The Effect of Cut Height on Ground Vibration and Collapse Area In Blasting Demolition of Cooling Tower

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ABSTRACT

Cut height is a major factor influencing ground vibration and collapse area due to blasting collapse of cooling tower. In this article, the effect of cut height on ground vibration and collapse area is simulated and analyzed by ANSYS /LS-DYNA dynamic finite element software. Meanwhile, the simulated collapse processes of the cooling tower with different cut height were completed in a parallel study, the results of which are briefly introduced in this paper. The results show that: as the cut height increases, ground vibration on surrounding structures and collapse area of cooling tower decreases. When the cut height was 8 m, the collapse area of cooling tower was 82m×71m and the ground vibration at the distance of 54m was 0.098 cm/s. At last, numerical simulation results were used in blasting project, which reduced hazard of collapse vibration and verify the scientific of this method.

KEYWORDS: cooling tower; numerical simulation; cut height; collapse area; ground vibration

INTRODUCTION

Blasting demolition is the preferred method for safely and efficiently demolishing larger structures. The basic idea of explosive demolition is quite simple [1-3]: If you remove the support structure of a construction at a certain point, the section of the building above that point will fall down on the part of the building below that point. If this upper section is heavy enough, it will collide with the lower part with sufficient force to cause significant damage. The explosives are just the trigger for the demolition. It's gravity that brings the building down.

In blasting demolition, Ground Vibration due to the Collapse (GVC) of a huge construction is hazardous for surroundings. Lots of blasting demolition results show that GVC of towering constructions is more harmful than blasting vibration. So it is very important to predict GVC before the operation of blasting demolition projects. In 1904, Lamb [4-5] studied on the ground vibration induced by a falling weight. He studied the vibration of a semi-infinite body under a vertically concentrated harmonic force and derived an analytical solution for the displacement in an integral form. In the 1980’s, scientists[6], in Institute of mechanics (Chinese academy of sciences) proposed a semi-empirical formula (Eq. 1) for predicting GVC in blasting demolition.

$$v = 0.08 \times \left(\frac{I^{\frac{1}{3}}}{R}\right)^{1.67} \quad (1)$$

where v is particle vibration velocity; I is collapse impulse; R is distance from collapse point to measure point. This formula was used as a guidance for vibration prediction of construction collapse in most blasting demolition projects in China. Subsequently, with the rapid development of computational technology, numerical simulation is being applied with increasingly frequency for the description of the ground motion. In 2009, Xie Chun-ming [7] simulated the GVC of frame-structure buildings with the finite element software of ANSYS /LSDYNA and proposed that the touchdown vibration is much smaller than the GVC of huge construction. In 2013, Zhang Guangtong [8] studied on chimney collapse process and collapse vibration law with ANSYS/LS-DYNA dynamic finite element software. He proposed that in reverse direction area of chimney collapse, the first peak collapse vibration is larger than the second collapse vibration; in chimney collapse direction, the second collapse vibration is larger than the first collapse vibration.

Collapse area is also a significant factor for evaluation blasting demolition result. If there is a reserved building inside collapse area, the collapse of demolition construction will hit the reserved building seriously. Few studies on GVC and collapse area in research papers were found for the evaluation of the collapse effect of a cooling tower, which is characterized as a huge thin-walled reinforced concrete structure. This study motivation comes from a cooling water demolition project. The most significant issues is the proper prediction of GVC and collapse area because the cooling tower is adjacent to the viaducts and residential houses with their spacing to be about 60 m and 55m respectively. In the event of the collapse of the cooling tower, the GVC and collapse area may detrimentally affect the safety of surrounding constructions. The study results will be used as guidance for the safety evaluation of this project. Therefore, this study has both academic and engineering significance.

