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Analysis of Reliability and Seismic Appraisal of a Reinforced Concrete Hyperbolic Cooling Tower

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Keywords: Hyperbolic cooling tower; Structural inspection; Finite element analysis; Reliability appraisal; Seismic appraisal

Abstract: A reinforced concrete hyperbolic cooling tower of a thermal power plant was built and put into operation in the late 1990s. To understand the current status of the structure, reliability, and seismic appraisal was carried out on the structure. Through field testing, investigations were conducted on structural damage, crack distribution, and tilting conditions. Through finite element analysis, combined with field testing conditions and previous design drawings, the safety and seismic performance of the structure were reviewed. This paper aims to provide guidance for the inspection and appraisal of reinforced concrete hyperbolic cooling towers and to provide valuable references for decision-makers and practitioners encountering similar problems in engineering practice.

1. Introduction

Natural-draft cooling towers are structures that use the principle of natural convection for cooling. Their working principle is to use the power generated by the rising hot air inside the tower to allow cold air to enter from the bottom of the tower, then through the packing layer inside the tower, to allow water and air to carry out large-area heat exchange, achieving the purpose of cooling. Natural-draft cooling towers are widely used in the cooling systems of power, chemical, metallurgical and other industries due to their high cooling efficiency, low energy consumption, low maintenance cost, and long service life.

The development of natural-draft cooling towers can be traced back to the end of the 19th century. With the progress of industrialization, the demand for cooling equipment has been increasing, and natural-draft cooling towers have been widely used due to their unique advantages. However, over time, problems such as structural aging of natural-draft cooling towers, the impact of environmental factors, and damage during use have gradually emerged. These problems may affect the normal operation of the cooling tower and may even lead to structural failure of the cooling tower.

In recent years, research on natural-draft cooling towers has mainly focused on performance optimization, application of new materials, and design of new cooling towers. However, for existing natural-draft cooling towers, how to evaluate the reliability of their structures, especially reinforced concrete natural-draft cooling towers, there is relatively little research in this area. Therefore, the reliability appraisal of reinforced concrete natural-draft cooling towers is of great practical significance for ensuring the safe operation of cooling towers and extending their service life.

The purpose of this paper is to carry out a reliability appraisal of a specific concrete natural-draft cooling tower, and explore the reliability appraisal method of concrete natural-draft cooling towers, to provide a reference for the maintenance and management of concrete natural-draft cooling towers.

2. Literature Review

Currently, in the field of architectural science and engineering in China, research on hyperbolic natural-draft cooling towers mainly focuses on structural design, seismic performance, and the impact of wind loads. However, there is not much research on inspection, appraisal, and reinforcement.

Zhou Changdong et al. conducted an in-depth study on the seismic reinforcement methods of hyperbolic cooling tower structures in their research[1]. They selected four different reinforcement schemes and compared the seismic vulnerability curves and vertex displacement envelope lines of the cooling tower structure under each scheme through finite element analysis. The results showed that all four reinforcement schemes could effectively reduce the damage to the structure, and the scheme of adding rubber bearings at the bottom of the structure was the most significant.

Lu Ming et al. detailed the steps and methods of inspecting and identifying the buttresses of a hyperbolic cooling tower in their research and proposed targeted reinforcement treatment plans[2]. They found that the concrete strength of most of the buttresses in this project did not meet the original design requirements, and there were cracks along the main reinforcement on some buttresses, which affected the bearing capacity of the structure. After the reinforcement treatment, the current use status of the structure is good, and the durability has been improved. This provides a reference for similar engineering inspection and appraisal and reinforcement.

Tan Yan et al. conducted an inspection and appraisal of the structural appearance damage and concrete strength of the shell of a hyperbolic cooling tower and used the finite element software ABAQUS to analyze the internal force distribution law of the hyperbolic cooling tower under wind load, temperature load, and self-weight load[3]. At the same time, the overall stable performance of the cooling tower was analyzed using the principle of eigenvalue buckling analysis. The analysis results provide a reference for the design and reinforcement of similar projects.

