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Effects of blast-induced random ground motions on the stochastic behaviour of industrial masonry chimneys

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Abstract. This paper focuses on the stochastic response analysis of industrial masonry chimneys to surface blast-induced random ground motions by using a three dimensional finite element model. Underground blasts induce ground shocks on nearby structures. Depending on the distance between the explosion centre and the structure, masonry structures will be subjected to ground motions due to the surface explosions. Blast-induced random ground motions can be defined in terms of the power spectral density function and applied to each support point of the 3D finite element model of the industrial masonry system. In this paper, mainly a parametric study is conducted to estimate the effect of the blast-induced ground motions on the stochastic response of a chimney type masonry structure. With this purpose, different values of charge weight and distance from the charge centre are considered for the analyses of the chimney. The results of the study underline the remarkable effect of the surface blast-induced ground motions on the stochastic behaviour of industrial masonry type chimneys.

Keywords: industrial masonry chimney; blast-induced ground motion; stochastic dynamic analysis; power spectral density function; charge weight; charge centre

1. Introduction

With the start of the industrial revolution in the 20th century, many factories with industrial chimneys were built in Turkey as well as in all over the world. Nowadays, the chimneys built in Turkey are under protection as historical artifacts.

Most of the masonry type industrial chimneys, which are the part of the culture heritage, were constructed usually with conical shape and considerable height. Depending on a variety of potential environmental (wind, earthquake, blast, etc.) threats, most of the industrial masonry chimneys failed to resist these loads and eventually partly or completely damaged. Very limited research has been carried out so far about the seismic assessment of industrial masonry chimneys. Pallarés *et al.* (2006) studied the seismic behaviour of an unreinforced masonry chimney. In that paper, a 3D finite element model which is capable of reproducing cracking and crushing phenomena were used in a non-linear analysis. Pallarés *et al.* (2009a) carried out a theoretical study using three well-known masonry analysis constitutive models to simulate the response of the considered structure to specific

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seismic forces. Pallarés *et al.* (2009b) presented the results of an experimental study to calibrate a numerical model of an industrial masonry chimney. From this calibrated model results of a seismic study were presented, in which the peak ground acceleration withstood by the chimney was calculated and an assessment of the efficiency of using carbon-fibre-reinforced polymer (CFRP) arranged in vertical strips as protection against seismic motions was made.

Ground vibrations due to blast loadings have been a major problem for designing structures above the ground. The essential threat about this problem is whether this type of vibrations will cause cracks or other kind of damages in buildings and other types of structural systems, or not. The effect of the blast loadings on structures depend primarily on vibration levels, excitation frequencies, site conditions, distances from the blast's source and structural properties. Blast type loadings generate ground vibrations and air blast pressures on nearby structures (Guzas and Earls 2010). The generated ground vibrations reach the foundations of the structure before the air blast pressure. Therefore, before investigating all the effects caused by the blast type loadings on structures, emphasizing the importance of the blast-induced ground motions can be more expressive for the dynamic response analysis of structural systems. The research conducted so far about the blast-induced ground motions is very limited (Wu *et al.* 2004, Ma *et al.* 2004, Hao and Wu 2005, Lu and Wang 2006, Wu and Hao 2005, 2007, Singh and Roy 2010, Bayraktar *et al.* 2012, Özcan *et al.* 2012). On the other hand, the potential threat of blast type loadings on above type structures has been also studied by a number of researchers in recent years. Hao *et al.* (2002) investigated the damage effect of infill masonry on reinforced concrete frames when subjected to surface explosion induced ground motions. A two-story reinforced concrete bare frame and frames with different masonry infill patterns were analyzed in this study. It was concluded that the infill masonry affects not only the damage level but also the damage pattern of the frames. Dhakal and Pan (2003) carried out a study to investigate the response characteristics of structures subjected to blasting-induced ground motions. The results demonstrated that the maximum structural response to blasting depends primarily on the amount of impulse, and it generally occurs after the major ground shock has ceased. Wu *et al.* (2005) examined the dynamic response and damage analysis of masonry structures and masonry infilled RC frames to blast induced ground motions. They performed a 3D dynamic response and damage analysis of masonry and masonry infilled RC frame structures to blast induced ground excitations. Numerical results indicated that under the same ground motion, the two-storey masonry structure suffers the most severe damage as compared with the two-story masonry infilled RC frame. Wu and Hao (2007) evaluated the influences of simultaneously acting ground shock and air blast forces on structural responses. It was found that in general, air blast loads govern the structural responses and damages when the scaled distance is small. However, under certain conditions, structural damage will be critically underestimated if the ground shock is neglected. Li *et al.* (2009) performed a case study to determine the effect of cladding panels on responses of reinforced concrete frames when subjected to distant blast loadings. The results obtained from the study showed that the dynamic responses of frame structures with claddings were more severe. Shi *et al.* (2009) modeled the bond slip between rebar and concrete using one-dimensional slide line contact model in LS-DYNA. The parameters of the one-dimensional slide line model were derived from common pullout test data. A comparison of numerical results is made with experimental data. A case study was also carried out to investigate the bond-slip effect on numerical analysis of blast-induced responses of a RC column. Singh and Roy (2010) described the effect of blast produced ground vibrations on the damage potential of residential structures to determine the safety levels of ground vibrations for residential structures and other types of buildings in mining areas. In this study, the impacts of 341 blasts detonated at two mines were monitored at the test structures and 1871 blast induced vibration signatures were recorded on or near the test structures.