COOLING TOWER-GROUND MODEL

Modeling of the ground

The model was built using a commercial finite element program, ANSYS/LS-DYNA. Firstly, for the modeling of the ground, the mechanical behaviors of the ground were assumed to be ideal elasto-plastic [9]. The commonly used non-reflecting boundaries (transmitting boundaries) were set in the undersurface and the four vertical surfaces of the ground model, so that the waves could transmit through these boundaries without reflections and refractions, as they actually did in the real ground without artificial boundaries. Thus the eight-node is isoparametric element Solid164 was also used, together with a elasto-plastic material model with key word * MAT_PIECEWISE _LINEAR _PLASTICITY *. The detailed parameter of ground is listed in Table 1.

Table 1: Parameters of the ground

Description	Density/ $kg{\cdot}m^{-3}$	Shear modulus / GPa	Poisson's ratio	Yield stress /MPa	Tangent modulus /MPa
rock	2000	31	0.21	30	110

In general, based on the wave propagation theory, the maximum mesh size[10], used in dynamic analysis based on finite element model should fit Eq. (2)

$$\mathrm{le} \le \left(\frac{1}{12} - \frac{1}{6}\right) \cdot \lambda_T \quad (2)$$

where λ_T is the wave length corresponding to the dominant frequency. For the determination of the mesh size of the ground, it was suggested that the accuracy and numerical efficiency should be both considered. Eventually, the mesh size, 2 m×2 m×2 m was adopted by computations. The dimensions of the ground model, as shown in Fig. 1, were adopted as 200 m×160 m×10m in the horizontal plane based on the theory of wave propagation and trial computations.

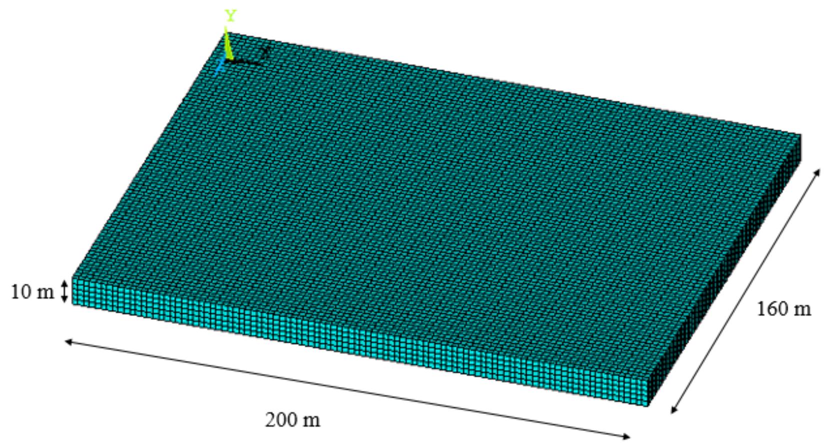

Figure 1: The model of ground

Modeling of the cooling tower

The cooling tower consists of three parts: shell, ring beam and truss- columns. The cooling tower was 86 meters (m) in height from the base and had a hyperbolic reinforced concrete shell, as shown in Figure 2. The thickness of the shell body varied continuously ranging from 0.2 m (at the bottom) to 0.5 m (at the top). The internal diameter at the top is 36 m, 32 m at the throat and 60 m at the bottom. The cooling tower had 80 truss-columns that support the shell which were 5.5 m high, as shown in Fig. 2. The truss-columns belong to cuboid structure and the cross sectional dimensions of was 0.4m×0.4m. The ring beam was also made of reinforced concrete with 1m height and 0.5 m thickness.

