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SIMULATED SPACE-TIME VARIATION OF EARTHQUAKE GROUND MOTION INCLUDING OBSERVED TIME HISTORY RECORD

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ABSTRACT

Records of past strong motion are often used as the ground motion input in earthquake analysis and design of buildings. The design of underground structures, however, requires more than just the time history at any particular point on the earth's surface. It also requires the space-time variation of the ground motion. The objective of this paper is to develop a method for simulating a space-time function, which produces the assumed cross-correlation function and includes the observed record.

KEYWORDS

Ground motion; underground structures; tunnels; pipes; bridges; waves; random processes; design; simulation; space-time variation.

INTRODUCTION

In the dynamic analysis and design of long underground structures such as tunnels, pipelines and buried pipes, the structure, soil and basement rock should be modeled and the seismic input motion should be determined at the soil or basement rock level as shown by Fig.1. Engineers are required to give input seismic motions at several points along the underground structure because the structural response is greatly affected by relative ground motion.

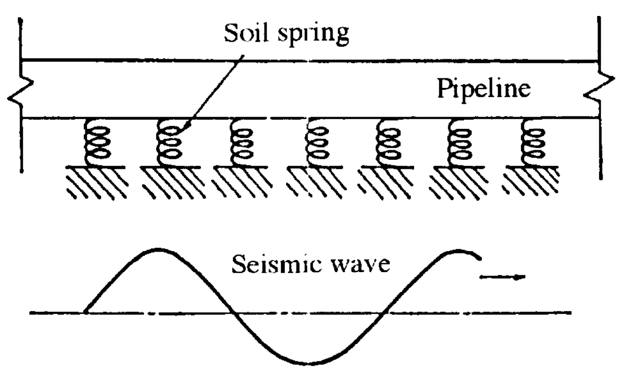


Fig.1. Physical model of underground pipelines (after Kubo, 1981)

From this point of view, estimating simultaneous motion is an important problem to be solved, and techniques to simulate the space-time variation should be developed. In previous structural designs, records obtained from the one site near epicenters caused by earthquakes, such as the Imperial Valley, Taft, Tokachi-oki and Niigata earthquakes, have been used. Further, one of the following has frequently been assumed in establishing relative motion and in estimating space-time variation.

1) One previously observed time history propagating horizontally with a constant finite propagating speed without distortion of wave form.
2) Waves propagating horizontally with an infinite speed. Therefore, input motions are the same at all locations including their arrival times.

Even when 1) is assumed, a problem still exists as to what value should be used for horizontal wave speed. This value differs greatly depending on whether the shear wave velocity of the surface layer is used as indicated by the standards for gas pipelines in Japan or whether the value estimated from calculated cross-correlation functions using array records is used. For example, at alluvial sites, shear wave velocities are several hundred m/s, while the latter is more than one thousand m/s (Tamura *et al.*, 1974; Tsuchida and Kurata, 1975). Using conventional theory (Sakurai,1971) strain on the pipeline can be approximately estimated by

$$\text{(Strain on pipeline)} = \text{(Particle velocity of soil)}/\text{(Horizontal speed of wave propagation)}. \qquad (1)$$

It can be understood that these two kinds of wave speeds will give us strains which differ as much as ten times. Even though the latter speed seems more rational, because distortion in the wave form has been neglected, strain will consequently be underestimated (Kawakami and Sato,1983).

Assumption 2) has mainly been applied to sites with greatly varying horizontal soil structures. However, at some sites where horizontal soil structures have been found to be uniform as a result of geophysical exploration, vertically incident seismic waves do not create strain on the ground surface. Consequently, assumption 2) is also unsafe in estimating such sites (Kawakami and Sato,1983). In addition, distortion in the wave form has been neglected in both assumptions 1) and 2). However, in recent studies based on an analysis of seismic array records (Kawakami and Sato,1983), distortion in the wave form has been shown to have a considerable effect on ground strains.

Several methods have been proposed to solve the above-mentioned problems. Shinozuka *et al.* (1976), Naganuma *et al.* (1987), Hoshiya *et al.* (1980), Harada *et al.* (1988) and Deodatis *et al.* (1988) developed simulation methods for space-time variations with cross-correlation functions and cross-spectra equal to assumed ones. These studies were based on the random process theory, and space-time variation is interpreted as a function of time lag, the distance between two points, frequency and wavenumber. Further, simulation was conducted by taking wave propagation and distortion into consideration.

