Synthesized earthquake ground motions for earthquake resistant design

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ABSTRACT: Some historical reviews on the past research works and achievements on synthesizing earthquake ground motions were first introduced with comments. Based upon the above reviews, it has been found that one of the practical procedures to generate synthetic earthquake ground motions is the one by superposition of sinusoidal waves with a set of phase angles of real accelerograms. The set of phases of real accelerograms gives synthetic waves the informations on nonstationarity corresponding to envelope functions. This discovery led to the technology to apply the specific unique functions on phases. Then was presented the synthetic ground motion combined seismological approach by fault model with the sinusoidal superposition procedure.

1 INTRODUCTION

In the earthquake resistant design of structures, if unlimited data of recorded earthquake ground motions (recorded EGMs) were available, representative stochastic models could be established directly by statistical analyses based upon those data. Unfortunately recorded strong EGMs are rather limited. Therefore one is forced to hypothesize a form of model of EGM for seismic design by generating synthetic earthquake ground motions (synthetic EGMs) on the basis of statistical characteristics of recorded EGMs, such as averaged power spectra, response spectra and so on.

In earlier studies the EGMs were synthesized by the procedure through which the white noise was first generated and filtered , or the EGM was directly synthesized under the specific power spectrum, then the envelope function was multiplied. In the next days, mainly for the purpose of seismic design of nuclear power plants, the methods to synthesize EGM appropriate to the design response spectrum (DRS) were developed. Those researches are first summarized.

It has been found by the group of authors that the phases of recorded EGMs are strongly correlated with the envelope functions of EGMs. Based upon this fact, the procedure to synthesize EGM by actual set of phases of recorded EGMs was proposed. The unique method was also proposed, by which synthetic EGM can be generated so as to fit DRSs simultaneously with two kinds of critical damping ratios.

2 SYNTHETIC STATIONARY WHITE NOISE

EGMs were first idealized into the stochastic model with random pulses by Housner (Ref.1). A series of impulses, Gaussian shot noise or white noise were utilized to synthesize EGMs by several researchers in those earlier days.

Housner (Ref.1) and Rosenblueth (Refs.2,9) idealized EGMs by a series of impulse randomly distributed in time space as shown in Fig.1. The acceleration a(t) is represented as

$$a(t) = \sum_i V_i \cdot \delta(t-t_i) \qquad (1)$$

in which v_i denotes the impulse magnitude and $\delta(t)$ is the Dirac delta function. The auto-correlation function $R(\tau)$ in terms of only time difference τ and the power spectral density function $S(\omega)$, of a(t) are

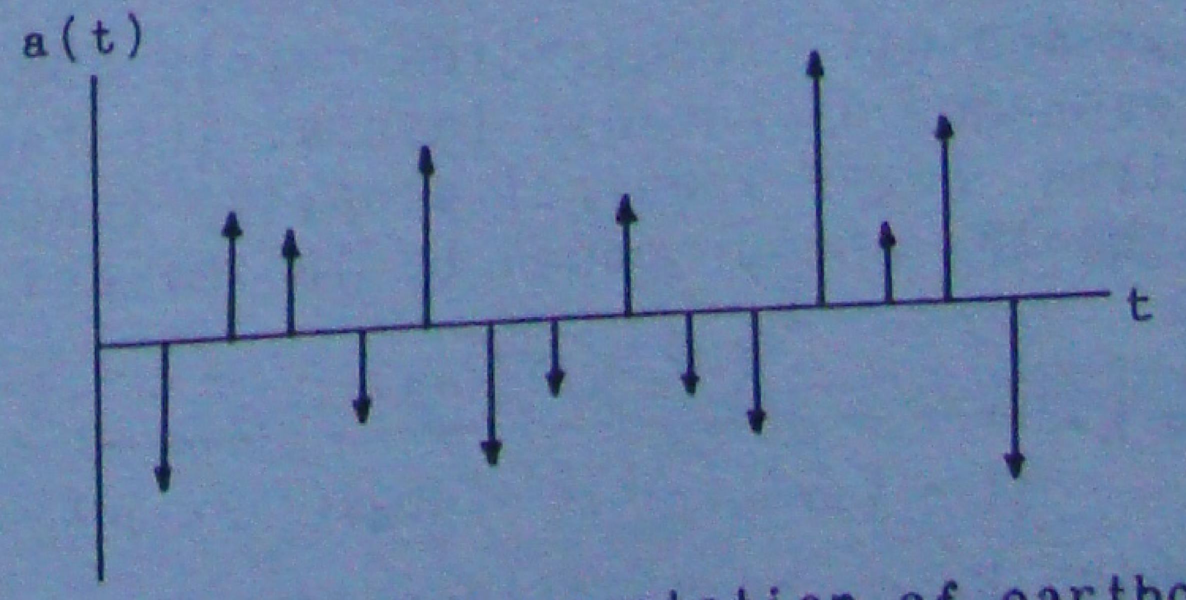

Fig.1 Impulse representation of earthquake

then obtained as follows. (2)

$$R(\tau) = \sum_i E[V_i^2]\cdot\delta(\tau) \quad (3)$$

$$S(\omega) = \sum_i 1/2\pi\cdot E[V_i^2] = const.$$

Therefore the synthetic EGM expressed by Eq.(1) has the constant amplitudes in all frequencies, the synthetic EGM of this type is well known as white noise.

The white noise was synthesized by the use of electrical simulator by Bycroft (Ref.4) and Naka et al. (Ref.12), or an electric analog computer by Ward (ref.13). The velocity response spectra excited by white noise (Bycroft) are shown in the circles of Fig.2, in comparison with the Housner's response spectra (Ref.3) derived

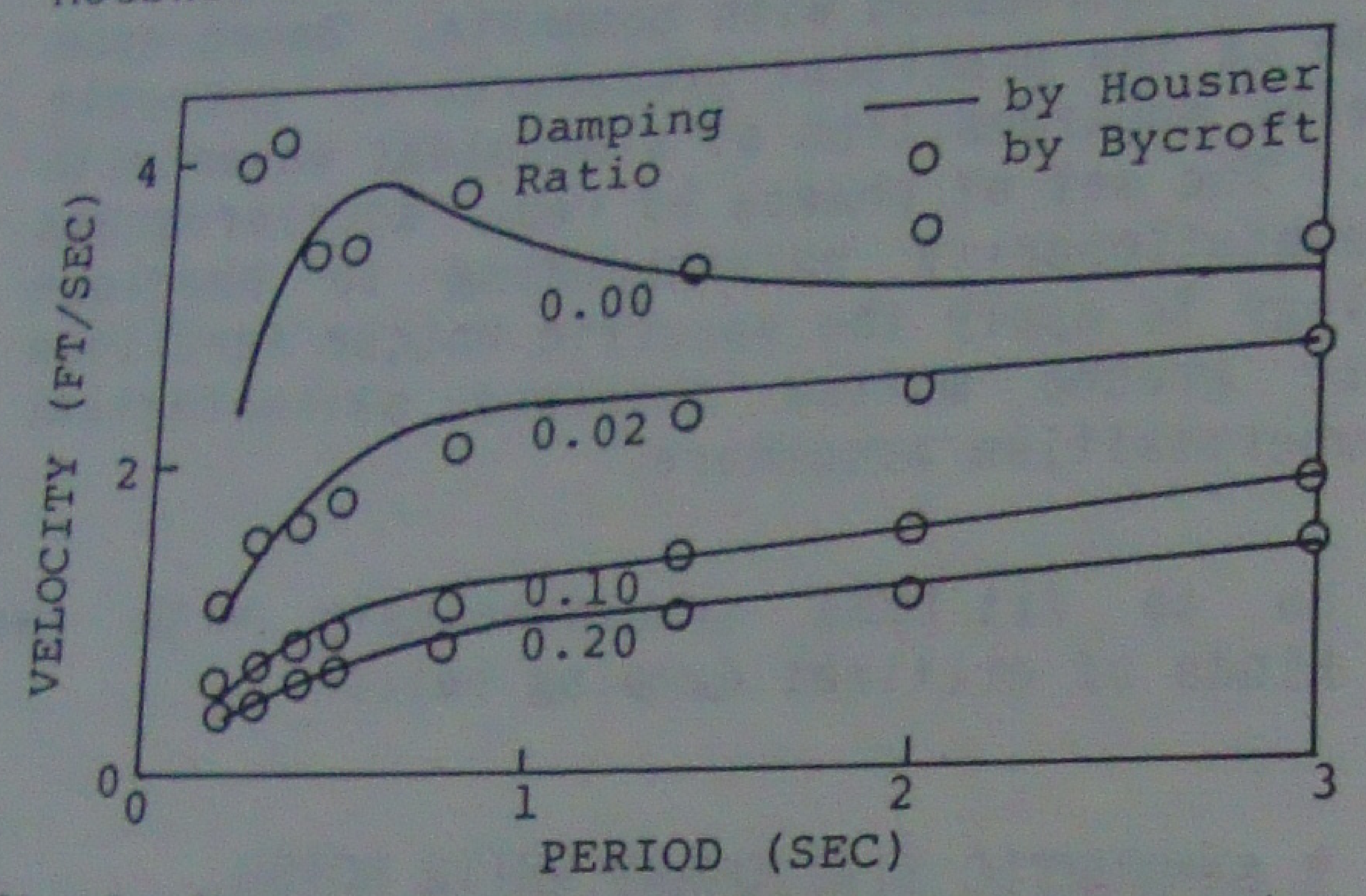

Fig.2 Housner's averaged response spectra and "white noise" spectra by Bycroft

from eight recorded strong EGMs. In the Bycroft's study, the velocity response spectra subjected to white noise with duration time of 25 seconds tend to be constant in the longer periods. As the result, the representation of EGMs by white noise having finite duration time seems to be reasonable at the first stage of the synthesizing. Then Ruiz and Penzien (Ref.18) generated white noise by the use of a function in terms of a pair of random variables.

3 FREQUENCY CONTENTS OF EARTHQUAKE GROUND MOTIONS

In the recorded EGMs, the power spectral density functions are not constant but have the predominat frequencies mainly due to the resonance of subsoil layers. The representative power spectral density function might be the one proposed by Tajimi(Ref.7);

$$S(\omega) = K\cdot\frac{1 + 4h_g^2(\omega/\omega_g)^2}{\{1 - (\omega/\omega_g)^2\}^2 + 4h_g^2(\omega/\omega_g)^2} \quad (4)$$

in which K is the magnitude of the spectrum, ω_g corresponds to the predominant frequency of EGM and h_g expresses the damping ratio of subsoil layers. The schematic shapes of power spectra proposed by some researchers (Refs.5-7,19-22) are illustrated in Fig.3.

