Generation of design ground motion time histories for the Lianyungang Nuclear Power Plant

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ABSTRACT: This paper presents an iteration scheme for the design of a stochastic model which will generate artificial ground acceleration time histories fitting to pre-determined ground response spectra. The scheme is applied on earthquake data at the, to be constructed, Nuclear Power Plant in Lianyungang, China.

1 INTRODUCTION

Ground accelerations during strong-motion earthquakes are generally extremely irregular, resembling random time functions; however, these irregularities show some common features. The motion is highly oscillatory and aperiodic, it is initiated with small amplitudes that rapidly build up until they reach an intensity that remains almost stationary for a certain time and then decay, steadily, until the end of the record. The purpose of this investigation is the design of a stochastic model that will generate artificial ground acceleration time histories fitting to pre-determined ground response spectra. The target site of the time history generation is the Lianyungang Nuclear Power Plant (four Russian 1000 MWe PWRs) site in China. The time histories will be generated to fit High-order Ambiguity Functions (HAF 0101 (1) target spectra) for ground motion. The damping coefficients to which the spectra are fitted are 2%, 4%, 5% and 7%.

In Sec. 2, the Lianyungang site will be briefly described, followed by Sec.3 on shot noise models for ground motion simulation (following Lin (1967) and Ruiz and Penzien (1969)). Sec. 4 describes the methods to generate time histories which spectrum matches a target response spectrum with a single damping coefficient (Housner (1969) and Gasparini and Vanmarcke (1976)). The target response spectra however are normally described in codes for several damping coefficients. In Regulatory Guide 1.60 (US Atomic Energy Commission, 1973), the given spectra are for 0.5, 2, 5, 7 and 10% damping. In HAF 0101 (01) the design spectra are given for damping coefficients of 0.5, 2, 3, 4, 5, 7 10, and 20% (Contract LYGNPP, 1997). The generation of synthetic time histories whose response spectra closely match the HAF 0101 target design spectra for multiple damping is the task to be described in Sec. 5. The approach is based on Lilhanand and Tseng, (1989). Sec. 6 contains conclusions, followed by a list of references.

2 LIANYUNGANG TO BUILD NUCLEAR POWER PLANT

Construction of a nuclear plant in Lianyungang, a port city in coastal Jiangsu Province, east China (Fig. 1), has started in October 2000. According to a contract on the design and technology service for the Lianyungang Nuclear Plant here recently, this will be China's sixth nuclear power project, which will be built jointly by China and Russia. The plant is scheduled to have four 1,000,000-kilowatt power generating units. The first phase includes construction of two 1,000,000 kw Russian AES-91 pressurized water reactors with a combined investment of 3.2 billion US dollars. One unit is expected to go on stream within 62 months and the other a year later. The Jiangsu Nuclear Power Company Ltd. will be responsible for the whole project.

Furthermore, Jiangsu has the largest thermal power plant in China, Jianbi Power Plant. A number of power generating units of over 300,000 kw have been installed in recent years. The total installed generating capacity of generators above 500 kw amounted to 15. 8 million kw.

Figure 1. Map of China; Lianyungang is located appr. 500km north of Shanghai.

Earthquakes in China are described by Lee et al., (1976).

3 SHOT NOISE MODEL FOR GROUND SIMULATION

The random fluctuations observed in records of strong-motion earthquakes usually follow general patterns that can be used in the design of a stochastic model to simulate their effect. They begin with small amplitudes, which increase in time until the stronger shocks occur. When the main shocks are over, the amplitudes decay steadily until the motion ends. It is also observed that real earthquakes do not show components in every frequency. Rather they show predominant frequencies within a relatively narrow hand. Earthquakes recorded on firm soil at moderate epicentral distances show predominant frequencies in the range of 2-5 Hz. These characteristics have led investigators to design various types of stochastic processes for the generation of pseudo-earthquakes.

3.1 *Filtered white noise*

The power spectral density function of filtered white noise can be written in form

$$S_x(\omega) = S_0|H(i\omega)|^2 \tag{1}$$

In Eqn. (1) $H(i\omega)$ is the complex frequency response function of the filter and S_0 is the power spectral density of the white noise excitation. For a second order linear filter, the power spectral of the output process becomes

$$S_y(\omega) = S_0\,(1 + 4\zeta^2\omega^2/\omega^2)/((1-\omega^2/\omega_0^2)^2 + 4\zeta^2\omega^2/\omega_0^2) \tag{2}$$

3.2 *Shot noise model*

The shot noise model appropriate for ground motion simulation is obtained by filtering a shot noise through a second order linear filter. Both the filter and the shot noise is selected so that relevant features of strong-motion records at moderate epicentral distances.