Available knowledge about the dynamic behaviour of masonry structures to blast-induced ground motions is also very limited (Hao *et al.* 2002, Wu *et al.* 2005, Hacıefendioğlu and Birinci 2011). Furthermore, a study investigating the dynamic response of masonry type industrial chimneys under blast-induced ground motions is not available. This paper carries out a 3D stochastic dynamic analysis of masonry type industrial chimneys when subjected to blast-induced random ground motions. ANSYS (2003) is used to perform the required numerical calculations.

2. Stochastic formulation

Surface excavations, mining research, etc. are the main reason of the surface explosions taking place in different parts of Turkey. Blast-induced ground motions occur due to these surface explosions. Severe damages or even collapses of nearby structures might be the potential results of these ground motions. Blast type loadings are inherently nondeterministic, since there are always considerable uncertainties about the intensity and frequency contents of blast type loadings expected in the future. Since blast loading is a random dynamic load, stochastic dynamic methods should be considered for the safe and economic design of structures when subjected to blast induced random ground motions.

The dynamic equilibrium equation of motion for a multi-degree of freedom system when subjected to ground excitation can be written as

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = M\delta\ddot{u}_g(t) \tag{1}$$

where M, C, K are $n \times n$, positive definite, mass, damping and stiffness matrices; $u(t), \dot{u}(t), \ddot{u}(t)$ are the vectors of displacement, velocity and acceleration, respectively. δ is the direction vector that links the mass terms to the ground acceleration, $\ddot{u}_g(t)$.

Stationary stochastic model of blast and earthquake-induced ground motions is specified in terms of the power spectral density function. If the power spectral density function of the input process is known, the power spectral density function of the output process can be determined easily. For the simulation of ground motions, generally the filtered white noise model is used as the power spectral density function of the ground motion.

Since the formulation of the stochastic dynamic analysis of structural systems has been given by many researchers (Lin 1967, Yang 1986, Manolis and Koliopoulas 2001), only the final equations will be considered in this study without any derivation.

The structural response $u_j(t)$ defined in Eq. (1) can be expressed in terms of modal coordinates as

$$u_j(t) = \sum_{r=1}^{N} \psi_{jr} Y_r(t) \tag{2}$$

where N is the number of modes which are considered to contribute to the response, ψ_{jr} is the contribution of the jth mode to the $u_j(t)$, and $Y_r(t)$ is the modal coordinate. Fourier transform of Eq. (2) reveals

$$U_j(\omega) = \psi_j^T Y(\omega) \tag{3}$$

where $Y(\omega)$ may be expressed as

$$Y(\omega) = H(\omega)\varphi^T P(\omega) \tag{4}$$

where $H(\omega)$ is the diagonal matrix of $H_j(\omega) = (\omega_j^2 - \omega^2 + 2i\xi_j\omega_j)^{-1}$. In this relation, ω_j and ξ_j are the natural frequency and the damping ratio corresponding to the jth mode.

