SEISMIC RESPONSE ANALYSIS OF A GRAVITY DAM WITH JOINT TIME-FREQUENCY NON-STATIONARITY MODEL

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SUMMARY

Joint time-frequency analysis technique (JTFA) was employed to simulate strong earthquake ground motions in this paper. The non-stationarities of both intensity and frequency of strong ground motion were emphasised in seismic response analysis of gravity dams. As an example, the seismic response of Feng Man gravity dam located in the Northeast China was investigated. The importance of time-varying frequency characteristics to the seismic response of dam structures was obviously demonstrated.

INTRODUCTION

The seismic response of a structure is mainly determined by its dynamic characteristics and earthquake ground motions. Since the lack of recorded data and the randomness of earthquake ground motion, artificially generated seismic ground motions are traditionally used in structural design. Therefore, an important challenge in earthquake engineering is how to simulate the strong earthquake ground motions and provide reasonable earthquake accelerograms. Measured ground motions are shown as nonstationary time series. The nonstationary characteristics manifest in two ways. Firstly, the intensity of the ground acceleration varies with time. The time history normally divides into three phases: (1) after the arrival of the first seismic waves, it develops rapidly to a maximum value over several circles; (2) the intensity keeps a constant value approximately. This duration can be treated as a stationary process; and (3) the intensity tends to decrease slowly until it vanishes into background noise. Secondly, the frequency content varies with time, with a tendency to shift to lower frequencies as time increase. A successful design hinges greatly on how well the generated artificial waves represent the behaviour of seismic ground motions.

The current method to generate artificial seismic wave is

$$a(t) = f(t) \cdot x(t) \tag{1}$$

in which $f(t)$ is a deterministic absolute amplitude envelope function with a maximum value of 1, and $x(t)$ is a stationary random process with a power spectral density function $s(\omega)$. The equation above is traditionally called a uniform modulating random process, which describes a class of random processes with nonstationary intensity, but time-invariant frequency content. It means that the artificial seismic waves generated by (1) include the nonstationary amplitude attributes, but neglected the temporal change of the frequency content.

Meanwhile, it was commonly believed that the time-varying frequency characteristics are important for the inelastic response of structures. Recent research results in dam engineering field showed that the gravity dams presented non-linear character in strong earthquake motions. Thus, investigation of joint time-frequency nonstationary response for gravity dams is much significant.

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JOINT TIME-FREQUENCY NONSATATIONARITY MODEL

The detailed theory and applications of joint time-frequency analysis including the simulation procedure of strong ground motions are described in references [1] and [2]. Follows is a brief introduction of the main idea.

Since currently used earthquake ground motion model in (1) failed to account the time-varying nature of frequencies in seismic action, the evolutionary random process model was used [3], that is,

$$a(t)=\int_{-\infty}^{\infty} A(t,\omega)e^{i\omega t}dF(\omega) \tag{2}$$

in which $i=\sqrt{-1}$,and $A(t,\omega)$ is a deterministic frequency-time modulating function. It represents an absolute amplitude envelope of a seismic process. $dF(\omega)$ is a zero-mean, mutually independent, orthogonal increment process with

$$E[dF(\omega)]=0$$

$$E[dF^{*}(\omega_1)dF(\omega_2)]=\delta(\omega_1-\omega_2)S(\omega_1)d\omega_1 d\omega_2 \tag{3}$$

where $E[.]$denotes the ensemble average, $\delta(.)$ is the Dirac delta function, "$*$"stands for the complex conjugate, and $S(\omega)$ is the power spectral density function of $dF(\omega)$.

It is interesting to note that when $A(t,\omega)=f(t)$, (2) reduces to (1). In other words, (1) is a special case of (2). While (1) is limited to those processes whose frequency contents do not change with time, (2) can be applied in much more general cases, such as the time-varying frequency process.

In earthquake engineering applications, the frequency-time modulating function $A(t,\omega)$ only makes sense when it is real and non-negative, that is,

$$A(t,\omega)\in R \text{ and } A(t,\omega)\geq 0 \tag{4}$$

$A(t,\omega)$ determines only the shape of the intensity envelope (for different frequencies) of seismic ground motion if it is normalized as

$$\max_{for\,all\,t}[A(t,\omega)]=1\text{, for all given } \omega \tag{5}$$

while the amplitude (for different frequencies) of seismic ground motion is controlled by $S(\omega)$.

To make (2) suitable for generating artificial seismic waves for digital computers, in real applications the following discrete model [4] is used,

$$a(t)=\sum_{k=1}^{n} A(t,\omega_k)\sqrt{2S(\omega_k)}\cos(\omega_k t+\phi_k)\Delta\omega \tag{6}$$

where $\Delta\omega$ is the frequency increment, ω_k is the discrete frequency, and ϕ_k is the random phase with uniform distribution between 0 to 2π .

