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PHASE ANGLE PROPERTIES OF EARTHQUAKE STRONG MOTIONS: A CRITICAL LOOK

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SUMMARY

This paper summarises the preliminary results of an investigation aimed at identifying the effects of ground motion phase content modelling of both earthquake ground acceleration simulation and non linear structural response. The influence of these effects is analysed by applying three phase simulation techniques to two earthquake ground motion models characterised by time invariant and time varying frequency contents. Time histories of typical quantities of interest such as artificial accelerations, intensity envelopes, input cumulative energy functions, instantaneous ground motion frequencies, non-linear displacement response and instantaneous stiffness degradation, have been examined. Moreover, a moving resonance based validation procedure that allows to select the most appropriate earthquake ground motion model to be used in order to obtain reliable time history earthquake response of non linear structures is proposed.

INTRODUCTION

The importance of phase angle properties on earthquake strong ground motion characteristics has long been recognised [1,2]. Studies of phase information contained in earthquake accelerograms have contributed significantly to the improvement of our understanding of the complex nature of the seismic waves recorded at various sites during strong motion earthquakes [3,4,5] Moreover, phase angle properties of earthquake strong ground motions play an important role in the development of stochastic models of strong motion time histories [6,7,8]. These models are currently used to simulate earthquake ground motions with prescribed characteristics in order to assess the time history response and the aseismic design of critical structures such as dams, nuclear power plants and other important facilities.

However, despite the importance of time history analyses to evaluate the dynamic responses of these sophisticated structures and the need to predict damages due to non linear behaviour under intense seismic excitation, the crucial question as to which phase generation technique should be used, has not been sufficiently addressed. In addition, one may very well ask whether the final choice of the phase simulation technique should be considered regardless of the characterising procedure of ground motion frequency content.

The purpose of this paper is to evaluate the relative performance of three phase generation models that are suitable for earthquake ground motion simulation. These models are 1) the uniform phase, 2) the phase derivative and 3) the minimum phase, models. The applicability of these three phase models has been examined in relation to two earthquake ground motion models characterised by time invariant and time varying frequency contents. A critical look on the effects of phase content properties of earthquake strong motions is then presented in light of the results obtained by applying the six resulting ground motion models to generate synthetic accelerograms and predict the seismic response of inelastic structures with degrading hysteretic behaviour.

Time histories of typical quantities of interest such as artificial accelerations, intensity envelopes, input cumulative energy functions, instantaneous ground motion frequencies, non-linear displacement response and instantaneous stiffness degradation, have been examined. Moreover, a moving resonance based validation procedure that allows to select the most appropriate earthquake ground motion model to be used in order to obtain reliable time history earthquake response of non linear structures is proposed.

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PHASE DISTRIBUTIONS, GROUND MOTION MODELS AND STRUCTURES CONSIDERED

Phase distributions

In this study, the effect of phase angle distributions on ground motion simulation and dynamic response of structures are examined by using the three above-mentioned phase generation techniques.

The first phase generation technique is based on the most commonly used assumption that the phase angle are random and uniformly distributed within the range $(-\pi, +\pi)$, or equivalently between $(0, 2\pi)$. This non deterministic generation technique implies that the rate of seismic energy at the site is constant over the duration of earthquake ground shaking. The application of this generation technique is very simple ; however, it is not expected to lead to realistic input ground motions, unless an empirical intensity envelope function is utilised.

The second phase generation technique corresponds to the phase derivative probabilistic distribution law which has been introduced by Nigam [4]in the early eighties after the pioneering work of Ohsaki [2] on the phase difference properties in earthquake ground motion processes. This distribution depends on the ratios of the so-called "three intensity moments" associated to the gross properties of the ground acceleration intensity envelope and is given by

$$
\begin{aligned}
P\left[\phi'(f)\right] &= \frac{t_d^2}{2\left[\left(\phi'(f) + t_m\right)^2 + t_d^2\right]^{3/2}} \quad \text{if } \phi'(f) < 0 \\
P\left[\phi'(f)\right] &= \frac{t_d^2}{2\left[\left(\phi'(f) - t_m\right)^2 + t_d^2\right]^{3/2}} \quad \text{if } \phi'(f) \geq 0
\end{aligned}
\qquad (1)
$$

Where $\phi'(f)$ denotes the phase derivative with respect to frequency, whereas, t_m and t_d represent, respectively, the "mean" and the "standard deviation" of the intensity envelope function. In contrast to the preceding generation technique, the present procedure takes implicitly into account the amplitude non stationarity of the dispersive seismic waves.