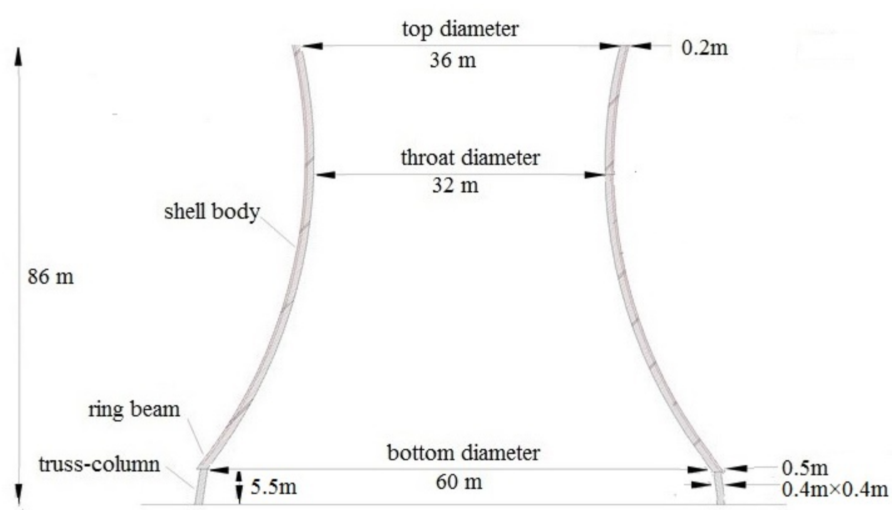

Figure 2: Profile of the cooling tower

The model was built by using the commercial finite element programs ANSYS/LS-DYNA. A three-dimensional model was built as shown in Figure 3.

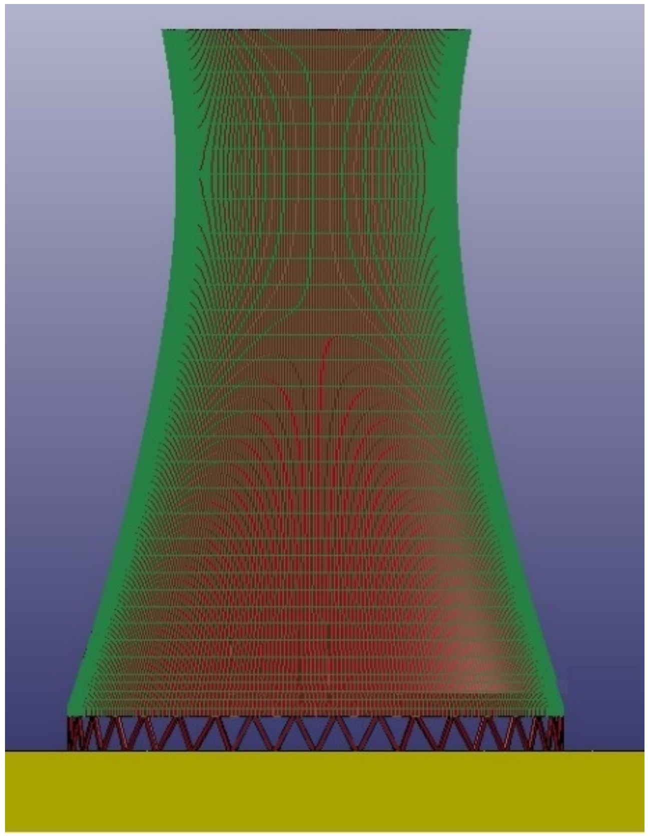

Figure 3: The model of the integrated cooling water

For simplification, the ring beam and shell was regarded as an integrated one: shell body[11]. The shell body was divided into 360 vertical “levels” modeled by eight-node shell elements with both bending and membrane capabilities. In this way, the continuously varied shell thickness was properly modeled by changing the thickness of shell elements at each “level.” All the shell elements were divided into 36 “layers” along the direction of thickness. For the modeling of the shell and truss-column, hexahedral elements (SOLID164) and beam elements (BEAM161)[12] were adopted for the concrete and the reinforcing steel bars, respectively, without consideration of the slip behavior between them. For the shell and column elements, the commonly used material model with the keyword * MAT _PLASTIC _KINEMATIC* was applied for the concrete and reinforcing steel bars. The detailed physical parameters of the materials is listed in table 2.