If all modes are considered, modal forces are then defined as

$$P(\omega) = \varphi^T M\delta A(\omega) \tag{5}$$

where φ is the modal matrix and $A(\omega)$ is the Fourier transform of the ground acceleration.

The cross power spectral density function, $S_{ij}(\omega)$, of response displacements $u_i(t)$ and $u_j(t)$, can be defined as (Yang 1986)

$$S_{ij}(\omega) = \lim_{T\to\infty} \frac{1}{n}\sum_{k=1}^{n} \frac{2U_{i,k}(\omega)U_{j,k}^*(\omega)}{T} \qquad n\to\infty \tag{6}$$

If only a single ground acceleration record due to the blast type loading or earthquake is used as input, the cross power spectral density function can be then simplified as follow

$$S_{ij}(\omega) = S_{\ddot{u}_g}(\omega)\sum_{r=1}^{N}\sum_{s=1}^{N} \psi_{ir}\psi_{js}H_{ir}(\omega)H_{js}^*(\omega) \tag{7}$$

where $S_{\ddot{u}_g}(\omega)$ represents the power spectral density function of ground motion, ω represents the frequency, $H(\omega)$ represents the frequency response function, N is the number of modes which are considered to contribute to the response, ψ_{ir} is the contribution of the rth mode to $u_j(t)$ displacement and * denotes the complex conjugate. For $i = j$, Eq. (7) gives the power spectral density function of the ith displacement. The standard deviation response of the structure can be computed from Eq. (8).

$$\sigma_{ij} = \int_0^\infty S_{ij}(\omega)d(\omega) \tag{8}$$

3. Blast-induced random ground motion model

An surface explosion creates a complex dynamic interaction with the surrounding bedrock. Many studies related to ground motions due to underground blasts have been performed in the last two decades. Both continuum and discontinuum models have been used to simulate blast-induced stress waves in rock masses (Wu and Hao 2005). These models give reasonable estimation of surface blast-induced ground motions on rock surfaces. In this paper, the power spectral density function proposed by Kanai (1957) and Tajimi (1960), which has been widely used in earthquake engineering, is used while analyzing the industrial masonry chimney under blast-induced ground shock. The power spectral density function of blast induced ground motion may be expressed as (Wu and Hao 2007)

$$S(f) = \frac{1 + 4\xi_{g_b}^2 f^2/PF^2}{(1 - f^2/PF^2)^2 + 4\xi_{g_b}^2 f^2/PF^2} \times S_{0_b} \tag{9}$$

where S_{0_b} is a scale factor which depends on the intensity of the ground motion, PF describes the principal frequency and ξ_{g_b} is a parameter governing the power spectrum shape.

The principal frequency derived from empirical observations may be expressed as (Wu and Hao 2007)

$$PF = 465.62(R/Q^{1/3})^{-0.13}, \quad 0.3 \le R/Q^{1/3} \le 10 \text{ (Hz)} \tag{10}$$

where R and Q indicate the distance in meters measured from the charge centre and the TNT charge weight in kilograms, respectively. The scale factor of the spectrum may be determined from the follow equation (Wu and Hao 2007)

$$S_0 = 1.49 \times 10^{-4} R^{-2.18} Q^{2.89} \text{ (m}^2\text{/s}^3\text{)} \tag{11}$$

Figs. 1(a),(b) illustrate the power spectral density functions for different values of charge weight and distance from the charge centre, respectively.

