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DYNAMICS OF A SINGLE-LAYER LATTICED DOME TO SPATIAL RANDOM GROUND MOTION

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ABSTRACT

Because of the large space of dome, spatial randomness of the ground motion should be taken into account, for studying the dynamic behavior of the dome caused by ground motion. This paper is to present two simulation methods to solve such problems, where the simulation results obtained from the two methods are same. From the results, it is clear that the vertical seismic response of domes caused by horizontal ground motion with spatial randomness becomes larger than that without spatial randomness, but the horizontal one becomes smaller. The results clearly show the importance of the spatial randomness of the ground.

KEYWORDS

Single-layer latticed dome, Spatial randomness, Seismic response

Introduction

Strong motion records obtained in dense arrays reveal a somewhat unexpected degree of variability over short distance. The observed spatial variation of the free-field motion over short distance may have important implication for the seismic response of large space structure with multiple supports, such like a single-layer latticed dome.

In the previous papers of the authors [1], [2], it has been clearly shown that vertical responses and horizontal responses are caused in the same time subjected to a horizontal ground motion, and the vertical responses are more important. Such characteristics differ from other constructions like dams or bridges where horizontal responses are mainly caused by ground motion. Thus it is necessary to investigate the characteristics of such responses if the ground motion is spatially random.

The dependence of the spatial randomness of ground motion has generally been considered on spatial domain and frequency domain, and has been defined by coherence functions. Because till now, a general way to present the dependence of the coherence function on distance and frequency has not been fully established, thus the most used Usinski's formulation [3] has been utilized in this paper.

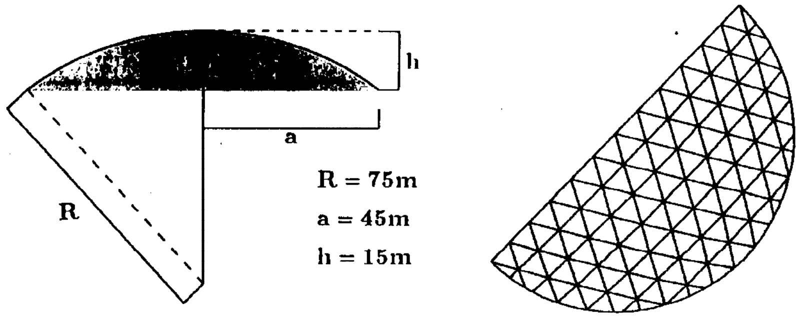

Figure 1: The model for simulation

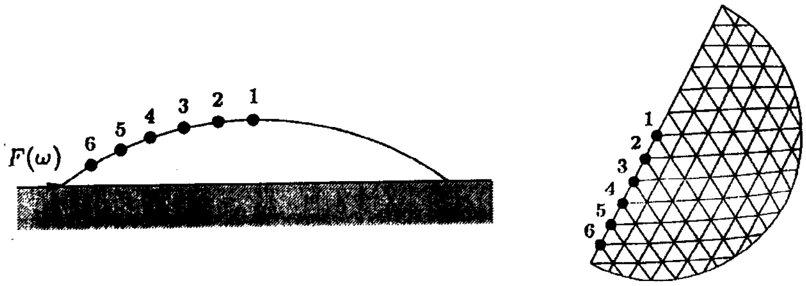

Figure 2: The observed points and the direction of input wave

The major difficulty of the simulation is to calculate the responses of the inner nodes of the dome. Because while the ground motion is spatial random, the inertial influences of ground motion to each node can not be considered equal. To solve such problem, two methods have been applied. One uses ground displacement of boundary nodes to calculate the response in which acceleration records must be transferred into displacement. The other one uses the general model superposition method in which the nodal displacements are assumed to be decomposed into dynamic displacement and quasi-static displacement.

The Model of Dome

The single-layer latticed dome shown in Fig.1 has been used, where the radius of the curvature is $R = 75m$, the base radius is $a = 45m$, and the rise is $h = 15m$. The members are steel tubes with $307mm$ in diameter and $9mm$ in thickness. In simulation the uniform weight is assumed to be concentrated at the joint point as a mass point. The damping of the dome is assumed to be Rayleigh damping with coefficient 2% for the first and second natural mode.