Xu Haitao et al. took a hyperbolic cooling tower of a thermal power plant built in the 1970s as an analysis case, summarized the differences in structural design calculations and construction requirements of hyperbolic cooling towers in the new and old versions of the code, and conducted an appraisal analysis of the safety, durability, applicability and seismic performance of the cooling tower, and proposed reinforcement opinions and treatment measures, providing practical engineering experience for future similar appraisal work and related research[4].

Liu Zhiming et al. conducted an inspection and appraisal of the concrete strength, settlement, tilt, and external corrosion damage of a cooling tower, used the large-scale general design software ANSYS to establish a finite element model, combined with local meteorological data, simulated the structural response under the action of gravity and wind load; and compared the most dangerous part of the structural response with the actual situation of the field inspection, analyzed its safety[5]. The dangerous parts of the software simulation results are relatively consistent with the damage conditions of the field inspection buttresses. The results obtained have certain reference significance for the design and safety assessment of related cooling towers.

Li Juan et al. took a hyperbolic cooling tower built in the 1990s as an analysis case, conducted an inspection and appraisal of its appearance defects, concrete carbonation degree, steel bar corrosion degree, and tilt degree, and used the finite element method to calculate the internal force and deformation of the cooling tower under various load combinations, and conducted overall stability and local stability analysis of the tower tube, checked the crack development situation of the tower body, and finally proposed corresponding reinforcement treatment measures based on the field appraisal situation and finite element calculation results[6].

Liu Zhiming et al. conducted a detailed analysis of the causes of corrosion of cooling tower reinforced concrete, summarized the mechanism of concrete corrosion damage, and combined with practical engineering cases, detailed the process of aggravating concrete corrosion due to the mutual influence of several corrosion methods[7]. Finally, suggestions were made for the protection of the durability of cooling tower concrete, which can be used as a reference for other similar projects.

Zhou Changdong et al. used numerical simulation methods to evaluate the seismic vulnerability of the structure of a reinforced concrete cooling tower in a project[8]. The analysis results showed that the damage probability of the cooling tower structure under the action of horizontal bidirectional earthquakes was significantly increased compared to the action of unidirectional earthquakes. If only the action of unidirectional earthquakes is considered, it will deviate significantly from reality. The structure meets the requirement of "not falling in a major earthquake" according to the safety reserve analysis.

Qin Wenke et al. combined with a specific engineering example, considered the influence of foundation soil, used the finite element analysis software ABAQUS to conduct structural analysis on a hyperbolic cooling tower, and focused on the displacement, stress, and internal force distribution law of the cooling tower tube under the action of self-weight, temperature, and wind loads.[9] The local stability of the tube wall was checked in combination with the code, and the overall stability of the tube was analyzed using the eigenvalue buckling analysis method. The analysis results provide a certain reference basis for the structural design and modification of hyperbolic cooling towers.

3. Engineering Case of Inspection and Appraisal

3.1 Project Overview

The aimed reinforced concrete hyperbolic cooling tower was built and put into operation in the late 1990s. The tower is 90 m high, the inlet height is 5.6 m, the outlet and throat diameter of the shell are 42.722 m (elevation 90.00 m) and 42.722 m (elevation 72.00 m) respectively, and the outer edge diameter of the annular foundation is 79.614 m. As the hyperbolic cooling tower has been in use for about 20 years, the shell, diagnoal columns, and filling and water distribution frame have all shown signs of rebar rust and concrete damage. To understand the current state of this structure, reliability, and seismic appraisal was carried out to provide a basis for subsequent use or engineering treatment. Figure 1 is an aerial view of the hyperbolic cooling tower.

Figure 1: Aerial View of the Reinforced Concrete Hyperbolic Cooling Tower

3.2 Summary of the Main Inspection

(1) The shell of the hyperbolic cooling tower is a reinforced concrete thin-shell structure with varying thickness, gradually thinning from the bottom up, and there are a total of 40 pairs of diagonal columns. The foundation of it is an inverted T-shaped annular foundation. The filling and water distribution frame is a concrete frame structure, with a total of 144 columns, using independent foundations.

(2) The axial size and structural layout of the on-site structure are consistent with the drawings. The main spacing of the filling and water distribution frame columns is 5.00m, the elevation of the secondary beam is 5.80m; the height of the cooling tower is 90.00m.