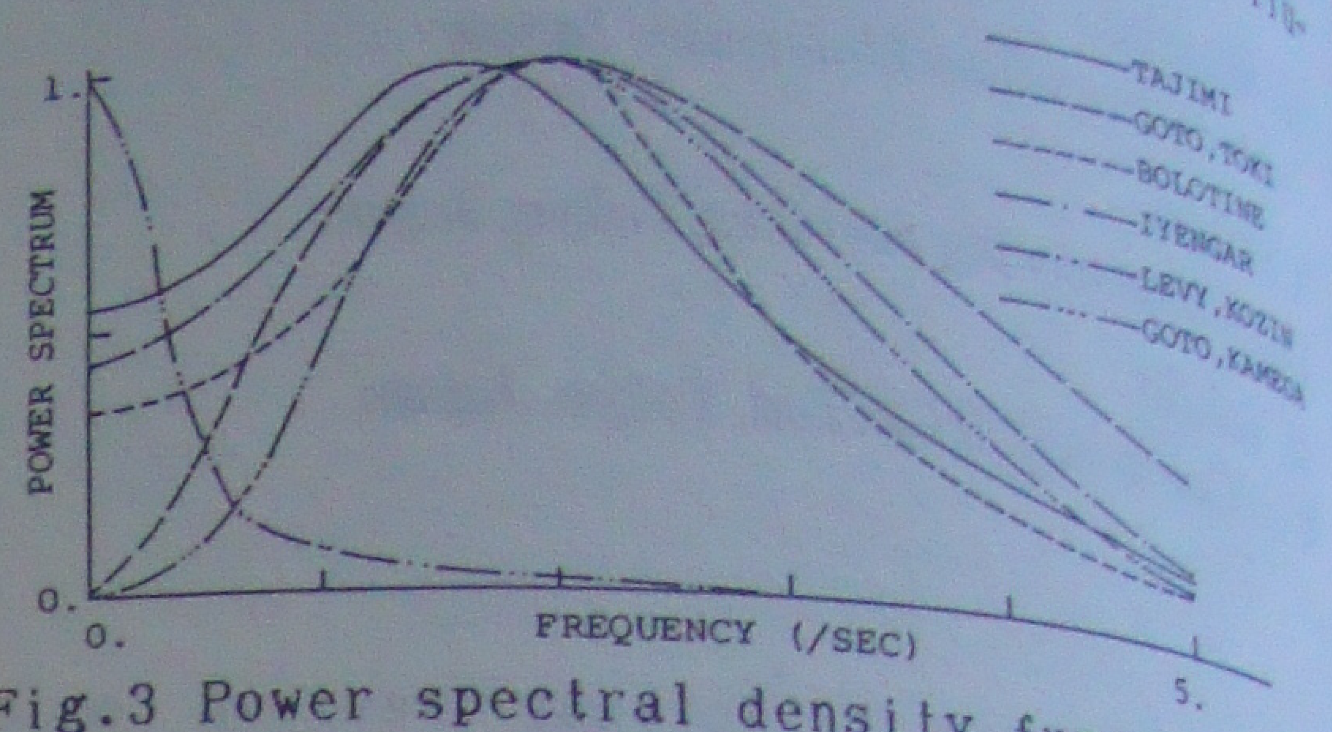

Fig.3 Power spectral density function

On the synthesizing of EGM with specific frequency contents, two methods have been found. One is based on the filtered white noise as expressed by Lin (Ref.10) and in the other method EGMs are directly synthesized by the superposition of sinusoidal waves. The power spectrum is once defined by Eq.(4), the synthesizing was carried out through the filter of Eq.(5) by Housner and Jennings (Ref.11).

$$\ddot{z}(t)+2h_g\omega_g\dot{z}(t)+\omega_g^2 z(t) = -\sqrt{K}\cdot N(t) \quad (5)$$

Where N(t) is the white noise with unit power spectrum.

The direct method by the superposition of sinusoidal waves is generally expressed by either Eq.(6) proposed by Toki (Ref.17) or Eq.(7) by Shinozuka and Jan (Ref.25).

$$a(t) = \sigma_y\cdot\sum_j COS(\omega_j t + \phi_j) \quad (6)$$

in which σ_y^2 is the variance of EGM, and ω and ϕ has the probabilistic density function of $S(\omega)/\sigma_y^2$ and uniform density, respectively.

$$a(t) = \sum_j A_j\cdot COS(\omega_j t + \phi_j) \quad (7)$$

$$A_j = \sqrt{4S(\omega_j)\cdot\Delta\omega}$$

where ω is the deterministic frequency equally spaced by $\Delta\omega$ and ϕ is with random variables for phases.

4 NONSTATIONARY EARTHQUAKE GROUND MOTIONS

The recorded EGMs are composed of the three parts of envelope in time space; build-up, nearly constant with high intensity level, and decaying (Ref.15). The simple model of nonstationary synthetic EGM is expressed as follows.

$$a(t) = I(t) \cdot b(t) \quad (8)$$

where b(t) is the stationary random process synthesized by the method as described in Sec.3 and I(t) is the envelope function. The variance of a(t) becomes

$$E[a^2(t)] = I^2(t) \cdot E[b^2(t)] \quad (9)$$

Where $E[b^2(t)]$ is independent of time, therefore the change of intensity of a(t) in terms of time can be given by only I(t). Derived from these properties I(t) is also called the deterministic intensity function. Fig.4 shows the envelope functions proposed by some researchers (Refs.5,14,15,19,21) and the similar functions are proposed by the others (Refs.8,16,24).

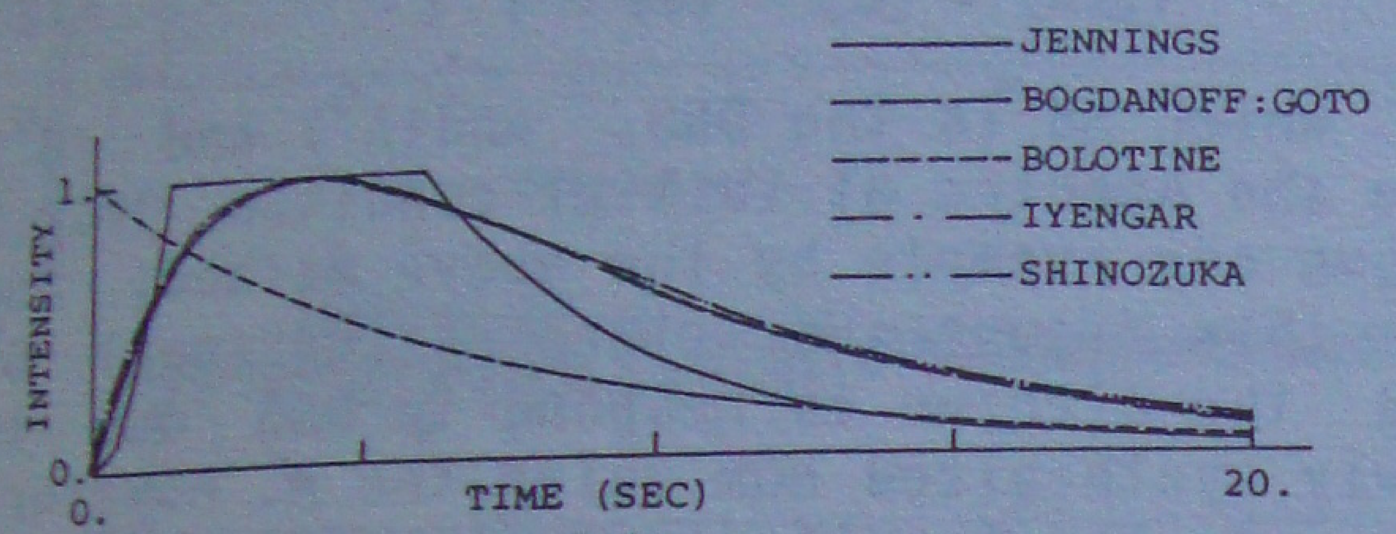

Fig.4 Envelope function

The above description was limited to the nonstationarity of intensity level in time domain. The nonstationarity of recorded EGMs has been found in frequency contents with respect to time as well. As for the synthetic EGM having the nonstationarity in both intensity and frequency, Saragoni and Hart (Ref.28) tried to synthesize EGMs by partitioning EGMs into some parts with different frequency characteristics in time space. Hoshiya and Isoshima (Ref.32) and Kameda and Sugito (Ref.33) proposed the synthetic methods by the use of similar expression of Eq.(7), in which the power specta are dependent on time. In these methods Hoshiya used the physical spectrum concepts and Kameda the evolutionary power spectrum.

5 SYNTHETIC EARTHQUAKE GROUND MOTIONS APPROPRIATE TO THE DESIGN RESPONSE SPECTRA

For the earthquake resistant design of structures, the response spectra are the principal factors on EGMs. From this point of view many investigations on the DRS derived from the recorded EGMs have been performed and some of them (Refs.38,39) have been often utilized for seismic design of nuclear power plants. When the DRS are given as the spectral characteristics of synthetic EGM, it is necessary to generate EGM appropriate to the DRS.

The earlier research in this direction was presented by Watabe (Ref.23). In this study the EGM was generated through an iterative procedure focussing on the pre established spectrum G. Using the spectrum Gc calculated by synthetic EGM, the pre-set amplitude A expressed in Eq.(7) was transformed into newly set amplitude A' at the next iterative step as follows.

$$A'(\omega) = A(\omega) \cdot G(\omega)/Gc(\omega) \quad (10)$$

Most of the later researches had the similar procedure to fit the DRS.

Tsai (Ref.26) and Rizzo et al. (Ref.27) obtained the synthetic EGM appropriate to the DRS Sd by modifying a recorded EGM. For the iterative procedure, Tsai used the suppressing technique passing through an transfer function if the response spectrum subjected to synthetic EGM (RSS) Sc>Sd, and the raising technique by adding a sinusoidal wave if Sc<Sd. Rizzo et al. carried out the procedure by the same way of Eq.(10) if Sc>Sd and the similar way by Tsai if Sc<Sd. In the method by Levy and Wilkinson (Ref.30), the amplitudes were modified by Eq.(10) and a sequence of 0 and π was selected for the phases expressed in Eq.(7).

The method for directly setting amplitude spectrum of the synthetic EGM modelled by Eqs.(7) and (8) was proposed by Vanmarcke and Gasparini (Ref.31) and Iyengar and Rao (Ref.34), by which synthetic EGM can be generated so as to fit the DRS without iteration. In the proposal by Vanmarcke et al. the relationships between amplitude spectra and response spectra based on the random vibration theory were applied. It is herein noted that the synthetic EGM by Vanmarcke is appropriate to the DRS in a stochastic sense such as ensemble average. Iyengar et al. set up the equations on the response time histories subjected to a synthetic EGM, and estimated the amplitude spectrum composed of 25 frequency components. Then their method was extended so as to satisfy simultaneously the DRSs with two different damping ratios. From their examples the fitness of spectra to DRS at the 1st iteration seems not to be improved.

6 SOME DISCUSSIONS ON THE ITERATIVE WAY TO SYNTHESIZE EARTHQUAKE GROUND MOTIONS FITTING THE DESIGN RESPONSE SPECTRA

The aspect of change of RSS due to the modification of amplitudes $A(\omega)$ of synthetic EGM in Eq.(7) has been studied by the authors as follows.

The EGM was generated by the model of Eq.(8), using the envelope function by Jennings et al. with the duration time of 30sec. As the spectral properties defined by Eq.(4), K=225gal^2*sec, $\omega_g=2\pi/0.4$rad/sec., and $h_g=0.6$ were assumed. At first, the response spectrum $\{S_v^0\}$ at the same frequencies $\omega_i(=i\cdot\Delta\omega;\Delta\omega=1.25$rad/sec., i=1-50) of sinusoidal frequency components in Eq.(7) was calculated by the synthetic EGM using the initial amplitudes $\{A^0\}$ in Eq.(7). Next an amplitude α(Gal) at a frequency ω_j was added to A_i^0, then new response spectrum $\{S_v^j\}$ subjected to the new synthetic EGM was computed. Using these results, the coefficients of influence C_{ij} were defined as follows.

$$C_{ij} = \{S_v^j(\omega_i) - S_v^o(\omega_i)\}/\alpha \qquad (11)$$

Figure 5 shows C_{ii} in three conditions (α=1, α=10 , and phase change in α =1), and Fig.6 shows C_{ij} in α=1. The results suggest that the increase of Sv at the frequency of resonance is roughly proportional to an additional amplitude , therefore the iterative procedure by Eq.(10) was affirmed to be one of the methods to success the synthesizing of EGM appropriate to DRS.