The third generation technique ensures that the simulated accelerogram will have all the characteristics of the minimum phase signal. In other words, rather than being generated stochastically, the phase content is deterministically estimated on the basis of a mathematical relationship, between the Fourier phase and Fourier amplitude spectra, compatible with the signal causal properties both in the time and the frequency domains. The minimum phase accelerogram represents the limiting case (i.e. the extreme phase condition) associated with the maximum seismic energy concentration in the neighbourhood of the time origin, t=0.

Ground motion models

The ground acceleration record selected for this preliminary investigation is the horizontal component of the October 17, 1989 Loma Prieta earthquake. This accelerogram, characterised by a long period of strong motion, a large peak ground acceleration (PGA) and strong non stationarities both in amplitude and frequency content, is used as the target record for application of the above-mentioned time invariant and time variant earthquake ground motion models.

For the sake of brevity, in the sequel the earthquake ground motion models with Time Invariant and Time Varying Frequency content will be referred to as the TIF and TVF models, respectively. In addition, the following notations will be used :

TIF(I) : time invariant frequency content model defined by utilising phase generation technique (I), I=1,2,3

TVF(I) : time varying frequency content model defined by utilising phase generation technique (I), I=1,2,3

where the index (I) is associated to the phase generation technique considered. It follows that six distinct simulation models of earthquake ground accelerations can be defined.

The stationary frequency content of the TIF models is represented by the Fourier amplitude spectrum of the target record. It should be noted that this spectrum can be defined in an equivalent way as a limiting case of the physical spectrum [9]. The constant mean frequency of the TIF model corresponds to the natural frequency associated with the centroïd of the area under the Fourier amplitude spectrum curve.

The non stationary spectral estimates of the TVF models are determined by applying an efficient computational algorithm [10] to the physical spectrum of the target accelerogram. The mean instantaneous frequency of the TVF model at a given time t_k, $f^0(t_k)$, corresponds to the frequency associated with the centroïd of the area under the instantaneous spectrum curve $P_{xx}(f,t_k)$ [11]. The mean instantaneous frequency $f^0(t_k)$ can be computed from the following equation :

$$f^0(t_k) = \frac{\gamma_1(t_k)}{\gamma_0(t_k)} \qquad (2)$$

where the instantaneous spectral moments $\gamma_i(t_k)$ i=0,1 are given by :

$$\gamma_i(t_k) = \int_{-\infty}^{+\infty} f^i \, P_{xx}(f,t_k)\, df, \quad \text{for } i = 0,1 \qquad (3)$$

Structural systems

In order to identify the predominant effects of the phase content modelling of earthquake ground accelerations on the seismic response of inelastic structures, simple systems typically represented by non linear dynamic single degree of freedom systems with idealised hysteretic behaviour have been considered. For illustration purposes, a non linear stiffness degrading model represented by the so called maximum oriented inelastic system without strain hardening [12] is shown in Figure 1 below.

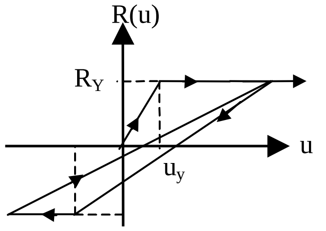

Figure 1 The maximum oriented stiffness degrading non linear model

The non linear dynamic single degree of freedom system associated to this restoring force model is uniquely defined by i) the initial value of angular frequency $\omega_0 = (k_0/m)^{1/2} = 37.69$ rad/s, where m denotes the system mass and k_0 the initial stiffness expressed as the ratio of the yield strength R_y to the yield displacement u_y, ii) the initial damping ratio $\xi_0 = c/[2(k_0/m)^{1/2}] = 5\%$ where c and m represent the constant damping coefficient and mass of the system, respectively and iii) the strength coefficient $\beta = R_y / mg$ expressing the yield strength $R_y = k_0 u_y$ of the system as a fraction of its own weight. A direct step by step integration of the damped non linear equation of motion based on Newmark's algorithm with $\alpha = 1/6$ and $\delta = ½$ has been used.

