Asynchronous and Non-Uniform Support Excitation Analysis of Large Structures

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ABSTRACT: *In the seismic response analysis of large structures the effects of differential support excitation should be considered. The differential support excitation may be due to asynchrony in excitation of different supports, caused by the finite speed of travelling earthquake waves and/or due to non-uniformity of these excitations, resulting from a change in the properties of the earthquake waves as they travel. In this paper, due attention is given to the question of non-uniformity of support excitation and its effects on the response of such structures as gravity dams and cluster buildings. Non-uniformity of ground excitation is modelled using a set of simulated acceleration time histories obtained from a representative spatial variability model. Comparative studies on the effects of asynchrony and non-uniformity of supports' motion on the structural response show that non-uniformity may, in some cases, amplify the effects of asynchrony and therefore should be considered in the analysis. It is also shown that for cluster buildings and buildings with large floor areas, the effects of differential support excitation could be considerable.*

Keywords: Asynchronous excitation; Multiple-support excitation; Seismic analysis; Large structures; Dams; Cluster buildings

. Introduction

During an earthquake, the motion of the ground changes, in both amplitude and frequency, as the earthquake waves travel with a finite speed away from their source. The earthquake waves travelling through the ground thus enforce two types of differential motion on structural supports. The first type is caused by the finite speed of wave propagation, as a result of which, depending on their relative distances away from the source, different points of contact between a structure and the ground receive the ground waves at different times. The second type is due to the fact that the earthquake waves received by different structural supports are not uniform and change in amplitude and frequency away from their source. The first type of differential support motion is termed asynchronous support excitation and the second type is sometimes known as multiple or non-uniform support excitation. To highlight the difference between these two differential support motions, it can be said that in an asynchronous excitation, two different structural support points undergo exactly the same motion (in amplitude and frequency) but with a time shift. Whereas, in a non-uniform excitation, the two support points undergo modified (in amplitude and frequency) versions of the same ground motion. In reality, the earthquake ground motion reaches two distant support points of a structure both asynchronously and non-uniformly.

The degree of asynchrony and non-uniformity of ground motion depends on the distance between the supports or the expanse of structural contact with the ground. It can be argued that, considering the relatively high speed of earthquake wave travel, the effects of asynchronous and non-uniform support excitation on the response of structures with a small area of contact with the ground are

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negligible. This, however, can not be said of large structures, such as suspension bridges, dams, power plants, long framed structures, cluster buildings and piping systems, which have distant support points.

A great deal of research has been directed at studying the effects of asynchronous support excitation on suspension bridges using both the time domain and frequency domain approaches [1, 9]. The main conclusion drawn from all these studies is that the vertical and horizontal response of the bridge to multiple support excitation is more than that of ordinary dynamic analysis. The bulk of research carried out in this field concentrate on the response of suspension bridges, however, other large structural systems such as dams, power plants and lifeline structures have also received attention in this respect. Response of dams to asynchronous base excitation has been studied by Calciati et al [10], Dumanoglu and Severn [11, 12], Dumanoglu et al [13], Priscu et al [14], Haroun and Abdel-Hafiz [15] and Bayraktar et al [16], whereas, Wu et al [17], Lembach et al [18], O'Rourke et al [19] and Lee and Penzien [20] have investigated asynchronously excited piping systems. Chen et al [21, 22] investigated the non-uniformity of ground excitation on earth dams and in a recent work, Price et al [23] also considered the non-uniformity of support excitation on short bridges.

Although the importance of non-uniformity of support excitation on structural response has long been realised, defining an appropriate ground motion attenuation model for short distances, such as the distance between piers of a suspension bridge, has been problematic. Harichandran and Vanmark [24] carried out a preliminary study on the recurrence of earthquakes in *SMART*-1 array. They considered the ground motion as a random process and obtained a spectral equation to be used in spectral analysis of multi-support excitation problems. As a practical example, Harichandran and Wang [25] investigated the effects of a wave passing through the supports of a simply supported beam. They used a semi-experimental random model and conducted probabilistic analyses of that problem. Perotti [26] used the theory of random vibration to study the effects of non-uniform ground excitation on large structures. In 1992, Nazmy and Abdel-Ghaffar [27] carried out dynamic analysis of a cable-stayed bridge under non-uniform ground excitation. They, however, applied four different accelerograms of El-Centro earthquake, recorded in different locations to the different piers of the bridge. In the same year, Der Kuireghian and Neuenhofer [28] presented a new spectral approach to analyse *MDOF* systems to different support excitations. In their method, they included variations of the ground motion due to wave passage, loss of coherency with distance and variation of local soil conditions. In 1996, Kahan et al [29] extended the spectral analysis carried out by Der Kiureghian and Neuenhofer and investigated the effects of support distance on the response of bridges.

Simulation techniques for generating random processes have enabled researches to generate such random processes as seismic events. Shinozuka used the concept of representation of Gaussian random processes, initially introduced by Rice [30], to generate simulations of random process [31]. He based his simulations on the spectral representation method in which simulations of zero mean, Gaussian random processes are obtained by adding up a large number of weighted trigonometric functions. The computational time required for simulation was however inhibiting. Yang [32] reduced the computational time for simulation by introducing the Fast Fourier Transform (*FFT*) technique. Shinozuka later adopted Yang's *FFT* technique to further his work on simulation of multi-variate and multi-dimensional random fields [33]. The simulations generated by *FFT* are however not ergodic in the mean and to obtain ergodicity the value of the field spectrum at the origin should be assumed zero. Zerva [34] overcame this problem by combining Shinozuka's original approach of using trigonometric series with *FFT*.