3.2.1 *Stochastic model*

A Gaussian non-stationary shot noise is used to represent the acceleration at bedrock during an earthquake. This process simulates the effect of random pulses arriving as seismic waves to the bottom of a superficial soil layer. The non-stationary character shows the variability in the random arrival times of these seismic waves. This stochastic process is completely characterized by $\phi(t)$, the variance intensity function of the shot noise.

3.2.2 *Mechanical model*

The second order linear filter, used in this investigation, represents a damped single degree of freedom system formed by a mass supported on a spring and a dashpot in parallel. The acceleration at bedrock is used as the acceleration of the support and the absolute acceleration of the mass simulates the acceleration of the ground surface. Roughly, this model simulates the fundamental shear mode response of the ground layer. The behavior of the mechanical model is completely defined by the parameters ζ and ω_0.

3.2.3 *Simulation procedure*

The acceleration at bedrock is simulated by a Gaussian shot noise obtained as the product of a stationary white noise, $w(t)$, of intensity S_0 and a deterministic function of time, $p(t)$; thus,

$$a_b(t) = p(t)w(t) \tag{3}$$

The shaping function, $p(t)$, must be zero for negative arguments, nonnegative e1sewhere, and, in general, a smoothly varying function of time. The filtering effect of a soil layer is simulated by a damped single degree of freedom linear system with damping ratio ζ and an undamped circular frequency ω_0.The ground acceleration $a_g(t)$ is obtained as the absolute acceleration of the mass from the set of equations

$$\ddot{z} + 2\zeta\omega_0\dot{z} + \omega_0 z = -\,a_b(t) \tag{4}$$

$$a_g(t) = -(2\zeta\omega_0\dot{z} + \omega_0^2 z) \tag{5}$$

If initial conditions of zero ground velocity and zero ground displacements are assumed, the ground acceleration process can be formally expressed as

$$a_g(t) = \int_{-\infty}^{\infty} a_b(\tau)\, h(t-\tau)\, d\tau \qquad (6)$$

In this equation the unit impulse response function of the filter, h(t), is given by

$$h(t) = \omega_0^2/\omega_d \exp(-\zeta\omega_0 t)\sin(\omega_d t + 2\alpha) \qquad (7)$$

with

$$\omega_d=\omega_0(1-\zeta^2)^{1/2} \text{ and } \alpha = \arcsin(\zeta) \qquad (8)$$

Through the frequency domain, the ground acceleration process can be obtained in terms of its Fourier transform, as

$$A_g(i\omega) = H(i\omega)A_b(i\omega) \qquad (9)$$

In this equation the complex frequency response function, $H(i\omega)$ is given by

$$H(i\omega) = (1 + 2\zeta i\omega/\omega_0)/(1-\omega^2/\omega_0^2 + 2i\zeta\omega/\omega_0) \qquad (10)$$

The stochastic characteristics of the ground acceleration process are represented by the covariance function:

$$Cov(t_1,t_2) = \int_{-\infty}^{\infty} \phi(\tau)h(t_1 - \tau)h(t_2 - \tau)d\tau \qquad (11)$$

For the particular case of $t_1 = t_2$, this covariance function becomes the variance function of the process, namely

$$\sigma^2(t) = \int_{-\infty}^{\infty} \phi(\tau)h(t-\tau)^2 d\tau \qquad (12)$$

It can be concluded that the ground acceleration process is Gaussian and is completely defined by filter parameters, ζ and ω_0 , and by $\phi(t)$, the variance intensity function of the shot noise.