As for that purpose, it might be expected to utilize the matrix [C] composed of the coefficients of influence. The method can

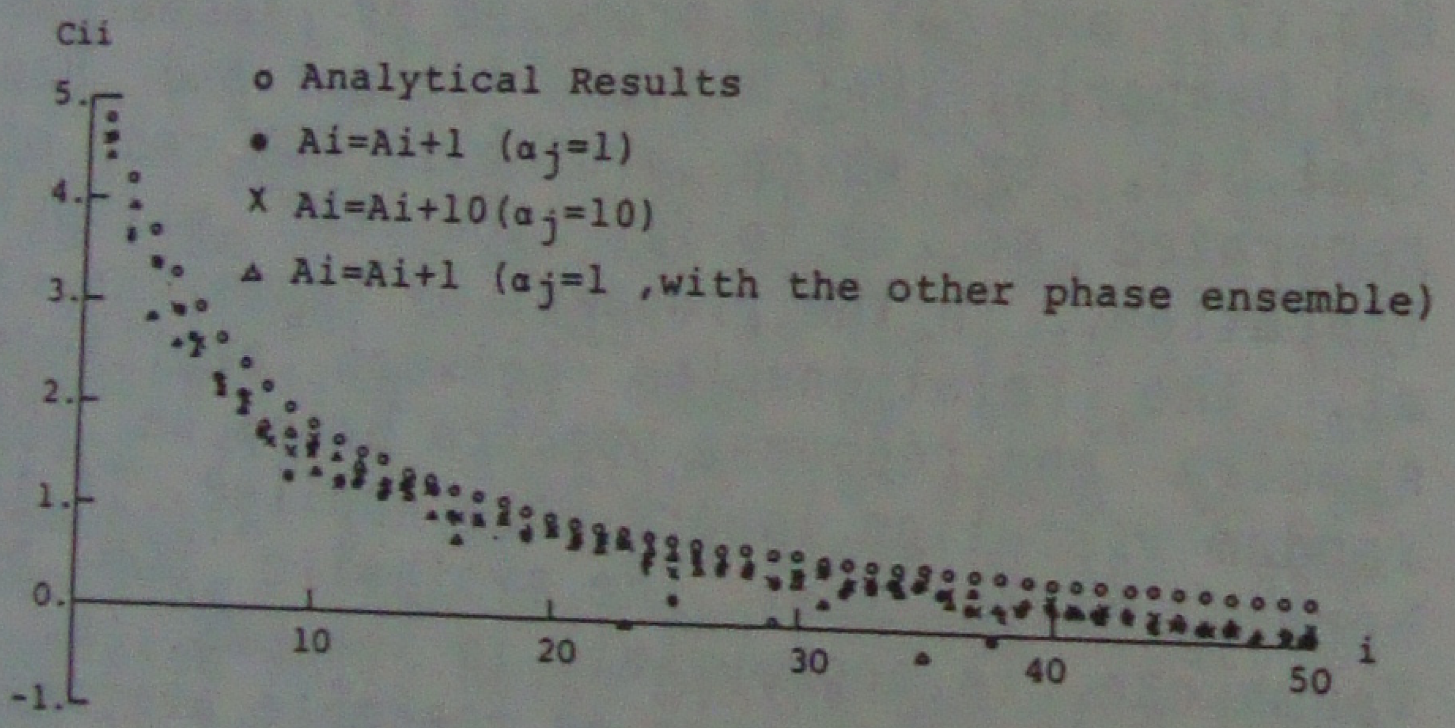

Fig.5 Effect of an added amplitude to response in resonance

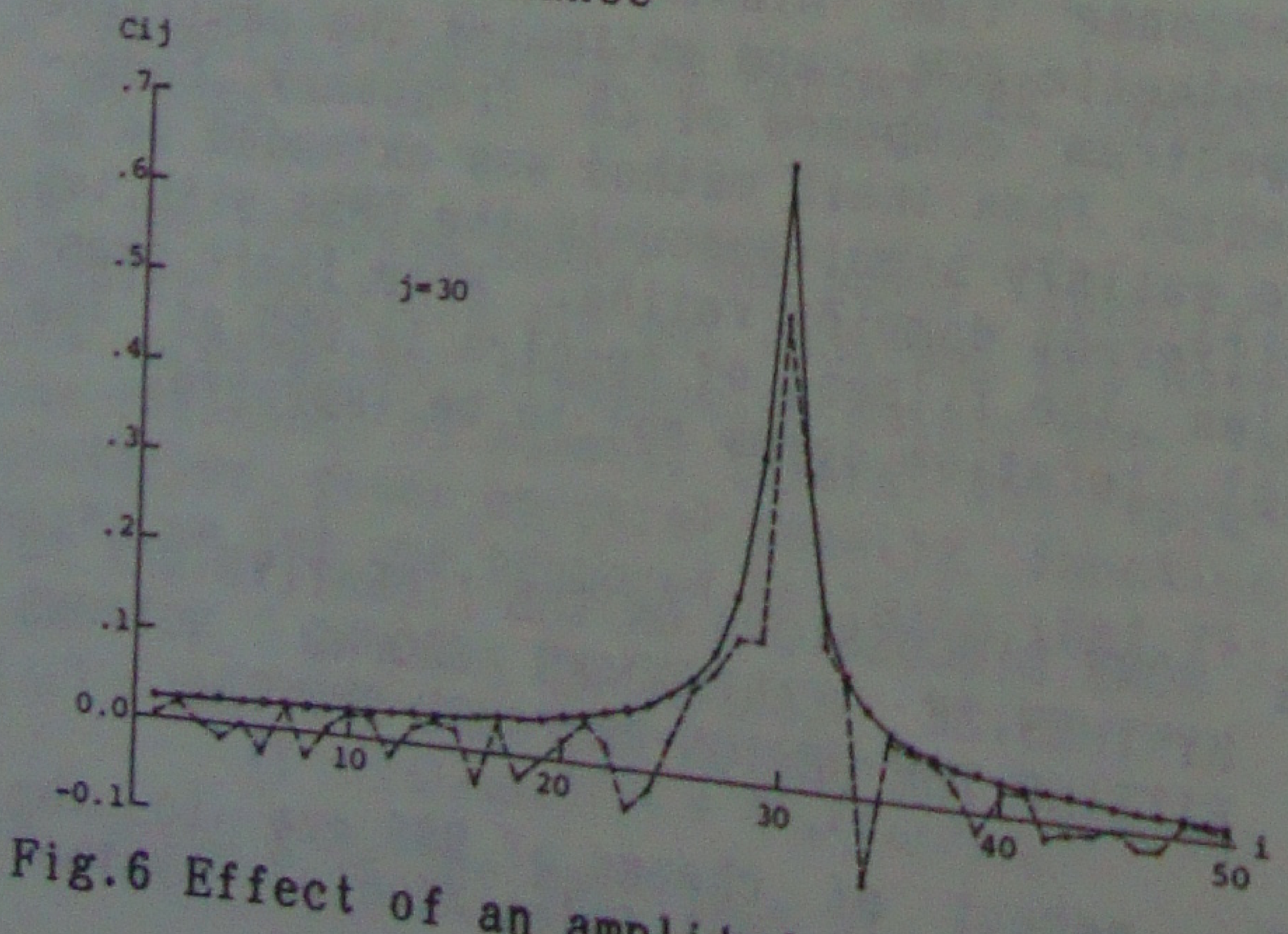

Fig.6 Effect of an amplitude to response

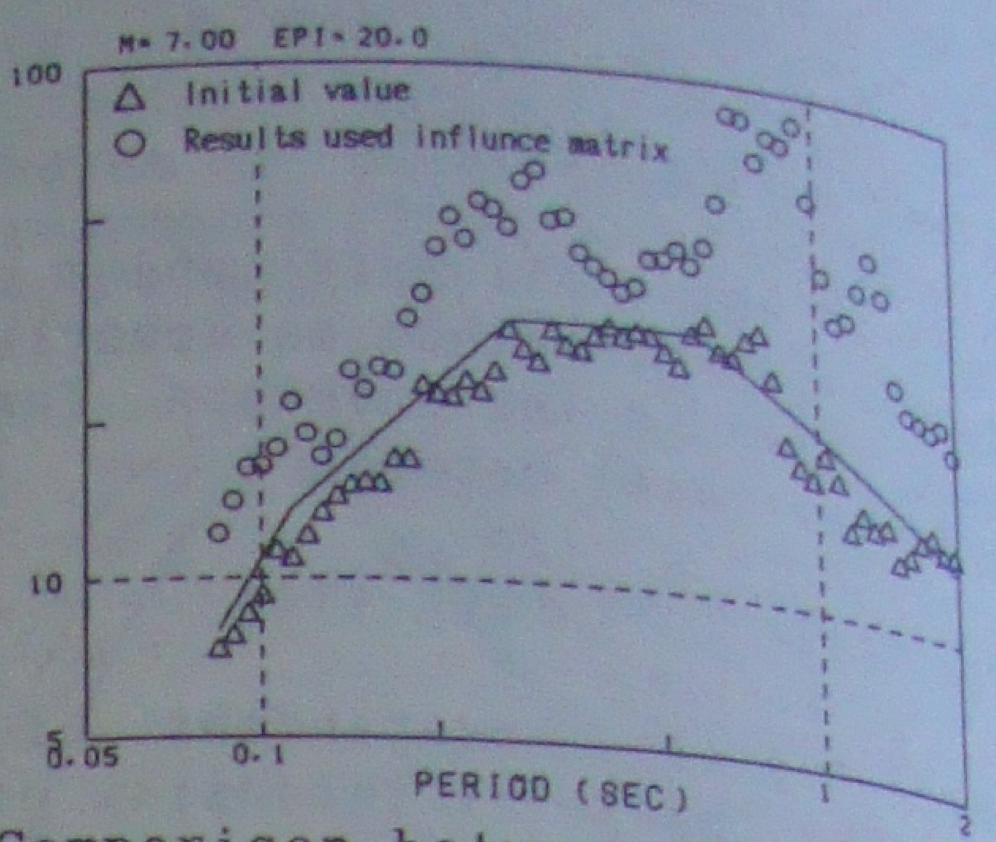

Fig.7 Comparison between DRS and RSS due to synthetic EGM using influence matrix

be written in the followings.

$$\{A\}^{j} = \{A^o\} + \{\Delta A\}$$

$$\{\Delta A\} = [C]^{-1}\cdot\{S_d - S^o\} \qquad (12)$$

in which Sd is the DRS, and $\{A^0\}$ and $\{S^0\}$ are the spectra at initial conditon. Fig.7 shows one example by the above method, and in this figure the triangles represent S^0 and the circles correspond to RSS due to newly synthesized EGM using the A^j. However, the example results in that the fitness is not acceptable, because the relationships between the increase of amplitudes and RSS are not linear as to be infered by the difference of Cii in Fig.6 and the occurence time of peak response changes in each synthesizing.

Incidentally the criterion of fitness in the following to judge the completion of iteration was proposed by the authors, by which the responses of structures less variate in spite of the procedure to synthesize or the selection of phases in Eq.(7).

$$\varepsilon(T_i)>0.85\ ,\quad |1-\bar{\varepsilon}|<0.02\ ,\quad \nu<0.05$$

in which $\varepsilon(T_i)=Sc(T_i)/Sd(T_i)$ and Sc and Sd are the RSS and DRS, respectively, and $\bar{\varepsilon}$ and ν are the mean value and the coefficient of variation of $\varepsilon(T_i)$.