To be able to simulate seismic ground motions which vary in space (i.e. non-uniform excitation), a representing spatial variability model is required. Data collected from closely spaced arrays of seismographs such as *SMART*-1 array in Loting, Taiwan have enabled researchers to produce useful spatial variability models to model non-uniformity of support excitation [35]. In this article, the Harichandran spatial variability model along with Hindy-Novak [36] earthquake response spectrum are utilised to simulate representing non-uniform earthquake accelerograms to be used as input for distant supports of structures. In simulation of these accelerograms, Zerva's improved spectral representation method [34] is used. Using simulated records, non-uniform as well as asynchronous support excitation studies of such structures as gravity dams and cluster buildings are carried out.

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2. The Theory of Differential Support Motion

The theoretical background to differential support input has long been established [1]. The theory is applicable to all forms of differential support excitations. When the same acceleration or displacement time history is applied to different supports of a structure simultaneously, the response of the structure consists of two parts. In the first part, known as the rigid part, all the points on the structure undergo exactly the same accelerations, or displacements, as those of the input. In the second part, the structure undergoes accelerations (or displacements) relative to the accelerations (or displacement) of its supports. It is the latter part of the response that produces stresses in the structure. When different acceleration or displacement histories are applied to different supports of the same structure, the first part of the response will no longer be rigid, as different components of the structure will move relative to each other. Stresses, therefore, are produced in the first part response which are additive to those of the second part response. In this case we may assume that the total displacement, u^t, that produces stresses in the system is composed of the pseudo-static first part response, u^s, and the usual second part relative response, u, i.e.

$$u^t = u^s + u \tag{1}$$

To be able to write the dynamic equation of motion, we need to separate the degrees of freedom of the system into two groups. One group houses the degrees of freedom, which receive the input time histories. This group is called the ground degrees of freedom (*GDOF*). The second group holds other, response, degrees of freedom (*RDOF*). The general equation of motion of the system can therefore be written in a partitioned form as

$$\begin{bmatrix} M_{rr} & M_{rg} \\ M_{gr} & M_{gg} \end{bmatrix} \begin{Bmatrix} \ddot{u}_r^t \\ \ddot{u}_g \end{Bmatrix} + \begin{bmatrix} C_{rr} & C_{rg} \\ C_{gr} & C_{gg} \end{bmatrix} \begin{Bmatrix} \dot{u}_r^t \\ \dot{u}_g \end{Bmatrix} \tag{2}$$

$$\begin{bmatrix} K_{rr} & K_{rg} \\ K_{gr} & K_{gg} \end{bmatrix} \begin{Bmatrix} u_r^t \\ u_g \end{Bmatrix} = \begin{Bmatrix} 0 \\ F \end{Bmatrix}$$

In the above equation, M_{rr}, C_{rr} and K_{rr} are mass, damping and stiffness sub-matrices relating to the *RDOF*, M_{gr}, C_{gr}, K_{gr} are sub-matrices representing forces developed in the *RDOF* by unit motion of each *GDOF* and M_{gg}, C_{gg} and K_{gg} are sub-matrices expressing forces developed in the *GDOF* by unit motion of each *GDOF*.

The pseudo-static displacements u^s, due to one *GDOF*, u_{gi}, may be expressed as

$$u^s = r u_{gi} \tag{3}$$

Where, r, is the ground displacement shape vector, determined by applying a unit static displacement at the ith *GDOF* and calculating all the *RDOF*. Using Eqs. (1), (2) and (3), the equation of motion for multi-support excitation will be

$$M\ddot{u} + C\dot{u} + Ku = -MR\ddot{u}_g \tag{4}$$

In Eq. (4), matrix R contains the displacement shape vectors (r) having m rows, representing the number of *RDOF* and n columns, representing the number of *GDOF*. After determining the ground displacement shape vectors, R, solution of the equation of motion may be carried out conventionally, using either the modal superposition method or the direct integration method.

3. Simulation of Non-Uniform Support Motion

The equation of motion just presented may equally be applied to the problems of asynchronous as well as non-uniform support excitation. Asynchrony in support excitation is performed by simply applying, n, number of identical ground acceleration records with different time-lags to, n, number of distant *GDOF*. Time lags are calculated by considering the speed of earthquake waves travelling through the ground. However, to perform a non-uniform support excitation analysis, we need, n, number of different ground acceleration records, representing spatial changes in earthquake wave amplitudes and frequencies, to be applied to the, n, number of distant *GDOF*. It is in this area that we focus our attention in the article.

A historical background to simulation of such random processes as earthquake waves was presented in the introduction. In this article the spectral representation method of simulation, first presented by Shinozuka [33] and later developed by Zerva [34], is used to simulate spatially varying ground acceleration records, ($\ddot{u}_g$). In this method the space-time random field, $f(x_r, t_s)$, is simulated through the following Eq. [34].

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$$f(x_r,t_s)=\sqrt{2}Re\left| e^{i\pi r/M_e \; i\pi s} \;\; \sum_{j=0}^{M-1}\sum_{n=0}^{L-1} \right.$$

$$\times\left(\left[2S(k_j,\omega_n)\Delta k\,\Delta\omega\right]^{1/2} e^{i\phi_{jn}^{(1)}}\right) e^{i2\pi rj/M_e - i2\pi sn/L} \Bigg\} \Bigg|$$

$$+\sqrt{2}Re\left[e^{i\pi r/ \; i\pi s/} \Bigg\{ \sum_{j=0}^{M-1}\sum_{n=0}^{L-1} \right. \tag{5}$$

$$\times\left(\left[2S(k_j,\omega_n)\Delta k\,\Delta\omega\right]^{1/2} e^{i\phi_{jn}^{(2)}}\right) e^{i2\pi rj/M_e \; i2\pi sn/} \Bigg| \Bigg|$$

In the above equation, the discrete wave numbers, k_j, and frequencies, ω_n, are given as

$$k_j=\left(j+\frac{1}{2}\right)\Delta k \qquad j=0,\quad J$$

$$\omega_n=\left(\quad {}_{2} \right)\Delta\omega \qquad n=0,\quad N \tag{6}$$

Also

$$x_r = r\Delta x; \quad \Delta x = 2\pi/(M\Delta k), \quad r=0,\quad M-1$$

$$t_s = s\Delta t; \quad \Delta t = 2\pi/(L\Delta\omega), \quad s=0,\ldots,L- \tag{7}$$

