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NUMERICAL SIMULATION OF GROUND VIBRATION CAUSED BY COLLAPSE OF A SUPER-LARGE COOLING TOWER UNDER STRONG EARTHQUAKE

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ABSTRACT

Super-large cooling towers, with their height over 200 m and drenching area more than 20000 m^2, are planned to be built in China recently. Engineers worried about that under strong earthquake the huge structure might collapse and cause intensive ground vibration. The collapse-induced ground vibration may enhance the earthquake-induced ground motion, leading to a higher risk for the adjacent nuclear island than that solely under the same strong earthquake. This study focuses on the prediction of the combination of ground motion induced by earthquake and collapse-induced vibration, in the event of a hypothetical collapse of a super-large cooling tower. In the simulation, a 3D model based on finite element method was built using software LS-DYNA. Seismic waves were applied to excite dynamic responses of the cooling tower. By means of an appropriate numerical approach the ground motion was obtained, as a result of a combination of collapse-induced ground vibrations and the earthquake-induced ground motions. It was found that, the cooling tower collapsed under several selected seismic waves. Ground vibration occurred in the vicinity of the cooling tower when the collapse happened. The maximum acceleration amplitudes of the combined waves were not larger than that of the earthquake in the field at a distance of 350m, where the nuclear island located in this study case.

INTRODUCTION

Historically, nuclear leak caused by earthquakes brought people severe damages and cruel lessons, such as the 2011 nuclear accident in Fukushima nuclear power plant in Japan. The imperfect of anti-seismic design might cause nuclear leak in nuclear power plants. The nuclear island has higher anti-seismic grade than cooling towers in a nuclear power plant, once large earthquakes come, cooling towers might collapse firstly. However, due to their huge bodies, the collapse of cooling towers would have a strong impact on the ground which can cause severe ground vibration. The combination of collapse-induced ground vibrations and the earthquake-induced ground motions may cause more tremendous responses of structures than that of the earthquake. As a supplementary anti-seismic design of structures in nuclear plants, it is necessary to study the impact, which is produced by the collapse of cooling towers, on the nuclear facilities in the area of nuclear island under earthquake.

The ground vibration induced by falling weight was recognized a long time ago. The earliest literature about it was published by Lamb et al. in 1904. 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. Barros et al. (1995) studied the dynamic response of a massless rigid strip soil of semi-circular cross-section embedded in a uniform or layered viscoelastic half-space. The soil was subjected to external harmonic forces and moments and to plane homogeneous P-, SV- and SH-waves. Numerical results were obtained using two indirect boundary integral equation methods, i.e. a reciprocity-based approach and a version of the least squares approach. The results for a uniform half-space were tested against the exact solution for longitudinal vibrations and against earlier results for the in-plane impedance functions and for the in-plane response to plane waves. Pan and Selby (2002) numerically simulated the dynamic compaction(DC) of loose soils under dynamic loads. A full axisymmetric elasto-plastic finite element representation was generated for the soils. The impact of the drop mass was modeled in two ways (a force-time input and a rigid body) both resulting in well simulated results of dynamic compaction. Tang (2004) studied the ground particle vibration law of the integer collapse of high-rise buildings using LS-DYNA software. Lin et al. (2013) studied the ground vibration due to the collapse of a 235 m high cooling tower, which can be caused by various accidental loads (explosion or strong wind). Some practical conclusions were obtained from the research on the vibration induced by the collapse of structures. However, for the evaluation of the ground vibration induced by the collapse of a cooling tower under earquake, which is characterized as a huge thin-walled reinforced concrete structure, few studies and suggestions were found in either technical handbooks or research papers. Therefore, the executed study has both academic and engineering significance.

RESEARCH METHODOLOGY

A reliable methodology is crucial for the solution of a complex problem. The methodology applied in the research project is to develop a "falling weight-soil"model and vertify it by falling weight test(Lin et al., 2013). Then a simulation model of "cooling tower-soil" was constructed to predict ground vibration based on the perivous one. The methodology could be achieved throuth the following steps:

(1) Conducting falling weight test;
(2) Developing a "falling weight-soil" model and verifying it;
(3) Building a "cooling tower-soil" model based on the "falling weight-soil" model;
(4) Predicting the ground vibration using the "cooling tower-soil" model.

