GROUND VIBRATION INDUCED BY COLLAPSE OF A 235M HIGH COOLING TOWER

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ABSTRACT

A complete approach for the prediction of the ground vibration due to the collapse of a cooling tower with a height of 235 meter is presented in this study. The causes to induce the tower to collapse could be various accident loads, e.g. explosion or strong wind. The purpose for the prediction of the ground vibration is for the safety evaluation and the plant planning of a planned nuclear power station in China. Firstly, falling weight tests were executed using dynamic compaction method at a construction site. The data for the ground vibrations were measured. Then a finite element method based “falling weight - soil” model was developed to simulate the ground vibration induced by the falling weight and it was verified by the in-site test results. Meanwhile, the simulated collapse processes of the cooling tower under various accident loads were completed in a parallel project, and the results were briefly referred in this paper. Finally, based on the “falling weight - soil” model, a “cooling tower - soil” model was developed to predict the ground vibrations induced by two types of the collapses of the cooling tower. To reduce the numerical consumption, appropriate modeling strategies were executed in building the “cooling tower – soil” model. It was found that, when collapsing, severe vibration occurred in near field of the cooling tower. However, the vibration attenuated rapidly with the increase of the distance.

INTRODUCTION

A new water draft cooling tower with an overall height of 235 m will be built in south China, as a part of the construction of a nuclear power station. Cooling tower with such a huge height, probably the highest one in plan worldwide, results in a full of innovation for both structural design and plant planning. Experience accumulated from this kind of structures with their height up to about 150 m in the past decades is not fully applicable for the new one. Consequently, a series of search projects have been initiated for the purpose of the safety evaluation of the nuclear-related facilities. The project in which the study of this paper was involved focused on two parts. One concerned the causes, process and mechanic behavior of the collapse of the cooling tower. The causes to induce the tower to collapse could be various accident loads, e.g. explosion or strong wind. The other dealt with the ground vibration induced by the collapse of the tower. The objective of this project is for the safety evaluation of the adjacent nuclear island. As a part of the project results, this paper mainly presents some results related to the ground vibration. The collapse of the cooling tower will not be introduced in detail, because another manuscript focused on this theme was submitted to SMiRT 21 too.

Studies on the ground vibration induced by a falling weight could be traced back at least to Lamb in 1904. He studied the vibration of a semi-infinite body under vertically concentrated harmonic force, and derived an analytical solution for the displacement in an integral form [1]. Subsequently, with the rapid development of computational technology, numerical simulation has been applied more and more to describe the ground motion induced by the collapse of structures. Gu and Lee studied the ground response to dynamic compaction of dry sand, using two-dimensional finite element analyses with a large-strain dynamic formulation and a cap model for soil behavior. As a result, the stress wave attenuation and improvement effects were realistically predicted [2]. Pan and Selby simulated the dynamic compaction of loose soils under dynamic loads numerically. A full axisymmetric elasto - plastic finite element representation was generated for the soils, whereas the impact of the drop mass was modeled by means of a force - time input and a rigid body [3]. However, for the ground vibration induced by the collapse of a cooling tower, no studies and suggestions were found either in research papers or in technical handbooks. To realistic evaluate the safety performance of the nuclear power facilities in the event of an severe ground vibration, it is necessary to understand the characteristics of the vibration and thus bridge the knowledge gap.

METHODOLOGY OF THE STUDY

A reliable methodology is crucial for the solution of a complex problem, such as the problem encountered

in this study, involving both structural collapse and ground vibration. The methodology applied in the research project was briefly illustrated in Fig. 1, and could be achieved through the following steps:
(1) Conducting falling weight tests;
(2) Developing a “falling weight - soil” model and verifying it by the tests;
(3) Simulating the collapse of the considered cooling tower;
(4) Building a “cooling tower - soil” model based on the “falling weight - soil” model;
(5) Predicting the ground vibration using the “cooling tower - soil” model;
(6) Proposing the suggestions for the design of the nuclear island and for the plant planning.

The contents in the boxes of Fig.1 with grey background are not presented in detail in this paper. Moreover, to keep the numerical consumption in step (4) at an acceptable lever when the current common used PC was used, we had to execute appreciate numerical strategies.