7 CHARACTERISTICS OF PHASES OF RECORDED EARTHQUAKE GROUND MOTIONS AND THEIR APPLICATIONS

Most of the researches on the field of synthetic EGM suggested the randomness and the uniform probability distribution, of phases in EGM. It is also the fact, however that EGM with nonstationarity is not composed only of Fourier amplitudes but of phase angles. If only phases of a recorded

EGM are transformed to the random phase angles having the uniform probability density and the time history is generated, the time trace should become stationary random process different from the recorded one. Therefore using a set of phases of a recorded EGM, independent of amplitude spectrum may be the one of the procedures to find out the role of phases on nonstationarity of EGMs.

Fig.8 shows the recorded EGM of Taft 1952, EW component, and synthetic one which has uniform amplitudes in each frequency component with the same set of phases of the Taft 1952. Let this kind of synthetic EGM be called as "phase wave". The phase wave is generated by the following way.

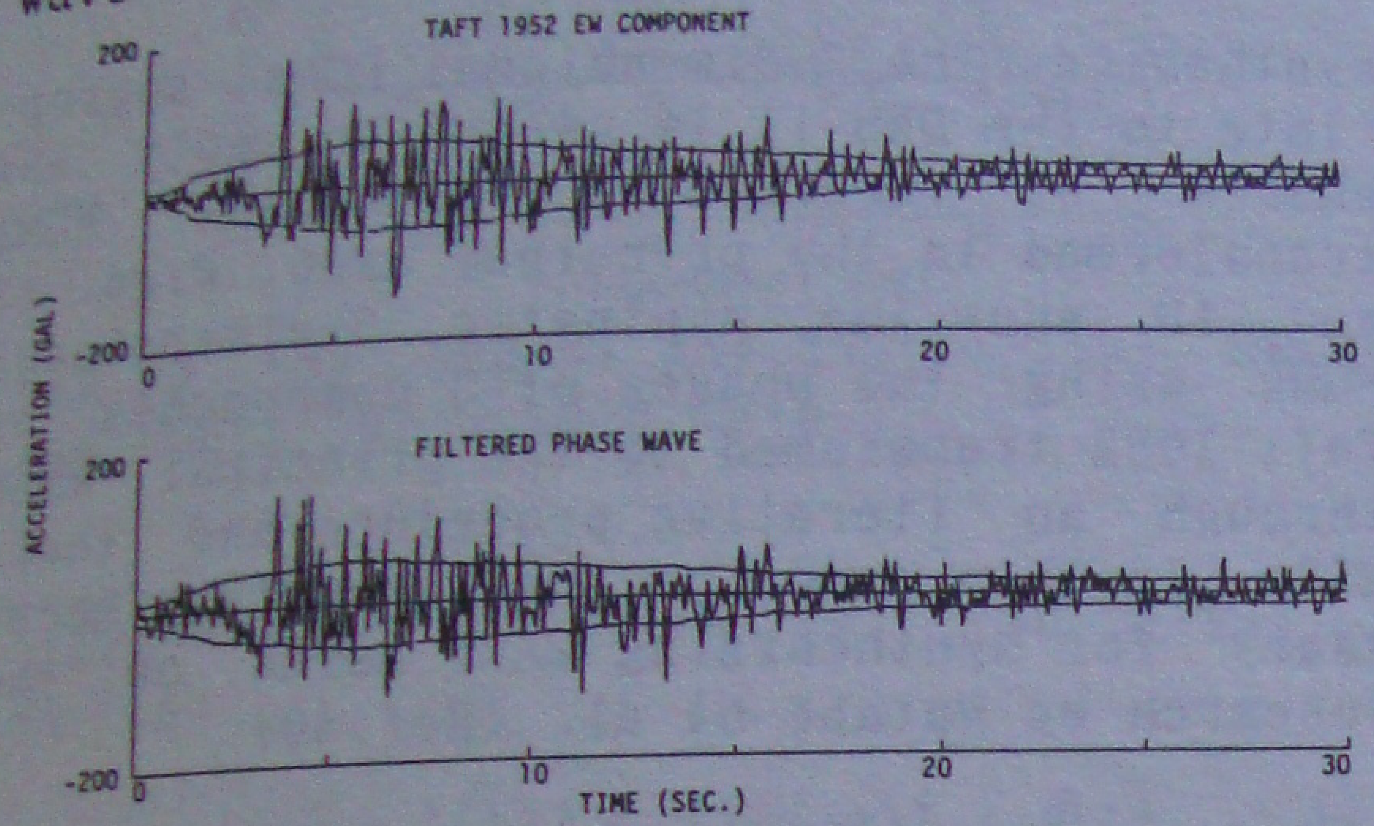

Fig.8 Original wave of Taft-EW and its phase wave

A digitized EGM $a_r(t)$ can be expanded into a Fourier series as follows.

$$a_r(t) = \Sigma A_j \cdot COS(\omega_j t + \phi_j) \quad (13)$$

The phase wave $a_p(t)$ in Fig.8 is generated by using the relation

$$a_p(t) = P \cdot \Sigma COS(\omega_j t + \phi_j) \quad (14)$$

where P is the scaling factor of intensity and the high frequency components in $a_r(t)$ are excluded in $a_p(t)$. It is clearly shown in Fig.8 that the envelope function of phase wave is quite similar to the original one.

It was pointed out by Ohsaki (Ref.36) that the characteristics of nonstationarity of recorded EGMs can be expressed by the distribution of phase difference $\Delta\phi$, that is given by

$$\Delta\phi_j = \phi_{j+1} - \phi_j \quad (15)$$

where $\Delta\phi$ is defined in the range $-2\pi < \Delta\phi < 0$. Fig.9 shows the probability density functions of phases and phase differences of Taft 1952-EW component in the duration of 30 sec. respectively. It is seen from

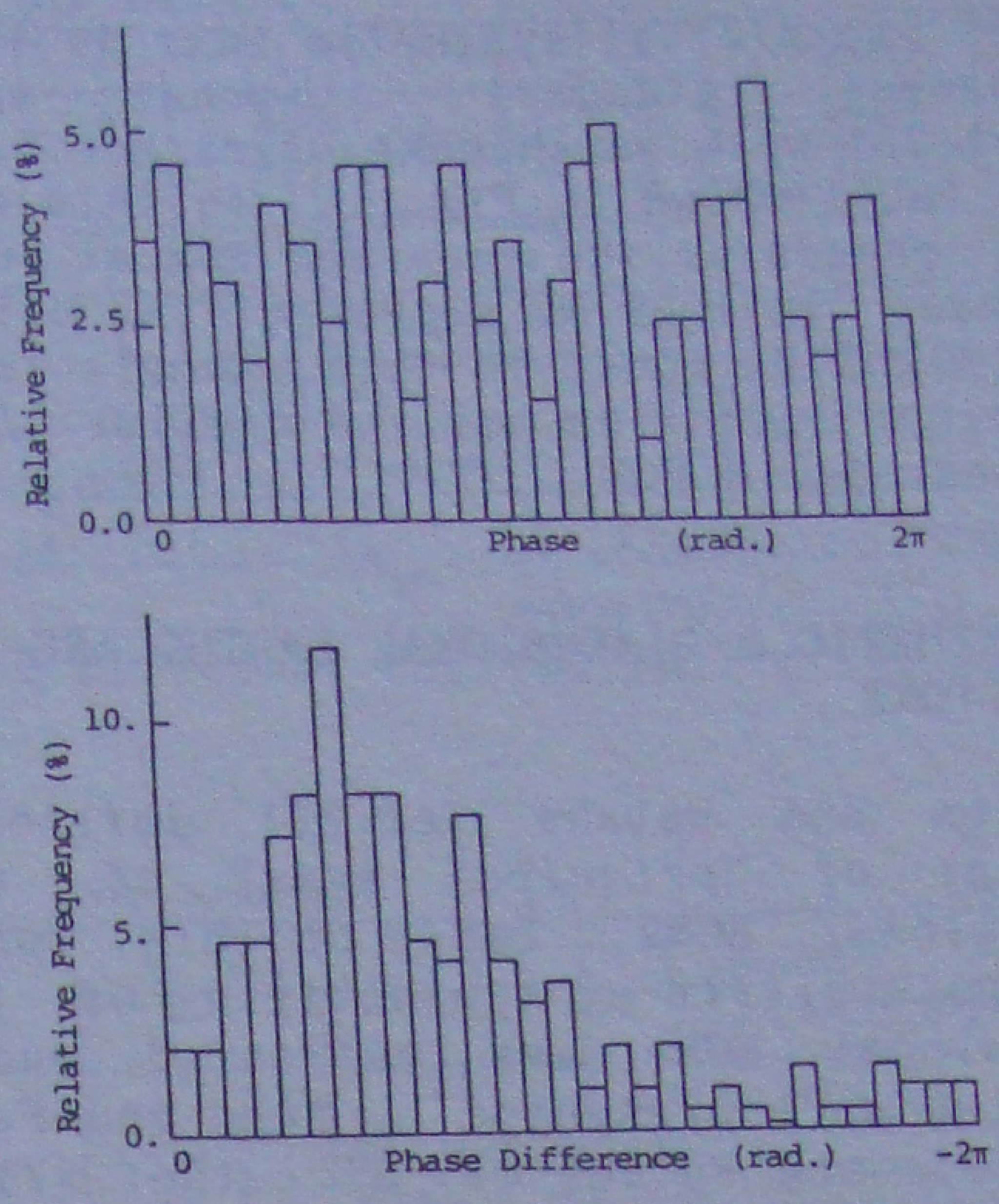

Fig.9 Probability density of phase (upper) and phase difference (lower) of Taft-EW

these figures that the probability density of phase angles is nearly uniform, while the probability density of phase differences has some characteristics similar to that of Normal-like. In addition as pointed out by Ohsaki, the distribution of phase differences normalized by -2π has a quite similar feature to the envelope function of time history normalized by the duration time.

The results discussed above suggest that it may be wise to utilize the properties of phases of recorded EGMs to controle envelope functions of synthetic EGMs. Fig.10 is