FALLING WEIGHT TESTS AND VERIFICATION

Falling weight tests were conducted to vertify the "falling weight-soil"model built by Lin et al. (2013). Dynamic compaction was adopted to increase the density of the underlying soils. As indicated in Figure 1, 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. As a numerical experimentation, 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 results of "falling weight-soil" model agreed well with those of site tests which indicated that the simulation model was feasible and reliable (Lin et al., 2013).

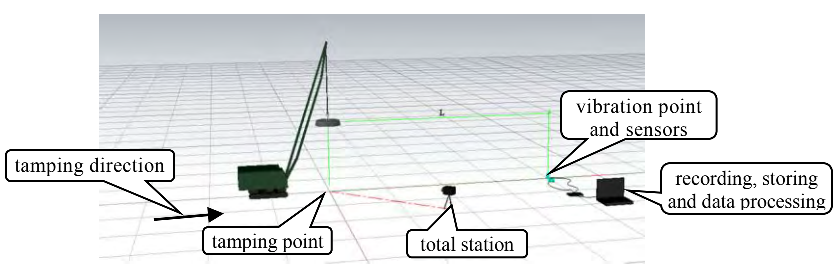


Figure 1.Equiment layout of drop hammer tests

MODELING

A “falling weight-soil” based “cooling tower-soil” model was developed for the prediction of the impact-induced ground vibration.

Finite Element Model of the Cooling Tower

The planned reinforced concrete (RC) cooling tower was of 215m high and weighed 140000 tons, with 46 columns of 19m high at bottom, as illustrated in Figure 2. The thickness of the tower was continuous gradient from 1800mm (top of the columns) to 270mm (the throat) and then to 310mm (top of the tower). A cooling tower model, which is demonstrated in Figure 3, was created by a dynamic finite element method based on software LS-DYNA. The cooling tower was characterized as a huge thin-walled reinforced concrete structure. Shell element was the first choice which could not only reduce the computation time but also simulate the changes of the thickness of the tower shell. Shell element had 4 nodes and the shell thickness could be defined at each node. The tower tube was meshed into 152 layers with the elements of appropriate thickness along the height, as illustrate in Figure 4. As a result, the geometric characteristics of the cooling tower were well simulated. Annular reinforced steel bars and meridional reinforced steel bars were embedded in the tower tube. Each element had 15 integration points in the thickness direction, with each point representing different materials (concrete and reinforcing steel bars).

Solid element and beam element were used to simulated concrete and reinforcing steel bars which were separately modeled in columns with consideration of the geometric characteristic of the columns. A good agreement was achieved between the model and the actual tower at different height. Figure 5 and Figure 6 show the mesh of columns and the mesh of reinforcing steel bars in columns.