3.3 *Estimation of model parameters*

The filter parameters and the variance intensity function of the shot noise are estimated using available earthquake records that are assumed to be sample wave forms generated by the model. The Fourier amplitude transforms of the excitation and output processes of the model are related as

$$|A_g(i\omega)|^2 = |H(i\omega)|^2|A_b(i\omega)|^2 \qquad (13)$$

Averaging across the whole ensemble and using the definition of the bedrock acceleration process, the ensemble average becomes

$$E[|A_b(i\omega)|^2] = \int_{-\infty}^{\infty} \phi(\tau)d\tau = \text{const} \qquad (14)$$

Thus, it may be seen that the ensemble average across the ground acceleration process has the same shape as the frequency response amplitude, namely

$$E[|A_g(i\omega)|^2] = |H(i\omega)|^2 *\text{const} \qquad (15)$$

This relation is used in the estimation of the filter parameters by computing $E[|A_g(i\omega)|^2]$ as an average of sample wave forms and estimating the values of ζ and ω_0 that give the best fit with

$$|H(i\omega)|^2 = (1 + 4\zeta^2\omega^2 /\omega_0^2)/[(1-\omega^2/\omega_0^2)^2 +4\zeta^2\omega^2/\omega_0^2] \qquad (16)$$

Letting $F_i(i\omega)$ be the Fourier transform of the sample wave form $f_i(t)$, the ensemble average is estimated as

$$E[|A_g(i\omega)|^2] = \sum_{i=1}^{n} 1/n\, |F_i(i\omega)|^2 \qquad (17)$$

The variance intensity function is estimated from

$$\Sigma^2(i\omega) = \Phi(i\omega)\, K(i\omega) \qquad (18)$$

$K(i\omega)$ is the Fourier transform of function $h(t)^2$. Substituting the computed expressions for $\Sigma^2(i\omega)$ and $K(i\omega)$ we obtain an estimate for $\Phi(i\omega)$, the Fourier transform of the variance intensity function, i.e.

$$\Phi(i\omega) = \Sigma^2(i\omega)/K(i\omega) \qquad (19)$$

An inverse Fourier transform provides an estimate of $\phi(t)$.

3.4 *Generation of artificial accelerograms*

First, samples of white noise are generated, then these samples are shaped using the shaping function and passed through the filter to obtain the wave forms representing ground acceleration.

A sequence of independent random numbers u_j with uniform distribution in the interval (0,1) is generated. A new sequence of independent random numbers w_j with Gaussian distribution having zero mean and unit variance is obtained with transformation

$$w_j = (-2 \ln u_j)^{1/2}\cos (2\pi u_{j+1}) \quad j=\text{odd} \qquad (20)$$

$$w_{j+1} = (-2 \ln u_j)^{1/2}\sin (2\pi u_{j+1}) \quad j=\text{odd}$$

This sequence of white numbers is now spaced at intervals $\Delta\tau$ with the origin time randomly sampled from uniform distribution in the interval $(0,\Delta\tau)$. Repeating this procedure a sufficient number of times, an ensemble of random waveforms w(t) is obtained. If the ordinates w_j of each of wave forms are multiplied by $(\pi S_0/\Delta\tau)^{1/2}$, the autocorrelation of the process becomes

(21)

$R(\tau) = 0 \qquad \text{if } \tau < 2\Delta\tau$

$R(\tau) = \pi S_0/\Delta\tau(4/3 + 2(\tau/\Delta\tau) + 1/6(\tau/\Delta\tau)^3) \qquad \text{if } -2\Delta\tau<\tau<-\Delta\tau$

$R(t) = \pi S_0/\Delta\tau(2/3 - (\tau/\Delta\tau)^2 -1/2(\tau/\Delta\tau)^3) \text{if } -\Delta\tau<\tau<0$

$R(t) = \pi S_0/\Delta\tau(2/3 - (\tau/\Delta\tau)^2 + 1/2(\tau/\Delta\tau)^3) \qquad \text{if } 0<\tau<\Delta\tau$

$R(t) = \pi S_0/\Delta\tau(4/3 - 2(\tau/\Delta\tau) + 1/6(\tau/\Delta\tau)^3) \qquad \text{if } \Delta\tau<\tau< 2\Delta\tau$

$R(t) = 0 \qquad \text{if } \tau< 2\Delta\tau$

In the limit, as $\Delta\tau$ approaches zero, R(t) approaches the form

$$R(t) = \pi S_0\delta(\tau) \qquad (22)$$

This limiting case corresponds to a white noise with constant power spectral density S_0.