For simplicity of simulation, the numerical analysis is carried out in the half of the dome, as shown in Fig.1, because of the symmetry of characteristics. The observed points on the meridian, which are numbered No.1, No.2, No.3, No.4, No.5 and No.6, and the direction of input ground motion are shown in Fig.2. As stated above, horizontal and vertical acceleration responses have been observed.

Spatial Randomness of the Ground Motion

Because a general model for spatial randomness of ground motion has not been established till now, in this paper, a special model [3], [4] which is often used has been utilized, as follows.

$$F(r_m, \omega) = F(\omega) \cdot \varepsilon(r_m, \omega) \cdot exp[i\theta(r_m, \omega)] \tag{1}$$

where $F(\omega)$ is the original input ground motion in frequency domain (for example an earthquake wave), r_m is the distance to the original wave input point, ω is the circular frequency, $\varepsilon(r_m, \omega)$ can be regarded as a coherence function which has been defined by Uscinski [3] and has been improved by Luco [4] and $\theta(r_m, \omega)$ is called phase difference function, expressed as follows.

$$\varepsilon(r_m, \omega) = exp[-(\gamma\omega r_m/v)^2] \quad where \quad \gamma = \mu(H/d)^{\frac{1}{2}},$$
$$\theta(r_m, \omega) = \omega r_m/v \tag{2}$$

where v is the velocity of S-wave, μ is the variation coefficient, d is the correlation distance, and H is the distance of wave propagation from the epicenter. According to Luco [4], generally $\gamma/v \approx 2 \sim 3\times10^{-4}$.

Numerical Analysis

This section is to present two methods of numerical analysis to calculate seismic response of the dome while considering the spatial randomness of the ground motion. Using finite element method and Rayleigh damping theory, the motion equation has been established as follows, where the mass of the elements is assumed to be concentrated at the nodes.

$$[M]\{\ddot{Y}\} + [C]\{\dot{Y}\} + [K]\{Y\} = \{F\} \tag{3}$$

where following Rayleigh's damping theory, we have.

$$\begin{aligned} [C] &= a_0[M] + a_1[K] \\ a_0 &= 2\omega_1\omega_2/(\omega_1+\omega_2) \\ a_1 &= 2h/(\omega_1+\omega_2) \end{aligned}$$

in the above equations, $[M]$ is mass matrix, $[C]$ is damping matrix, $[K]$ is stiffness matrix, $\{Y\}$, $\{\dot{Y}\}$ and $\{\ddot{Y}\}$ are nodal displacement, velocity and acceleration vector respectively. $\{F\}$ is the external force vector. ω_1 and ω_2 are the first and the second natural circular frequency of the dome. The damping factor is fixed as $h = 0.02$.

Eq.(3) is motion equation for the dome, in which each term contains two parts, Each term of eq.(3) contains two parts, one is those inner nodes at the dome and the other is boundary nodes. The motion of the boundary nodes is the input ground motion which is known, then the displacement vector can be rewritten as follows.

$$\{Y\}^T = \left\{\{X\}^T \quad \{X_0\}^T\right\} \tag{4}$$

where $\{X\}$ and $\{X_0\}$ are the displacement vectors of the inner nodes and the boundary nodes, respectively. The motion equations have been derived, to meet the needs of Forced Displacement Method and Quasi-static Method in the following two sections.