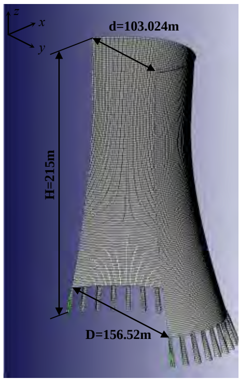


Figure 2. Profile of the cooling tower

Figure 3. Model for cooling tower

Figure 4.Mesh of tower shell

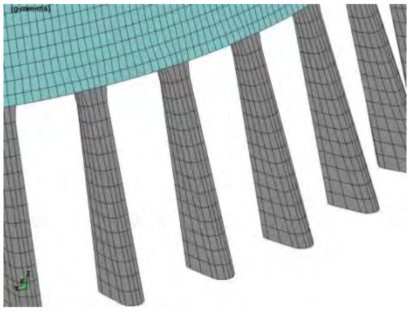


Figure 5.Mesh of columns

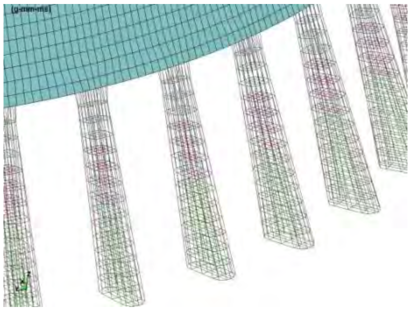


Figure 6.Mesh of reinforcing steel bars in columns

Finite Element Model of Soil

Soil model was established based on the geological conditions provided by geologic report. Soil was usually regarded as a half-space body. A cuboid was intercepted with its center at the center of the cooling tower. Based on the theory of R-waves propagation and previous research by Lin et al. (2013), the dimension of the soil model was set as 1000m×1000m in the horizontal plane with a thickness of 35m.

For the modeling of the soil, the eight-node isoparametric element solid164 was used, and the mechanical behaviors of the layered soils were assumed to be ideal elastic-plastic described by using the Drucker-Prager model (Ducker et al. 2013). Two reasons were taken into consideration to determine the mesh size of the elements. First, to ensure that the propagating waves were spatially resolved with sufficient accuracy, the maximum dimensions of the elements were defined as a fraction between 1/8～1/5 of the shortest wavelength of interest (i.e. between 8 and 5 nodes per wavelength). Second, in order to ensure the computational efficiency, the mesh size could not be too small. As a result, mesh sizes of 5m×5m×5m were used and the total number of soil elements was 280000.

Simplified integral soil element, with only one center integral point, was applied. This integral element was computationally efficient and worked well in the large deformation analysis. However, one problem of one-point integration is the need to control the zero energy modes (sometimes called hourglass modes). Undesirable hourglass modes tend to have periods that are typically much shorter than the periods of the structure response, and they were often observed to be oscillatory. In order to resist undesired hourglass mode, a viscous damping and small elastic stiffness capable to stop the formation of the anomalous modes were used in the simulation. Additionally, contact and collision actions occurred between the falling shells and the soil during the collapse of cooling tower. To describe these actions, the widely used penalty function method was adopted to implement the contact-collision algorithm. To simulate the real soil, the material damping was implemented through mass weighted approach (LS-DYNA Keyword User’s Manual). It was fixed to be 1% for stone and 5% for weak soil.

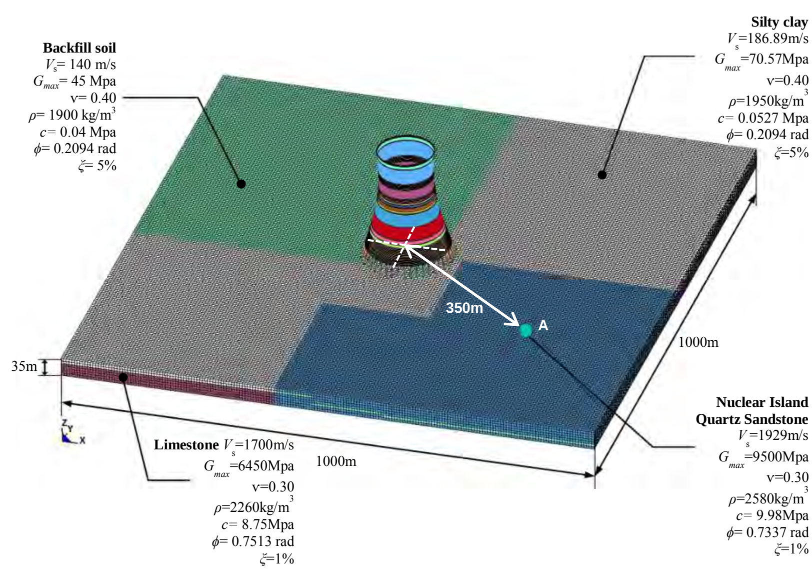


Figure 7. Finite element model of the cooling tower and the soil

The commonly used non-reflecting boundaries (transmitting boundaries) were set in the undersurface and the four vertical surfaces of the soil model. By doing this, the waves could transmit through these boundaries without reflections and refractions, as they actually did in the real soil without artificial boundaries. As illustrated in Figure 7, the distance between nucler island (point A) and the center of the cooling tower was 350m, different colors represented different soil materials and the typies of the soil changed with spatial coordinates. The symbols V_s, G_{max}, v, ρ, c, ϕ, ξ in Figure 7 represent shear-wave velocity, elastic shear modulus, possion's ratio, mass density, cohesion value, angle of friction and damping ratio, respectively. These datas were taken from the geological report and the experiments carried out by the authors.

