# The Synthesis and Correction of Simulated Earthquake Wave

**NIU Zhiguo[1,2] , LI Tongchun[2] and HU Shaowei[1]**

[1] *Department of Materials and Structural Engineering, Nanjing Hydraulic Research Institute Nanjing，China*
[2] *College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing，China*
*Email: nzg_197901@163.com, niuzhiguo@yahoo.cn*

**ABSTRACT :**

In order to obtain the earthquake waves that satisfied with engineering specification, the method for the synthesis of simulated earthquake wave with time-frequency, based on hydraulic design response spectrum, is introduced in the seismic design of hydraulic structure. Because of the remaining long period components, the integrated displacement data, by double integral of the acceleration history of the simulated earthquake wave, have great baseline shift from the true one. Least square method is used in this paper to simulate average value of the acceleration history. By this method, the shift is corrected. Finally, in connection of actual project of Xiluodu arch dam，the simulated earthquake wave is synthesized and adjusted, the result shows that the method is simple and easy to grasp, has high precision.

**KEYWORDS:** simulated earthquake wave; design response spectrum; baseline shift; least square method

## 1.INTRODUCTION

China lies between the large active seismic belts in the world and is a country of high seismicity. Based on the historical records, destructive earthquakes have occurred many times in every province of china. Earthquakes in china are mostly of shallow focal depth, high magnitude and have a wide distribution as well as a high frequency of occurrence. So the country deeply suffered from earthquake disaster.

China is also a country rich in hydropower resources. Abundant hydropower potential, about 80%of the national total, is concentrated in the south west and northwest of China; however, this region is well known for its high seismic intensity and frequency of occurrence. Recently a series of critical hydropower projects with dams of 300m high are now being under construction and will be constructed in the regions. The problem in seismic resistance design of hydropower projects is especially prominent [Chen Houqun,2006]. The artificial earthquake wave compatible with the design response spectra is indispensable for the seismic design and dynamic model test of hydraulic structures. The method for the generation of artificial ground motions is briefly introduced. Aiming at the problem of baseline drift in the time history of displacement of seismic integration, an effective time domain corrector method is proposed in this paper.

## 2. SYNTHESIS OF SIMULATED EARTHQUAKE WAVE

Ground motions can be simulated by multiplying a deterministic envelope function to a stationary time history, such as

$$a(t) = f(t) \cdot a_s(t) \tag{2.1}$$

Where *f(t)* is a deterministic envelope function , The time intensity function used is of the form

$$f(t)=\begin{cases}(t/t_1)^2 & t<t_1\\ 1 & t_1\le t\le t_2\\ \exp(-c(t-t_2)) & t_2<t\le t_3\end{cases}$$

$c$ is attenuation coefficient; $t_1$,$t_2$ and $t_3$ are time control points.
$a_s(t)$ is a Gaussian stationary random process； It can is given by

$$a_s(t)=\sum_{0}^{N}C_k\cdot\cos(\omega_k t+\varphi_k) \tag{2.2}$$

Where $\varphi_k$ is the phase angle which distributes randomly in range $\left(0,2\pi\right)$; $C_k$ is amplitude of trigonometric series and can be obtained by traditional formulas shown as following:

$$S(\omega_k)=\frac{\xi}{\pi\omega_k}\cdot\left[S_a^T(\omega_k)\right]^2\cdot\frac{1}{\ln\left[\dfrac{-\pi}{\omega_k T}\ln(1-P)\right]} \tag{2.3}$$

$$C_k=\left[4S(\omega_k)\cdot\Delta\omega\right]^{1/2} \tag{2.4}$$

$$\Delta\omega=2\pi/T_d\,,\quad \omega_k=\Delta\omega\cdot K\quad ,\ (K=1,2,3\cdots\cdots N)$$

Where $S_a^T(\omega_k)$ is the target acceleration response spectra； $\xi$ is damp ratio，$P$ is exceeding probability，$P\leqslant 15\%$； $S(\omega_k)$ is acceleration power spectrum density function of Gaussian stationary random process； $T_d$ is the total duration of the random process $a(t)$; $N$ is the number corresponding to the cut-off frequency [Du XiuLi，Chen Houqun ,1994 ].