In addition, a key structural response parameter is introduced to describe the instantaneous effective structural frequency defined as :

$$\omega_{\text{eff}} = \sqrt{\frac{R(u_i,\, u_i' = 0)}{m\, u_i}} \qquad (4)$$

where the ratio $R(u_i, u'_i=0)/u_i$ is associated to the effective cyclic stiffness of the hysteretic system for a given amplitude oscillation and $R(u_i, u'_i=0)$ is the restoring force at a turning point u_i which is either a local maximum or a local minimum of the response u (i. e., $u_i'=0$) [13].

On the basis of these considerations, the non linear displacement time history and the time evolution of effective instantaneous structural frequency, were computed and systematically compared to the corresponding quantities computed from the synthetic accelerograms generated by using the six above-described earthquake ground motion models.

RESULTS AND DISCUSSION

In order to identify the phase content effects of earthquake ground motions on both strong ground motions simulation and non linear structural response, the applicability of the three phase generation techniques has been examined in relation to the TIF and TVF earthquake ground motion models. Characteristic features are successively examined in terms of time histories of ground motion characteristics of engineering significance such as input cumulative energy functions, simulated accelerations, accelerogram intensity envelopes, ground motion mean instantaneous frequencies on the one hand and time histories of typical response quantities of interest such as effective structural frequency and non linear displacement responses on the other hand. Maximum values of interest and corresponding times of occurrence, ground motion intensity envelope parameters, time of occurrence of resonant points, structural effective frequency drop, distance between ground motion mean instantaneous frequency and effective structural frequency have also been used to interpret or quantify the magnitudes of the engineering parameters of interest.

A summary of the most important numerical results obtained from this preliminary study is presented below:

Effects of phase content modelling on ground motion characteristics

Case of TIF earthquake ground motion models

The cumulative energy functions corresponding to the original accelerogram (solid line) and to three artificial earthquake accelerograms (dashed lines) generated from the TIF1, TIF2 and TIF3 simulation procedures are shown in Figure 2. The time histories of the target and the simulated accelerograms along with their associated intensity envelope functions (thick dashed lines) computed by utilising the analytical signal technique [14] are displayed in Figures 3a, 3b, 3c and 3d respectively.

It is noticed from Figure 2 that although the total input energy is, as expected, the same at the end of the shaking for all the phase distributions considered, the rate of energy arrival of the seismic waves at the site is closely controlled by the phase content properties in the time domain. In particular, the energy distribution of the uniformly distributed phase accelerogram is practically linear while that of the minimum phase delay motion presents, in the vicinity of the time origin, a sharp peak corresponding to a 40 % level of the total input energy.

It is also of interest to note that the cut off times associated to the duration of the strong motion phases [15] exhibit wide ranges of variations [2.6 sec. – 18.9 sec.]for the target record and [0.02 sec. – 39.9sec.], [2.6 sec. – 39.8sec.] and [0.0 sec. – 39.9 sec.] for the artificial accelerograms derived from the TIF1, TIF2 and TIF3 respectively. It thus may be concluded that strong motion duration, which is known to be an important factor in structural damage evaluation, may be significantly affected by the phase content characteristics.

These results are consistent with the large discrepancies observed in terms of PGA values, intensity envelope shapes and their characteristic parameters t_m and t_d indicated respectively by the solid and the dashed vertical lines in Figures 3a to 3d. The parameters, t_m and t_d, reported in Table 1 below, may be interpreted as measures of the centroïd and the radius of giration of the area under the intensity envelope function.