GROUND VIBRATION

Earthquake is a random process, remarkable changes of responses of structures would appear when seismic excitation changes. Therefore, it is particularly important to select the rational ground motions in time history analysis. In this study, five ground motions were selected based on the peak ground acceleration (PGA), duration and spectrum characteristics, which were the three essential factors for description of earthquake waves.Table 1 lists the initial information of these waves, where g represented acceleration of gravity and was set to be 9.81m/s^2. Figure 8 shows the comparison between seismic acceleration response spectrum and the standard response spectrum of the Chinese code for seismic design of nuclear power plants (GB50267-97). The samples x, y and z in Table 1 and Figure 8 represent three directions in cartesian coordinate system.

Table 1: Information of the selected seismic waves

Name	Duration (s)	Station name	Average shear wave velocity of the site(m/s)	Peak accelerations (g)		
				x-direction	y-direction	z-direction
RG1.60	25	Artificial wave	-	0.1	0.1	0.67
Chi-Chi	64	TCU073	508.7	0.03362	0.02055	0.01679
Hector Mine	59.96	Twentynine Palms	684.9	0.06581	0.06706	0.04307
Landers	54.96	Silent Valley Poppet Flat	684.9	0.04988	0.04105	0.03804
Tabas	32.84	Tabas	766.8	0.8358	0.08517	0.6885

Collapse Process of the Cooling Tower

The selected waves were all obtained by recording the motion of the earth surface. Therefore, the cooling tower was excited by applying three directions of ground waves to the bottom of the columns. Soil model and tower model were built separately. In order to avoid penetration between the soil foundation and the bottom of columns during the input of seismic excitation, the initial distance between them was set to be 0.5m. However, the interaction between tower and soil foundation was not considered.

The PGAs of seismic waves were first set to be 0.05g in horizontal direction and 0.033g in vertical direction. The threshold PGAs were defined by increasing the initial PGAs until the cooling tower collapsed. Table 3 lists the threshold PGAs of each selected earthquake waves. For simplicity, only the case of RG1.60 earthquake waves and the case of Chi-Chi earthquake waves were listed detailly in this paper. Figure 9 shows the collapse process of these two scenarios during the collapse. For the case of RG1.60 earthquake, the PGA arised at about the tenth second. Local failure first appeared at the top of the columns and then extended quikely along the ring beam. Meanwhile, cooling tower began to inclined about 2° owing to the unbalanced counterforce of the columns. At about the eleventh second, the separation of the columns and the tower body developed into an global collapse and ground vibrations were detected at about the thirteenth second. Cooling tower did not capsize and kept the initial angel during the collapse as a result of its small height-width ratio. The shell fragments were not throwed out of the range of the cooling tower.