The evolutionary spectral density of $a(t)$ in (6) is given by

$$S(t,\omega_k)=A^2(t_1,\omega_k)S(\omega_k) \tag{7}$$

Obviously, the key point here is to estimate the function $A(t,\omega)$. In this paper, $A(t,\omega)$ is simply defined by the mean of seismic record time-dependent power spectra.

The adaptive chirplet signal approximation and adaptive spectrogram are model-based joint time-frequency analysis methods, For a given signal $s(t)$, the adaptive chirplet signal approximation is defined as [5]

$$s(t)=\sum_{k=0}^{K} p_k(t)+s_{K+1}(t) \tag{8}$$

Note that

$$s_0(t)\equiv s(t) \tag{9}$$

The function $p_k(t)$ is the regular chirp function with Gaussian envelope, i.e.,

$$p_k(t)=A_k e^{-\alpha_k(t-t_k)^2}\cos\left[\omega_k(t-t_k)+\frac{\beta_k}{2}(t-t_k)^2+\varphi_k\right] \tag{10}$$

Therefore, it is commonly known as the chirplet. The parameters (A_k , α_k , t_k , ω_k , β_k , φ_k) are chosen such that the mean square error between $p_k(t)$ and $s_k(t)$ is minimum. Numerical simulations indicate that by adaptive chirplet approximation, we can use fewer chirplet $p_k(t)$s to approximate seismic signals than in the case of either a Gabor expansion or wavelet representation. This implies that the chirplet fits the seismic signal better than the other schemes.

Applying the Wigner-Ville distribution, we can further derive the adaptive spectrogram (AS), i.e.,

$$AS(t,\omega)\approx\sum_{k=0}^{K}\frac{2\pi}{\alpha_k}(A_k)^2 e^{-\alpha_k(t-t_k)^2-[\omega-\omega_k-\beta_k(t-t_k)]^2/\alpha_k} \tag{11}$$

Obviously, it is real and non-negative because $\alpha_k > 0$. In particular, due to higher time-frequency resolution, we chose the adaptive spectrogram to represent the seismic signal energy distribution in the joint time-frequency domain. Fig. 4 illustrates an adaptive spectrogram of the time sequence in Fig. 2. Apparently, the frequency contents of a seismic signal change with time.

To obtain the frequency-dependent modulating function $A(t,\omega)$, the following normalization process is performed,

$$A(t,\omega_k)=AS(t,\omega_k)/\max_{for\ all\ t}[AS(t,\omega_k)],\ k=1,2,\dots \tag{12}$$

NONLINEAR ANALYSIS OF GRAVITY DAM WITH CONTACTION JOINTS

It is known that gravity dams are not integrally cast concrete structures but rather consist of a series of monoliths. The contaction joints between two monoliths. Grout is poured into these joints when the dam temperature reaches its design value. Normally, the tensile strength of this grout is much lower than the dam concrete. The joints formed by this grout are compressed under the static loading. However, this compression can be neutralised by the superposed tensile loading when an earthquake occurs, so that strong seismic loading will separate the joints due to the grout being unable to withstand the large tensile stresses. Dynamic contact of such separated joint surfaces causes the response of dam to be non-linear. Therefore, it is reasonable to design and analyse high gravity dam using non-linear mechanism even though the main parts of the dam concrete retain their linear characteristics under strong earthquake.

The factors contributing to the non-linearity of the joints are generally summarised as (1) opening and closing of the joints; (2) compression of the joint surfaces; and (3) sliding between the joint surfaces. Many research has focused on constitutive models of the joints and on computational codes. The contactor-target contact model [6] is adopted herein. According to the model, one surface of a joint is defined as the active contactor and another surface is target. The basic assumption for the contaction equation is: (1) there are no embedment between two surfaces; (2) the contaction force on the two surfaces are the same magnitude but opposite directions; and (3) Coulomb’s friction law is used to analyse the contaction of sticking, frictional sliding and separation situations.

The contaction equation was derived by variation principle, that is

$$\delta\Pi_m = \delta\Pi - \delta\Pi_c = 0 \tag{13}$$

in which $\delta\Pi_m$ is the variation of modified potential. It meets the compatible condition for surface deformation by applying Lagrange multipliers. $\delta\Pi$ is the variation of the potential without contact conditions. It derives the motion equation. $\delta\Pi_c$ is the supplemental item including contact conditions. It derives the contaction equation. The contact conditions control the iteration procedure in computation. ADINA non-linear finite element program is used in response analysis of Feng Man gravity dam.