However, space-time variations obtained by each of these methods have not directly taken observed records into account, and consequently are too unrealistic and unconvincing to be used in actual design. Therefore, these simulated waves have not often been used as input motions, and one observed record and assumption 1) or 2) are still frequently being used in practice.

Such a tendency is also true in the design of buildings, and observed actual records, such as those from Imperial Valley, Taft and Tokachi-oki, have often been used as input seismic motions rather than simulated time histories based on random process theory. This tendancy is due to the idea that the observed must be more realistic than the simulated. Furthermore, in the design of underground structures, not only observed time history records but also space-time variations around the structure are required, because relative motion is the main cause behind strain induced in the structure. Because of reasons such as these, one seismic record is insufficient in designing, and space-time variations are still required. In particular, several representative space-time variations including well-known observed records are believed to be essential when designing underground structures such as in building extensions.

The first author has already proposed a method using a double Fourier series for the rational simulation of space-time variations considering the distortion of wave forms during propagation (Kawakami,1989). The objective of this paper is to develop another method extending the theory of multiply-correlated random processes instead of the double Fourier series and to demonstrate the effectiveness of the proposed method.

In this paper, space-time variation is represented by multiply-correlated random processes $U_i(t)$ in which i and t denote location and time, respectively. Also, similar to previous papers (Kawakami,1989,1990;

Vanmarcke and Fenton, 1991; Kameda and Morikawa, 1992; Hoshiya and Maruyama, 1993; Noda *et al.*, 1994; Kiyono *et al.*, 1994), the following conditions have been assumed for simulated space-time variation.

Condition A: Auto-correlation functions of both simulated space-time variation and observed record should be identical. Based on the auto-correlation function of the observed record, wave propagation speed and the degree of wave distortion, cross-correlation functions or cross-spectra have been assumed. Cross-correlation functions of simulated space-time variations should also be identical with assumed ones.

Condition B: Simulated space-time variations should include the observed record.

In this paper, regarding condition A, cross-correlation functions have been assumed to represent wave propagation in the positive direction and a decrease in correlation with increasing distance between two points. Concerning condition B, space-time variation whose component $U_1(t)$ matches the observed record has been simulated. A case study is presented using the El Centro record during the Imperial Valley earthquake, satisfying the above two conditions.

THEORY

Simulation of Space-time Variation with Continuous Cross-spectra

Space-time variation of earthquake ground displacement is expressed by m cross-correlated stochastic processes $U_i(t)$ $(i = 1, ..., m)$, where i and t denote location and time, respectively. The formulation presented in this paper is applicable not only to displacements but also to velocities and accelerations.

Shinozuka and Jan (1972) have shown that stochastic processes $U_i(t)$ $(i = 1, ..., m)$ can be expressed by using one-sided continuous cross-spectra $S_{XT}(x_0, \omega)$, where ω and x_0 respectively denote the angular frequency and distance between two points, as follows.

$$U_i(t) = \sum_{p=1}^{i}\sum_{n=1}^{N} |H_{ip}(\omega_n)\sqrt{\Delta\omega}|\sqrt{2}\cos\{\omega_n t + \theta_{ip}(n) + \phi_{pn}\}, \quad (i=1,2,\cdots,m), \tag{2}$$

where ϕ_{pn} are mutually independent and uniformly distributed random variables from zero to 2π, ω_n is the nth discretized angular frequency,

$$\omega_n = n \cdot \Delta\omega = \frac{2n\pi}{T}, \qquad (n=1,2,\cdots,N), \tag{3}$$

and T is the duration of the record. In this paper, the constant component has been neglected, and the stationarity of the random process has been assumed over the period from 0 to T.