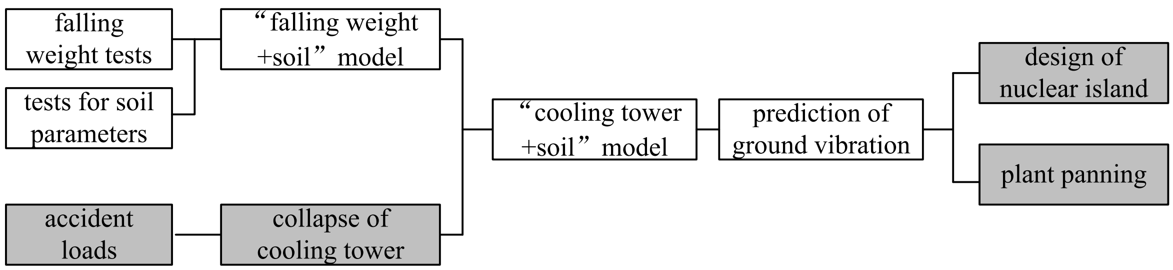


Fig. 1: Methodology applied in the research project

FALLING WEIGHT TESTS

Falling weight tests were executed in a construction site near Hangzhou, China. The tests made use of the facilities of the common dynamic compaction, which is an effective method for the consolidation of the soft soil foundation. As indicated in Fig 2, dynamic compaction machinery slung a weight (with 12 ton in weight and about 2.5 m in diameter) to an appropriate height (about 5.9 m in the tests), and then made the weight fall with the aid of a self-release mechanism. The weight dropped freely and impacted the soil surface at a tamping point and, consequently, induced ground vibration. The equipment layout is schematically shown in Fig. 3. As illustrated in the figure, the considered vibration point is L far from the tamping point. A recording, storing and data processing system was used, including acceleration sensors, which placed in the position of the considered vibration point as accurate as possible, and were used to measure the acceleration histories in vertical and radial direction, respectively. The vibration in tangential direction was not measured, because it was relative small and was regarded as insignificant due to approximately axisymmetry of the site soil [4]. Typical test results for different distances L are illustrated in Fig 5 and Fig 6. It can be seen that the vibration times lasted from 0.5 to 1 second and then the vibration point tended to revert to their stationary positions. The acceleration amplitude, both in vertical and radial direction, decreased significantly with the increase of distance L. For the requirement of further numerical analysis, the soil parameters were investigated through pre-conducted soil tests.