The non-stationary shot noise chosen to represent the bedrock acceleration process is obtained multiplying a white noise of intensity S_0 times a shaping function p(t). The shaping function p(t) is obtained in terms of variance intensity function as follows

$$p(t) = [\phi(t)/\pi/S_0]^{1/2} \qquad (23)$$

For purposes of numerical calculations, the shaping function can be lumped with the scaling factor. Thus bedrock acceleration wave forms become

$$a_b(t) = (\phi(t)/\Delta\tau)^{1/2}w(t) \qquad (24)$$

The waveforms of the bedrock acceleration ensemble were filtered trough second order linear filter to obtain the ground acceleration $a_g(t)$ from the differential equation

$$\ddot{z} + 2\zeta\omega_0\dot{z} + \omega_0^2 z = -a_b(t) \qquad (25)$$
$$a_g(t) = -2\zeta\omega_0\dot{z} - \omega_0^2 z \qquad (26)$$

The solution of this equation is obtained step-by-step procedure with piecewise linear acceleration assumption.

4 FITTING THE SYNTHETIC ACCELERATION TIME HISTORY TO MATCH TARGET RESPONSE SPECTRUM WITH SINGLE DAMPING COEFFICIENT

The 5% bedrock field ground spectra according to HAF 0101(1) were adopted for targets for ground motion simulation. The horizontal ground motion spectrum was anchored to 0.2g and the vertical ground motion spectrum was anchored to 0.1g. The limitations and paucity of recorded acceleration time-histories together with the widespread use of time-history dynamic analysis for obtaining structural and secondary systems' response are the primary motivations for the development of simulation capabilities. Individual real earthquake records are limited in the sense that they are conditional on a single realisation of a set of random parameters (magnitude, focal depth, attenuation characteristics, frequency content, duration, etc.), a realisation that will likely never occur again and that may not be satisfactory for design purposes.

The intent herein is to focus on one commonly used method of numerical simulation, the one based on the fact that any periodic function can be expanded into a series of sinusoidal waves:

$$x(t) = \sum_{i=1}^{n} A_i \sin(\omega_i t + \phi_i) \qquad (26)$$

A_i is the amplitude and ϕ_i is the phase angle of the ith contributing sinusoid. By fixing an array of amplitudes and then generating different arrays of phase angles, different motions which are similar in general appearance (i.e., in frequency content) but different in the local details, can be generated. The computer uses a "random number generator" subroutine to produce strings of phase angles with a uniform distribution in the range between 0 and 2π. The total power of the steady state motion, x(t) is $\sum(A_i^2/2)$. Assume now that the frequencies ω_i are chosen to lie at equal intervals $\Delta\omega$ so that $G(\omega_i)\Delta\omega = A_i^2/2$. Allowing the number of sinusoids in the motion to become very large, the total power will become equal to the area under the continuous curve $G(\omega)$, which is in effect the spectral density function.

When $G(\omega)$ is narrowly centred around a single frequency, then x(t) will generate nearly sinusoidal functions. On the other hand, if the spectral density function is nearly constant over a wide band of frequencies, components with widely different frequencies will compete to contribute equally to the motion intensity, and the resulting motions will resemble portions of earthquake records. Of course, the total power and the relative frequency content of the motions produced do not vary with time. To simulate in part the transient character of real earthquakes, the stationary motions, x(t), are usually multiplied by a deterministic intensity function such as the exponential compound function shown in Figure 2.

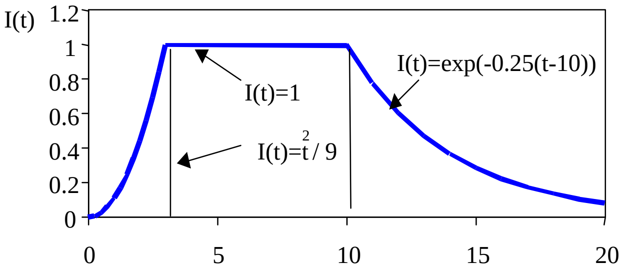

Figure 2. Compound intensity function used in seismic motion simulation.

The most widely used equation for power spectral density function is so called filtered white-noise spectral density function expressed by Eqn. 27 as follows:

$$G(\omega)=\frac{\left[1+4\varsigma_g^2(\omega/\omega_g)^2\right]G_0}{\left[1-(\omega/\omega_g)^2\right]^2+4\varsigma_g^2(\omega/\omega_g)^2} \tag{27}$$

Assume a filtered white noise power spectral density function with the following arbitrary parameters: G_0=100, ω_g=50, ζ_g=0.5. In actual simulation task the parameters are so selected that the power spectral density function corresponds as closely as possible the given target response spectrum. Theoretical spectral density shapes such as above are obtained by examining, smoothing and averaging of the squared Fourier amplitudes $|f(\omega)|^2$ of actual strong motion records. This stems from the basic fact that, for stationary random processes, the expected value of $|f(\omega)|^2$ and the spectral density functions $G(\omega)$ are proportional.