In general，the interation method using both the power and amplitude spectra is applied in order to get a simulated earthquake wave well to fit a target response spectra [Zhai Ximei, Wu Zhifeng ,1995].

## 3. LEAST SQUARE CORRECTION

Ground motions simulated by the above method usually yield satisfactory results. However the integrated displacement data, by double integral of the acceleration history, has great baseline shift from the true one because of the remaining long period components. If the wave is used to study on viscous-spring boundary in the seismic analysis of high concrete dams, the results will have great error [Fan Mingliu, Huang Runqiu,2000].Based on a series of investigations have been widely seen in some literatures, a simple method to eliminate long period components and correct baseline drift in the time history of displacement is proposed in this paper.

### *2.1. no-zero baseline*

Comparing with some fitting average value lines of displacement histories, the quadric polynomials fit well because the displacement point is uniform distribution in both sides of the average value line and the order of polynomials is low, i.e.,

$$\bar{s}(t) = a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 \qquad (2.5)$$

Where $\bar{s}(t)$ is the fitting average value lines of displacement history，Considering integral relations of acceleration, velocity and displacement, the average value lines of velocity and acceleration history can be expressed as:

$$\bar{v}(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 \qquad (2.6)$$

$$\bar{a}(t) = a_2 + 6a_3 t + 12a_4 t^2 \qquad (2.7)$$

Because the initial value of velocity histories is zero, the coefficient $a_1$ also is zero; Eqn.2.7 is the expression of no-zero baseline. If the order of polynomials is high, the calculation for baseline becomes very tedious. Moreover, because the remaining long period components cause the baseline shift from the true one and the quadratic polynomial can filtrate the long period components which periods are twice the duration of the acceleration history. To subtract no-zero baseline from the original acceleration history can avoide the phenomenon of the evidently shifted baseline existed in the corresponding displacement history [Li Janbo, Chen Jianyun and Lin Gao,2004].

### *2.2. baseline correction*

Suppose that $\bar{a}(t) = a_0 + a_1 t + a_2 t^2$ is a no-zero baseline of the acceleration history, the acceleration history is given as

$$(t_i,\ g_i)\ (i=0,1,2,3,\cdots,n) \qquad (2.8)$$

Then the deviation and least square of every discrete point are expressed as follows:

$$u_i = a(t_i) - g_i \qquad (i = 1, 2, 3, \cdots, n) \qquad (2.9)$$

$$(\sum_{i=1}^{n} u_i^2)_{\min} = \sum_{i=0}^{n} \left[a(t_i) - g_i\right]^2 = \sum_{i=0}^{n} \left[a_0 + a_1 t_i + a_2 t_i^2 - g_i\right]^2 = \varphi(a_0, a_1, a_2)$$
$$(i = 1, 2, 3, \cdots, n) \qquad (2.10)$$

In fact, the question how to determine the form of $\bar{a}(t) = a_0 + a_1 t + a_2 t^2$ is equivalent to solute the minimal point $(a_0^*, a_1^*, a_2^*)$ of $\varphi(a_0, a_1, a_2)$， in term of multivariate function differential calculus, it is evident that $a_0^*, a_1^*, a_2^*$ satisfied with this equations, as follows：

$$\begin{cases} \dfrac{\partial \varphi}{\partial a_0} = 2\sum_{i=1}^{n}\left[a_0 + a_1 t_i + a_2 t_i^2 - g_i\right] = 0 \\ \dfrac{\partial \varphi}{\partial a_1} = 2\sum_{i=1}^{n} t_i\left[a_0 + a_1 t_i + a_2 t_i^2 - g_i\right] = 0 \\ \dfrac{\partial \varphi}{\partial a_2} = 2\sum_{i=1}^{n} t_i^2\left[a_0 + a_1 t_i + a_2 t_i^2 - g_i\right] = 0 \end{cases} \quad (2.11)$$