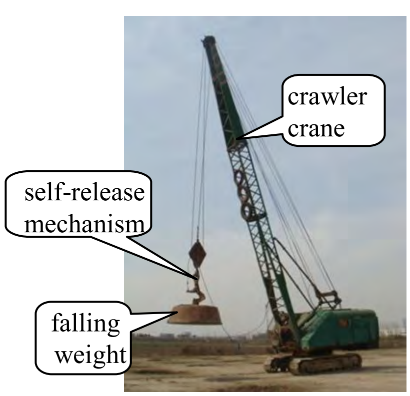


Fig 2: Set-up of dynamic compaction

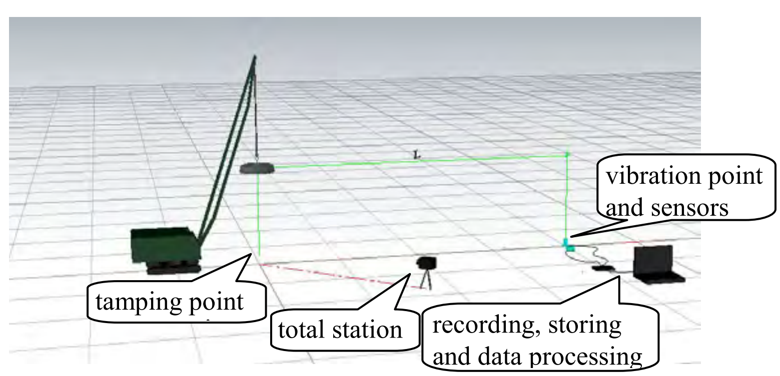


Fig 3: Equipment layout of drop hammer tests

"FALLING WEIGHT – SOIL" MODEL AND VERIFICATION

A finite element method (FEM) based "falling weight - soil" model was developed for the prediction of the ground vibration caused by a falling weight impacting onto the surface of the soil. For verification of the model, the results from the falling weight tests were used. The model was built using a commercial finite element program (ANSYS / LS-DYNA), as illustrated in Figure 4. Both the soil and the falling weight were simulated using the 8-noded isoparametric element Solid164. For material models, ideal elasto – plastic behavior was assumed for the soil, described by Drucker - Prager model [5], whereas a rigid model was applied for the falling weight. This was because the weight is made of concrete filled steel shell and thus could be handled as a rigid comparing with the soft soil. Moreover, several aspects related to the model had to be considered appropriately. Firstly, the soil parameters were ascertained from in - site soil tests and listed in Table 1. Secondly, for the determination of the mesh size of the soil, both the accurate requirement and the numerical efficiency should be considered properly. In general, based on wave propagation theory, the maximum mesh size l_e used in a dynamic analysis based on FEM should meet Eq. (1) [6],

$$l_e \le (\frac{1}{12} \sim \frac{1}{6}) \cdot \lambda_{\mathrm{T}} = (\frac{1}{12} \sim \frac{1}{6}) \cdot \frac{v}{f_{\mathrm{T}}} \tag{1}$$

in which, λ_{T} is the wave length corresponding to the dominant wave frequency f_{T} under consideration. v denotes wave velocity and may be taken as 172 m/s following a calculation with the parameters from Table 1. The dominant wave frequency f_{T} can be taken as 5 Hz following a frequency spectrum analysis of Fig. 5 and Fig.6. As a result, Eq. (1) becomes:

$$l_e \le 2.9\,\mathrm{m} \sim 5.8\,\mathrm{m} \tag{2}$$

Thus, the general mesh size of 5m × 5m × 5m was eventually adopted after two different meshes size were trialed. However, in order to fit the actual thickness of the soil layers, mesh sizes of 4 m ~ 5 m were also used. Thirdly, non - reflecting boundaries were set in the undersurface and the four vertical surfaces of the soil model, so that the waves could transmit through these boundaries without reflection and refraction, as they actually did in real soil. Fourthly, the dimension of the soil model was adopted as 400 m × 400m in horizontal plane and 30m of thickness based on trial computations. Finally, to consider the impact action among blocks, the common penalty function method was used to implement the contact - collision algorithm.

With the aid of the developed model, the acceleration histories of the considered vibration point were simulated and then plotted in Fig.5 and Fig.6 with comparison to the measured data. Good agreement was achieved both in the acceleration amplitudes and vibration duration. The reasons for the differences may contribute to:

(1) In the tests the sensors might be not exactly placed in the vibration point and in the expected directions. Moreover, the sensors were probably not in good contact with the soil surface to insure a synchronous motion;
(2) The weight could fall down onto the ground with a minor obliquity, which was not considered in the model;
(3) The soil parameters and the thickness of the soil layers used in the model were not exactly in conformance with these of the in - site soil.

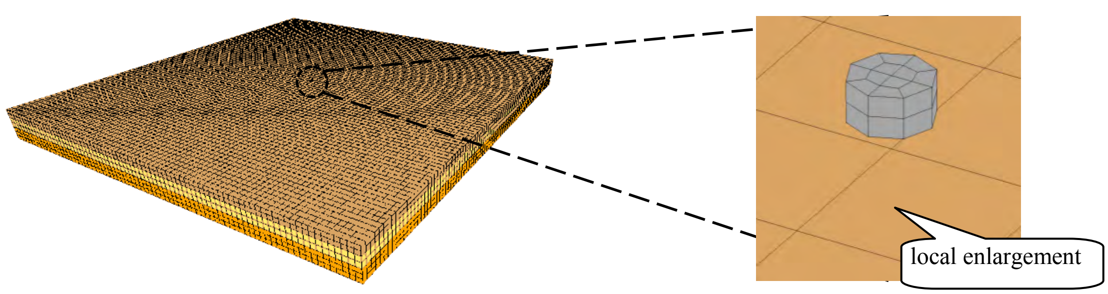


Fig. 4: "Falling weight - soil" model

Table 1: Soil layers and soil parameters

parameters	symbols	units	values		
			clayey silt (uppermost)	sandy silt	mucky silt clay
thickness of soil layer	h_i	m	8	10	12
density	ρ	$\mathrm{kg/m^3}$	1929	1948	1813
shear elastic modulus	G_d^0	MPa	28.88	77.22	99.30
Poisson's ratio	ν	-	0.4	0.4	0.4
cohesion	c	kPa	7.40	5.89	13.85
Internal friction angle	ϕ	degree(°)	30.9	30.4	13.8
damping ratio	ξ	%	1.15	0.92	1.13

Note: 1. Thickness of the soil layer was simplified and used in this study to fit the mesh size; 2.Poisson's ratio was determined empirically.