Tableau 1

Model	$\mathbf{t_m}$	$\mathbf{t_d}$	**PGA** (cm/s2)	$\mathbf{t_{PGA}}$ (sec.)
Original	8.3	4.2	255.9	6.1
TIF1	10.4	8.2	187.3	7.8
TIF2	18.3	11.7	126.5	4.7
TIF3	13.6	13.6	567.3	0.02

Case of TVF earthquake ground motion models

The cumulative energy functions corresponding to three artificial earthquake ground motions (dashed lines) generated from the TVF1, TVF2, and TVF3 simulation procedures are now compared in Figure 4 to the cumulative energy function of the target record (solid line). The corresponding ground acceleration time histories and their associated intensity envelope functions (thick dashed lines) are plotted in Figures 5a, 5b, 5c and 5d respectively.

Contrarily to the stationary case, it is now observed from Figure 4 that the cumulative energy functions corresponding to the original and the synthetic accelerograms follow practically the same pattern of variations. Moreover, from Figures 5a to 5d, it is seen that the corresponding ground acceleration shape functions exhibit similar characteristics in terms of strong motion durations and intensity envelope characteristic parameters. The PGA values and the corresponding times of occurrence of the artificial accelerograms are very close to those of the original record, as clearly shown in Table 2 below, regardless of the phase generation technique considered.

Tableau 2

Model	t_m	t_d	**PGA** (cm/s2)	t_{PGA} (sec.)
Original	8.3	4.2	255.9	6.1
TVF1	8.2	4.3	253.5	6.1
TVF2	7.8	4.0	257.7	6.2
TVF3	8.1	4.2	242.7	6.2

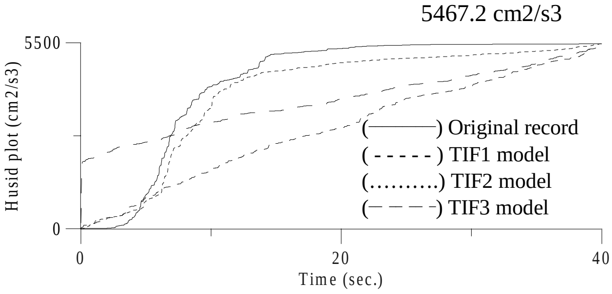

Figure 2 : Cumulative energy functions of the target and TIF simulated accelerograms.

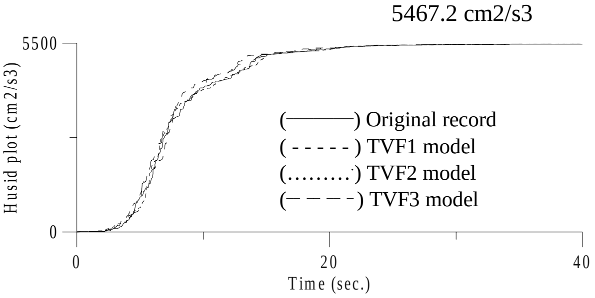

Figure 4 : Cumulative energy functions of the target and TVF simulated accelerograms