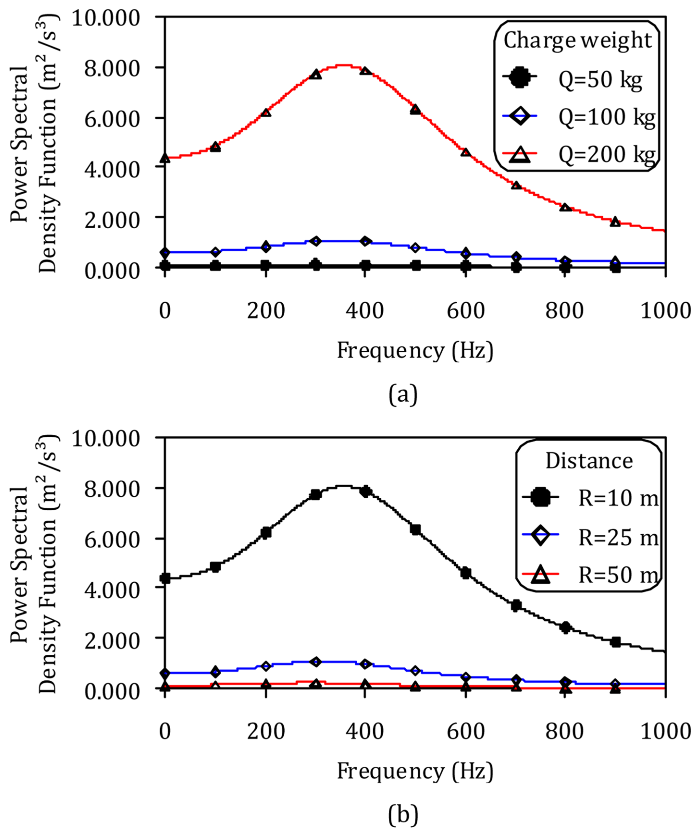


Fig. 1 Power spectral density functions for different (a) charge weight and (b) distance from the charge centre

4. Numerical application

An industrial masonry chimney located in Turkey is considered as a numerical example in this study. The masonry chimney, which was made from brick and has an elevation of 60.0 m, consists of three parts of base, shaft and crown which have straight and prismatic forms. A picture of the chimney, its dimensions and a cross section at 30 m height are shown in Figs. 2(a), (b). The internal diameter and wall thickness of the chimney are assumed to be linearly varying. The 3D finite element model of the chimney prepared to examine its stochastic behaviour due to the blast type loading is given in Fig. 2(c). Three-dimensional (3D) hexahedral solid elements are used while modelling the chimney. The considered solid element has 8-nodes with three degrees of freedom (translations in the nodal *x*, *y*, and *z* directions) at each node. Vertical degrees of freedoms at the base of the chimney are fixed against translational movements. Soil-structure interaction effects and base rotations are not taken into account in the analyses.

The modulus of elasticity, Poisson's ratio and mass density of the masonry material are considered as 5.886×10^9 N/m^2, 0.2 ve 1600 kg/m^3, respectively. In the model, linear elastic material behaviour is assumed and the stiffness degradation is neglected.