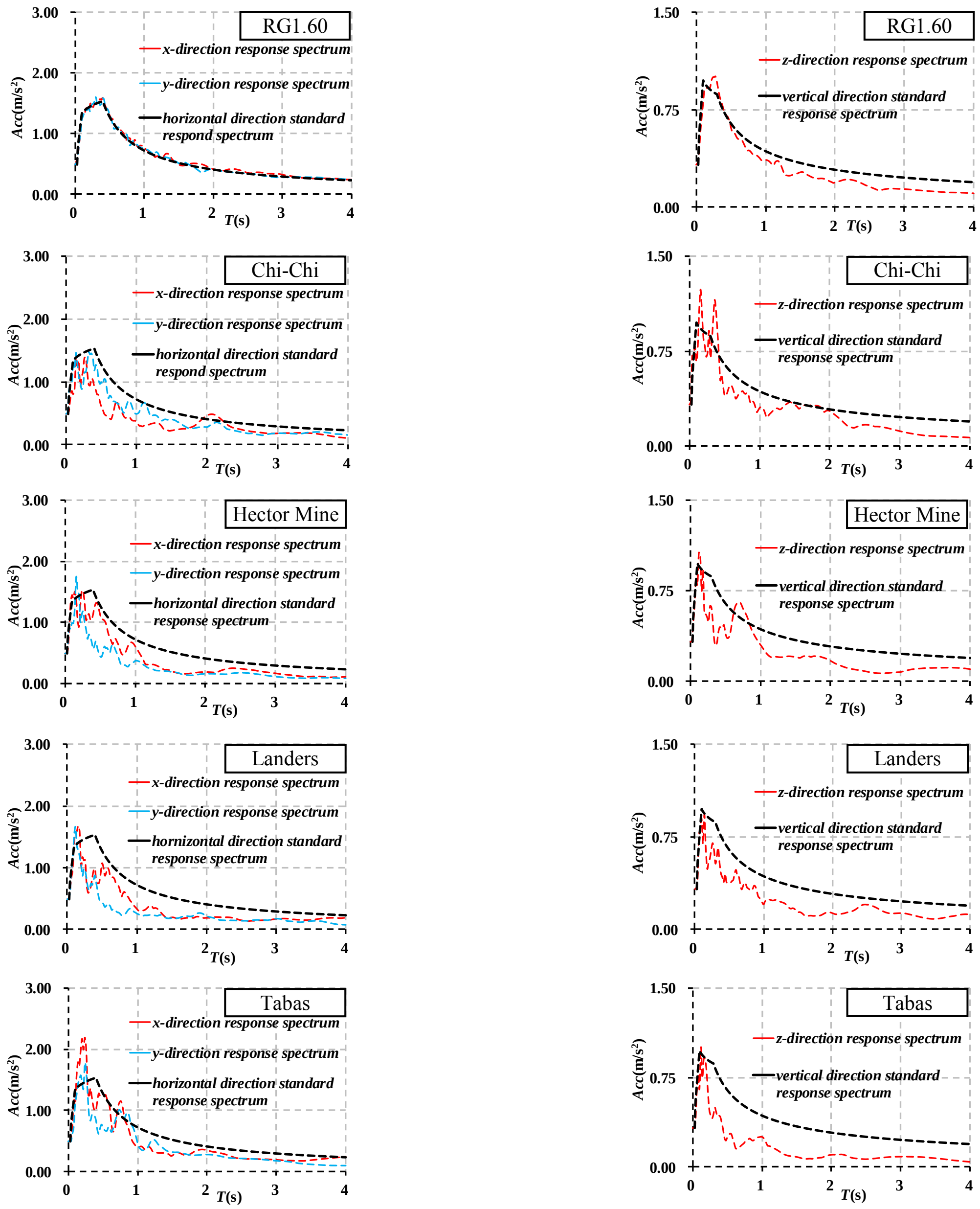
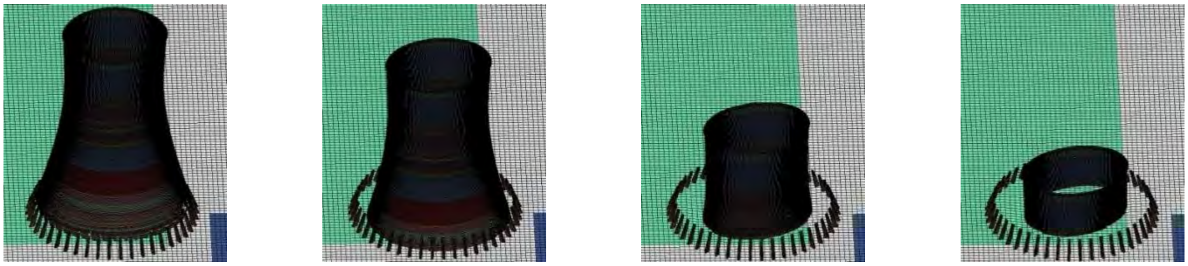