Where, J, N, M, and L should be integers of power of 2 and are related in the following form:

$$M \ge 2J \qquad L \ge 2N \tag{8}$$

The parameters, J and N are also related to pre-specified upper cut-off wave number, k_u, and cut-off frequency, ω_u, as follows:

$$J = k_u/\Delta k, \qquad N_u = \omega_u/\Delta \tag{9}$$

Also, $\Delta x, \Delta t, \Delta K,$ and $\Delta\omega$, are, respectively, distance, time, wave number and frequency steps at which time histories are simulated. Also, $\phi_{jn}^{(1)}$ and $\phi_{jn}^{(2)}$ are two sets of independent random phase angles, uniformly distributed between zero and 2π. And finally, $S(k_j,\omega_n)$ is the frequency-wave number (*F-K*) spectrum.

The *F-K* spectrum presented by Zerva uses the Harichandran-Vanmarcke (*H-V*) spatial variability model, derived from *SMART*-1 array data in the following form:

$$S(k,\omega)=\pi^{-1}S(\omega)\left\{\frac{A\gamma_1(\omega)}{[\gamma_1^2(\omega)+k^2]}+\frac{(1-A)\gamma_2(\omega)}{[\gamma_2^2(\omega)+k^2]}\right\} \tag{10}$$

In which,

$$\gamma_1(\omega)=\frac{2(1-A+aA)}{a\theta(\omega)}$$

$$\gamma_2(\omega)=\frac{2(1-A+aA)}{\theta(\omega)} \qquad 1)$$

$$\theta(\omega)=K\left[1+\left(|\omega|2\pi f_0\right)^b\right]^-$$

Using data from event number 20 of *SMART*-1 array, the values of constants needed for evaluation of Eqs. (10) and (11) are determined as; $A = 0.736$, $a = 0.147$, $k = 5210m$, $f_0 = 1.09Hz$ and $b = 2.78$.

To evaluate the *H-V* spatial variability model, the power spectral density of ground motion, $S(\omega)$, should first be established. Zerva used the Clough-Penzien spectrum to determine her spatial variability model. In the present study, we utilised the Clough-Penzien double filter spectrum adopted by Hindy and Novak [36] and expressed as

$$S(\omega)=\left[\frac{\left[\omega_g^4+4\zeta_g^2\,\omega_g^2\omega^2\right]}{\left[\left(\omega_g^2-\omega^2\right)^2+4\zeta_g^2\,\omega_g^2\omega^2\right]}\right]\times\left[\frac{\omega^4}{\left[\left(\omega_f^2-\omega^2\right)^2+4\zeta_f^2\,\omega_f^2\omega^2\right]}\right]S_0 \tag{12}$$

Where, S_o, is a scaling factor and $\omega_g, \omega_f, \zeta_g$, and ζ_f are constants, values of which depend on the type of underlying soil.

Assuming $S_o = 0.5$, $\omega_g = 15.46rad/sec$, $\omega_f = 1.636\ rad/sec$, $\zeta_g = 0.623$ and $\zeta_f = 0.619$, all representing a hard soil, the Clough-Penzien response spectrum will be that shown in Figure (1). Using this spectrum, together with the values of constants given earlier, the spatial variability model, Eq. (10) used for generating non-uniform time histories in this study is evaluated as that shown in Figure (2). The generation of non-uniform time histories is then carried out solving Eq. (5) and assuming, $k_u = 0.0628rad/sec$, $\omega_u = 15.7rad/sec$, $L = 128$, $M = 1024$, $\Delta x = 50m$ and $\Delta t = 0.2sec$. Four generated acceleration histories together with the corresponding velocity and displacement histories, covering a distance of $450m$ ($x_r = 0$, $150m$, $300m$ and $450m$) are shown in Figure (3).

Based on the formulation presented for asynchronous and non-uniform support excitation, a

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computer program was developed. The program is capable of generating different non-uniform acceleration time histories ($\ddot{u}_g$) and solving the general equation of differential support motion, see Eq. (4).

4. Comparative Analyses of A3-Bayed Portal Frame

A 3-bayed portal frame was analysed by Dumanoglu and Severn [17] in which the S16*E* component of San Fernando earthquake recorded at Pacoima (PGA=1.0g) was input synchronously and asynchronously to the supports of the frame. The geometry of the frame used for their analyses is shown in Figure (4a). The frame is reinforced concrete, having a modulus of elasticity of $2.1\text{x}10^7 kN/m^2$ and Poisson's ratio of 0.15. Damping ratio was assumed as 5% of critical. They found that asynchrony caused a large increase in bending moments (up to 60%) [17].

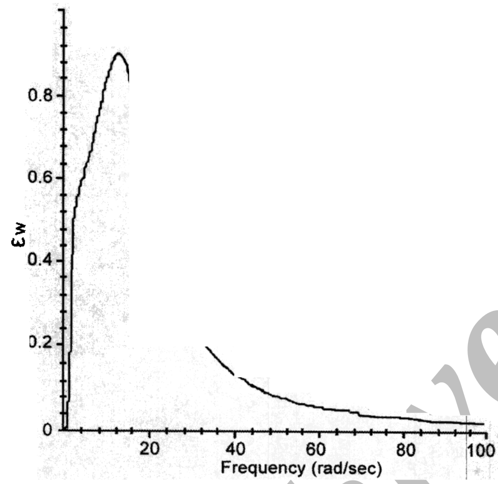

Figure 1. Clough-Penzien power density spectrum.