Forced Displacement Method

Substitution of eq.(4) into eq.(3), the motion equation can be rewritten as follows.

$$\begin{bmatrix} M_{11} & 0 \\ 0 & M_{22} \end{bmatrix} \begin{Bmatrix} \ddot{X} \\ \ddot{X}_0 \end{Bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{X}_0 \end{Bmatrix} + \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} X \\ X_0 \end{Bmatrix} = -\begin{Bmatrix} 0 \\ P \end{Bmatrix} \tag{5}$$

$\{P\}$ is external force vector of boundary nodes. From the upper half of eq.(5), we have

$$[M_{11}]\{\ddot{X}\} + [C_{11}]\{\dot{X}\} + [K_{11}]\{X\} = -[K_{12}]\{X_0\} - a_0[K_{12}]\{\dot{X}_0\} \tag{6}$$

According to our previous studies [1], [2], it is obvious that $a_0\,[\,K_{12}\,]\,\{\,\dot{X}_0\,\}$ can be omitted in comparison with $[\,K_{12}\,]\,\{\,X_0\,\}$. Thus eq.(6) becomes.

$$[\,M_{11}\,]\,\{\,\ddot{X}\,\} + [\,C_{11}\,]\,\{\,\dot{X}\,\} + [\,K_{11}\,]\,\{\,X\,\} = -\,[\,K_{12}\,]\,\{\,X_0\,\} \tag{7}$$

It is obvious from eq.(7) that multiple point inputs are possible, which enables us to consider the spatial randomness of the ground motion as to input the displacements of boundary nodes $\{\,X_0\,\}$ which are different with each other. Such method is thus called Forced Displacement Method.

To solve eq.(7), displacement ground motion is necessary. Earthquake waves are generally recorded in acceleration, which must be transferred into displacements ($\{\,\ddot{X}_0\,\} \rightarrow \{\,X_0\,\}$) for simulation.

Quasi-static Method

Here the displacements of inner nodes in eq.(5) are represented by two parts as follows

$$\{\,X\,\} = \{\,\{X_s\} + \{U\}\,\} \tag{8}$$

where the vectors X_s and U will be explained in the following.

By substitution of eq.(8) into eq.(7) and considering the upper half, the following equation can be obtained.

$$\begin{aligned}[\,M_{11}\,]\,\{\,\ddot{U}\,\} + [\,C_{11}\,]\,\{\,\dot{U}\,\} + [\,K_{11}\,]\,\{\,U\,\} + [\,K_{11}\,]\,\{\,X_s\,\} + [\,K_{12}\,]\,\{\,X_0\,\} \\ = -\,[\,M_{11}\,]\,\{\,\ddot{X}_s\,\} - [\,C_{11}\,]\,\{\,\dot{X}_s\,\} - [\,C_{12}\,]\,\{\,\dot{X}_0\,\}\end{aligned} \tag{9}$$

In eq.(9) there are two unknown terms, $\{\,X_s\,\}$ and $\{\,U\,\}$. To solve such equation, one term must be eliminated by assuming the following relation equation between $\{\,X_s\,\}$ and $\{\,X_0\,\}$.

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} X_s \\ X_0 \end{Bmatrix} = -\begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{10}$$

Thus eq.(9) can be rewritten as.

$$\begin{aligned}[\,M_{11}\,]\,\{\,\ddot{U}\,\} + [\,C_{11}\,]\,\{\,\dot{U}\,\} + [\,K_{11}\,]\,\{\,U\,\} = \\ [\,M_{11}\,]\,[\,K_{11}\,]^{-1}\,[\,K_{12}\,]\,\{\,\ddot{X}_0\,\} + a_0\,[\,M_{11}\,]\,[\,K_{11}\,]^{-1}\,[\,K_{12}\,]\,\{\,\dot{X}_0\,\}\end{aligned} \tag{11}$$

With the same reasons in the previous section, it is clear that the term $a_0\,[\,M_{11}\,]\,[\,K_{11}\,]^{-1}\,[\,K_{12}\,]\,\{\,\dot{X}_0\,\}$ can be omitted in comparison with $[\,M_{11}\,]\,[\,K_{11}\,]^{-1}\,[\,K_{12}\,]\,\{\,\ddot{X}_0\,\}$. Thus eq.(11) becomes

$$[\,M_{11}\,]\,\{\,\ddot{U}\,\} + [\,C_{11}\,]\,\{\,\dot{U}\,\} + [\,K_{11}\,]\,\{\,U\,\} = [\,M_{11}\,]\,[\,K_{11}\,]^{-1}\,[\,K_{12}\,]\,\{\,\ddot{X}_0\,\} \tag{12}$$

It is obvious from eq.(12) that the response of inner nodes can be solved, while considering the spatial randomness of the ground motion. Eq.(10) is a equation in the same form with static equation of the dome, where no external force exists at the inner nodes of the dome, while the boundary nodes are subjected to external displacement. And thus such simulation method is called Quasi-static Method.