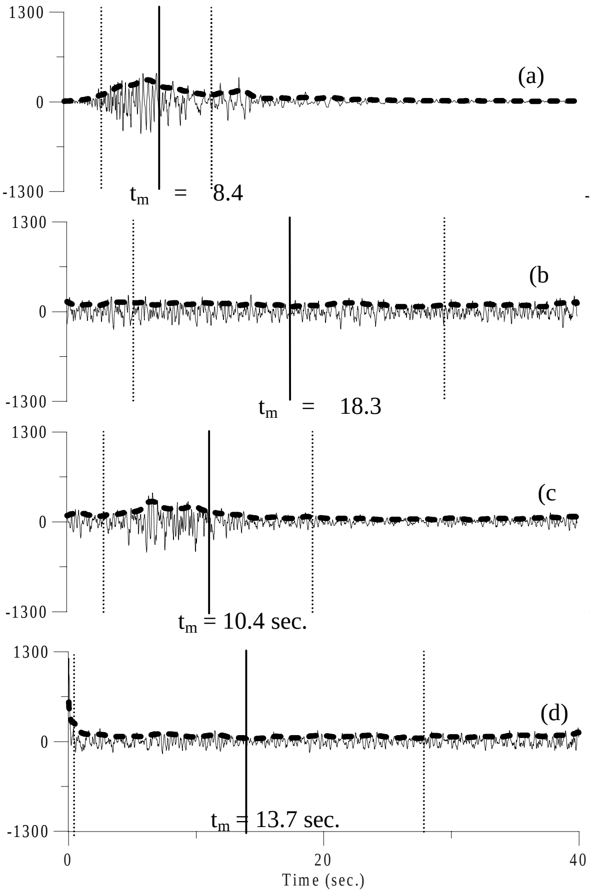

Figure 3 : Time histories of the (a) target, (b) TIF1, (c) TIF2 and (d) TIF1 simulated accelerograms

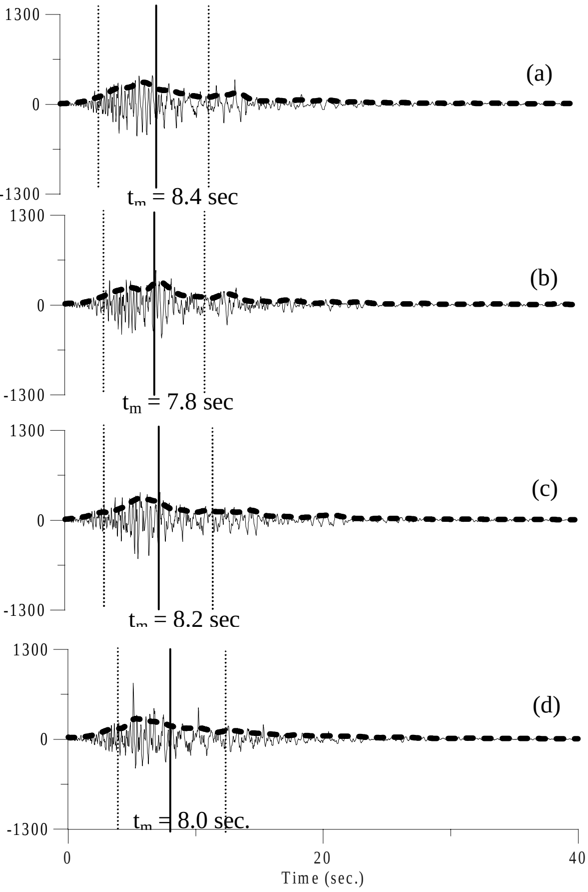

Figure 5 : Time histories of the (a) target, (b) TVF1, (c) TVF2 and (d) TVF3 simulated accelerograms

Effects of phase content modelling on structural response

For a given ground motion simulation procedure (i. e. for a given TIF or TVF earthquake ground acceleration model) and for each phase generation technique, the corresponding earthquake response of the non linear maximum oriented model is determined and its sensitivity to phase content modelling illustrated essentially in terms of non linear response spectra and time histories of effective structural frequency as well as inelastic structural displacement.

Effects on non linear response spectra

For illustration purposes, Figure 6a shows the variations of acceleration response spectra computed for the original record and three TIF models, by using the bilinear non degrading inelastic model shown in Figure 6b. As expected, it is seen that the spectral shapes follow more or less the same pattern of variations, since they have been obtained from three motions with identical Fourier spectra. Nevertheless, the same figure clearly suggests that very wide differences may exist especially for the short periods systems (i. e. rigid structures with periods shorter than 0.4 sec.). Variations in spectral estimates of two or three orders of magnitude may be observed. Clearly, a substantial reduction of these variations could have been achieved if the Fourier phase angle distribution was appropriately determined.

