taller towers are more prone to seismic damage.
- Failure Sensitivity Zones:
  Based on stress and moment results, the shell's throat region and base intersection consistently

showed peak values for Mxy (twisting) and principal stresses, indicating potential failure points under extreme seismic conditions.

Overall, the study concludes that cooling towers in Zones IV and V must be designed with enhanced structural capacity for optimal structural safety and performance, including greater wall thickness and careful load distribution analysis. This is essential to meet code requirements (IS 1893:2002) and ensure long-term resilience under seismic events.

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