SIGNIFICANCE OF NONSTATIONARY FREQUENCY CHARACTERISTICS TO FENG MAM GRAVITY DAM

In this paper, we select 11 seismic waves of San Fernando earthquake as samples and apply adaptive algorithm of joint time-frequency technique to extract full non-stationary information. The artificially generated seismic waves based on (1) and (2) are shown in Fig. 1 and Fig. 2. The adaptive spectrograms of seismic waves are also illustrated in Fig. 3 and Fig. 4. Compared to the time series in Fig.2, it is obvious that the artificial waves generated by (2) are much closer to the real seismic data than those based on (1). Essentially, there is no frequency change in Fig. 1 because the artificial seismic waves are based on (1). Moreover, (2)-based artificial seismic waves in Fig. 2 clearly show that the time series start with high frequencies and are gradually dominated by low frequency. Significant improvement is reached by preserving the non-stationary frequency feature in the artificial seismic waves.

The artificial seismic waves shown in Fig. 1 and Fig. 2 are used as earthquake ground motions in computing seismic responses of Feng Man gravity dam. Feng Man, an aged dam in Northeast China, was constructed in 1937. The dam height was 90.5m. The storage of the dam was $108\times10^8\ m^3$. Dam safety is much concerned by engineers and researchers in the recent year. In this study, 3 joints are simulated on the dam as shown in Fig. 9. The initial width of the contaction joints is assumed to be 4.0 mm. The maximum ground acceleration is 0.161g. The static and dynamic loadings of the dam include dam gravity, water and soil pressure, and seismic force. The calculated response acceleration histories on dam top are illustrated in Fig. 5 (based on (1)) and Fig. 6 (based on (2)), respectively. It is found that the response acceleration histories are similar in the first 10 seconds. Then, the response acceleration based on (2) keeps larger than that of based on (1). The average incremental is 25%, approximately. Fig. 7 and Fig. 8 are the joint motion histories based on (1) and (2), respectively. It is clear that the relative displacements between a joint surfaces based on (2) are also larger than that of based on (1). Furthermore, the joint opens more frequently as shown in Fig. 6. This phenomenon reminds designers that the evaluation of dam safety based on (1) may be not reliable enough. The reason why the response accelerations are much larger after peak acceleration excitation is the artificially seismic waves based on (2) contain more low frequency contents. When joints open under the strong ground motion, the fundamental frequency of the gravity decrease. The larger the intensity of the excitation, the larger the response of the dam. Meanwhile. the joints also open more wilder and more frequently. This causes the fundamental frequency of the dam lower and coincide with the low frequency contents of the earthquake ground motion, and makes the seismic response of the dam remains relatively large even the peak acceleration of ground motion is already passed.

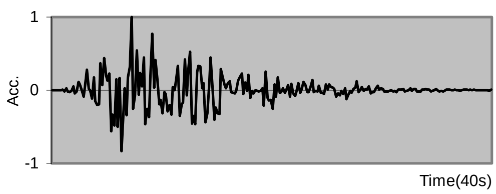


Fig. 1 Artificial Seismic Wave Based on (1)

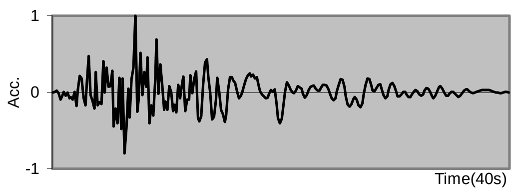
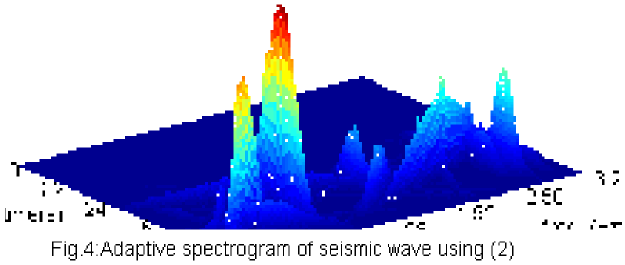


Fig.2 Artificial Seismic Wave Based on (2)



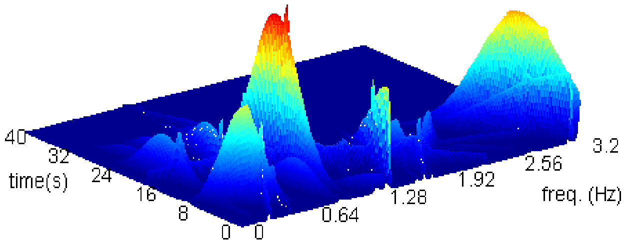


Fig. 4 Adaptive Spectrogram of Seismic Wave Based on (2)