The Eqn. 2.11 can be changed as

$$\begin{cases} (n+1)a_0 + (\sum_{i=1}^{n} t_i)a_1 + (\sum_{i=1}^{n} t_i)a_2 = \sum_{i=1}^{n} y_i \\ (\sum_{i=1}^{n} t_i)a_0 + (\sum_{i=1}^{n} t_i^2)a_1 + (\sum_{i=1}^{n} t_i^3)a_2 = \sum_{i=1}^{n} t_i y_i \\ (\sum_{i=1}^{n} t_i^2)a_0 + (\sum_{i=1}^{n} t_i^3)a_1 + (\sum_{i=1}^{n} t_i^4)a_2 = \sum_{i=1}^{n} t_i^2 y_i \end{cases} \quad (2.12)$$

Let $S_k = \sum_{i=1}^{n} t_i^k$ , $f_j = \sum_{i=0}^{n} y_i x_i^j$ （$k = 0,1,2,3,4$ , $j = 0,1,2$） (2. 13)

Substituting Eqns.2.13 into 2.12 leads to

$$\begin{cases} S_0 a_0 + S_1 a_1 + S_2 a_2 = f_0 \\ S_1 a_0 + S_2 a_1 + S_3 a_2 = f_1 \\ (S_2 a_0 + S_3 a_1 + S_4 a_2 = f_2 \end{cases} \quad (2.14)$$

When the equations are solved， the values of $a_0$, $a_1$ and $a_2$ can be obtained.

## 3.EXAMPLE

Xiluodu hydropower station, the gigantic one on Jinsha River with installed capacity 15GW, has multiple purposes of flood control, sediment retention, improving downstream navigation and others besides power generation. By the above method of simulated earthquake wave, the initial acceleration history is easily synthesized based on hydraulic design response spectrum, as shown in figure.1. According to least square principle, the no-zero baseline can be obtained; that is,

$$\bar{a}(t) = -0.00841239 + 0.00084661t + (-2.4609158 \times 10^{-5})t^2$$

Subtract the no-zero baseline from the initial acceleration history, namely the modified acceleration history may be expressed as follows:

$$a(t) = g(t) - \bar{a}(t) \quad (2.15)$$

Further, the modified displacement and velocity history in term of theorem of the integral calculus, shown in figure.2~11.

From figure.2~11, we can see that:

(1) Least square correction of the simulated earthquake wave dose not have significant influence on velocity and acceleration history, this shows the method only filters out the low-frequency signal. However, the baseline shift be effectively corrected.

(2) In the Fourier spectra of view, the periodic components of more than 15s are obviously decreased after the simulated earthquake wave is corrected, but this does not change the characterization of the Fourier spectra.

(3)In the acceleration response spectra of view, the values corresponding to periodic components of 1.2~3s are changed and the changes are very small.

Therefore, least square correction dose not influence on the waveform and spectra of the simulated earthquake wave.