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Table 2: Parameters of the cooling tower

Type	Density / kg·m^{-3}	Shear modulus /GPa	Poisson's ratio	Yield stress /MPa	Tangent modulus /MPa
Concrete	3000	31	0.21	35	300
Reinforcing steel bars	7800	210	0.27	235	2100

Elements of different types were appropriately connected in the model. Solid and beam elements in the shell and columns were connected at the common nodes. However, the shell elements could not directly connect to the column elements, because the shell and column elements had inconsistent nodal degrees of freedom and the moments could not appropriately be transferred. Also the size of shell elements is not the same as column elements. To connect them in a realistic way, we used a specific technique named with the keyword "CONSTRAINED_SHELL_TO_-SOLID."[ ] As illustrated in Figure 4, Then the node A', B', C', D', E', F' in the shell element was tied to the nodes A, B, C, D, E, F in the adjacent column element. By doing this, the three rotational displacements in the shell–column connections were continuous, resulting in appropriate transferring of the elements.

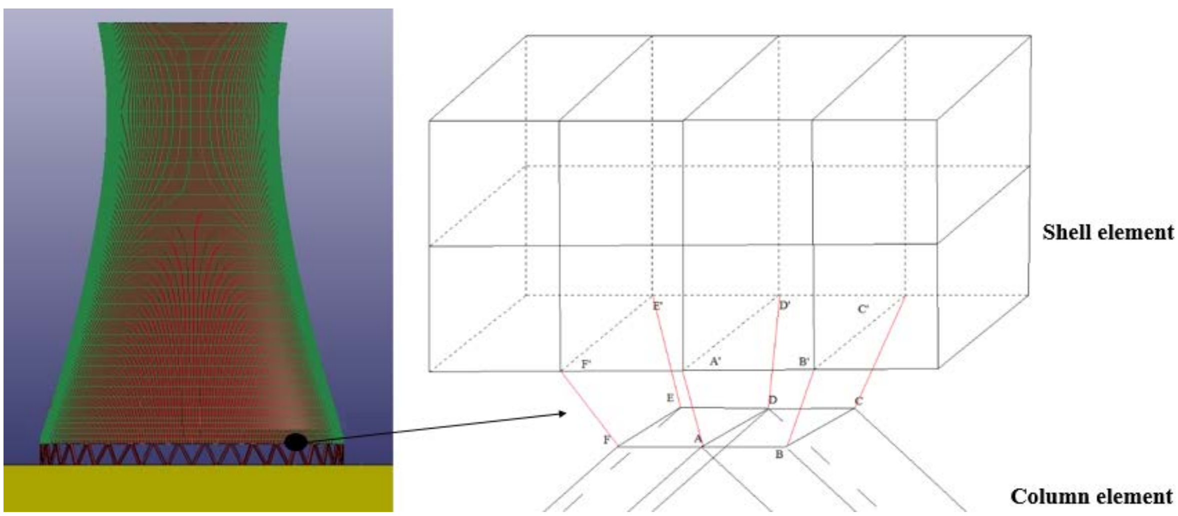


Figure 4: Connection of shell elements with column elements.

Modeling of blasting cut

The proposed demolition technique required that approximately 60 percent of the circumference of bottom section of the shell and columns would be removed by explosive charges. The removal section of cooling tower by explosion before collapse is named blasting cut in this paper, as shown in Figure 5. The formation of blasting cut could then causes the cooling tower to deform, rotate and collapse into the basin directly. Thus all the element of blasting cut model must be deleted at specific time. The keyword * MAT_ADD_EROSION * was applied for the concrete in blasting cut model [ ].

Additionally, for blasting cuts with different height, different model should be built separately. Thus, three cooling tower-ground model with different cut height were built eventually.