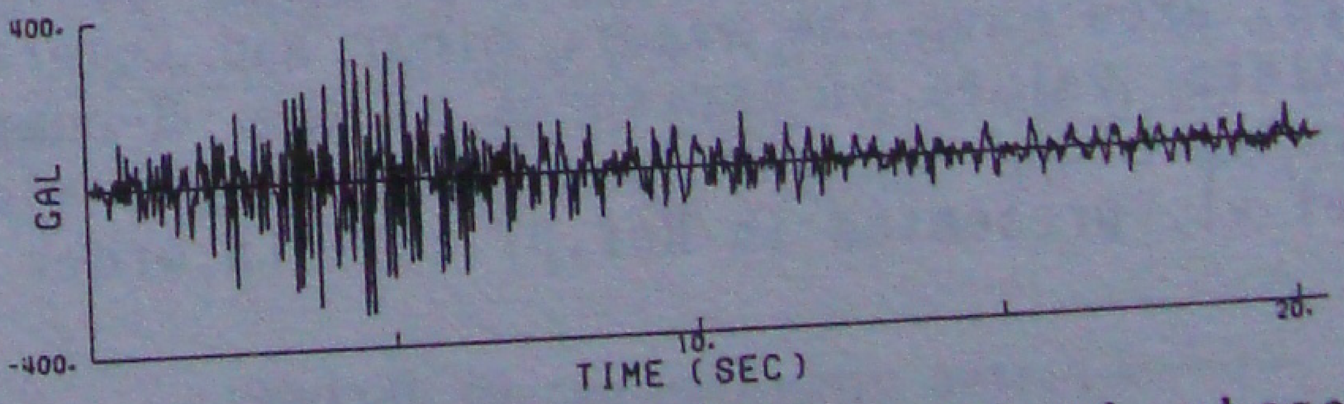

Fig.10 Synthetic EGM using a set of phases of recorded Cholame Shandon-NS

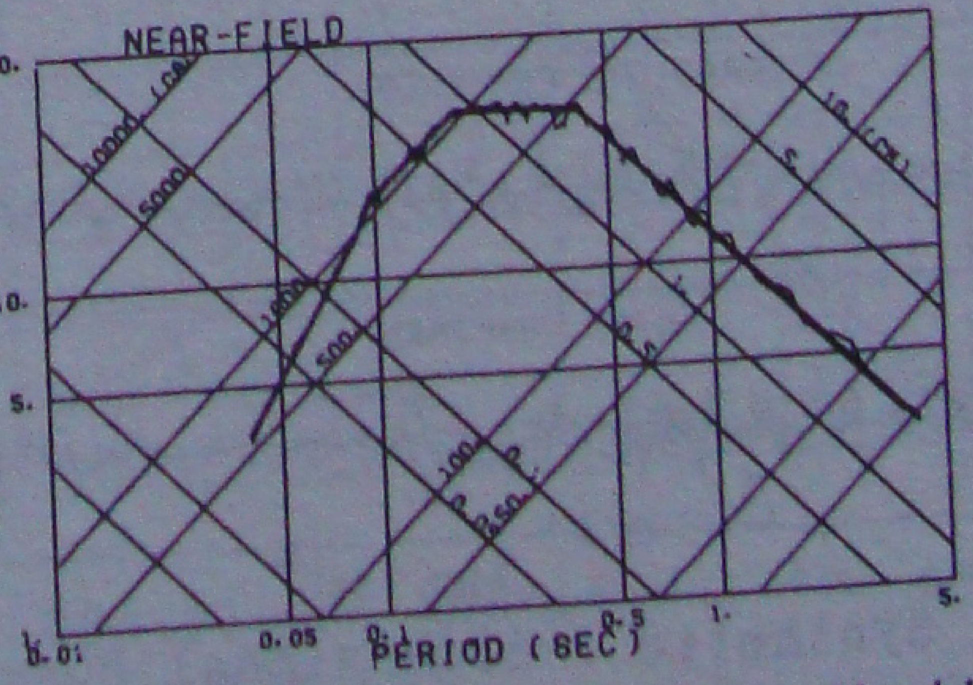

Fig.11 DRS and RSS due to synthetic EGM shown in Fig.10

one example of synthetic EGMs as to fit Japanese standard response spectrum (Ref.39) with earthquake magnitude 6.5 near the fault shown in Fig.11. In this example the phases of the recorded EGM at Cholame Shandon in 1966-NS component is utilized. It might be found in this example that the envelope function has the similar feature of near field EGM.

8 SYNTHETIC 3-DIMENSIONAL EARTHQUAKE GROUND MOTIONS

Penzien and Watabe (Ref.29) defined the concept of "principal axes" of multi-dimensional EGMs. Based on this concept, the possibility of synthesizing of three-dimensional EGMs was suggested and the examples were presented by Kubo and Penzien (Ref.35) and Watabe et al. (Ref.37). In theses studies the components along principal axes were represented by the similar form of Eqs.(7) and (8) through the relation

$$a_k(t)= I_k(t)\cdot b_k(t),\ k=x,y,z \qquad (16)$$

Where $bx(t)$, $by(t)$ and $bz(t)$ are stationary random motions stochastically uncorrelated with each other, therefore the covariance matrix of components becomes the diagonal matrix as follows.

$$\underline{\mu(t)} = \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix} = \begin{bmatrix} \mu_{xx} & 0 & 0 \\ 0 & \mu_{yy} & 0 \\ 0 & 0 & \mu_{zz} \end{bmatrix} \qquad (17)$$

$$\mu_{ij} = E[a_i(t)a_j(t)]$$

From the relation, it is apparent that the components of synthetic EGMs along principal axes have the major, minor and intermediate values of variances of the 3-components along the any axes tranformed. Watabe et al. presented in Ref.37 that in order to

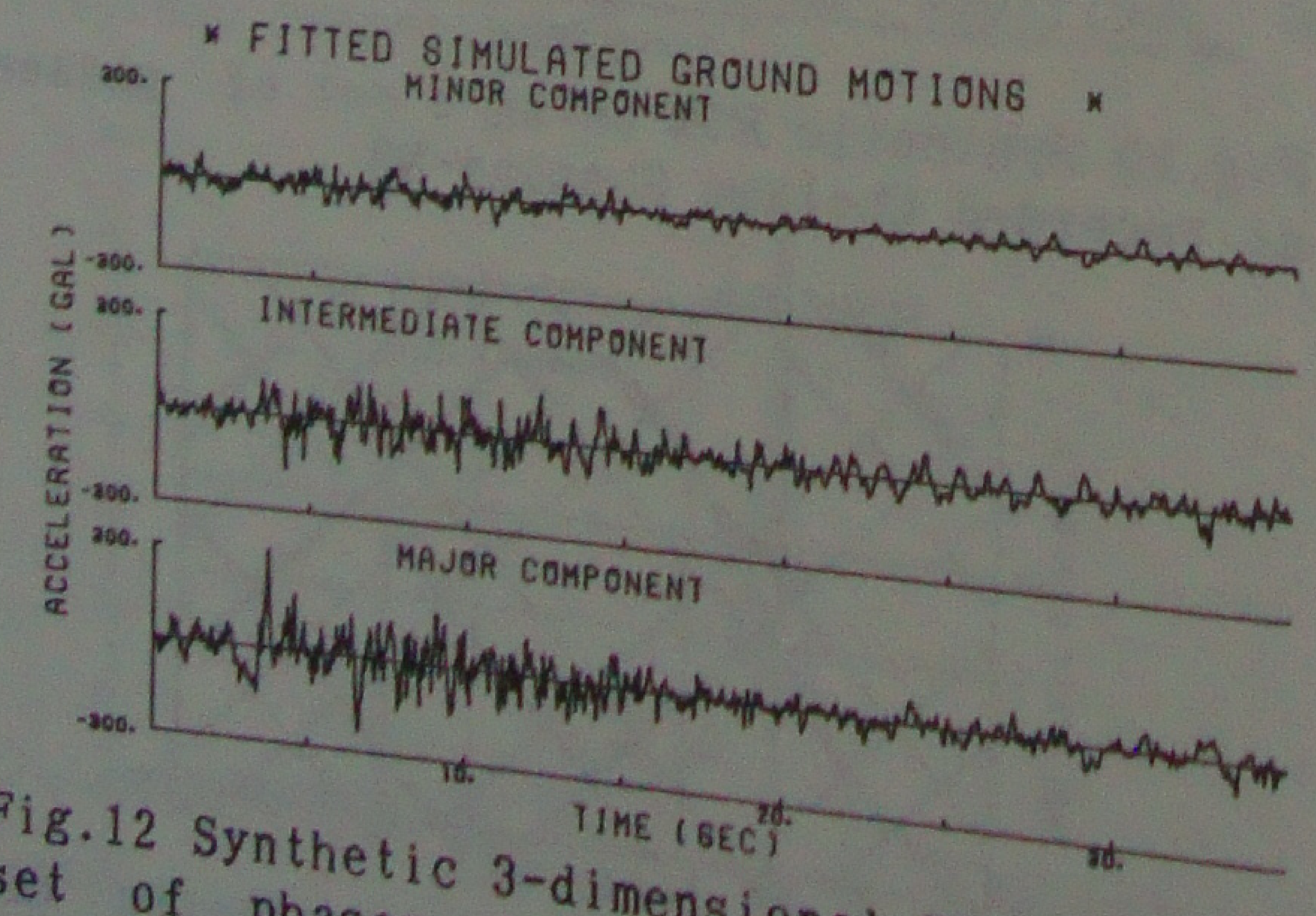

Fig.12 Synthetic 3-dimensional EGMs using a set of phases of Taft transformed into principal axes

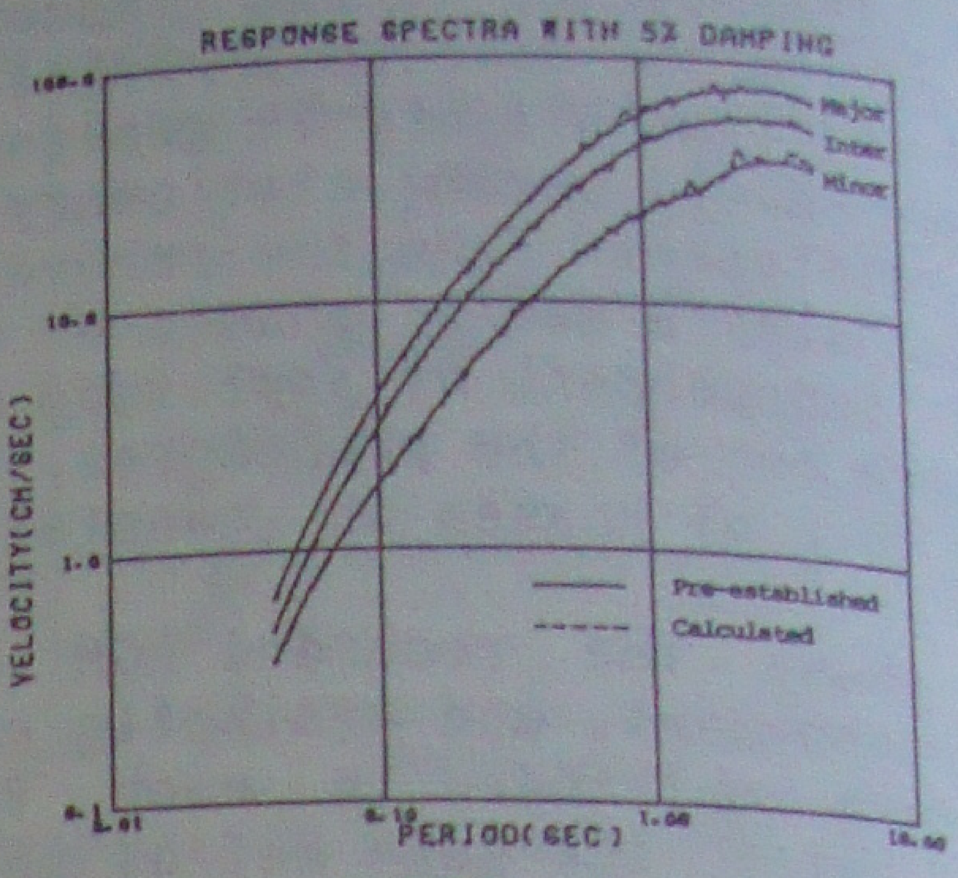

Fig.13 DRSs and RSSs due to synthetic 3-dimensional EGMs in Fig.12

synthesize the 3-dimensional EGMs appropriate to the DRS it is useful to apply the phases of recorded 3-dimensional EGMs transformed to the principal axes. Figs. 12 and 13 show the synthetic 3-dimensional EGMs using the phases of 3 components of Taft 1952 transfomed to the principal axes through an iterative procedure and their RSSs. In this example, the parameters necessary for synthesizing were based on the research by Watabe et al. (Ref.40).