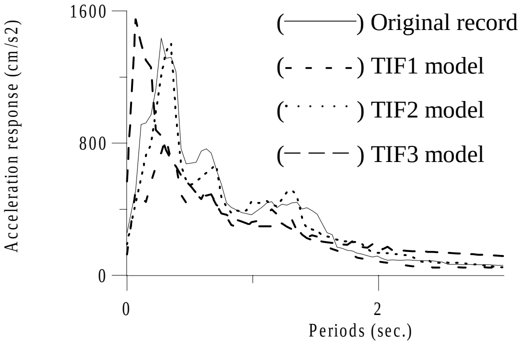

Figure 6a : Elasto plastic response spectra of the target and the TIF simulated accelerograms

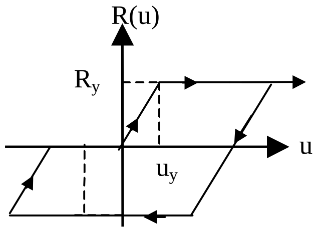

Figure 6b : The bilinear non degrading inelastic model

Effects on effective structural frequency

By examining Figure 7 it is found that a poor overall fit over ground motion duration between the smoothed simulated and target effective structural frequencies is obtained for the three TIF models. More specifically, it is also seen that, for these models, the use of different phase generation models leads to significant differences in the response characteristic parameters such as onset of yielding points, time of occurrence of resonant frequencies, temporal variation pattern of structural stiffness degradation and final values of residual structural rigidities.

However by considering Figure 9, it is now observed that, unlike the preceding TIF model, the TVF model produces a much better overall fit between the smoothed effective structural frequencies of the target and the synthetic accelerograms, independently of the phase generation technique considered. It is noticed from the same figure that the structural response characteristic parameters, computed from the target and the artificial accelerograms, are now quite similar. Moreover, it may be observed that, for each phase generation model, the distance, over the ground motion duration, between the effective structural frequency and the ground motion instantaneous mean frequency is much smaller in the case of TVF model than in that of the TIF model. This may be explained by the moving resonance phenomenon [16]. As yielding occurs, the decreasing effective structural frequency tracks the decreasing ground motion instantaneous mean frequency, causing over the duration of the strong motion phase, large amplifications in the response quantities of interest at or near the resonant frequency points (see Figure 9a to 9d). The number of crossing points depends on the time evolution of the ground motion mean instantaneous frequency and the structural properties of the inelastic structures considered.

On the basis of the above results obtained for the TIF and the TVF models, it is suggested that the moving resonance phenomenon be advantageously used as a testing procedure in order to check the validity of ground acceleration simulation models for a reliable prediction of time domain earthquake response of inelastic structures.

Effects on the time history of non linear displacement response

To further illustrate the effects of phase content modelling on structural response, let us now consider the response time history of the target accelerogram (Figure 8a) and that of the response derived from the TIF1 model (Figure 8b). It is noted that although both non linear displacement responses were computed from accelerograms with identical Fourier spectra, the corresponding response time histories exhibit quite different characteristics in terms of shape functions, onset of significant structural vibrations, number of zero crossings and maximum non linear displacement response. Again, it is observed that, in the case of TIF earthquake ground motion models, structural response is extremely sensitive to changes in phase content modelling.

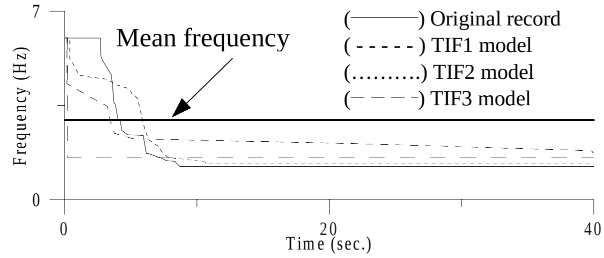

Figure 7 : Time histories of the TIF accelerogram instantaneous mean frequency and SDOF effective frequencies

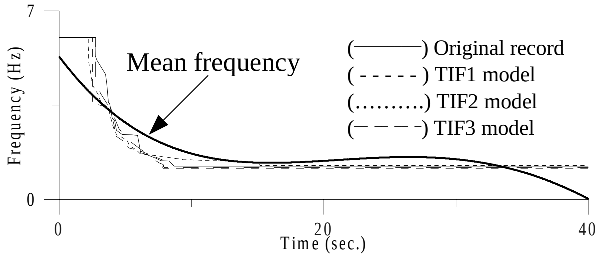

Figure 9 : Time histories of the TVF accelerogram instantaneous mean frequency and SDOF effective frequencies