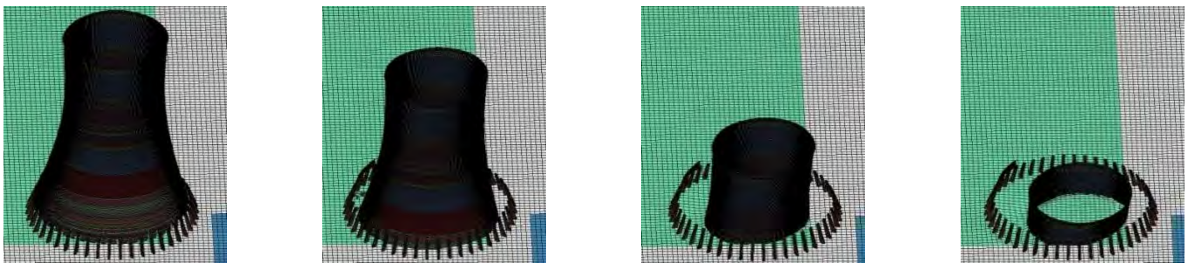
Figure 8. Comparison of response spectra

The case of Chi-Chi earthquake had the almost same process as the case of RG1.60 earthquake. The separation of columns and the tower body occurred at the twenty-second second and grouud vibrations were detected at about the twenty-third second, with no capsizing of the tower. Shell fragments were not throwed out of the range of the cooling tower.

The five scenarios had some similar characteristics for the process of collapse of the cooling tower and the range of scattered shells. It could be concluded that (1) Scattered range of shell fragments were not beyond the range of the cooling tower. As nuclear island was always more than 200m far from the center of the cooling tower, the influence of scattered fragment could be ignored. (2) Weak parts of the cooling tower were the top of the columns under earthquakes (see Figure 10).

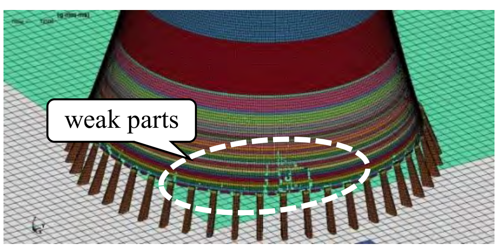


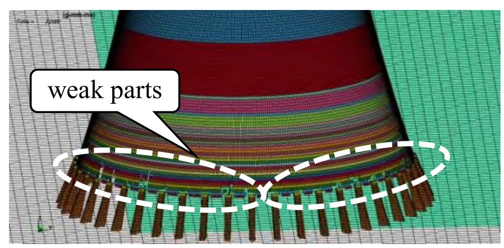
(a) RG1.60, time=11s (b) RG1.60,time=13s (c) RG1.60,time=15s (d) RG1.60,time=16s



(e) Chi-Chi, time=22s (f) Chi-Chi, time=24s (g) Chi-Chi, time=26s (h) Chi-Chi, time=27s

Figure 9. Collapse processes of the cooling tower





(a) RG1.60, time=10.5s (b) Chi-Chi, time=21.18s

Figure 10. Weak parts of cooling tower under the selected earthquakes

Results of Ground Vibration

As previously described, the “cooling tower-soil” model was divided into the tower body and the soil foundation, the seismic excitation was applied to the bottom nodes of the columns. So the ground vibrations obtained were only collapse-induced which did not include influence of earthquake-induced. Figure 11 shows the acceleration histories of different places in the case of RG1.60 earthquake. Parameter L represents the distance from the center of the cooling tower to the point at 150m, 250m and 350m respectively, which was along the connection between the center of the cooling tower and the nuclear island. The duration of collapse was about eight seconds. Table 2 lists the PGAs of three directions of different distances. It shows that the collapse-induced vibration attenuated with increasing distance.