In summary, the problem in simulation with the model represented is, then, one of selecting a proper shape and intensity of either the power spectral density function or the Fourier amplitude spectrum and estimating the duration of the motion. Development of design criteria has evolved along different paths, however. In the nuclear industry, for example, a set of smooth response spectra has been adopted for use in seismic design. In this practice the power spectral density function is generated from smooth target response spectra. In the simulation generation process the match of the generated motion is improved by iterative process where the spectral density function is corrected by the response spectrum match ratio as follows:

$$G(\omega)_{i+1} = G(\omega)_i \,(S^t(\omega)/S^i(\omega)) \tag{28}$$

$S^t(\omega)$ is the target response spectral value.

The generated time histories shall have the following characteristics:

1. The mean of the zero-period acceleration (ZPA) values (calculated from the individual time histories) shall equal or exceed the design ground acceleration.
2. In the frequency range 0.5 to 33 Hz, the average of the ratios of the mean spectrum (calculated from the individual time history spectra) to the design spectrum, where the ratios are calculated frequency by frequency, shall be equal to or greater than 1.
3. No one point of the mean spectrum (from the time histories) shall be more than 10% below the design spectrum. When responses from the three components of motion are calculated simultaneously on a time-history basis, the input motions in the three orthogonal directions shall be statistically independent. Two time histories shall be considered statistically independent if the absolute value of the correlation coefficient does not exceed 0.3.

The generated time histories and corresponding response spectra together with target spectra are depicted in following figures.

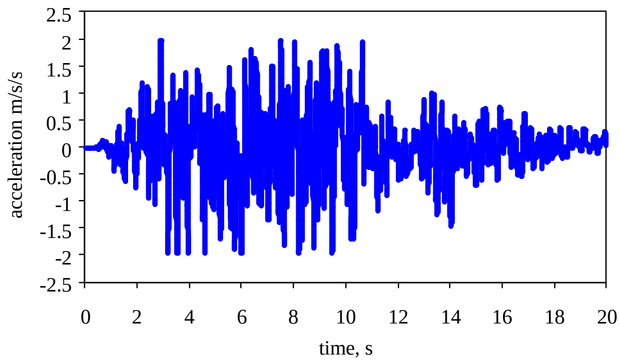

Figure 3. Horizontal x-axis ground acceleration time history.

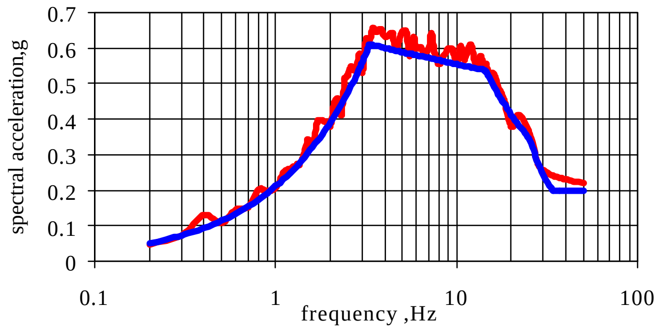

Figure 4. Horizontal x-axis ground response spectra fit.

5 FIT TO MULTIPLE TARGET SPECTRA

Individual observed earthquake records are limited in a sense that they are conditional on a single realisation of a set of random parameters such as magnitude, focal depth, attenuation characteristics, frequency content, duration and so on. Such a realisation will likely never occur again and therefore not very satisfactory for design purposes. The method used for numerical simulation in this study is based on the fact that any periodic function can be expanded into a series of sinusoidal waves:

$$x(t) = \Sigma A_i \sin(\omega_i t + f_i) \quad (29)$$

The motion is generated in such a way that the frequency content will vary during the duration of the time history. In other words the power spectrum of the motion has evolutionary characteristics. The power spectral density function of such a motion can expressed in the form:

$$G(\omega,t) = U(t(\omega))\, G(\omega) \quad (30)$$

The iteration scheme used to fit the response spectra of the motion to the target spectra is based on the assumption that a small change in the spectral acceleration at frequency ω and damping z i.e. dR(ω,z) can be related to a small adjustment in input acceleration time history dZ"(t) through the Duhamel integral as follows:

$$dR(\omega,z) = \int dZ''(t)\, h(tm - t)\, dt \quad (31)$$

where

- h is the impulse response function for oscillator having frequency ω and damping coefficient z;
- tm is the time at which the spectral response occurs.