(3) The concrete strength is inspected through on-site core drilling for sampling and subsequent compressive strength testing. The sampling results show that the standard value of the concrete compressive strength of the shell and diagonal columns is 36.7 MPa; the standard value of the concrete compressive strength of the column components of the filling and water distribution frame is 37.4 MPa; the standard value of the concrete compressive strength of the main beam components of the filling and water distribution frame is 25.0 MPa.

3.2.1 Foundation and Base

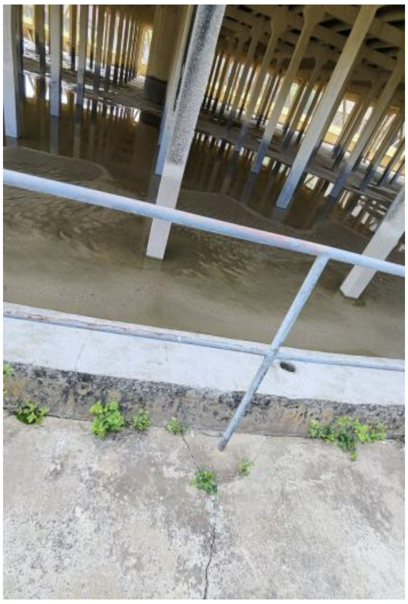

Figure 2: Outdoor Floor Crack 1

(1) Inspection of the outdoor floor damage defects: Near the polar coordinate system X-41, there is a crack on the outdoor floor that is perpendicular to the arc and extends outward, with a maximum crack width of about 3mm (as shown in Figure 2); Inspection of the relative displacement at the junction of the outdoor floor and the main structure: There is a separation between the outdoor floor and the outer side of the annular foundation, with a maximum crack width of 1.5mm (as shown in Figure 3).

Figure 3: Outdoor Floor Crack 2

(2) Inspection of the indoor floor (pool bottom plate) damage defects: There are a large number of cracks on the indoor floor near the central vertical well (near the H axis) (as shown in Figure 4); no relative displacement phenomenon was found at the junction of the indoor floor and the main structure.

Figure 4: Indoor Floor (Pool Bottom Plate) Crack

3.2.2 Shell and Diagonal Column

(1) The cross-sectional size of the diagonal column is 450mm×450mm, and the measured value of the protective layer thickness is 12mm～40mm.

(2) The cross-sectional size and rebar configuration of this type of sampled component meet the original design requirements, and the rebar protective layer thickness of some components does not meet the original design requirements and does not meet the requirements of the Code for Quality Acceptance of Concrete Structure Construction [10] and other relevant specifications.

(3) The shell and diagonal columns have damage such as exposed bars, rebar rust, and concrete surface defects (as shown in Figure 5), and no obvious stress cracks and structural defects caused by tilting were found.

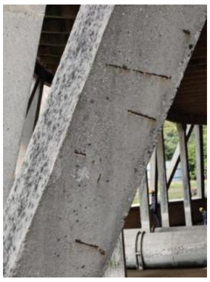

Figure 5: The Exposed Bars and Rebar Rust of Diagonal Columns

There is a large amount of scale on the inner wall concrete surface of the shell (as shown in Figure 6), and some of the concrete surface protective layers fall off and bulge, and no obvious stress cracks are found.

Figure 6: Scale on the Inner Wall Concrete Surface of the Shell

3.2.3 Filling and Water Distribution Frame

(1) The cross-sectional size of the columns of the filling and water distribution frame is 350mm×350mm, and the measured value of the protective layer thickness is 18mm～37mm; the cross-sectional size of the beams is 250mm×500mm, and the measured value of the protective layer thickness is 25mm～34mm.

(2) The cross-sectional size and rebar configuration of this type of sampled component meet the original design requirements, and the rebar protective layer thickness of some components does not meet the original design requirements and does not meet the requirements of the Code for Quality Acceptance of Concrete Structure Construction [10] and other relevant specifications.

(3) There is a large amount of scale on the concrete surface of the filling and water distribution frame, and some of the concrete surface protective layer falls off and bulges and no obvious stress cracks are found.

(4) The sampled columns, with a relative measurement height of 7.80m, have a lateral displacement of the top point between 2mm and 18mm, none of which exceed the lateral displacement limit of the structure top specified in the Standard for appraisal of reliability of industrial buildings and structures [11].