Simulation Results

For simulations the velocity of S-wave v is assumed as $300m/s$ or $400m/s$, γ/v is fixed as 2.5×10^{-4}. The original ground motion is EL Centro-NS (1940) wave which is standardized with the maximum acceleration of $100gal$.

The motion equations, eq.(7) and eq.(12), which have been derived in the last sections with different methods have been solved using $Newmark - \beta$ method in the time domain. Same results have been obtained from the two methods, which have been shown in Fig.3 $\sim$ Fig.8.

The vertical acceleration responses of points No.1, No.2 and No.5 are shown in Fig.3, Fig.5 and Fig.7 respectively, while the horizontal acceleration responses of points No.1, No.2 and No.5 are shown in Fig.4, Fig.6 and Fig.8 respectively, all compared with the responses without spatial randomness of the input.

In each figure, there are three lines named without randomness, $v = 300m/s$ and $v = 400m/s$, which represent the response to the input without spatial randomness, the response to the input with spatial randomness of S-wave velocities $300m/s$ and $400m/s$.

In considering the spatial randomness of the ground motion, it is obvious that the vertical response becomes larger, but the horizontal response becomes smaller. The response of a point varies while changing the velocity of the S-wave. That means if the soil material changes, the seismic response will change.

Conclusions

As conclusions, it is obvious that:

1). The calculation of seismic responses of dome during ground motion with spatial randomness becomes possible by use of the two methods.

2). It is clear that the vertical seismic response caused by horizontal ground motion with spatial randomness becomes larger than that without spatial randomness, but the horizontal one becomes smaller.

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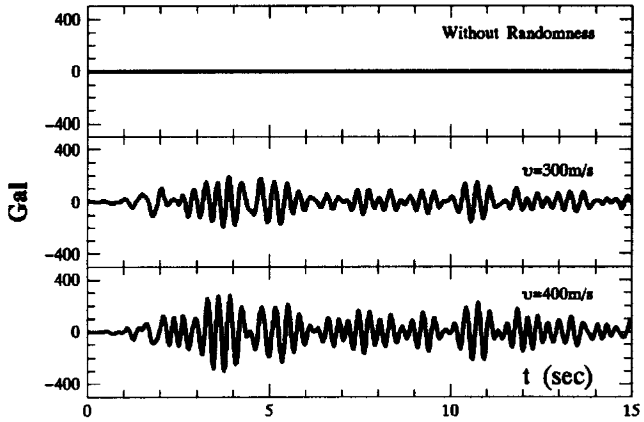