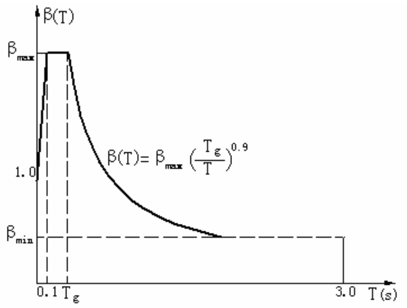


Figure 1 Hydraulic design response spectra

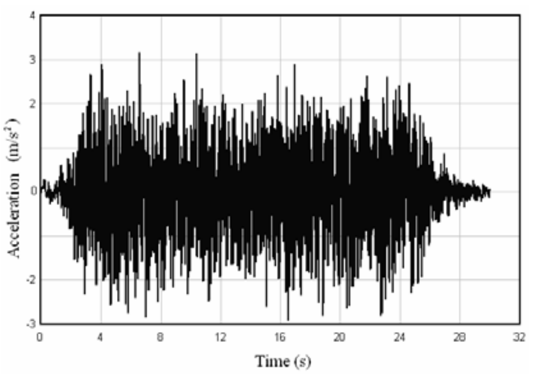


Figure 2 The initial acceleration history

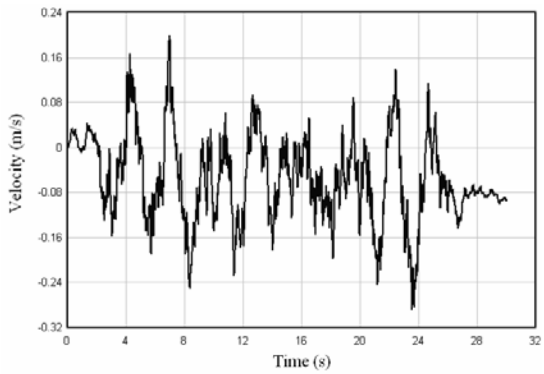


Figure 3 The initial velocity history

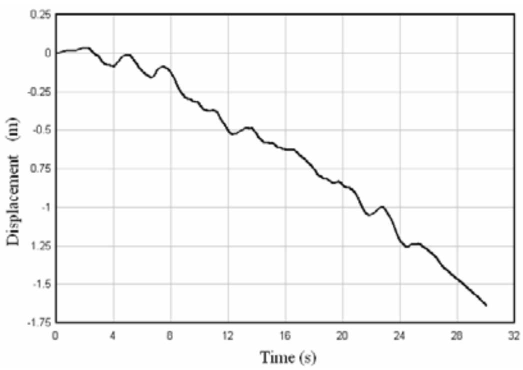


Figure 4 The initial displacement history

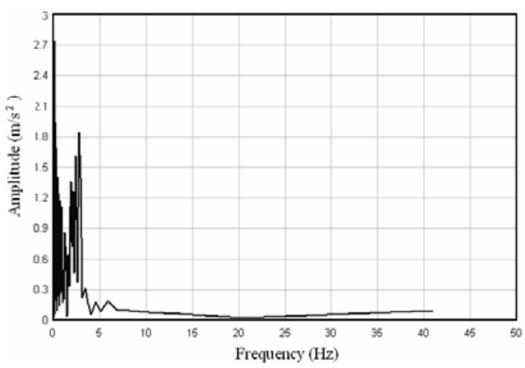


Figure 5 The Fourier amplitude spectra

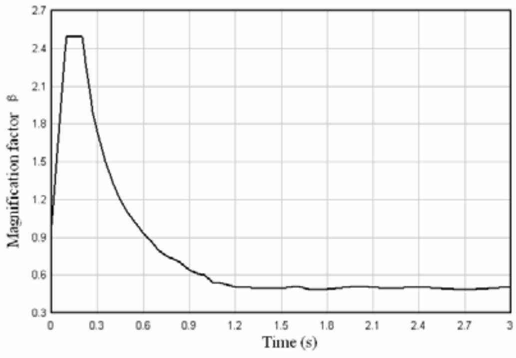


Figure 6 The response spectrum

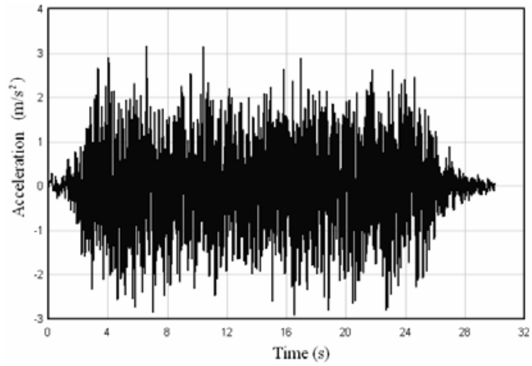


Figure 7 The acceleration history obtained by modifying the initial wave

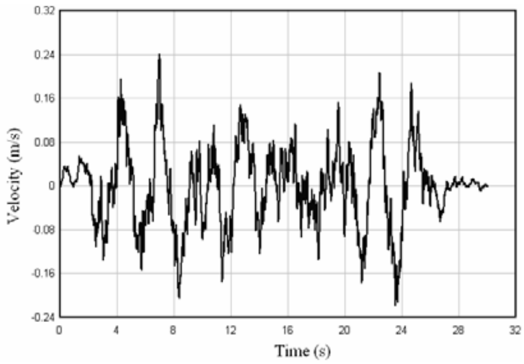


Figure 8 The velocity history obtained by modifying the initial wave

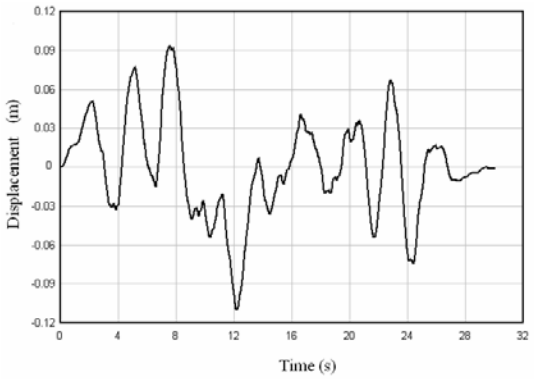


Figure 9 The velocity history obtained by modifying the initial wave

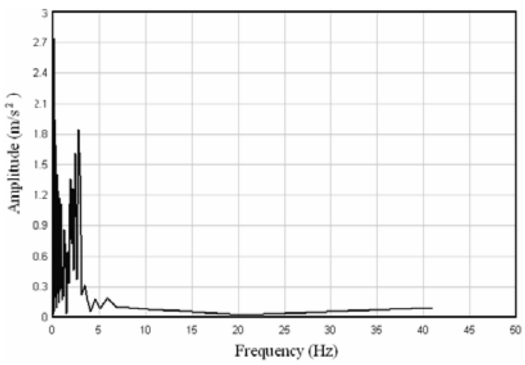


Figure 10 The response spectra obtained by modifying the initial wave

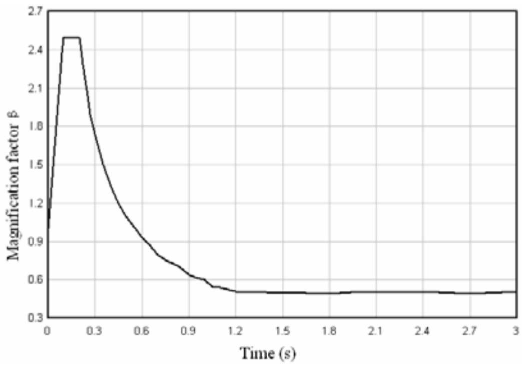


Figure 11 The Fourier amplitude spectra obtained by modifying the initial wave

## 4. CONCLUSION

In this paper, the method of simulated earthquake wave ,according to hydraulic design response spectrum ,are produced in the seismic design of hydraulic structure; Least squares method is used in this paper to simulate average value of acceleration [Guo Zixiong,Wang Miaofang ,1994]. By this method, the simulated earthquake wave is adjusted and the shift is corrected, the method has following features:

(1) The least square curve fitting method can effectively improve the integral property of acceleration data with little change in the content of the spectrum characteristics.

(2) The correction method for baseline shift did not affect the natural integral relationship of displacement, velocity and acceleration; this will be beneficial to keep the numerical stability of dynamic calculations of structures.

## REFERENCES

Chen Houqun (2006). Progress in Seismic Aspects of Dams in China.*100th Anniversary Earthquake Conference.*

Du XiuLi，Chen Houqun (1994). Random Simulation and Its Parameter Determination Method.*Earthquake Engineering and Engineering Vibration* **14:4**,1-12.

Zhai Ximei, Wu Zhifeng (1995). Improvement in the Fitting Technology Earthquake of Response Spectra for Simulated Wave. *Journal of Harbin Institute of Technology* **27:6,**130-133.

Fan Mingliu, Huang Runqiu (2000). Analysis of Compution Errors in Synthesizing Artificial Ground Motion.*Journal of Engineering geology* **8:3**,369-373.

Li Janbo, Chen Jianyun and Lin Gao (2004). Study of long-period correction of seismic accelerogram for dynamic interaction analysis. *Journal of Dalian University of Technology* **44:4**,551-552.

Guo Zixiong,Wang Miaofang (1994). State of the Art and Prospect of Artificial Ground Motion.*Journal of Huaqiao University* **27:1**,8-9.