5. Appraisal of Reliability

According to the Standard for Appraisal of Reliability of Industrial Buildings and Structures [11], the natural-draft cooling tower should be evaluated in terms of the foundation, shell, diagonal columns, and water tank and filling and water distribution frame. The reliability of each structured system should be comprehensively judged based on the evaluation results of safety and serviceability.

5.1 Appraisal of Safety

Based on the existing drawing materials and on-site inspection, the project uses the finite element analysis software SAP2000 to model and analyze the shell and its diagonal columns. The analysis results show that the shell and its support structures meet the requirements of bearing capacity. Some of the calculation results are shown as table 1.

Table 1: Partial Reinforcement Envelope Diagram

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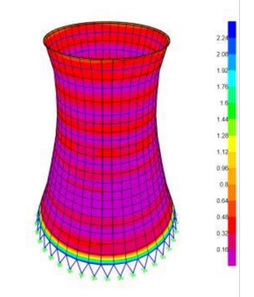
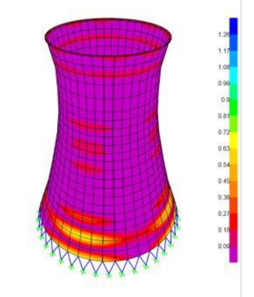
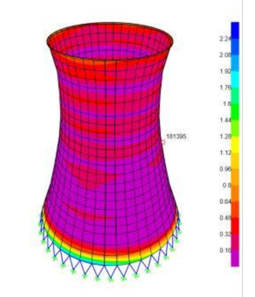
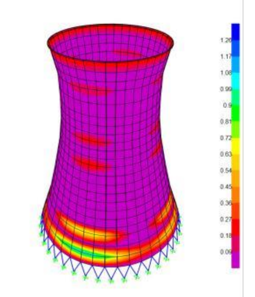
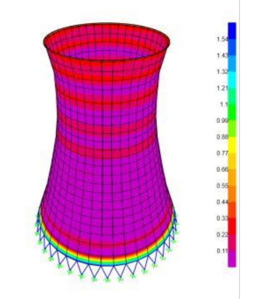
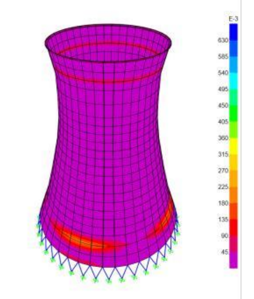
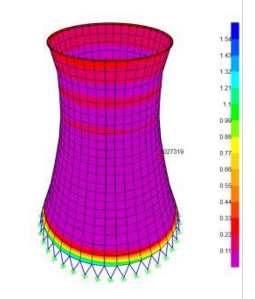
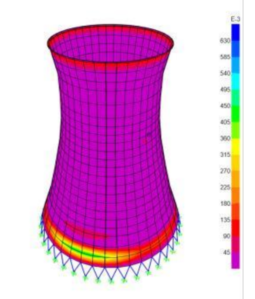
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>BCED-1-A</td><td>BCED-1-B</td><td>BCED-2-A</td><td>BCED-2-B</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>ECED-1-A</td><td>ECED-1-B</td><td>ECED-2-A</td><td>ECED-2-B</td></tr>
<tr><td colspan="4">Note:
1) BCED represents Basic Combination Envelope Diagram.
2) ECED represents Earthquake Combination Envelope Diagram.
3) "-1" and "-2" respectively represent "outer cylinder wall" and "inner cylinder wall".
4) "-A" and "-B" respectively represent "meridional reinforcement" and "circumferential reinforcement.</td></tr>
</table>

5.2 Appraisal of Serviceability

5.2.1 Foundation and Base

Based on the on-site inspection, cracks were found in the outdoor floor and indoor floor (pool bottom) of the structure, but the usage condition of the upper load-bearing structure is normal. Therefore, the serviceability grade of the foundation is rated as B.

5.2.2 Shell and Diagonal Column

According to the on-site inspection, the damage project level of the structure is rated as b, and the crack and tilt project level is rated as a. Therefore, the serviceability grade of the shell and diagonal column is rated as B.