9 PHASE CHARACTERISTICS FOR TWO RESPONSE SPECTRA WITH DIFFERENT DAMPING RATIOS

In generating synthetic EGM with DRS, the iterative calculation is carried out to fit design response spectrum with 5% damping(DRS(5)). By this procedure, response spectrum with 5% damping subjected to synthetic EGM(RSS(5)) nearly converges to DRS(5). However RSS(1) due to the above synthetic EGM does not always converge to DRS(1) if uniform random numbers for phases are used, and this RSS(1) is generally larger than DRS(1). As one example, DRS(5) due to EGM recorded at Golden Gate is shown in solid line and RSS(5) in dotted line in Fig.14(a) where the quite reasonable agreement between the two can be seen. Solid line in Fig.14(b) is DRS(1), while dotted line in Fig.14(b) expresses RSS(1), which may be judge to be over response than DRS(1) and irregular. This trend can be recognized in other EGMs. When EGM is applied to the structural system with composed of members with different damping ratios, it is desired that synthetic EGM should be in comformity with response spectra simultaneously with two different damping ratios in performing seismic analysis of above structure systems. From this point of view, one idea to generate such synthetic EGM is herein presented.

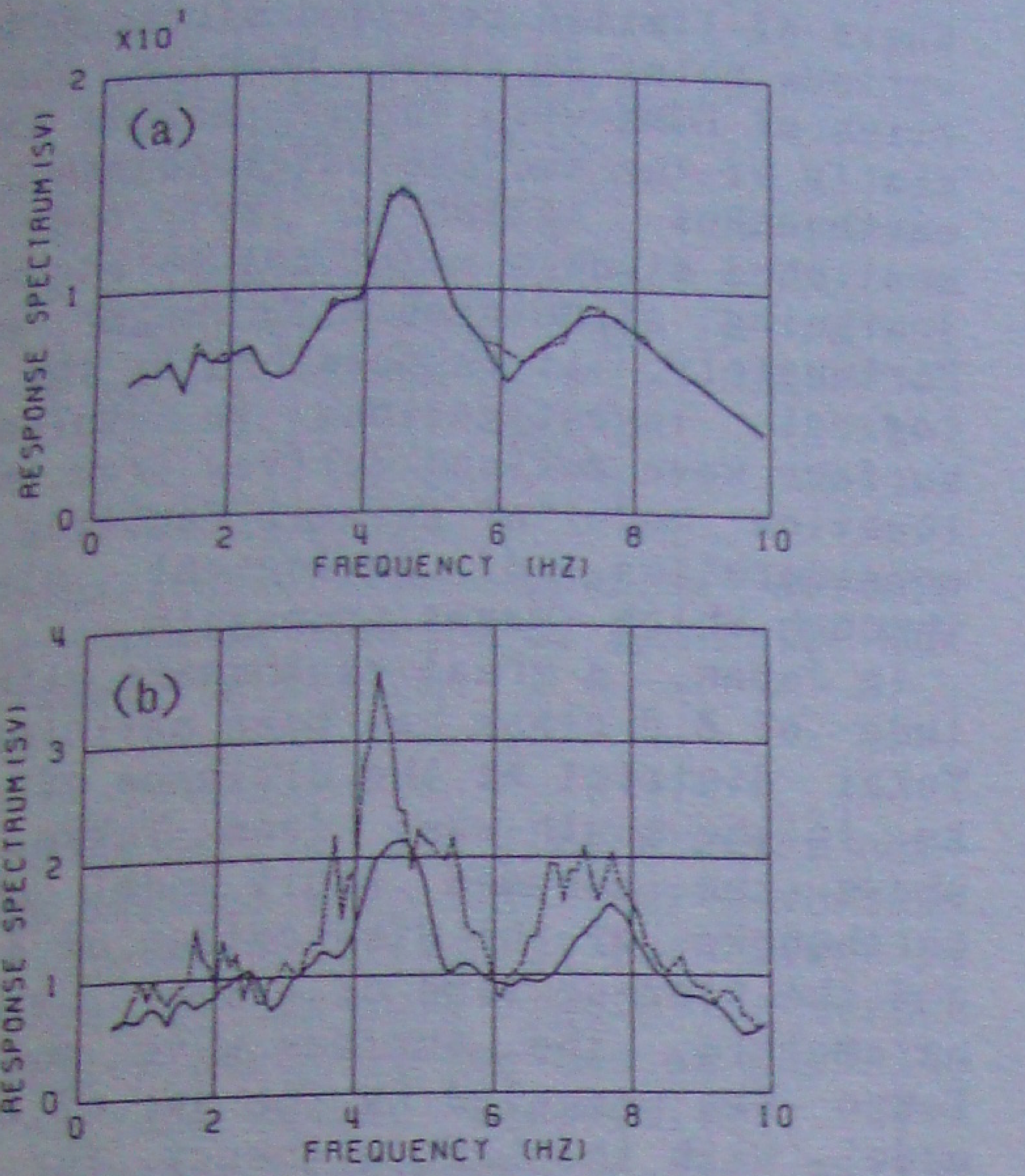

Fig.14 (a) DRS(5) and RSS(5) ,(b) DRS(1) and RSS(1) of Golden Gate

Synthetic EGM can be expressed in Eq.(18).

$$a(t) = I(t)\sum A_j \cdot \cos(\omega_j t + \phi_j) \quad (18)$$

Envelope function I(t) in Eq.(18) is not taken into account in the following discussion. Amplitude A is determined so as to fit RSS(5) to DRS(5). Then the remained freedom to control the other characteristics of synthetic EGM is only phase ϕ.

Therefore, extensive researches on the role of phase angle have been conducted by the group of authors in order to realize the generation of synthetic EGM which satisfy the above requirement to fit the two DRS with different dampings. As the result the following function for phase of synthetic EGM is proposed.

$$\phi(f) = \alpha f + de^{-\kappa f} - d + we^{-zf}[-\pi, \pi] \quad (19)$$

Where $[-\pi, \pi]$ is uniform random number between $-\pi$ and π Coefficients "α","d", "κ","w", and "z" are arbitrary constants. The term of coefficient "α" in Eq.19 corresponds to Fourier phase spectrum of an impulse wave over the duration and contributes to the shift of a wave form of synthetic EGM. "α" does not influence the maximum value of synthetic EGM, and still more the RSS(1). When coefficient "w" is assumed to zero, randomness element in Eq.(19) diminished, phase ϕ reduces to only the exponential function.

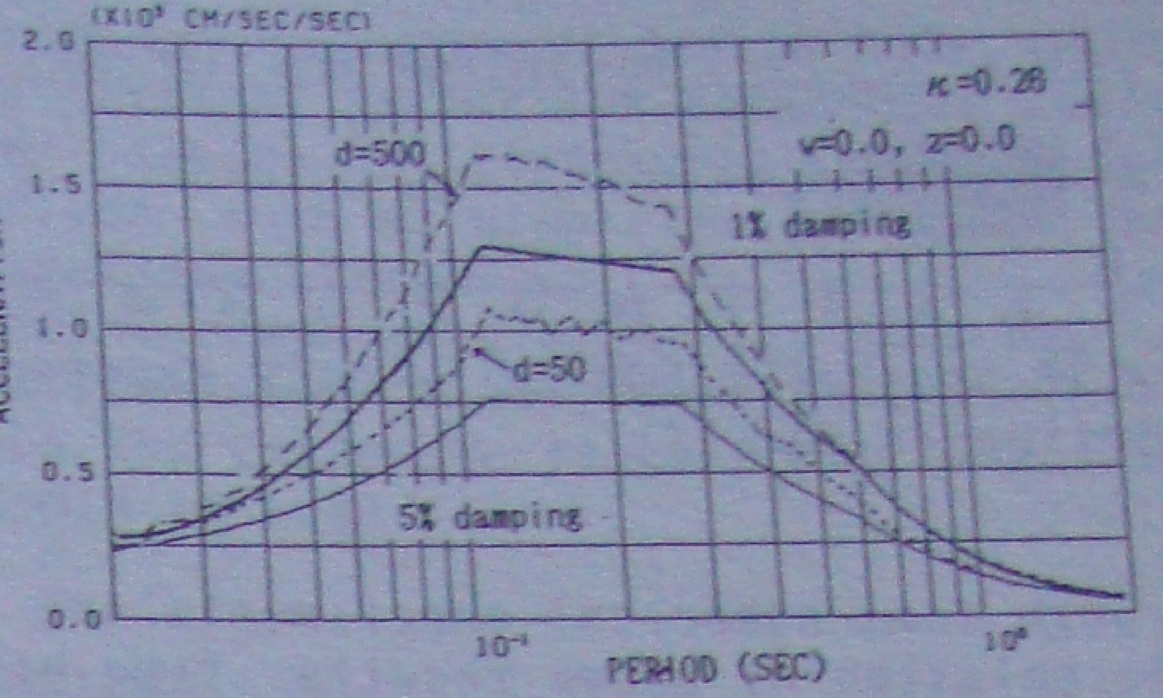

Fig.15 Effect of coefficient "d" to RSS(1)

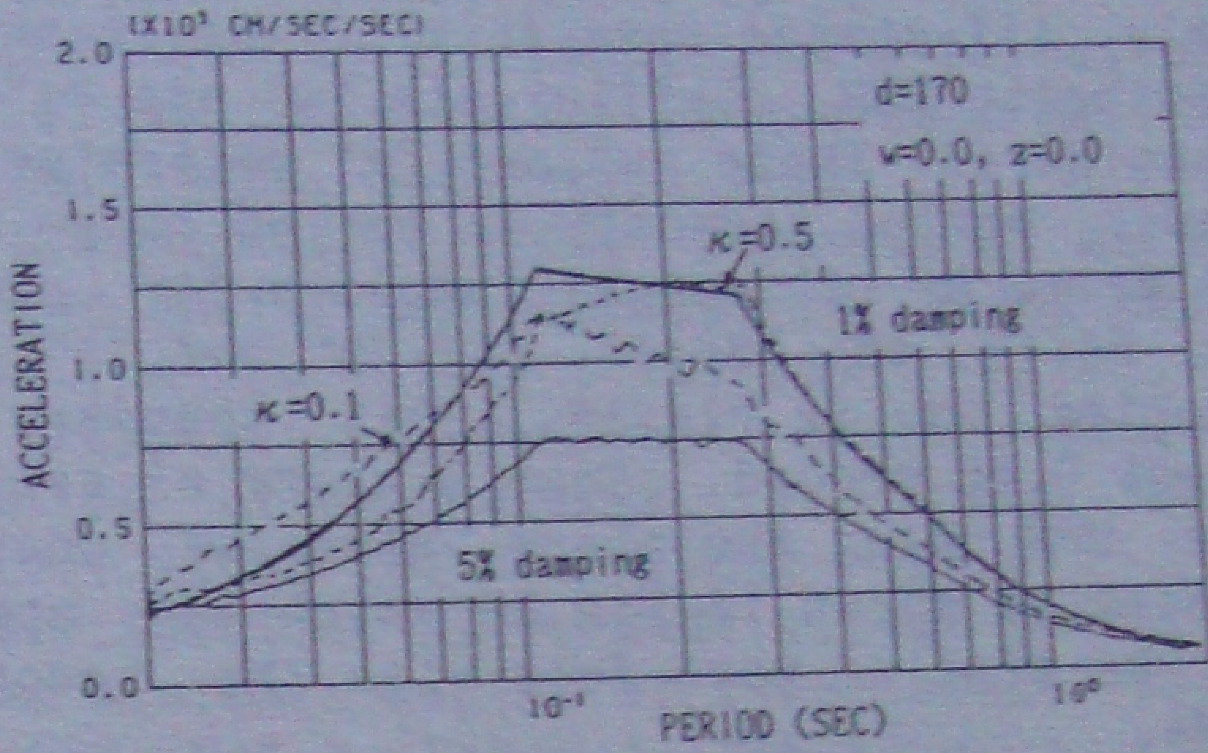

Fig.16 Effect of coefficient "κ" on RSS(1)

The effect to RSS(1) by variation of coefficient "d" is shown in Fig.15, in which the RSS(1) with d=50 becomes smaller than DRS(1) while the RSS(1) with d=500 larger.