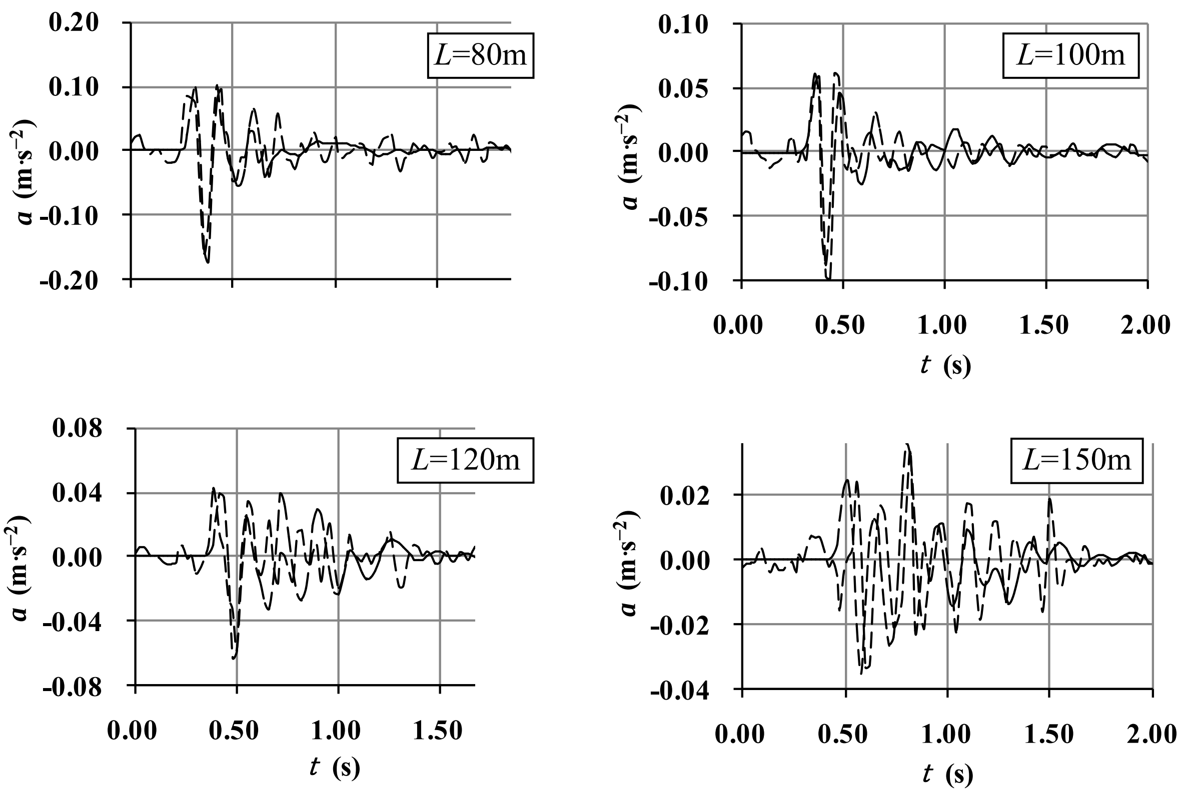
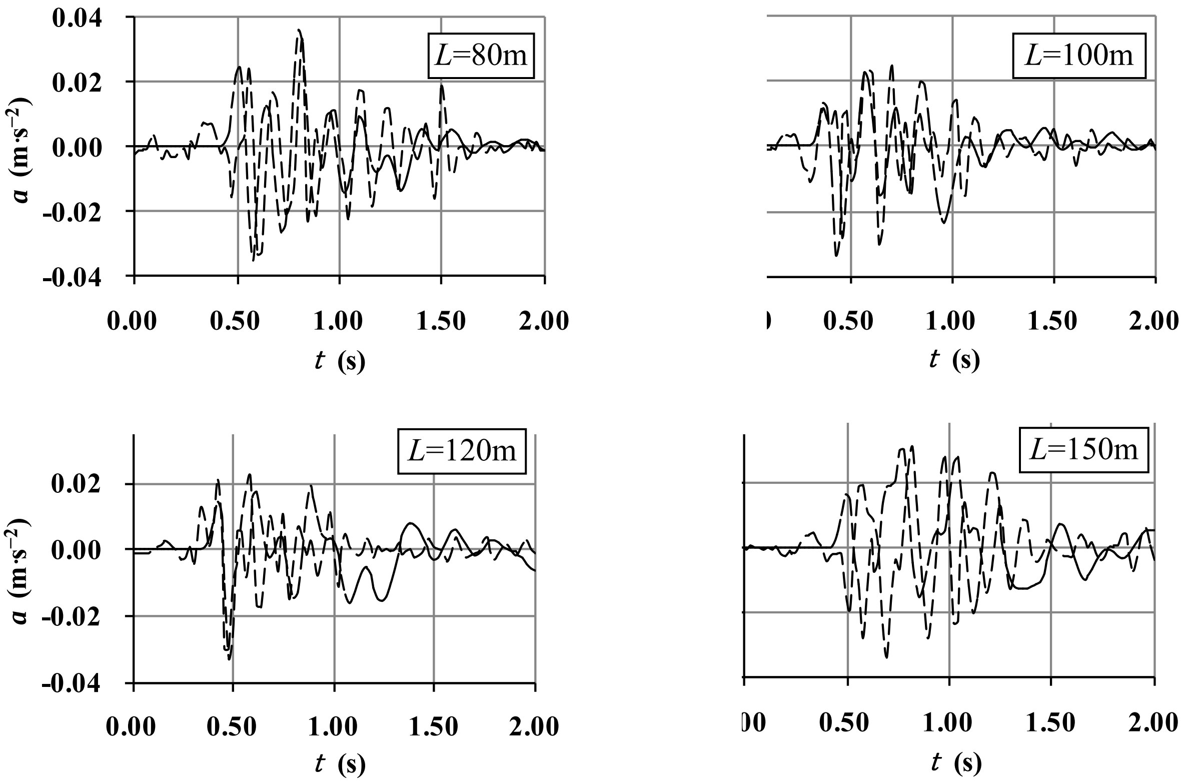