(1) Damage Project

Based on the on-site inspection, the shell and diagonal columns all have exposed rebar, rebar rust, concrete surface falling off, etc. There is a large amount of scale on the inner tube wall of the shell, and some concrete surface protective layers are falling off and bulging, and no obvious stress cracks were found.

(2) Crack Project

According to the on-site inspection, no obvious stress cracks were found on the shell and diagonal columns.

(3) Tilt Project

According to the on-site inspection, no cracks in the outdoor floor and indoor floor (pool bottom) caused by the tilt of the structure were found, and no related cracks were found in the shell and diagonal columns.

5.2.2 Filling and Water Distribution Frame

According to the on-site inspection, the damage level of the filling and wter distribution frame is rated as b, and the crack and tilt project level is rated as a. Therefore, the serviceability grade of the filling and wter distribution frame of the structure is rated as B.

(1) Damage Project

According to the on-site inspection, it was found that there is a large amount of scale on the concrete surface of the filling and water distribution frame, and some concrete surface protective layers are falling off and bulging.

(2) Crack Project

According to the on-site inspection, no obvious stress cracks were found on the filling and water distribution frame columns and main beams of the structure.

(3) Tilt Project

According to the on-site inspection, the top lateral displacement of the sampled columns did not exceed the structural top lateral displacement limit specified in the standard.

5.3 Results of Appraisal of Reliability

The results of an appraisal of reliability are shown in the table 2.

Table 2: Reliability Evaluation Results of Assessment Unit

<table>
<tr><th colspan="5">Appraisal Unit</th></tr>
<tr><td>Appraisal Project</td><td>Structural System</td><td>Evaluation Level</td><td colspan="2">Reliability Level of Appraisal Unit</td></tr>
<tr><td rowspan="3">Safety Evaluation</td><td>Foundation and Base</td><td>A</td><td rowspan="3">Level One</td><td rowspan="6">Level Two</td></tr>
<tr><td>Shell and Diagonal Column</td><td>A</td></tr>
<tr><td>Filling and Water Distribution Frame</td><td>A</td></tr>
<tr><td rowspan="3">Serviceability Evaluation</td><td>Foundation and Base</td><td>B</td><td rowspan="3">Level Two</td></tr>
<tr><td>Shell and Diagonal Column</td><td>B</td></tr>
<tr><td>Filling and Water Distribution Frame</td><td>B</td></tr>
</table>

6. Seismic Appraisal of Special Structure

According to the Standard for Seismic Appraisal of Special Structures [12] and the relevant provisions of the Code for Seismic Design of Special Structures [13], although the cooling tower is a Class B structure, the structural form of the cooling tower has a strong seismic performance. Therefore, it is exempt from the requirement of "increasing by one degree" for seismic design by the seismic fortification intensity of this region, that is, seismic design is carried out according to the seismic fortification intensity of this region. In addition, according to Article 3.1.2 of the "Code for Seismic Design of Special Structures" (GB 50191-2012), Class B structures with a seismic fortification intensity of 6 degrees may not perform earthquake action calculations and only design seismic measures. Therefore, this seismic appraisal of the structure only checks and appraises the seismic construction measures of the structure. The seismic construction measures inspection items for Class A structures are shown in the table 3.

According to the on-site inspection, there is a small amount of concrete peeling and exposed and rusted rebar in some areas/components of the shell and diagonal columns, and the rest of the seismic construction measures inspection items meet the requirements of the natural-draft cooling tower for seismic appraisal category A as stipulated in the code.

Table 3: Class A Structure Seismic Construction Measures Inspection

Unit	Appraisal Content		Appraisal Standard Requirement	Current Status of Special Structure	Appraisal Conclusion
Shell and Diagonal Column	Concrete strength grade		Not less than C20	C25.0 (lowest)	Satisfactory
	Crack		No obvious cracks	No obvious cracks	Satisfactory
	Tilt		No obvious tilt	No obvious tilt	Satisfactory
	Concrete damage		No serious spalling and freeze-thaw damage	The shell and diagonal columns both have minor concrete spalling	Unsatisfactory
	Reinforcement exposure or rust		No exposed rust	The shell and diagonal columns both have minor reinforcement exposure, rust	Unsatisfactory
	Shell	Reinforcement	Double-layer bidirectional	Double-layer bidirectional	Satisfactory
		Reinforcement rate	Not less than 0.15%	Minimum 0.15%	Satisfactory
	Diagonal column	Size	b, h should not be less than 300mm	b, h are both 450mm	Satisfactory
Columns and Beams of the Filling and Water Distribution Frame	Concrete strength grade		Not less than C20	Columns: C37.4; Beams: C25.0	Satisfactory
	Crack		No obvious cracks	No obvious cracks	Satisfactory
	Tilt		No obvious tilt	No obvious tilt	Satisfactory
	Concrete damage		No serious spalling and freeze-thaw damage	No serious spalling and freeze-thaw damage	Satisfactory
	Reinforcement exposure or rust		No exposed rust	No exposed rust	Satisfactory

