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Collapse-resistant performance of super-large cooling towers subjected to seismic actions

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ABSTRACT

In this paper, a shaking table test was conducted on a 1/55 scaled reinforced concrete super-large cooling tower. Structural dynamic responses corresponding to different levels of seismic actions were measured and analysed. The structural weakness, collapse mode and failure mechanism were investigated. A numerical model was also developed for elasto-plastic time history analysis of the prototype tower. It was found that the columns were the weakest part of the tower. The acceleration and displacement responses at the top of the columns increased most as the peak ground accelerations increased. Under strong-motion earthquake actions, the tower lost support after the columns failed and collapsed aslant overall. The research presented in this paper can contribute to the improved design of future cooling towers.

1. Introduction

Reinforced concrete super-large cooling towers under construction in China have now reached a height of 252 meters and a maximum weight of 120,000 tons. For these towers, their base diameters exceed 185 m and the minimum thickness of shell structures is only 0.35 m. They will be the largest thin-walled structures in the cooling tower industry when finished. Normally, cooling towers of a nuclear power plant are allocated in short distance with nuclear islands for operational requirements. Structural failures, e.g., total collapse, of cooling towers caused by strong seismic actions can produce strong ground vibrations, and affect the operation safety of nuclear facilities, and even trigger off catastrophic secondary disasters [1,2]. Therefore, it is necessary to understand the failure mechanism, collapse mode and the weakest components of super-large cooling towers when subjected to strong earthquake actions.

Some of the most significant research on collapse-resistant performance of cooling towers can be traced back to investigations of three cooling towers at the Ferrybridge power station that collapsed in November of 1965. As the Ferrybridge incident report pointed out, the incident was mainly due to the underestimation of wind forces and inadequate design theories, which failed to account for the dynamic effects of wind loads; furthermore, the disturbance effects of tower groups were not considered [3]. Thereafter, extensive research was conducted on wind pressure properties of tower surfaces and wind effects on towers. Niemann and Pröpper [4] went on site to measure the distribution of average wind pressures on a tower surface and analysed the fluctuating wind pressure. Kawarabata et al. [5] studied the wind pressures outside and inside of a tower surface, fluctuating wind pressure and wind pressure spectrum from wind tunnel tests with both rigid and aero-elastic models. An empirical formula was also proposed. Liu et al. [6] discussed the scale effect of a single tower and the disturbance effect of two towers based on different Reynolds numbers by using computational fluid dynamics (CFD). Der and Fidler [7], Mungan [8,9], and Mungan and Lehmkamper [10] presented systematic experimental studies on the aerostatic stability of cooling towers and put forward methods for checking their overall and local stabilities. These studies [7–10] were also incorporated into design codes of cooling towers in many countries. Mang et al. [11] theoretically analysed a typical cooling tower made of reinforced concrete and demonstrated that it failed when the materials reached the ultimate strength rather than buckling. In Noh [12], the ultimate load bearing capacity of a cooling tower shell was evaluated, where various nonlinear factors were taken into consideration, including material nonlinearities and geometrical nonlinearities. Krätzig and Zhuang [13] numerically simulated the collapse behaviour of reinforced concrete natural draft cooling towers under dead weight and quasistatic wind action. It was indicated that the weak points of the cooling tower located in tension, where the concrete cracked and the reinforcement yielded. After the Ferrybridge power station incident, cooling towers collapsed at Ardeer Nylon Works in Ayrshire, UK (1973) [14], Fiddlers Ferry

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Power Station in Cheshire, UK (1984) [15], Allegheny Power System in Willow Island, West Virginia, USA (1978) [16], and in Bouchain, France (1979) [17]. Incident reports indicated that design errors [18], inadequate construction [19], geometry defects of cooling towers [19,20] and degradation of material properties [17] may also cause collapses.

The aforementioned research work was mostly focused on wind induced loadings, while for countries in the earthquake active zones, research on earthquake related cooling tower collapse-resistant performance may be of particular interest since seismic actions may be a dominating factor in these areas. However, in comparison with frame structures and bridges [21–25], seismic resistance analysis of cooling towers was less reported. Gupta [26] studied methods to analyse the seismic-resistant behaviour of cooling towers and stated that results obtained by using the response spectrum analysis gave the maximum value of actual responses. Although the seismic action was composed of excitations in three directions, it was sufficient to only take the horizontal movement into account. Sabouri-Ghomi et al. [27] conducted a nonlinear time history analysis of a 134-m-high cooling tower in Iran subjected to actual seismic waves with numerical simulation and evaluated its overall stability. It was found that plastic hinges appeared in columns. After the columns failed, the cooling tower lost stability and finally collapsed. Wolf and Skrikerud [28] analysed a 144-m-high tower and found that it was possible to bring down forces in columns under earthquake actions by increasing the in-plane angles of inclination. In comparison with numerical results by using elastic material models for the columns and foundations, seismic responses of the tower by using nonlinear material models were smaller, and the seismic-resistant capacity was higher and more accurate.