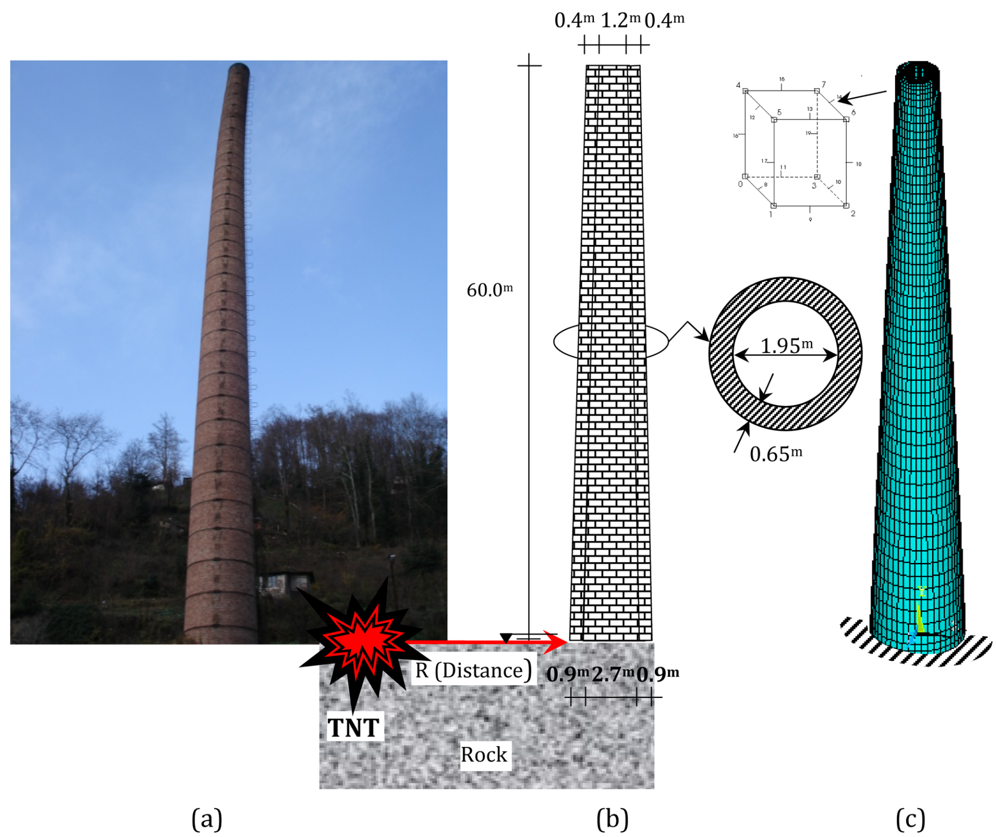


Fig. 2 (a) A picture, (b) geometrical and cross-sectional properties and (b) finite element model of the chimney

5. Numerical results and discussions

In the literature, the parameters to determine the power spectral density function for the stochastic analyses are applied between 0.1 Hz and 10 Hz, according to Eq. (10) (Wu and Hao 2007, Wu *et al.* 2005, Singh and Roy 2010). For this reason, the distance, R, from the charge centre is generally taken as 10-50 meters. 50-1000 kg equivalent charge weight of TNT, Q, more affects the structures in experimental and theoretical studies relating to blast induced ground motion.

In this study, a parametric work is conducted to show the blast-induced ground motion effect on the stochastic response of the considered industrial masonry chimney for different values of charge weight and distance from the charge centre. 50, 100 and 200 kg TNT charge weights and 10, 25 and 50 m distances from the structure to blast centre are used in the simulations.

5.1 Effect of the Charge weight

The x-direction displacement and stress power spectral density (PSD) values for the TNT charge weights of 50, 100 and 200 kg are shown in Figs. 3-4, respectively. The displacement values at the top of the chimney and the stress values at the base of the chimney are obtained as a function of the frequency (ranging from 0.0 to 2.0 Hz). In this section, the distance from the structure to blast centre is chosen as 10 m. As can be observed from the figures, the displacement at the top and the stress at the base of the chimney change significantly with the variation of the charge weight (TNT). The displacement and stress PSD values clearly increase with the increasing values of the charge weight.

The shaded image contours of the one standard deviation (1σ) of the Von Misses stress responses (N/m^2) of the industrial masonry chimney are also shown in Fig. 5 for different values of TNT charge weight. It can be observed from these figures that the maximum value of 1σ Von Misses stress contour is clearly increasing, depending on the increase in the TNT charge weight. The maximum stress accumulations occur at the base of the chimney for all the considered TNT charge weights.

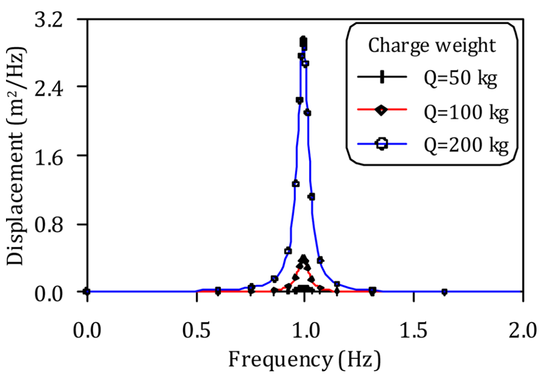


Fig. 3 The x-direction displacement power spectral densities for different values of the TNT charge weight