7. Appraisal Conclusion and Handling Suggestions

7.1 Appraisal Conclusion

The reliability level of this structure is rated as Level 2, which means "slightly below the current national standard of reliability requirements, not significantly affecting the overall safety, not affecting normal use, and only very few components should take measures".

There are small areas/components of the shell and diagonal columns where concrete has peeled off, and reinforcement bars are exposed and corroded. The rest of the seismic construction measures meet the requirements of the specifications for natural-draft cooling towers of seismic appraisal category A.

7.2 Handling Suggestions

(1) It is recommended to repair the shell and diagonal columns which have exposed

reinforcement bars, corroded steel bars, and fallen protective layers.

(2) It is recommended to repair the inner wall of the shell which has a lot of scale on the concrete surface, and some concrete surface protective layers have fallen off and bulged.

(3) It is recommended to repair the filling and water distribution frame which has a lot of scale on the concrete surface, and some concrete surface protective layers have fallen off and bulged.

(4) It is recommended to repair the corroded ancillary facilities and replenish the missing ancillary facilities.

(5) It is recommended to strengthen the maintenance and management of the structure during subsequent use. If structural damage is discovered, it should be dealt with promptly.

References

[1] Zhou Changdong, Wang Pengguo, Zhang Xu, et al. Study on seismic reinforcement method of hyperbolic cooling tower structure [J]. Earthquake Resistant Engineering and Retrofitting, 2019, 41(03):130-137.

[2] Lu Ming, Wen Zhihui, Zhao Yanyuan, et al. Detection, appraisal, and reinforcement of a chevron column of a hyperbolic cooling tower [J]. North China Earthquake Sciences, 2015, 33(S1):59-61.

[3] Tan Yan, Tong Yao. Detection, appraisal and stability analysis of a hyperbolic cooling tower [J]. Journal of Hubei University of Technology, 2019, 34(04):81-85.

[4] Xu Haitao, Chen Min. Appraisal analysis of a hyperbolic cooling tower in a power plant [J]. Industrial Construction, 2010, 40(S1):1019-1022+1139.

[5] Liu Zhiming, Zheng Yonglai. Detection and safety analysis of cooling tower structure [J]. Structural Engineers, 2010, 26(04):114-119.

[6] Li Juan, Lu Yuyan, Yang Xingqian, et al. Detection, appraisal and finite element analysis of cooling tower [J]. Journal of Disaster Prevention and Mitigation Engineering, 2017, 37(01):154-161.

[7] Liu Zhiming, Zheng Yonglai. Durability analysis of reinforced concrete in cooling tower [J]. Industrial Construction, 2010, 40(S1):796-798+802.

[8] Zhou Changdong, Wang Pengguo, Tian Miaowang, et al. Vulnerability analysis of reinforced concrete hyperbolic cooling tower structure under multi-dimensional earthquake [J]. Vibration and Shock, 2017, 36(23):106-113+151.

[9] Qin Wenke, Chen Mingxiang, Zhou Jianbo. Strength and stability analysis of hyperbolic cooling tower structure based on finite element [J]. Journal of Wuhan University (Engineering Edition), 2012, 45(S1):209-212.

[10] GB 50204-2015, Code for Quality Acceptance of Concrete Structure Construction [S].

[11] GB 50144-2019, Standard for Appraisal of Reliability of Industrial Buildings and Structures [S].

[12] GB 50117-2014, Standard for Seismic Appraisal of Special Structures [S].

[13] GB 50191-2012, Code for Seismic Design of Special Structures [S].