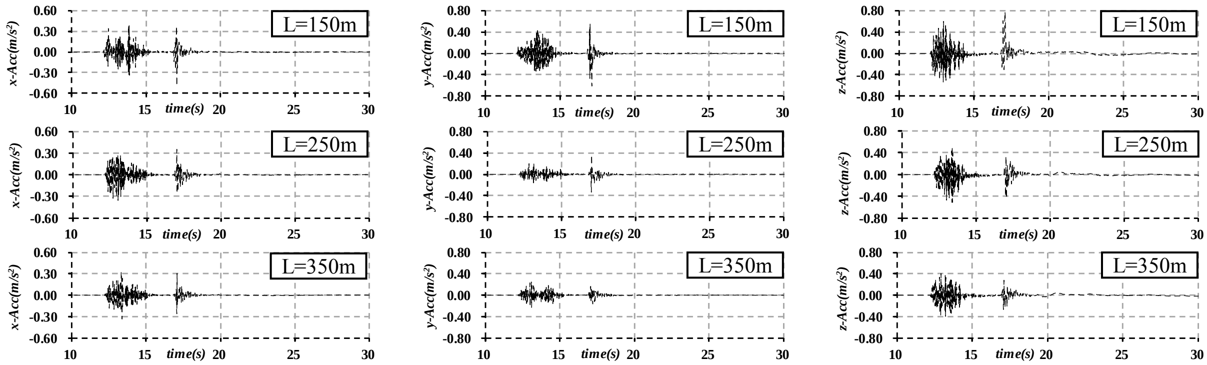


Figure 11. Collapse-induced vibration in the case of RG1.60 earthquake

Table 2: PGAs of three directions of different distances in different cases (collapse-induced vibrations)

Scenario	Direction	Maximum Acceleration Amplitudes (m/s^2)		
		L=150m	*L*=250m	*L*=350m
RG1.60	*x*	0.494	0.357	0.331
	y	0.613	0.362	0.248
	z	0.771	0.511	0.407
Chi-Chi	*x*	0.529	0.466	0.296
	y	0.286	0.238	0.171
	z	1.019	0.351	0.349
Hector Mine	*x*	0.534	0.324	0.298
	y	0.613	0.376	0.321
	z	0.854	0.402	0.357
Landers	*x*	0.450	0.329	0.240
	y	0.270	0.202	0.163
	z	0.447	0.282	0.258
Tabas	*x*	0.434	0.179	0.204
	y	0.265	0.180	0.161
	z	0.656	0.218	0.257

Superposition of Ground Vibration

A superposition of collapse-induced vibration and earthquake-induced vibration should be performed to predict the combined vibration of the ground. Two assumptions were proposed here: (1) Two waves (or more) were independent of each other during propagation, which means waves pass through each other without being disturbed (2) The net displacement of the medium at any point in space or time, was simply the sum of the individual wave displacements. The superposition here means the value addition of accelerations of three directions at the same time-point. Figure 12 and Figure 13 show the differences of acceleration history influenced by superposition. It could be seen that the acceleration histories hardly changed after superposition, indicating that the collapse-induced vibration had little influence on the earthquake-induced vibration. All the results of PGAs listed in Table 3 also support the above conclusion.

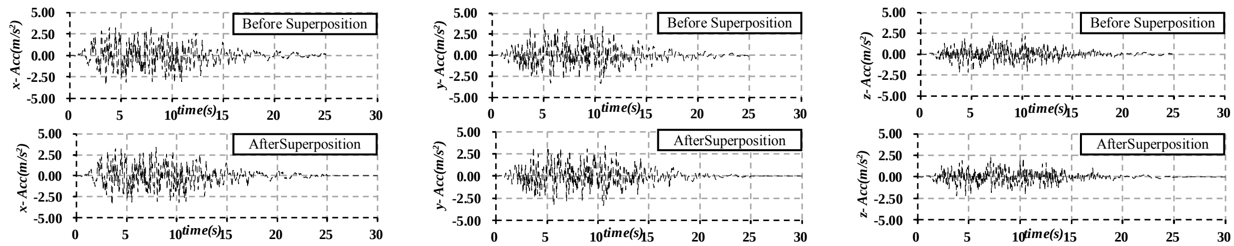


Figure 12. Comparison between earthquake waves and superposed waves (L=150m, RG1.60)