Fig. 5: Tested and simulated results (
("— " denotes the tested results and "– –" denoted the simulated results)

COLLAPSE SIMULATION OF THE COOLING TOWER

The planned cooling tower was of 235 m high, with 120 columns of 18 m high at bottom, as illustrated in Fig. 7. The tower was designed to be constructed with reinforced concrete. In this paper, two categories of accident loads were considered to cause the tower to collapse. One was a sudden failure of 60 columns (simply named load case 1), as a result of, for example, foundation settlement or a bomb attack. The other was an extremely strong wind load (simply named load case 2). The simulated collap



— - - the simulated results)

ted different characteristics under different
or degree (about 3 degree in this study), and
tower. Meanwhile, the residual 60 columns
were crushed into pieces sequentially due to the action of the tower gravity. Then the tower shell impacted the ground intensively and finally disintegrated. This collapse type was labeled as "collapse in integrity" in this study. Unlike this, for load case 2 (wind velocity 44.3 m/s, Beaufort Scale 14), at the early stage a large part of the upper shell was disintegrated, broke into big fragments and then failed onto ground. However, the under portion of the shell do not broke and survived in the wind load. This collapse type was labeled as "collapse in fragments".

It should be noted that, the columns were failed in the collapse type of "collapse in integrity", but survived in "collapse in fragments". To simulate the failure of the columns, we had to use a lot of solid elements by ANSYS / LS-DYNA, i.e. a column including 432 elements for concrete (SOLID164) and 288 elements for steel bars (BEAM161). In total 120 columns contained 864 00 elements, resulting in a tremendous numerical consumption. This disadvantage was to be modified in the study of ground vibration, as described in the next section.