Fig.3 The V-Responses of the Point NO.1

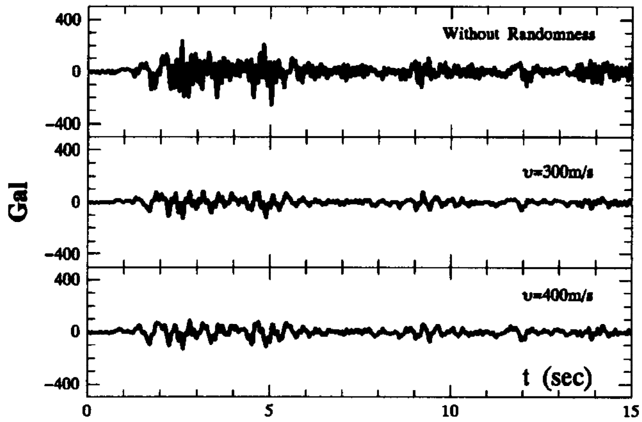

Fig.4 The H-Responses of the Point NO.1

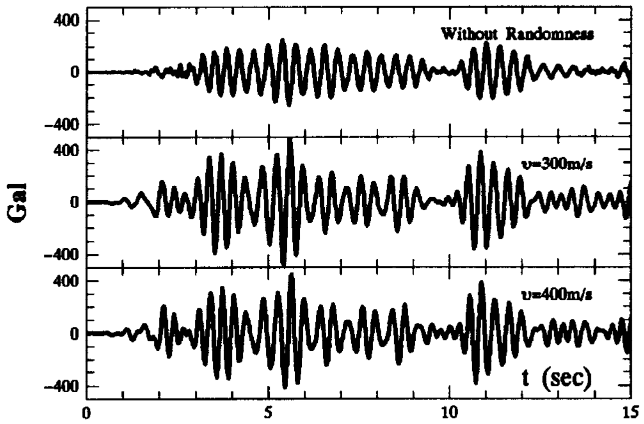

Fig.5 The V-Responses of the Point NO.2

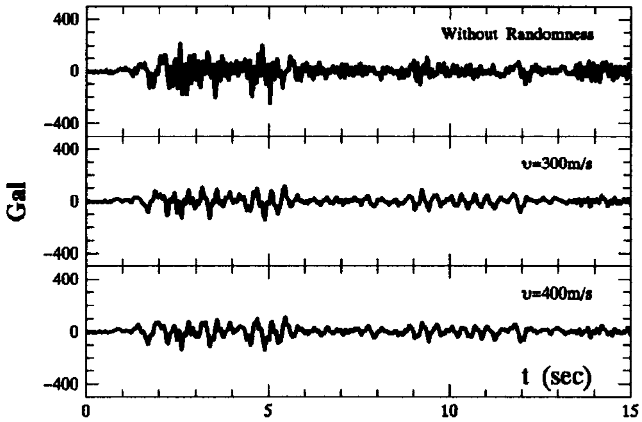

Fig.6 The H-Responses of the Point NO.2

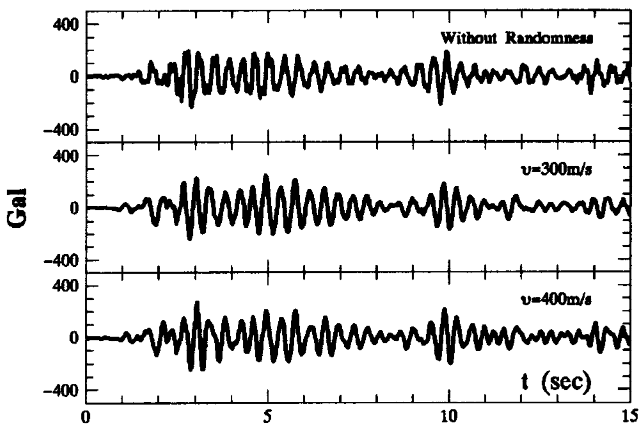

Fig.7 The V-Responses of the Point NO.5

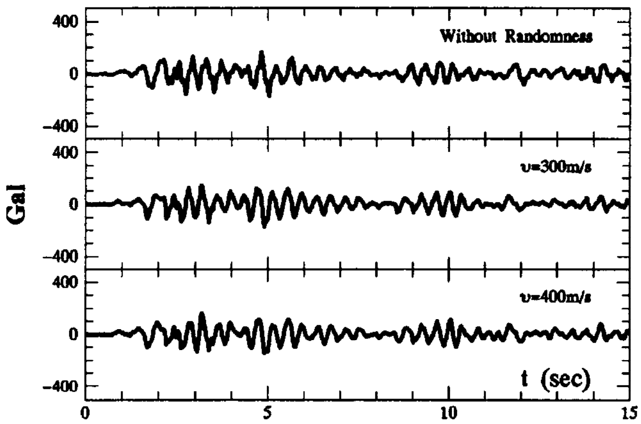

Fig.8 The H-Responses of the Point NO.5