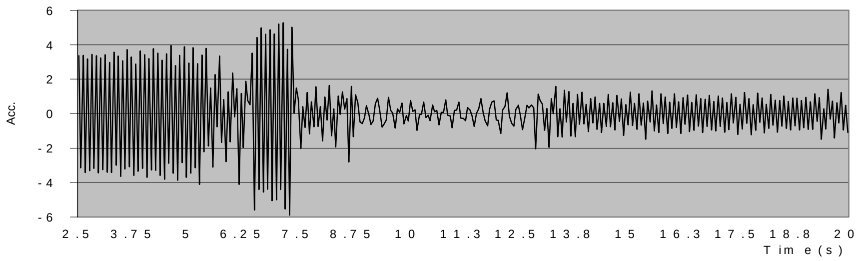


Fig. 5 Response Acceleration History on Dam Top Based on (1)

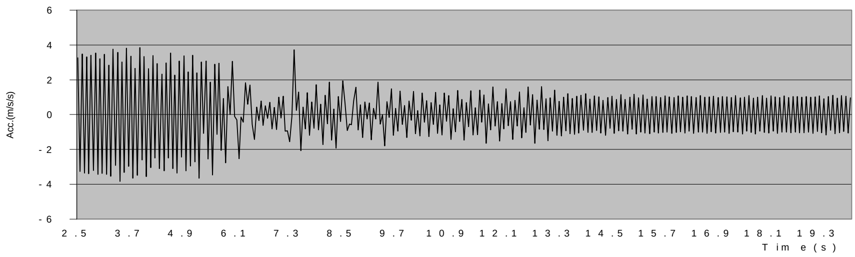
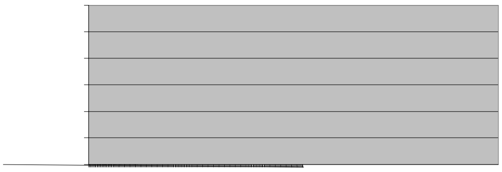


Fig. 6 Response Acceleration History on Dam Top Based on (2)



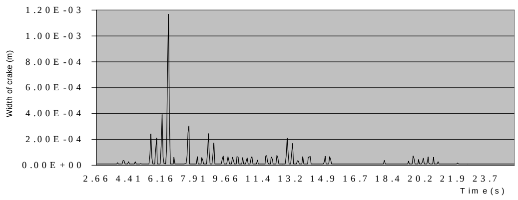
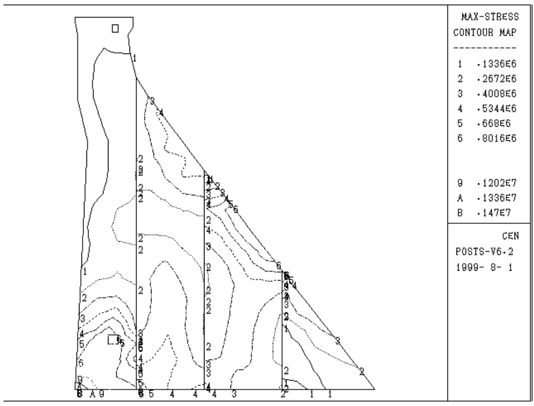


Fig. 7 Joint Motion Based on (1)

Fig. 8 Joint Motion Based on (2)



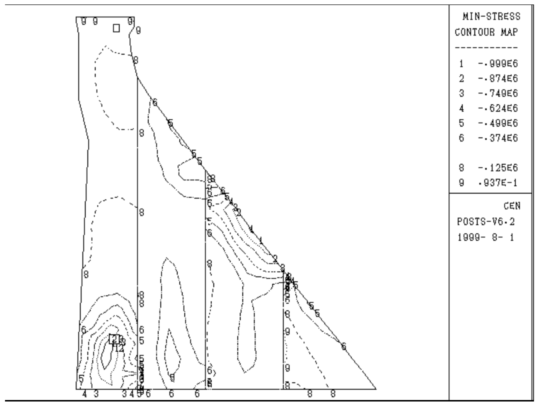


Fig.9:Max.Principle Stress Envelop of Dam

Fig.10:Min.Principle Stress Envelop of Dam

CONCLUSIONS

1. Chirplet adaptive spectrogram is ideal to extract the joint time-frequency information of seismic wave exactly and value in time. The artificial seismic waves reserve the intense and frequency nonstationarity of natural waves.

2. The dynamic response of Feng Man gravity dam is obviously different when it is excited by the seismic wave generated from (1) and (2). The dynamic response based on (2) is greater than that of (1). Because the seismic waves based on (1) and (2) with the same characteristics in intensity nonstationarity, the difference of dynamic response lies in the frequency nonstationarity.

3. The nonstrationary frequency characteristic of seismic ground motion may have important effects on the non-linear response of dam structures. It is unreliable to evaluate the dam safety without analysing the full nonstationarity of earthquake ground motions.

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