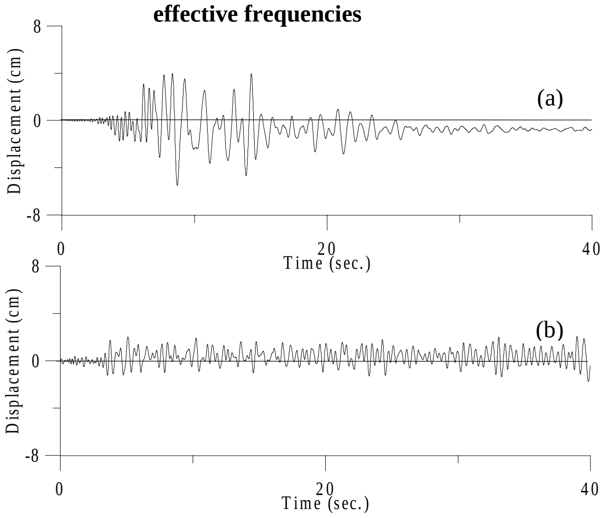

Figure 8 : Non linear displacement response of (a) the target and (b) the TIF1 simulated accelerogram

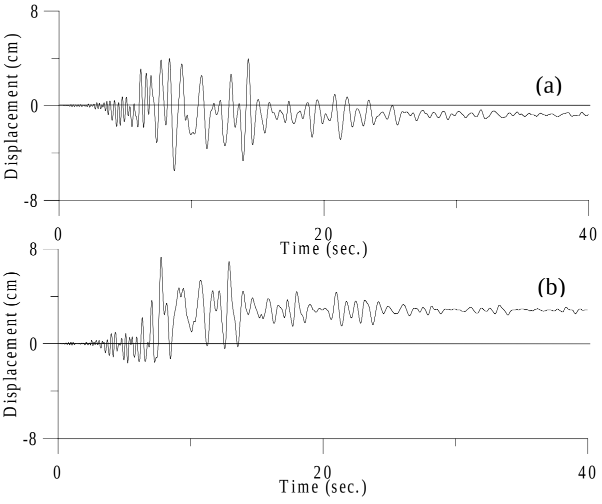

Figure 10 : Non linear displacement response of (a) the target and (b) the TVF1 simulated accelerogram

However, it should be emphasised that these observations should be re-examined when considering the TVF ground motion models. This fact is clearly illustrated in Figures 10a and 10b which show that the target record and the TVF1 simulated accelerogram are in good agreement in terms of times of occurrence of the major peaks and other response characteristic parameters.

CONCLUSIONS

The influence of phase content distribution of earthquake ground motions on both ground acceleration simulation and inelastic structural response has been examined by utilising TIF and TVF earthquake models. From a critical analysis of simulation results obtained in this preliminary investigation, it was found that this influence can be important especially when using the TIF earthquake ground motion models. However, these effects were found to be practically of negligible importance for the TVF models, regardless of the phase angle distribution considered. As clearly confirmed by the results of the moving resonance analysis, this striking result can be explained by the fact that the TVF earthquake model, presented in this study, has the capability of capturing the key features of actual earthquake accelerograms influencing ground motion characteristics and inelastic structural response. Furthermore, the results obtained by utilising the TIF and the TVF simulation models, show that the moving resonance phenomenon can be advantagely utilised as a testing procedure in order to check the validity of ground simulation models to be used for reliable time domain earthquake response of inelastic structures.

It is believed that more investigations on these significant effects, including the consideration of various classes of world-wide recorded accelerograms, other stiffness degrading hysteretic structural models, and realistic seismological ground motion simulation models, should be conducted by using the methodology described in the present paper to further consolidate the above simulation results and reveal probable new findings.

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