Despite the great deal of research effort asserted on the seismic analysis of cooling towers, there are a few issues that have not been adequately addressed:

(1) Most existing studies were either analytical or numerical while experimental validations are rare and in great need. Shaking table tests of scaled models are desirable and of great importance to the research of seismic performance of super-large cooling towers [29–32].
(2) The structural weakness and possible collapse mechanism were traditionally determined according to the locations where the maximum responses occurred [33,34]. Further research should include analyses of entire collapse processes of super-large cooling towers based on experimental study and numerical simulation, which would provide a more solid foundation for research on the collapse mode and failure mechanism.
(3) Currently, the highest cooling tower in the world is 200 m high located at Niederaussem Power Station, Germany [35,36]. Its wind-resistant behaviour and durability were emphasized in the design [37,38]. Generally, seismic behaviour analysis was performed for cooling towers less than 150 m in height [39], which is insufficient for any super-large cooling tower over 200 m high.

In this paper, a shaking table test was conducted to investigate the seismic responses of cooling towers subjected to strong seismic excitations. The model was scaled from a natural draft cooling tower of 252-meter-high by a scaling factor of 1:55. Non-contact high speed photography technology was adopted to record the member failures and collapse process. A numerical analysis model was developed and verified, with which a parametric study was carried out to further quantify the influence of design parameters on the performance of the tower. The study presented in this paper will help to clarify the seismic performance and collapse mechanism of super-large cooling towers and provide a basis for disaster prevention designs of super-large cooling towers.

2. Shaking table test of the cooling tower model

2.1. Scaled model of the super-large cooling tower

The prototype structure is a proposed natural draft cooling tower, which is 252 m high. According to the working performance, site conditions and lifting capacity of the shaking table at the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, the scaling factor of dimension S_l was chosen to be 1/55. Dimensions of the scaled cooling tower were all determined based on the dimensions of the prototype structure and S_l, as presented in Fig. 1 and Table 1. The scaling factor of elastic modulus S_E was set as 0.3 according to laboratory conditions. Since self weight has considerable effect on the collapse process, the scaling factor of acceleration S_a was determined to be 1. Scaling factors of other physical parameters were calculated by the similarity theory [40], as listed in Table 2. The scaling factor of mass density S_ρ equalled 16.5; therefore, additional mass was required to be arranged on the tower model. Different from normal building structures, there was no floor inside the tower, so the additional weight blocks were symmetrically hung on screws positioned inside and outside of the shell structure. The mass distribution, which varied with the diameter and thickness of the shell structure, was realized by changing the number and weight of blocks circumferentially at every height. The scaled model with templates removed and with weight blocks added is displayed in Fig. 2, respectively. The total weight of the model was estimated to be 16,318 kg, including the scaled cooling tower of 577 kg, the additional weight of 11,378 kg and the foundation weight of 4363 kg.

The prototype was constructed by using grade C45 concrete and HRB400 reinforcement. Mortar and iron wires were selected to build the scaled cooling tower based on the similar mechanical properties shared by mortar and concrete, and by iron wires and steel bars. The tested cubic compressive strength and elastic modulus of the mortar were 13.86 MPa and 9806 MPa, respectively [41], which met the similarity requirements listed in Table 2. Iron wires with four different diameters, i.e., 16#, 18#, 20# and 24#, were selected to reflect the reinforcement variation of the shell structure. Their corresponding material properties were tested according to the standard method [42] and are presented in Table 3.

2.2. Selections of seismic waves and input cases

The shaking table test was carried out in two stages. The first stage was designed to compare dynamic responses of the tower

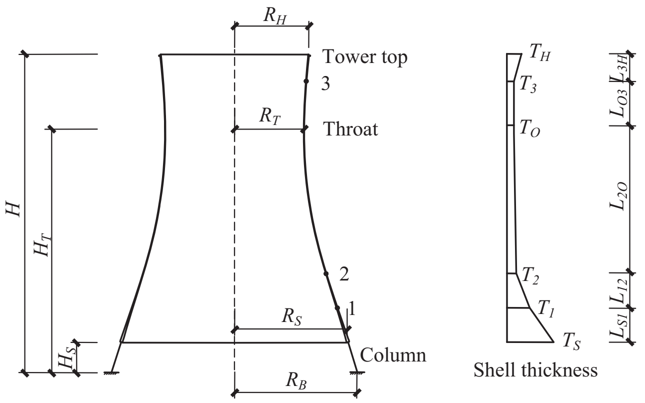

Fig. 1. Definitions of geometry and dimensions of the super-large cooling tower.