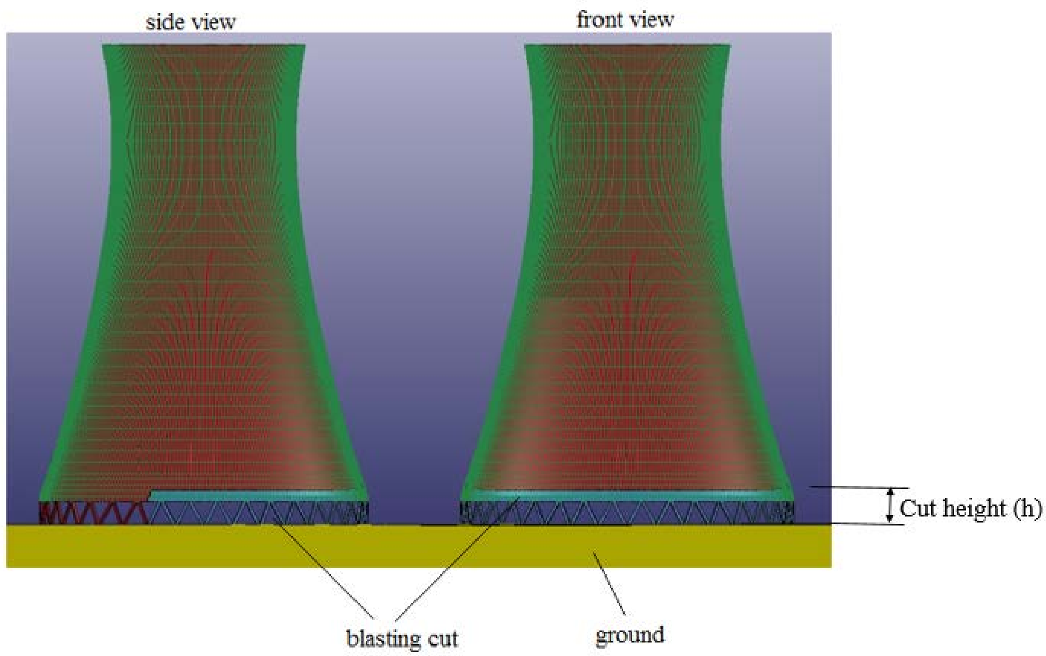


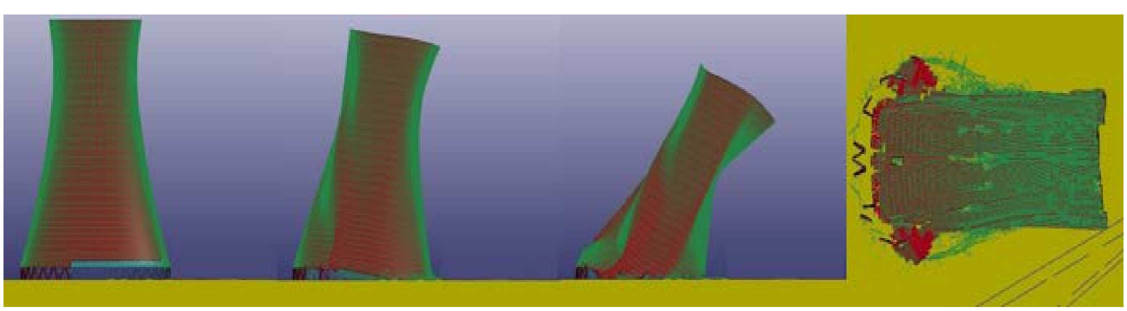
Figure 5: The model of the cooling water with blasting cut

COLLAPSE SIMULATION OF BLASTING DEMOLITION

Simulated collapse process

The numerical simulation of cooling tower collapse was achieved by ANSYS/LS-DYNA software. Due to the limitation of relevant theory and technology, the software could not simulated the whole progress completely. Thus, the sudden removal of blasting area in this model was considered as the blasting progress. There were some simplicity and assumption: a. all the cut plane made by blasting cut is flat; b. ignoring the effect of blasting vibration and air pressure on the residual structure. And the basic assumption of this model is that rebar and concrete have common node, concrete unit and rebar unit were deleted separately when loading pressure surpass ultimate tensile (compressive) strength. This model can simulate real situation of cooling tower collapse.