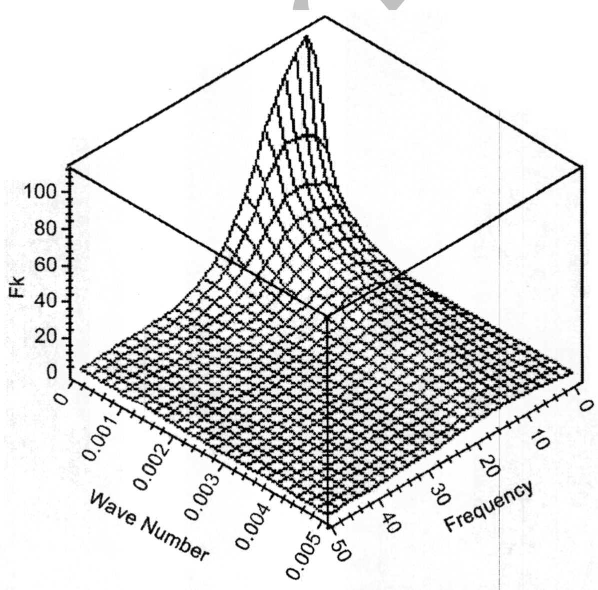

Figure 2. Frequency-Wave number spectrum (F-K) based on the Hindy-Novak spectrum and Harichandran-Vanmarck's spatial variability model.

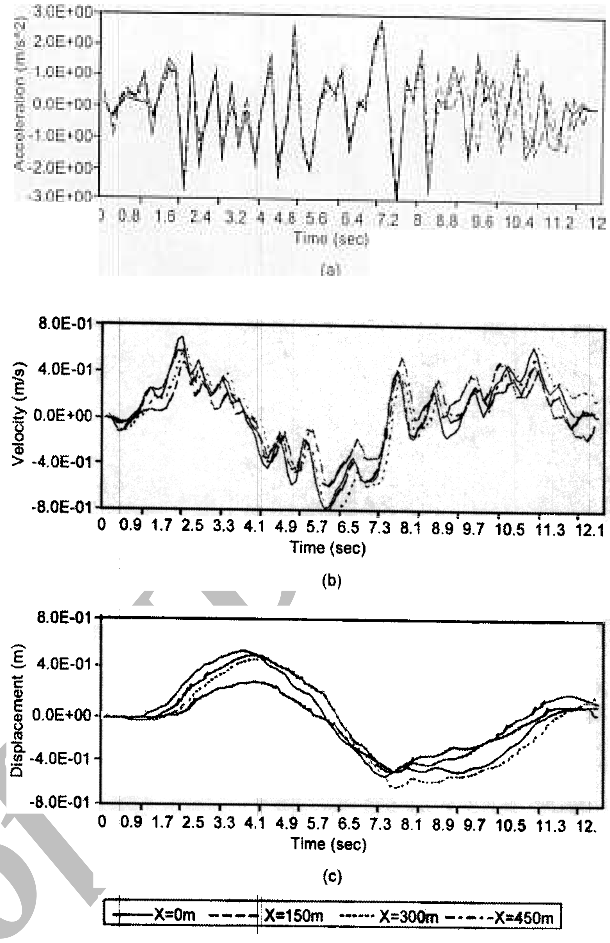

Figure 3. Simulation of spatial variability of seismic ground motion based on F-K spectrum.

In the present study, the same portal frame was analysed, using generated earthquake records. The ground displacement shape vectors for four, support points (R) were first calculated. Then four non-uniform acceleration time histories, to be applied to the four supports, ($\ddot{u}_g$), were generated. The generated records had a PGA = 0.4g. To compare the separated and coupled effects of asynchrony and non-uniformity of support motion on the response, four different analyses were carried out. These include:

i) Synchronous and uniform support motion: This analysis represents an ordinary seismic response analysis.

ii) Asynchronous and uniform support motion: Two different time lags, representing wave velocities of 2000m/s and 4000m/s were considered to investigate two different asynchronous cases.

iii) Synchronous and non-uniform support motion: This analysis was carried out to investigate the

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effects of non-uniformity in a separate manner.

iv) Asynchronous and non-uniform support motion: This is the real situation when the differential support excitation consists of both asynchrony and non-uniformity.

The maximum bending moments evaluated from the four aforementioned seismic analyses are given in Figures (4b to 4e). A general conclusion drawn from these figures is that moments are appreciably increased in both asynchronous and non-uniform cases when considered separately, asynchrony appearing to have a more pronounced effect. The maximum increase in the asynchronous case was found to be 46%. Considering the different earthquake records used in the two analyses, these increases correspond well with those reported by Dumanoglu and Severn [11]. However, the combined effects of asynchrony and non-uniformity appear to be less than that of