The variation of coefficient "κ" governes the inclination of rather flat part in RSS(1) in Fig.16. AS shown in Fig.16, when "κ" is 0.5, the level of RSS(1) in shorter period range is smaller than DRS(1), while if "κ" is 0.1 the level of RSS(1) in longer peiord range is smaller than DRS(1).

Suitable values for "κ" and "d" to fit DRS(1) are finally found out as 0.26 and 170 respectively as shown in Fig.17

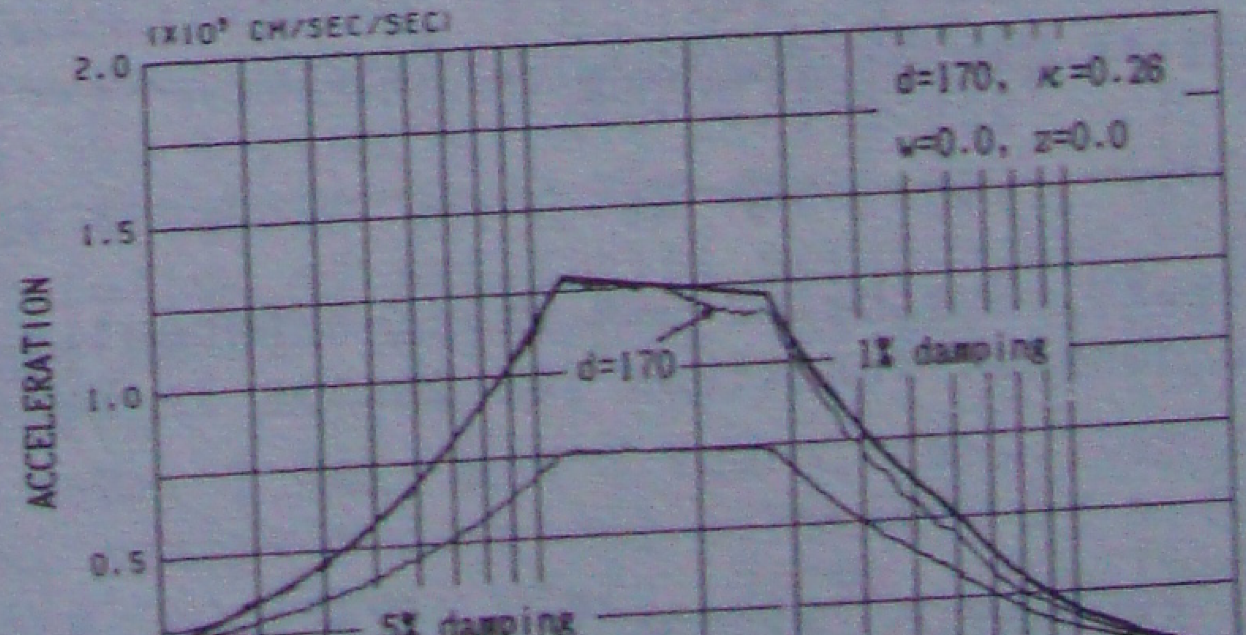

Fig.17 DRS(1) and RSS(1) due to synthetic EGM shown in Fig.18

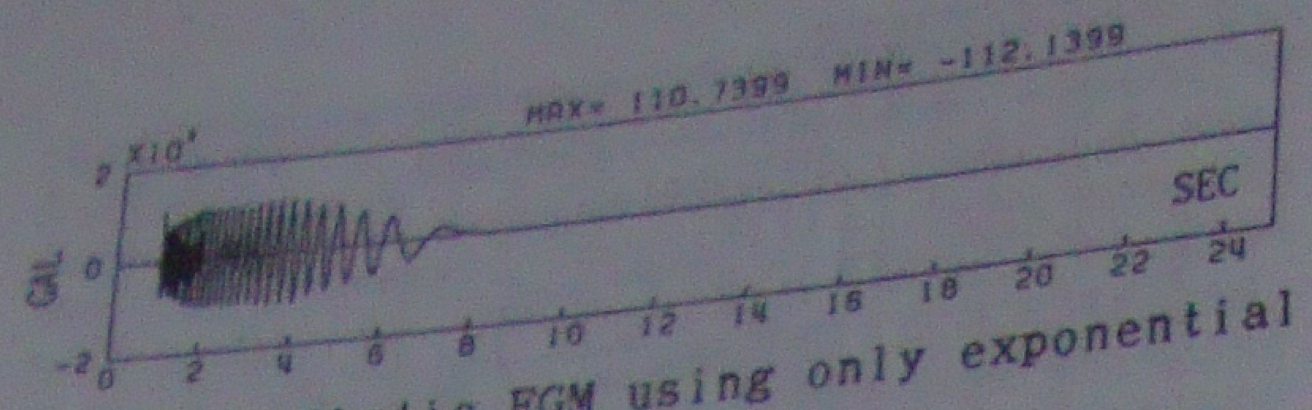

Fig.18 Synthetic EGM using only exponential function in Eq.(19)

through some numerical experiments and the interpolation of above results. Time history applied to these coefficients for synthetic EGM is shown in Fig.18, where the wave form is not so familiar as the one for ordinary recorded EGMs. In order to modify this ill-shaped wave form of the resulted synthetic EGM, coefficients "w" and "z" are considered. These "w" and "z" determine the lower period boundary in period range more affected by randomness function for phases in Eq.19 on RSS(1). If "w" and "z" are adopted as in Fig.19, this boundary is about 0.15 second. Time history of synthetic EGM using the above values of coefficients is shown in Fig.20 which may appear to be similar wave form with the recorded EGMs.

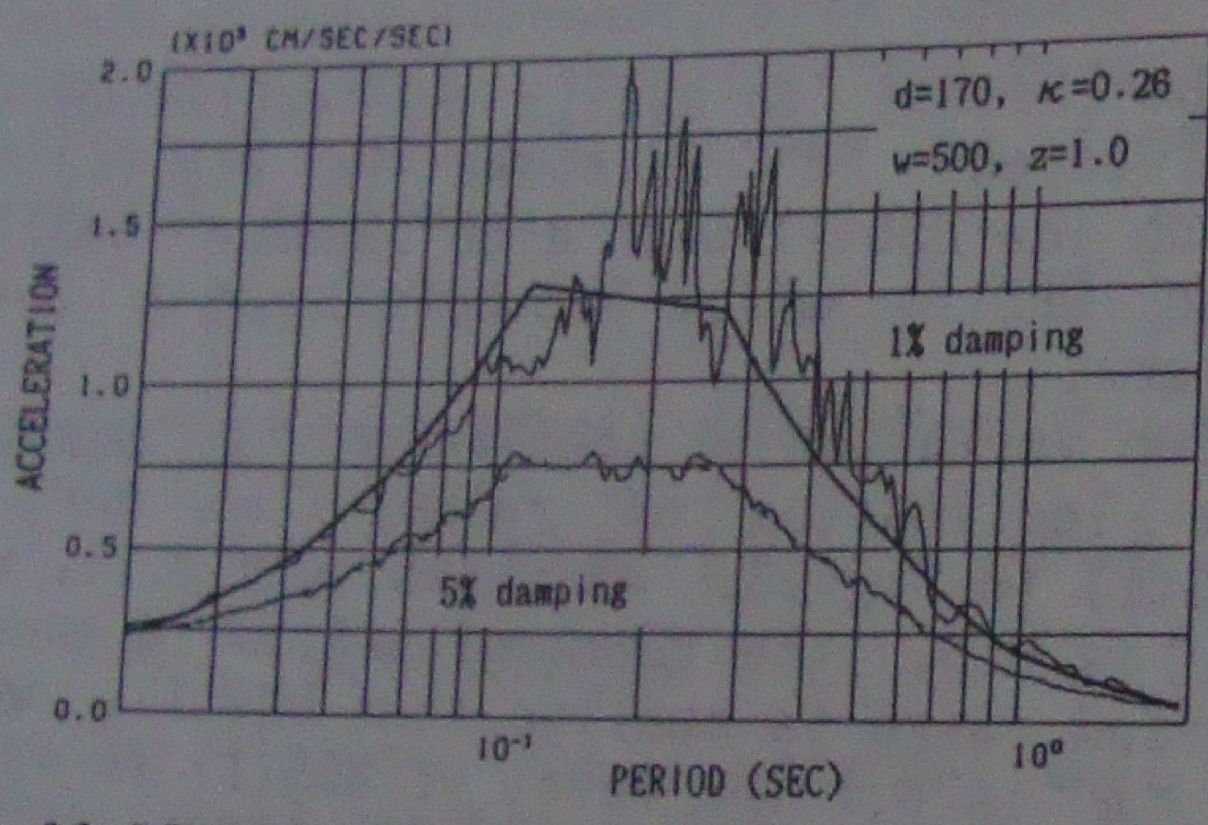

Fig.19 DRSs and RSSs due to final obtained synthetic EGM shown in Fig.20

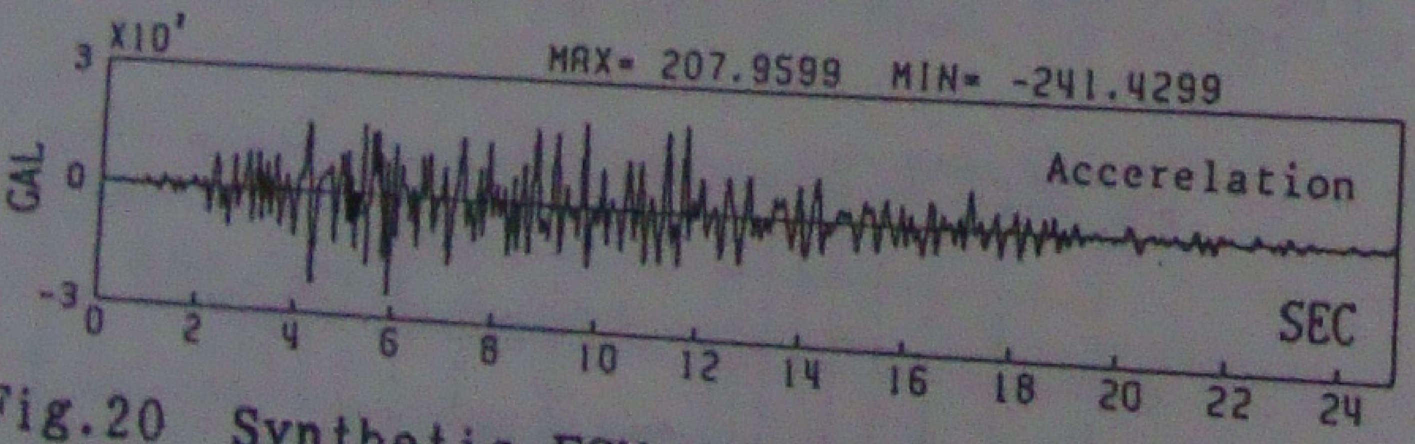

Fig.20 Synthetic EGM using exponential and randomness functions for phases in Eq.(19)

10 SYNTHETIC EARTHQUAKE GROUND MOTIONS USING FAULT MODEL

The characteristics of EGMs within the shorter periods than 2-3 seconds have been investigated with better accuracy on the basis of limited recorded strong EGMs from various point of views. However, the properties of EGMs with longer periods and especially of the surface waves caused by great earthquakes estimated by the above-mentioned studies might not be adequate for designing structures with longer periods. Fortunately, it is possible by the seismological investigations to evaluate the surface wave motions derived from the dislocation model of seismic faulting and the consideration of geological structures through which waves propagate.