The simulated result was presented in Figure 6.

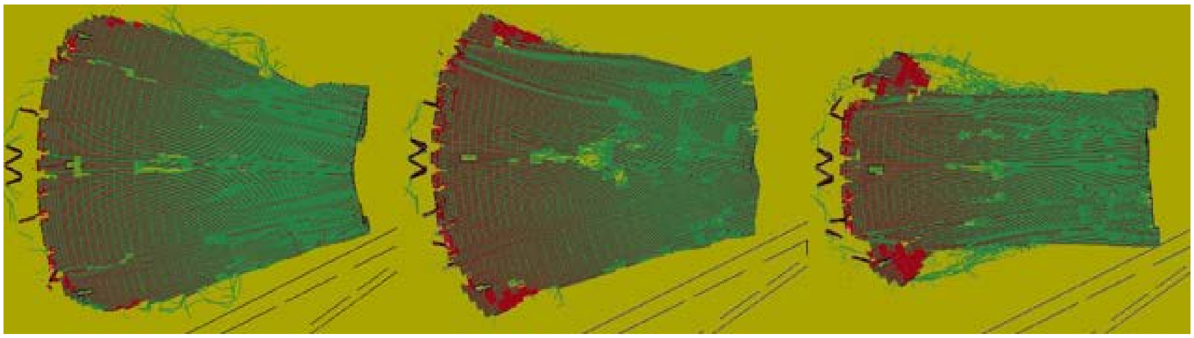


0.2 s 2 s 4 s 8 s

Figure 6:Simulated collapsed process of the cooling tower

After the formation of blasting cut at 0.2 s, firstly, the tower shell began to incline in the “removal” direction, sinking in integrity, almost without changing the profile of the whole tower shell. Meanwhile, the residual 20 columns near the blasting cut were crushed into pieces sequentially, due to the action of the tower gravity. The tower shell then contacted the ground surface with an inclination angle of about 5◦ at 2 s. Subsequently, the evident torsional deformation happened at 4s. In the end, the tower strongly struck the ground and finally disintegrated at 8s.

Simulated collapse area



cut height is 6m   cut height is 7 m   cut height is 8m

Figure 7: The tower collapsed range under different cut height

From Figure 7, we can clear see that collapse area decreases with the increase of cut height. The detailed value of three collapse area were listed in Table 3. From chapter 3.1, it can be seen that when the tower shell contacted the ground surface, the shell hit the ground heavily. Because of strong compressive strength of shell material, the touched section did not break into fragmentation and front shell suffered huge counter-acting force from the ground. At the interaction of gravity of back shell and counter-acting of front shell, the shell body deformed seriously. The larger the torsional deformation is, the smaller the collapse area of shell body becomes. Thus, if the blasting cut is higher, the velocity of shell body hitting on the ground and this can arise a stronger counter-acting force from the ground. This can cause the shell body deformed mores seriously and collapse area become smaller.

Table 3: The simulated collapse area of cooling towers with different cut height

	Cut height		
	h=6 m	h=7 m	h=8 m
Collapse area	85m×80m	82m×75m	80m×70m

Simulated ground vibration

With the aid of cooling tower-ground model, simulated GVC were obtained in the form of peak particle velocity (PPV) in radical direction at various distance. The simulated vibration points were chosen because they were the location of surround constructions which were surveyed and mapped on site. All the results were listed in table 4.

Table 4: The vibration data of numerical simulation

Distance /m	Peak Particle Velocity/cm·s^{-1}		
	Cut height=6 m	Cut height=7 m	Cut height=8 m
54	0.1104	0.1078	0.0978
60	0.0987	0.0932	0.089 3
80	0.0861	0.0835	0.0792
88	0.0652	0.0641	0.0614

It can be seen that:

a. The maximum GVC reached 0.1104 cm/s at the distance of 54 m.

b. GVC decreased with increases in distance, indicating a quick attenuation of the wave during propagation.