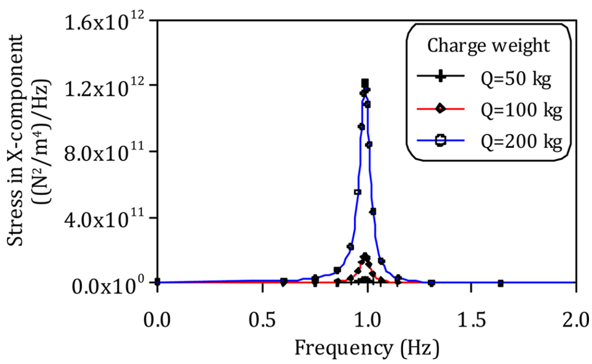
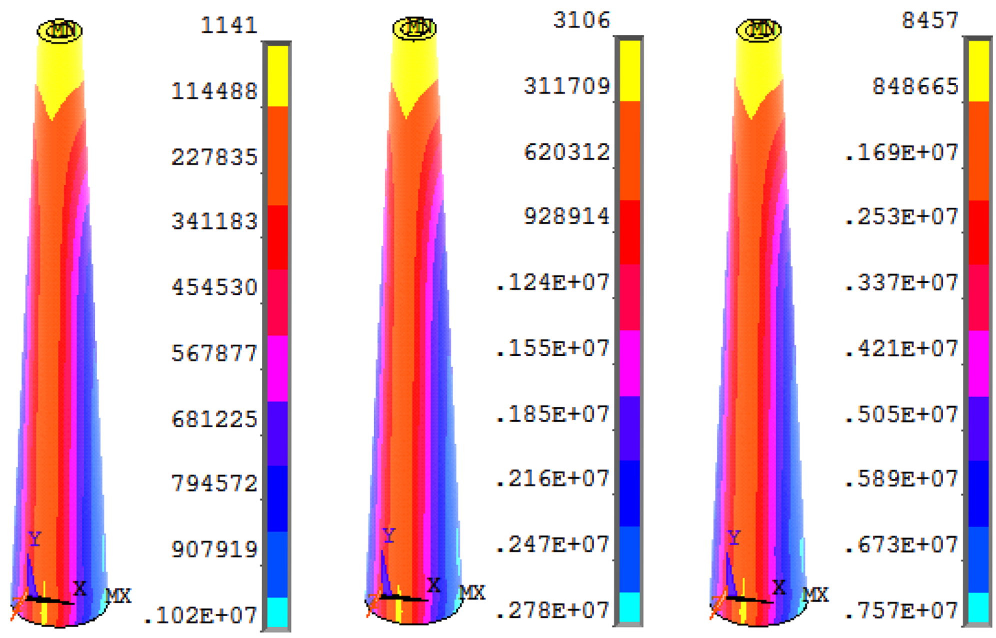


Fig. 4 The x-direction stress power spectral densities for different values of the TNT charge weight



(a) (b) (c)

Fig. 5 1σ Von Misses stress contours for (a) TNT = 50 kg, (b) TNT = 100 kg and (c) TNT = 200 kg

5.2 Effect of the distance from the blast centre

The stochastic responses of the industrial masonry chimney are also determined for 25, 50, 100 m distances from the structure to blast centre and are illustrated in Figs. 6-7. In this section, the TNT charge weight is considered as 200 kg. The *x*-direction displacement power spectral density (PSD) values ranging to 2.0 Hz are shown in Fig. 6 for different distances from the structure to the blast centre. The *x*-direction stress power spectral density values at the base of the chimney due to the

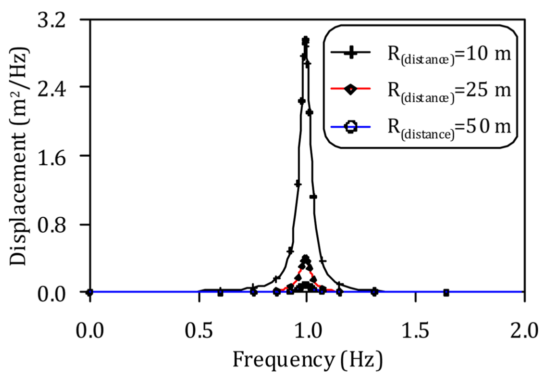


Fig. 6 The *x*-direction displacement power spectral densities for different distances from the blast centre

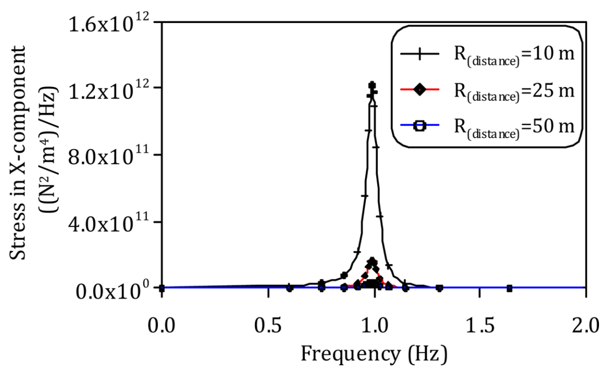


Fig. 7 The *x*-direction stress power spectral densities for different distances from the blast centre