In Japan, a great earthquake with magnitude of 8.0 class has been anticipated in Tokai district at the distance of 150-200 km in the south-west from Tokyo. Fig.21 shows the assumed fault model of Tokai earthquake by the dislocation of 4 meters and the rise-up time of 4 sec. Using these parameters, the surface wave motions in Tokyo was computed by the use of the fault model with the Lamb's theory for surface wave propagation. As for the body-wave motions by S-wave, the synthetic EGM appropriate to DRS (Ref.39) with the shorter period range was generated by the procedure

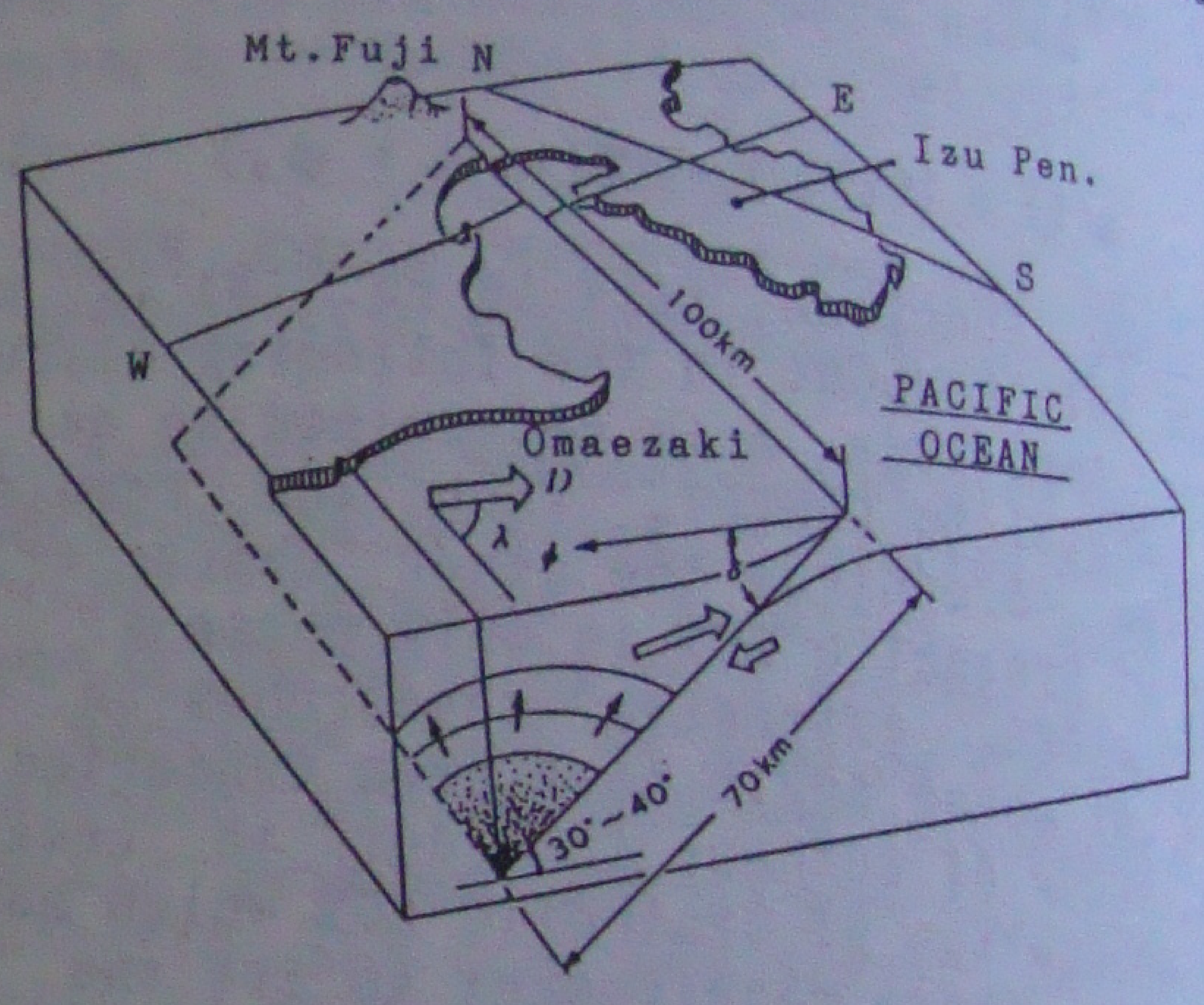

Fig.21 Fault model of Tokai earthquake

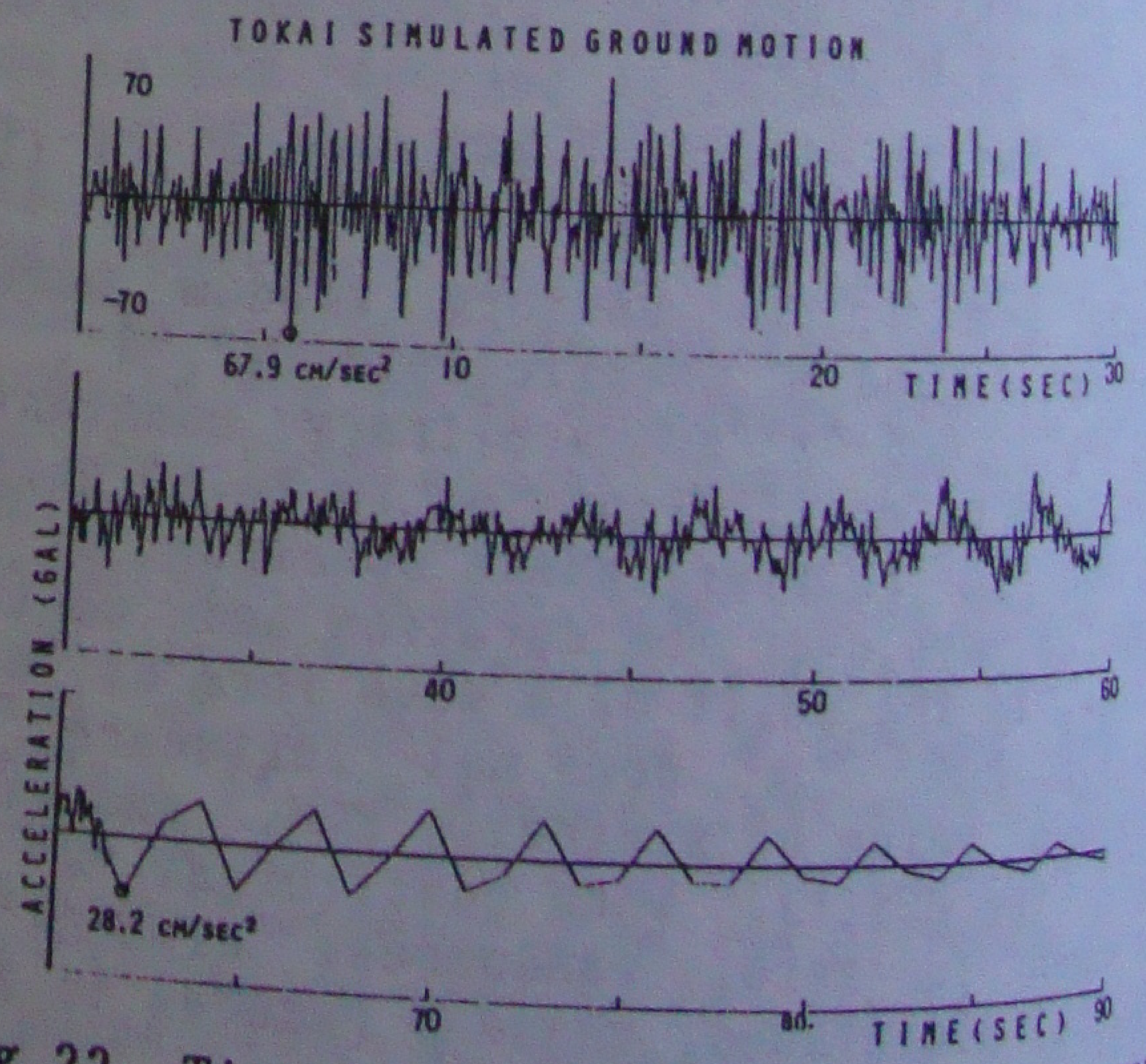

Fig.22 Time history combined surface wave by seismological approach with body wave

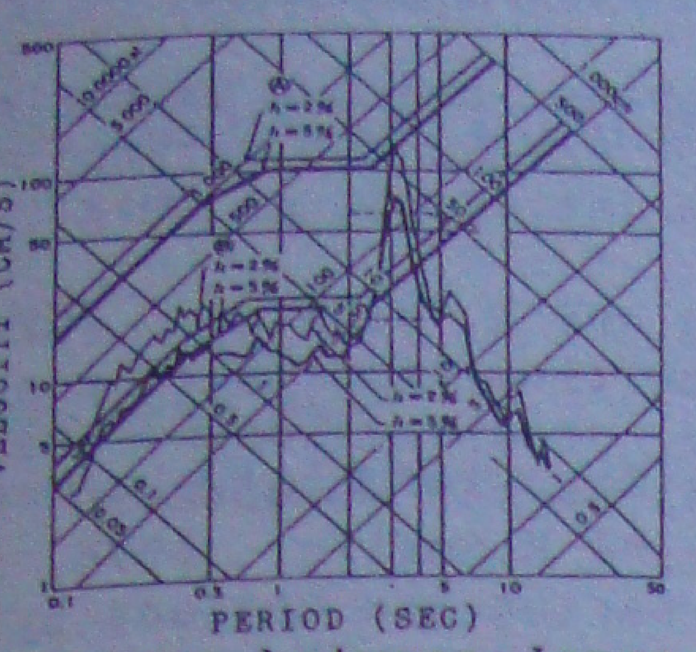

Fig.23 Comparison between Japanese seismic code and response spectra of synthetic EGM in Tokyo shown in Fig.22

introduced in Sec.7. The time history combined the surface wave with body wave considering the arrival time of each wave is shown in Fig.22. In this figure the former and the latter parts of the motion show the body and surface wave, respectively. The response spectra subjected to the motion are shown in Fig.23 in comparison with acceleration values equivalent to the design base shear coefficients illustrated in solid linear lines. The pair of upper linear lines (Ⓐ) indicate response values equivalent to the ultimate seismic capacities required by National Building Code in Japan for steel structures (thin line) and for the other structures (thick line), while lower pair (Ⓑ) are for elastic design. From these comparisons, it was pointed out that the surface wave due to Tokai earthquake may excite as large response nearly close to the ultimate state.

As is introduced, the synthetic EGM combined the theoretical approach by seismological way with the sinusoidal superposition procedure may be quite useful for practical engineering design purposes.

11 CONCLUSIONS

The procedure by the sinusoidal superposition method to generate synthetic EGMs may be regarded to be established at least in the domain of the linear response. Yet the following future tasks in this field may be pointed out.

1) Nonstationality property in frequency domain should be extensively investigated for practical use.
2) Research on the procedure to generate synthetic EGMs by establishing fault models which can be compatible with recorded EGMs in shorter period range should be more encouraged in order to be served for practical earthquake resistant design of the critical structures. This kind of research may contribute to the one on the longer period range of design EGMs, which are critical factor for earthquake resistant design of structures with longer periods such as high-rise buildings and suspension bridges.
3) Multi-components of design EGMs may be indispensable in very near future. Therefore the extensive research on this field should be urged.

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