GVC decreased with increases in cut height of blasting cut. It mainly because that when the tower shell contacts on the ground, the higher blasting cut means lower barycenter of cooling tower before final collapse. Thus when the shell body totally hits the ground, lower barycenter of cooling tower could reduce the kinetic energy of impact.

TEST RESULT OF COLLAPSE DUE TO BLASTING DEMOLITION

Collapse area test

According to the simulated result, 8m cut height was adopted in practical blasting project due to the smaller GVC and collapse area. The actual collapse process was videoed and typical pictures were shown in Figure 8.

Figure 8: The videoed process of cooling tower collapse

It was found that there are little difference between actual collapse process and the simulated one. The whole process is incline-touchdown-torsional deformation-collapse-disintegration. In addition, the test collapse area, 82×71 m, is nearly the same as simulated area. It indicates that the collapse model built by ANSYS/LS-DYNA software can be used in blasting demolition engineering effectively.

GVC TEST

Equipment for vibration measurement

A recording, storing and data processing system was used. This system included acceleration sensors that were placed in the position of the considered vibration point as accurately as possible and were used to measure peak particle velocity of the vibration point in the radial directions. The vibrations in the tangential and vertical direction were not measured, because they were relatively small compared to those in the radial directions and, hence, were regarded as insignificant in this study.

TC-4850 Blasting Vibration Meter, manufactured by Chengdu Zhongke Measurement LTD, was used. The frequency range of the sensors was 0–1000 Hz, and the sensitivities of the sensors were 0.01cm/s. The maximum measurement of peak particle velocity was 35 cm/s (where g is the radial direction). The recording, storing and data processing system was a Blasting Vibration Analysis（BVA）system, with 3 channel data logging and an amplifier system connected to a notebook computer for storing and processing data. The resolution of the analog-to-digital (A/D) interface was 16 bits, and the maximum sampling rate was 50 kHz.

GVC test result

The ground vibrations were recorded in the form of peak particle velocity (PPV) of the planned vibration point at various distances in radical direction. The result of test cases are presented in table 5 at distance of 54 m, 60 m, 80 m, and 88 m with different cut height.

Table 5: The vibration data measured in the field

Distance/m	Test PPV/ $cm \cdot s^{-1}$	Simulation PPV / $cm \cdot s^{-1}$	Deviation /%
54	0.0867	0.0978	11.35
60	0.0767	0.0893	14.11
80	0.0685	0.0792	13.51
88	0.0538	0.0614	12.38

It can be seen that the test PPV were all smaller than the simulation PPV and the deviations were all between 10%-15%. The reasons for the differences may be mainly attributed to the following aspects:

a. The material parameters used in the shell element, column element and ground element may not have been exactly in conformance with those of the site, due to survey errors and quality simplification for computation.

b. In the tests, the sensors may not have been exactly placed in the expected vibration point and in the desired directions.

c. In the tests, the sensors were probably not in perfect contact with the soft surface of the ground to ensure a synchronous motion due to the inertia of the sensors.

CONCLUSION

This study presents a comprehensive approach for the prediction of the GVC and collapse area of cooling tower due to blasting demolition. The GVC was predicted in the form of peak particle velocity in radical direction at different distances from the ground center of the cooling tower. The following conclusions can be drawn from the study:

a. A severe ground vibration may occur in the considered region. Due to a quick attenuation of the wave during propagation, GVC decreased with increases in distance,

b. Due to torsional deformation of tower shell before collapse on the ground, collapse area decreases with the increase of cut height.

c. In consideration of the results of GVC and collapse area of blasting demolition simulated by ANSYS/LS-DYNA software. We choose blasting cut with 8 m height as blasting parameter of actual demolition project. The demolition result was good and the effect of GVC on the surrounding constructions could be ignored.

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