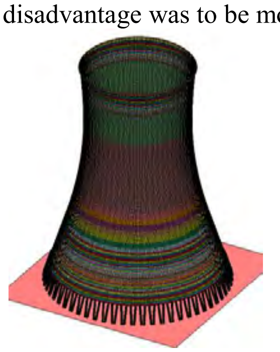
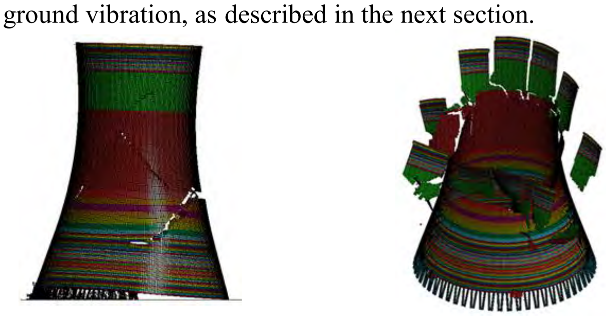


Fig. 7: Profile of the planned cooling tower



(a) (b)

Fig. 8: Collapse of the cooling tower in load case of (a) a sudden failure of 60 columns and (b) an extremely strong wind

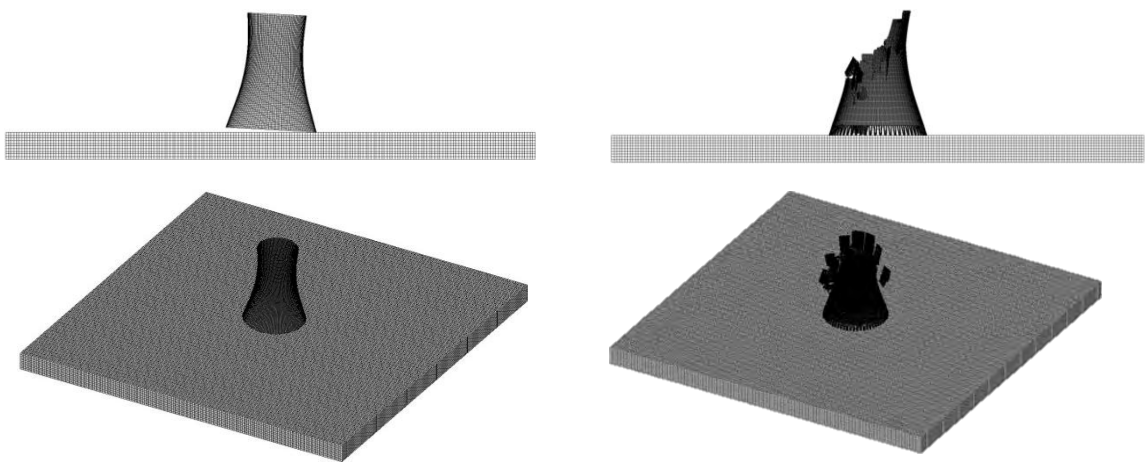
GROUND VIBRATION CAUSED BY COLLAPSE OF THE COOLING TOWER

The ground vibrations caused by the collapse of the cooling tower in case of different accident loads were predicted using a "cooling tower - soil" model, developed from the "falling weight - soil" model described above. To avoid tremendous numerical consumption, we held different simulation strategies for the two collapse types.

For load case 1, the "cooling tower - soil" model is illustrated in Fig. 9(a). At the beginning, the whole tower shell free fell down with an inclination angle of 3 degree, at an average height of 18 m from the bottom of the tower shell to the surface of the ground. The residual 60 columns were deleted intentionally and hence not included in the model. The advantage of this treatment was that, the element number reduced remarkably and computational time was limited to one day using the current common PC. Whereas, the collapse process was believed to have no significant change with comparison to that using the model with columns.

For load case 2, the model was illustrated in Fig. 9(b). In this model, one column was simulated as one beam element. The beam element overestimated the load bearing capacity of the real column. However, the collapse process was almost the same as that using the model in Fig. 8(b), because actually no columns failed in the two models. By doing this the element number of the columns reduced remarkably and thus numerical consumption was reduced significantly.

Additionally, the soil under the cooling tower was rock, and the soil parameters were taken as: density ρ= 2700 kg/m^3, elastic modulus E=4.00 × 10^4 MPa, Poisson's ratio ν=0.2 and damping ratio ξ=5%. The dimension of the soil model was applied as 1000 m × 1000 m × 50 m, which was enough for the considered plant planning.