For matching a set of target spectrum values for m frequencies and n damping coefficients, the solution of Eqn. 31 can be transformed to the solution of a set of algebraic equations as follows:

Let dZ"(t) be a linear combination of pre-selected functions f_{jl}:

$$dZ''(t) = \Sigma\Sigma\, b_{jl}\, f_{jl}(t) \quad (32)$$

substituting Eqn. 32 into Eqn. 31 gives:

$$dR(\omega,z) = \Sigma\Sigma C_{ijkl}\, b_{jl} \quad (33)$$

After computing coefficients b_{jl} the adjustment of dZ" (t) for the next iteration cycle can be obtained and the new time history for cycle g + 1 can be obtained from the history for cycle g as follows:

$$Z''_{g+1}(t) = Z''_g(t) + dZ''_g(t) \quad (34)$$

By repeatedly applying the above scheme the time history of the desired matching accuracy can be obtained. As a result the time histories for three components of motion that match with the HAF 0101 (1) spectra for 2, 4, 5 and 7% with an error less than 10% have been generated (see Fig. 5, Tables 1).

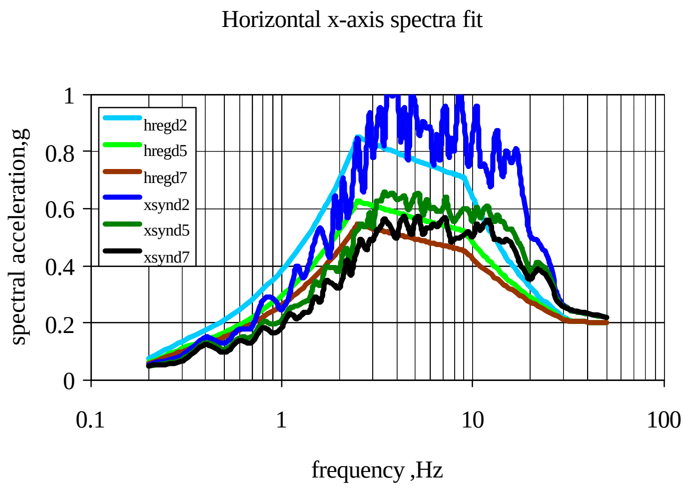

Figure 5. Fit to HAF 0101 spectra for 2%, 5% and 7% damping for horizontal x-component.

Table 1. ASCE 4-86 Compliance for HAF 0101 (01) spectrum fit for horizontal x-component.

	xsd2/hhd2	xsd4/hhd4	xsd5/hhd5	xsd7/hhd7
Mean	1.099459	1.067751	1.054395	1.045159
Standard Error	0.014223	0.007884	0.007566	0.009221
Median	1.096131	1.066293	1.049826	1.028668
Standard Deviation	0.123991	0.068731	0.065959	0.080387
Sample Variance	0.015374	0.004724	0.004351	0.006462
Kurtosis	-1.08625	2.522115	7.299763	7.60409
Skewness	0.088206	0.657131	1.51506	1.811882
Minimum	0.863208	0.922366	0.91907	0.926471
Maximum	1.329877	1.343968	1.381915	1.453901

As can be seen from the results of Table 1 the synthetic time histories comply with the requirements of ASCE 4-86 excluding minor discrepancies for 2% spectra. These points are for very low frequencies and in most cases outside the area for the compliance requirements, namely 0.5 to 33 Hz. The soil conditions in Lianyungang NPP site are those of very stiff solid bedrock. In these soil conditions the low frequency end of the target spectra compliance is not essential. The conclusion of this section is that the synthetic time histories fulfil the requirements for compliance for multi-spectra matching with HAF 0101 (01).

6 CONCLUSIONS

The match of Lianyungang Nuclear Power Plant design acceleration time histories with HAF 0101 (01) Design spectra is studied. The compliance of design time histories with HAF 0101 (01) design spectra according to ASCE 4- 86 and NUREG 0800 rules are shown.

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