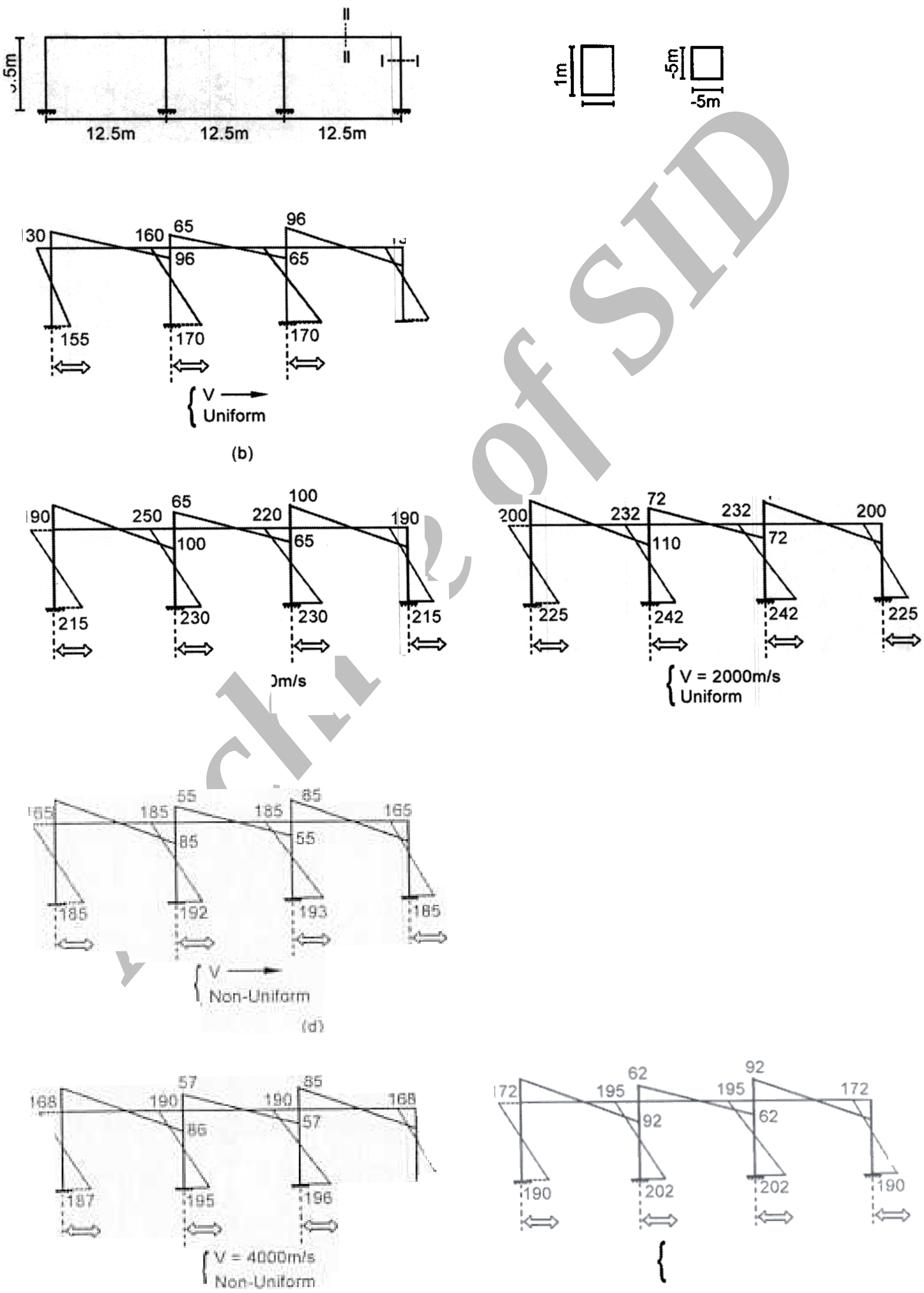

Figure 4. Maximum bending moments (kNm) in the frame, (a) for various cases of differential support excitations, (b) synchronous and uniform, (c) asynchronous and uniform, (d) synchronous and non-uniform and (e) asynchronous and non-uniform.

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asynchrony alone. The reason for this might be all too apparent as non-uniformity, means reducing amplitudes at distant supports. However, non-uniformity may also mean changing frequencies of the ground motion, which in some cases may cause higher amplification of the response.

5. Asynchronous and Non-Uniform Analyses of A Model Representing Cluster Buildings

Buildings are built in clusters, adjoining each other without proper seismic joints, in many parts of the world. The extent of the clusters may be many hundreds of meters. Considering that, under