(a) (b)

Fig. 9: "Cooling tower - soil" model for prediction of ground vibration caused by collapse of the cooling tower in load case of (a) a sudden failure of 60 columns and (b) an extremely strong wind

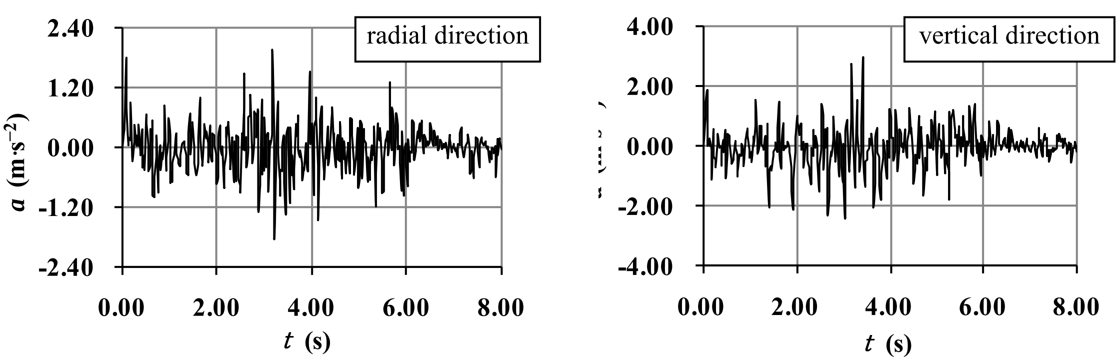


Fig. 10: Predicted ground vibration caused by collapse of the cooling tower in load case of a sudden failure of 60 columns for point at distance L = 200 m

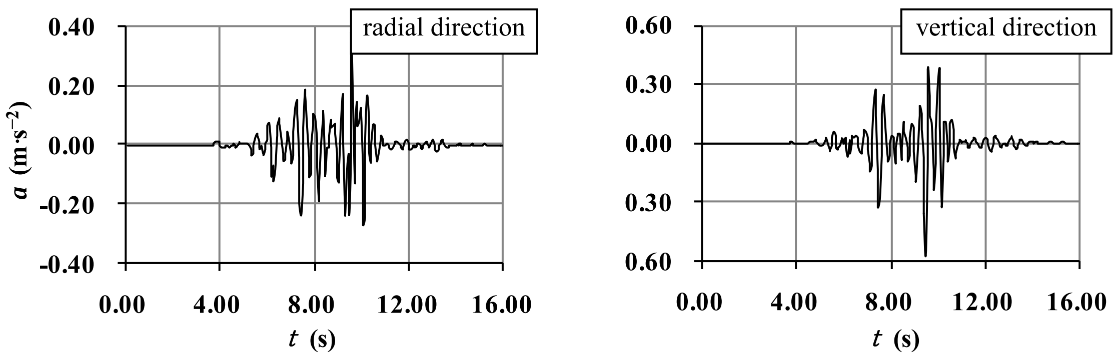


Fig. 11: Predicted ground vibration caused by c(
wind for pc

With the aid of the "cooling tower - soil" model and the appropriate simulation strategies, the ground vibrations were obtained in the form of acceleration histories of the points at different distances L to the ground center of the cooling tower. The results indicated that, severe vibration occurred in near - field (L less than 300 m). However, with the increase of distance L, the vibration attenuated rapidly. In Fig.10 and Fig.11 the results of the two load cases for distance L = 200 m were displayed as examples. It can be seen from the figures that, for load case 1, the maximum acceleration amplitudes are about 0.2g and 0.3g in radial and vertical direction, respectively. However, for load case 2, they were about 0.04g and 0.06g, respectively. The vibration time lasted for about 7 seconds for load case 1 and 9 seconds for load case 2. Based on the assessment method for seismic intensity in China, it can be concluded that a strong earthquake with a seismic intensity of IX occurs in this point.

CONCLUSIONS

This study presents an approach for the prediction of the ground vibration caused by the collapse of a huge cooling tower. The adopted "cooling tower - soil" model was based on a "falling weight - soil" model verified bu means of the in – site falling weight tests. The ground vibration was predicted in the form of acceleration histories of the points at different distances to the ground centre of the cooling tower. It was found that severe vibration occurred in near - field, but attenuated rapidly when distance increased.

Due to the limited page number secrecy reasons, technique details were not presented here. A further study on the characteristics of the ground and underground vibration under various conditions is under way. Moreover, suggestions for vibration reduction based on this study are also planned.

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