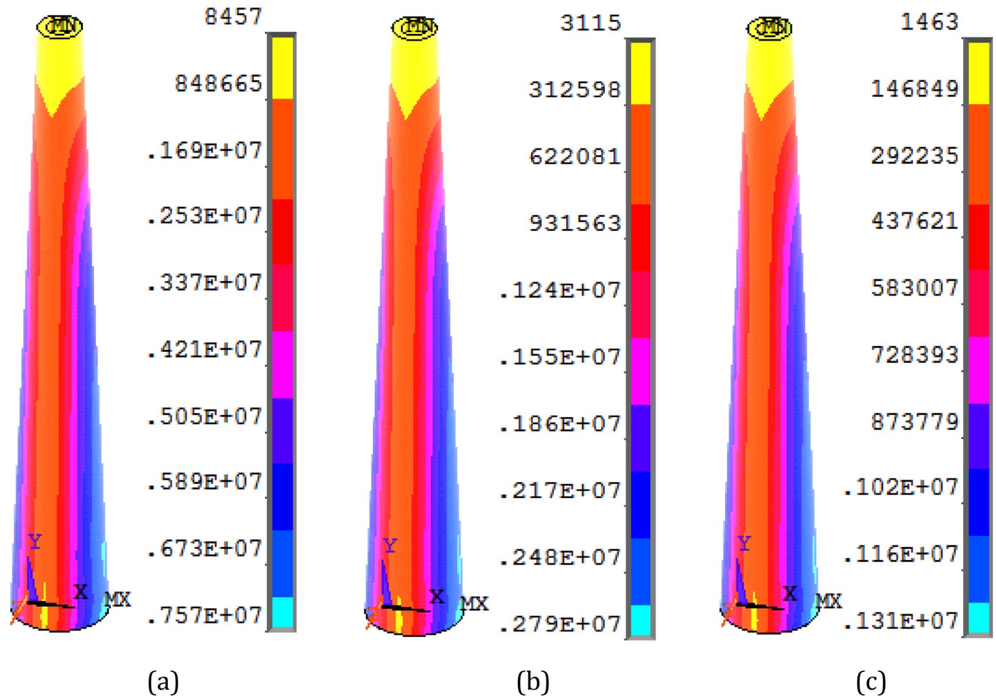


Fig. 8 1σ Von Misses stress contours for distances of (a) 25 m, (b) 50 m and (c) 100 m from the structure to blast centre

different distances from the structure to blast centre are also displayed in Fig. 7. It can be observed that the displacement and stress values decrease as the distance from the structure to blast centre increases. The same variation also applies to the one standard deviation (1σ) of the Von Misses stress responses (N/m^2) due to the different distances as illustrated in Fig. 8. The maximum stress accumulations occur similarly at the base of the chimney for each distance considered in the study.

6. Conclusions

The main goal of this paper is to illustrate the stochastic response of industrial masonry chimneys due to the randomly applied surface blast type loadings. The finite element model of an industrial masonry chimney is formed and its stochastic response under the blast type loading is obtained with the ANSYS computer software.

The effects of the blast-induced ground motion on the industrial masonry chimney are specifically investigated for different values of the charge weight and the distance from the charge centre to the structure. The effect of the blast induced ground motion on the masonry chimney decrease with the increase of the scaled distances. Moreover, larger peak structural responses take place with the increase of the charge weight. The maximum stress accumulations occur at the base of the masonry chimney. These numerical results demonstrate the importance of the blast-induced ground motions on the masonry chimney type structural systems.

The results of the parametric study underline the remarkable effect of the surface blast-induced random ground motions on the stochastic behaviour of industrial masonry type chimneys. Therefore, stochastic dynamic methods should be considered for the safe and economic design of industrial masonry chimneys when subjected to blast induced random ground motions.

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