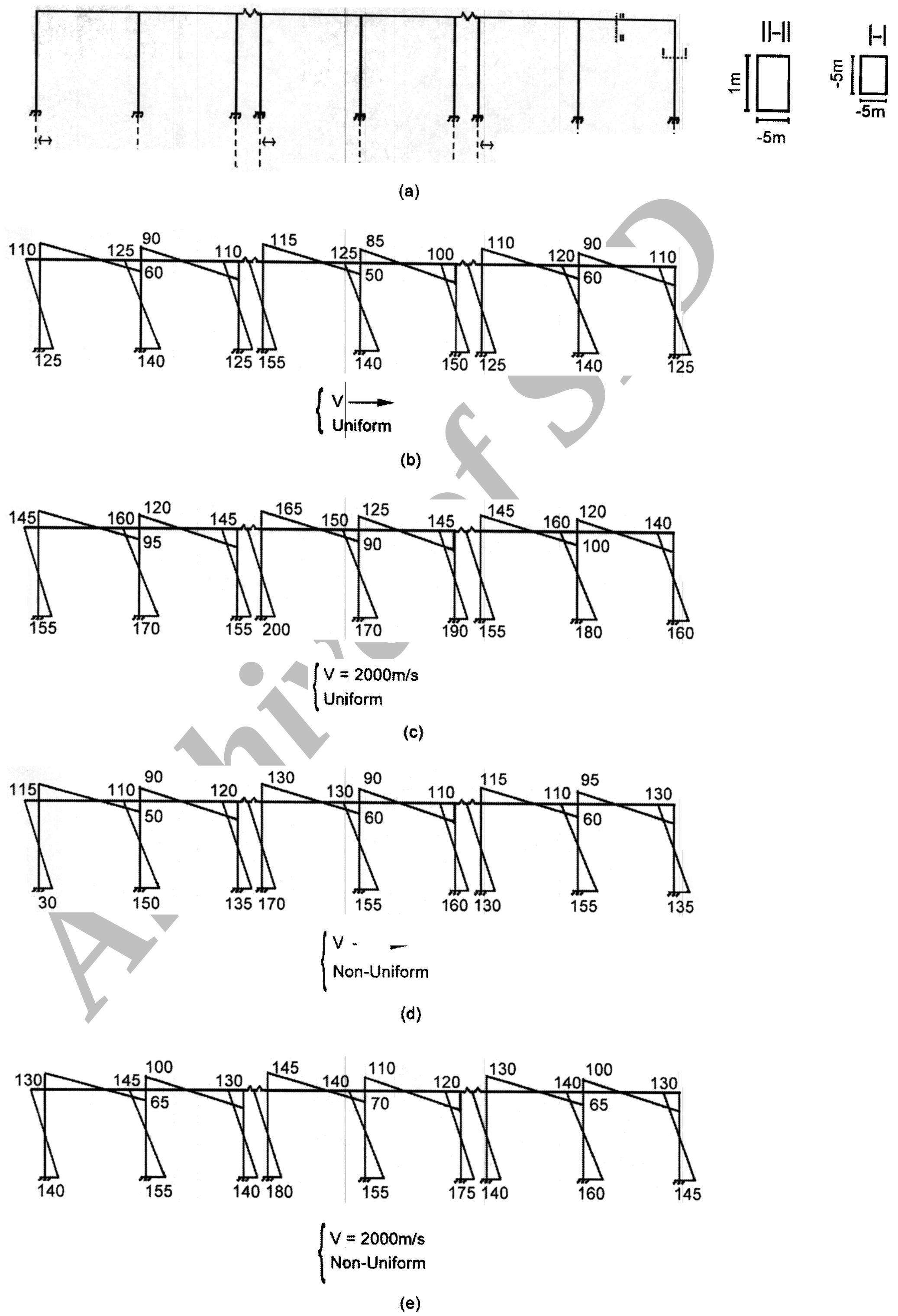

Figure 5. Maximum bending moments (kNm) in the cluster building, (a) for various cases of differential support excitation, (b) synchronous and uniform, (c) asynchronous and uniform, (d) synchronous and non-uniform and (e) asynchronous and non-uniform.

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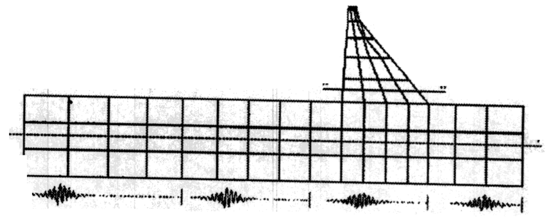
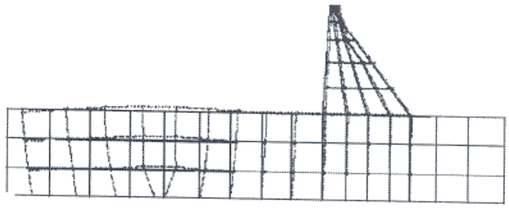
earthquake motion, forces are transferred between these buildings, an investigation of the effects of differential support excitation on the response of the cluster appears useful. Although the majority of the clustered buildings are of old masonry type, many framed clusters may also be found. Cluster buildings under consideration are individual buildings in contact with each other. Under earthquake excitation they may move away from or push against each other. As a simple case of a set of cluster buildings, 3, two-bayed portal frames were modelled connected through springs active only in compression. The geometry of the model cluster is shown in Figure (5a). Other properties of the frames are assumed to be the same as those used for the previous example. Similar to that example, four different analyses were carried out using asynchrony and non-uniformity of support motion, separately and combined. Maximum bending moments evaluated from the four analyses are shown in Figure (5). Comparing results from the four different cases, asynchrony alone appears to have the most profound effect on the moments with increases up to 40%. The combined effects of asynchrony and non-uniformity are somewhat less than asynchrony alone and the non-uniformity alone shows the least effect on the bending moments.

6. Asynchronous and Non-Uniform Analyses of Pine-Flat Dam

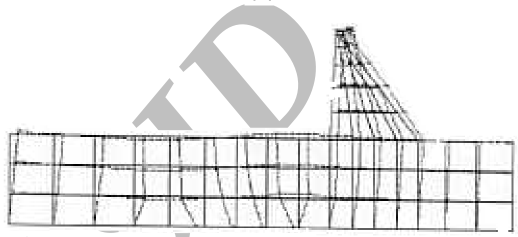
To further investigate the effects of asynchrony and non-uniformity of support excitation on the seismic response of structures, as a practical case study, the pine-flat concrete gravity dam was selected. This gravity dam has been the subject of a great deal of seismic investigations and is a favorite for such analysis. The dam is 121.98*m* high and 98.8*m* wide at the base. To model the differential support excitation a section of underlying rocks and soil, extending a distance of 3 times the height of the dam upstream and equal the height of the dam downstream, were included in the *FE* model. Twenty-eight, two-dimensional, plane-strain, elements were used to represent the dam and forty-eight. Plane strain elements were also selected to model the soil. Properties of the soil were assumed to be $E = 40 \times 10^6 kN/m^2$, $\nu = 0.2$, $\rho = 2.5 ton/m^3$ and those of the concrete were assumed as $E = 34.7 \times 10^6 kN/m^2$, $\nu = 0.2$, $\rho = 2.5 ton/m^3$. The *FE* representation of the dam-soil model is shown in Figure (6a). As the solution procedure for differential support excitation requires, the ground displacement shape vectors were first evaluated. For this purpose the *FE* model of the underlying soil was divided into four sections, each of which was assumed to have the same ground input in its associated *GDOF*. The four shape vectors evaluated in this way are shown graphically in Figures (6b) to (6e). The dam-foundation model was then analysed four times, each time using a different combination of asynchrony and non-uniformity of support motion as follows:



(a)



(b)



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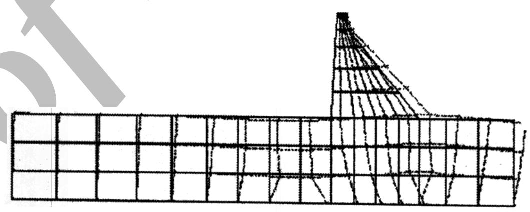
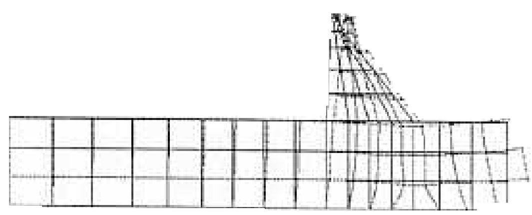


(d)



(e)

Figure 6. (a) The finite element model of Pine Flat dam and its foundation for differential support excitation and its four r vectors, (b) r_1, (c) r_2, (d) r_3 and (e) r_4.