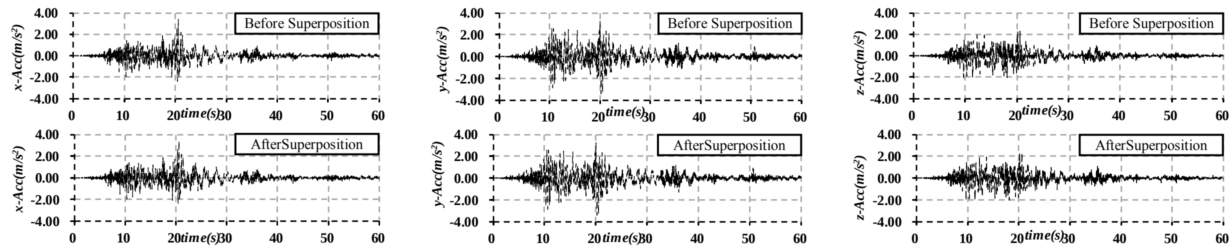


Figure 13. Comparison between earthquake waves and superposed waves (L=150m, Chi-Chi)

Table 3: PGAs of different distances before and after superposition

Name	Threshold peak of acceleration (before superposition)		Peak acceleration of the three direction after superposition L=150m/250m/350m	
	x=y	z	x=y	z
Tabas	0.35g	0.233g	0.35g	0.233g
Chi-Chi(073)	0.35g	0.233g	0.35g	0.233g
Hector Mine	0.35g	0.233g	0.35g	0.233g
Landers	0.45g	0.300g	0.45g	0.300g
RG1.60	0.35g	0.233g	0.35g	0.233g

Discussion

The results obtained above indicated that the maximum acceleration amplitudes of the combined waves were equal to those of the earthquake in the field at a distance of 150 m. In the “far” field (L is more than 150 m) the situations were the same. This may attribute to: (1) PGAs of the collapse-induced vibration were much smaller than those of earthquake-induced vibration when L is no less than 150m. The proportion was about 5%～10% at nuclear island. (2) The cooling tower always collapse at the time of peak acceleration in the study cases. The peak of collapse-induced vibration would always arrive after the peak of earthquake-induced vibration in time history owing to time delay. Time delay was composed by two parts, first was the propagation time of wave in soil, second was the falling time of the tower body.

The peak acceleration used in this simulation was just high enough to make the tower collapsed, so the tower collapsed at the time of peak acceleration and the superposition wave was not higher than earthquake due to time delay. If earthquake is so high to make the tower collapse before the peak acceleration, this may make the two peaks meet at the same time and the earthquake-induced vibration would be enhanced. According to the result above, the process of the collapse of the cooling tower were similar for the five scenarios and the collapse-induced peak accelerations were at the same level. So the upper limit could be obtained by adding the peak accelerations of collapse-induced vibration to those of earthquake. As mentioned above, the PGAs of collapse were about 5%～10% of PGAs of earthquake at nuclear island. So when the earthquake is very strong, the upper limit of the peak accelerations for the design of nuclear island would be about 1.05～1.1 times of the earthquake itself.

CONCLUSIONS

Based on the "falling weight-soil"model, this study presented a methodology for the prediction of the combination of ground motion induced by earthquake and collapse-induced vibration, in the event of collapse of a super-large cooling tower. The following conclusions can be drawn from the study:

(1) The processes of the collapse of the cooling tower were similar in the five scenarios and the collapse-induced PGAs were at the same level. The time of collapse was about 8s～10s. Scattered range of shell fragments was not beyond the range of the cooling tower.

(2) The maximum acceleration amplitudes of the combined waves were not higher than those of the earthquake in the field at the nuclear island area.

(3) The upper limit of the peak accelerations at nuclear island is about 1.05～1.1 times of the earthquake itself.

Owing to the limitation of our knowledge, there is still something more to be desired in this work.

(1) The characteristics of waves would change with geologic site condition. Therefore, new model should be built if geologic site condition changes.

(2) The Soil model and the tower model were built separately. The interaction between them was not considered.

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