i) Synchronous and uniform: The acceleration

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history generated for $x_r = 0$ was applied simultaneously to all the horizontal *GDOF* of the *FE* mesh (bottom of the soil layer). In this way synchrony and uniformity of ground input was maintained.

ii) Asynchronous and uniform: Three different levels of asynchrony represented by wave velocities of 1000*m/s*, 2000*m/s* and 4000*m/s* were applied in three different analyses. For this purpose, the acceleration history generated for $x_r = 0$ was applied to the horizontal *GDOF* in each of the four areas with time lags representing the mentioned wave velocity.

iii) Asynchronous and non-uniform; Three analyses with three different wave velocities (1000*m/s*, 2000*m/s* and 4000*m/s*) were again carried out. In each analysis, the four generated acceleration histories ($x_r = 0$, 150m, 300*m* and 450*m*) were applied at horizontal *GDOF* at each of the four support areas with the time lag representing the selected wave velocity. Time histories of horizontal stresses developed in the dam (section II-II) at the distance of 40*m* using the four combinations of asynchrony and non-uniformity are plotted in Figure (7). To compare the results of the above analyses, maximum horizontal, vertical and shear stresses at different locations in the soil (section I-I) and dam structure (II-II) from the last three analyses are also drawn against those of the first analysis (synchronous and uniform) in Figures (8) and (9).

We first consider the stresses evaluated for section I-I (soil). Figures (8a) and (8b) show a marked increase in the stresses due to either asynchrony or non-uniformity of ground acceleration. Asynchrony appearing to have a more pronounced effect on the vertical stresses, whereas non-uniformity gives higher stresses in the horizontal direction. By comparing the stresses evaluated from the combined effects of asynchrony and non-uniformity, Figure (8c) with those of each one alone, a marked increase in the stresses can be seen for most sections. This shows that for this section, non-uniformity has, in most parts, magnified the effects of asynchrony. Turning to the results of stresses for section II-II (dam structure), the situation is somewhat different. Again, large increases in the stresses may be obtained by either asynchrony or non-uniformity acting alone, see Figure (9). However, asynchrony appears

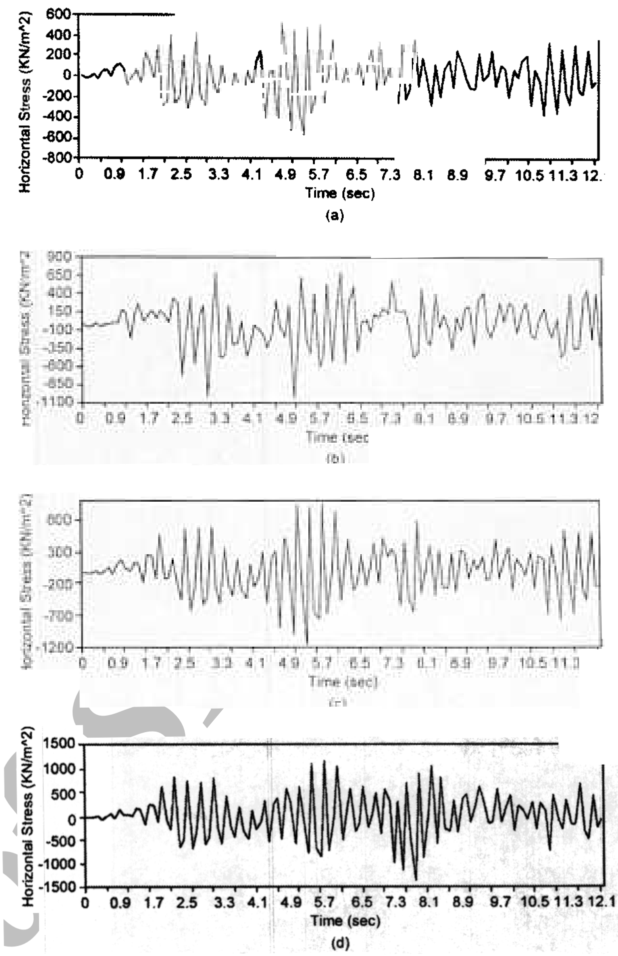

Figure 7. Variation in stresses at the specified location on section I-I (soil) due to (a) asynchronous, (b) non-uniform and (c) combined asynchronous and non-uniform support excitations.

to have produced the highest stresses for most parts. This means that for these parts, non-uniformity has caused a reduction in the effects of asynchrony. This, however, is not applicable to all forms of asynchrony. As the speed of wave increases the effects of asynchrony is reduced and that of non-uniformity is increased. As expected, all the results also indicate that in an asynchronous case stresses generally increase as the wave velocity decreases. It should be noted that the many folds increase in the stresses due to asynchrony was also noted by Byraktar et al [16] in a similar study on Sariyar concrete gravity dam. However, in that study the effects of non-uniformity alone or the combined effects of asynchrony and non-uniformity was not investigated.

7. Conclusions

The effects of non-uniformity of support excitation on the seismic response of real structures are

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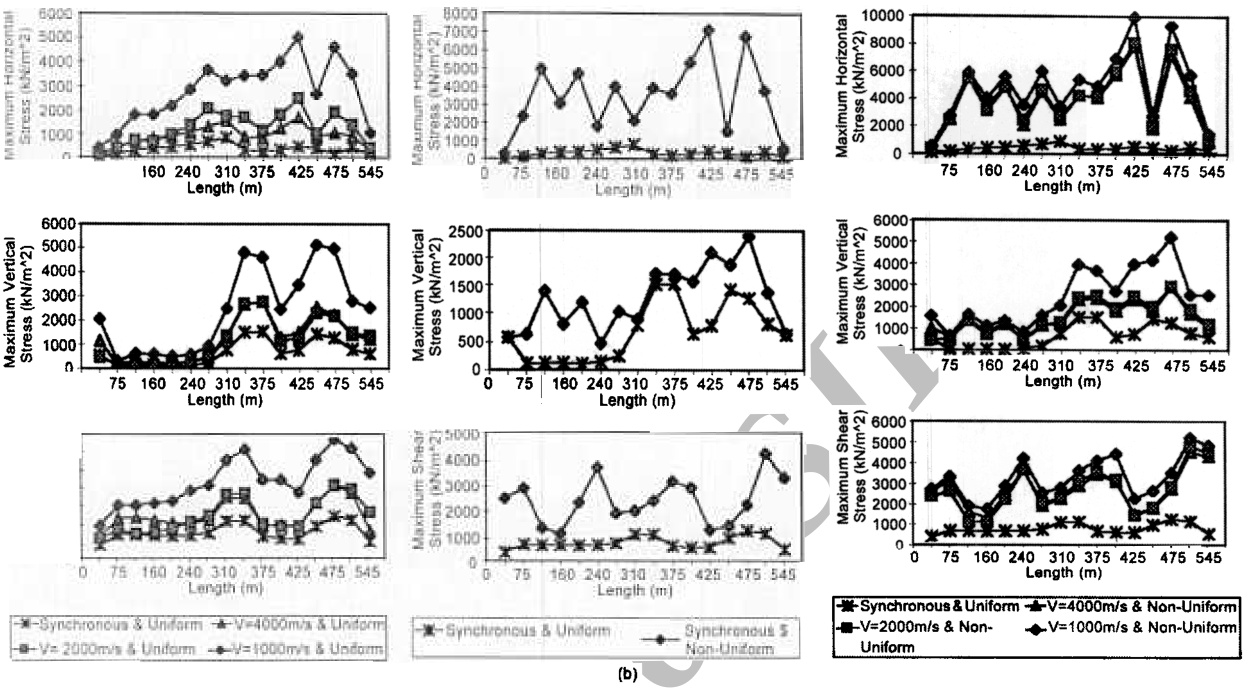

Figure 8. Variation in stresses at the specified location on section I-I (soil) due to (a) asynchronous, (b) non-uniform and (c) combined asynchronous and non-uniform support excitations.

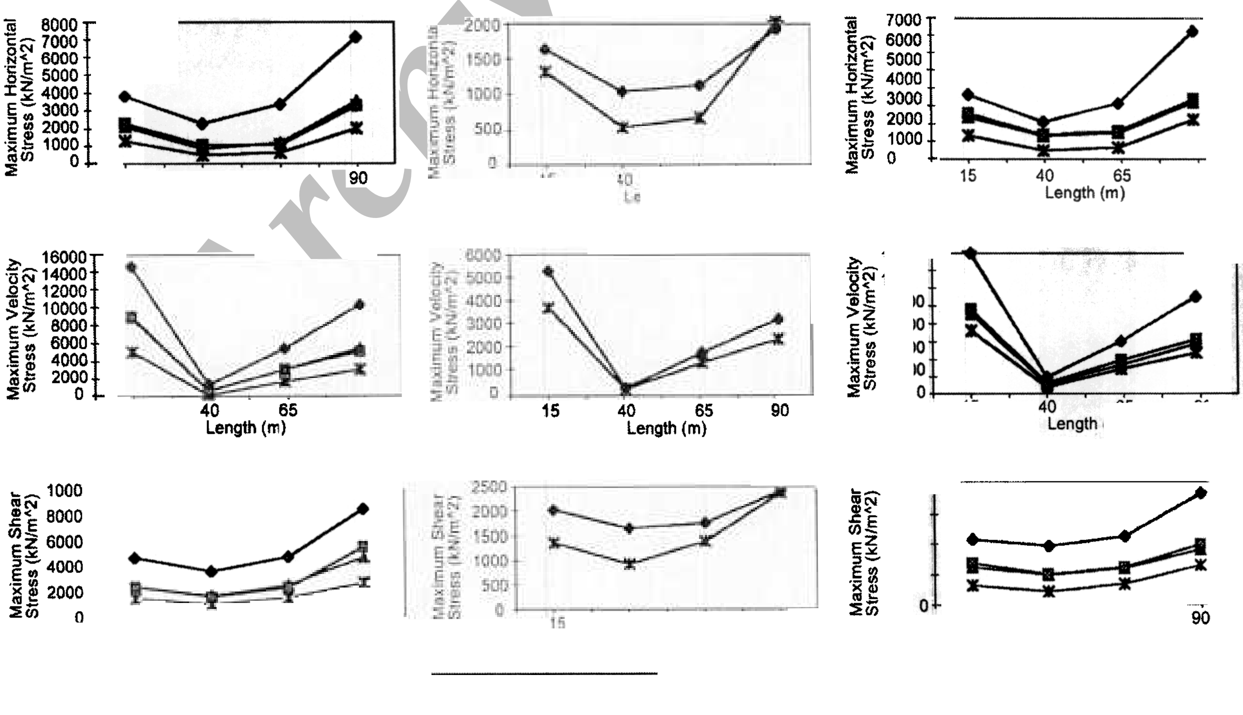

Figure 9. Variation in stresses at the specified location on section II-II (dam structure) due to (a) asynchronous, (b) non-uniform and (c) combined asynchronous and non-uniform support excitations.

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Therefore, the combined effects of asynchrony and non-uniformity of support excitation should be considered for seismic response analysis of large structures.

- ❖ The effects of differential support excitation (either asynchronous or non-uniform) on the response of large structures are so profound that in certain cases the stresses may increase many folds.
- ❖ The influence of differential support excitation on the response of smaller structures such as long buildings and cluster buildings is also shown to be considerable.

Such as long buildings and cluster buildings is also shown to be considerable. The present study was carried out using available models for simulation of closely spaced ground motion time histories. Since the response of a structure is highly sensitive to properties of the ground motion, further improvements on the simulation techniques or possible use of recorded, closely spaced, real time histories will enhance the accuracy of the results.

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