Term $H_{ip}(\omega)\sqrt{\Delta\omega}$ can be obtained by factoring the matrix as follows.

$$\begin{bmatrix} S_{11}(\omega)\Delta\omega & \cdots & S_{1m}(\omega)\Delta\omega \\ \vdots & \ddots & \vdots \\ S_{m1}(\omega)\Delta\omega & \cdots & S_{mm}(\omega)\Delta\omega \end{bmatrix} = \begin{bmatrix} H_{11}^*(\omega)\sqrt{\Delta\omega} & & 0 \\ \vdots & \ddots & \\ H_{m1}^*(\omega)\sqrt{\Delta\omega} & \cdots & H_{mm}^*(\omega)\sqrt{\Delta\omega} \end{bmatrix} \cdot \begin{bmatrix} H_{11}(\omega)\sqrt{\Delta\omega} & \cdots & H_{m1}(\omega)\sqrt{\Delta\omega} \\ & \ddots & \vdots \\ 0 & & H_{mm}(\omega)\sqrt{\Delta\omega} \end{bmatrix}, \tag{4}$$

where $*$ indicates the complex conjugate, and

$$S_{ij}(\omega)\Delta\omega = S_{XT}(x_0|_{ij}, \omega)\Delta\omega, \tag{5}$$

where $x_0|_{ij} = x_i - x_j$ is the relative distance between two points i and j. Further, term $\theta_{ip}(n)$ in (2) is given by

$$\theta_{ip}(n) = \tan^{-1}\left(\frac{I_m[H_{ip}(\omega_n)\sqrt{\Delta\omega}]}{R_e[H_{ip}(\omega_n)\sqrt{\Delta\omega}]}\right), \tag{6}$$

where Re, Im indicate real and imaginary parts, respectively.

Power Spectrum of Observed Record

As mentioned in condition A, simulated space-time variation should have the same power spectrum as the observed record. The Fourier series expansion of the observed record is given as

$$F(t) = \sum_{n=1}^{N} \{a_n \cos(\omega_n t) + b_n \sin(\omega_n t)\} . \tag{7}$$

From (7), ground motion at time $t + \tau$ can be expressed as

$$F(t+\tau) = \sum_{n=1}^{N} [a_n \cos\{\omega_n(t+\tau)\} + b_n \sin\{\omega_n(t+\tau)\}] , \tag{8}$$

where τ is time lag. By considering the product of $F(t)$ and $F(t+\tau)$ and taking the temporal average from 0 to T, auto-correlation function $R_{XT}(0,\tau)$ is obtained as

$$R_{XT}(0,\tau) = \overline{F(t) \cdot F(t+\tau)} = \frac{1}{2}\sum_{n=1}^{N}(a_n^2 + b_n^2)\cos(\omega_n \tau), \tag{9}$$

where $\overline{}$ indicates the temporal average. The Fourier transform of (9) yields the two-sided power spectrum

$$\frac{1}{2\pi}\int_{-\infty}^{\infty} R_{XT}(0,\tau)\exp(-i\,\omega\tau)\,d\tau = \frac{1}{4}\sum_{n=1}^{N}(a_n^2 + b_n^2)\,\{\delta(\omega-\omega_n) + \delta(\omega+\omega_n)\} , \tag{10}$$

where $\delta(\omega)$ denotes Dirac's delta function. Therefore, the one-sided power spectrum $S_T(\omega)$ can be given by

$$S_T(\omega) = \frac{1}{2}\sum_{n=1}^{N}(a_n^2 + b_n^2)\,\delta(\omega-\omega_n). \tag{11}$$

By integrating (11) from $\omega_n - \Delta\omega/2$ to $\omega_n + \Delta\omega/2$, a relationship can be established between the one-sided power spectrum and Fourier coefficients.

$$S_T(\omega_n)\,\Delta\omega = \frac{(a_n^2 + b_n^2)}{2} , \tag{12}$$

Assumptions of Cross-spectra

Simulated space-time variation should have an identical power spectrum to that of the observed record as mentioned in condition A, and the correlation between two simulating points should decrease with wave propagation. From previous studies (Ishii,1981; Sawada,1988; Katayama *et al.*, 1990) on comparisons between two actually observed time histories, correlation is known to decrease with increasing distance between observation points, $|x_0|$, and with increasing frequencies.

Hence, one-sided cross-spectrum $S_{XT}(x_0,\omega)$ is assumed as

$$S_{XT}(x_0,\omega) = S_T(\omega)\,\exp(-i\,\omega x_0/c)A(|\omega||x_0|/c), \tag{13}$$

where $A()$ is a function of frequency $|\omega|$ and travel time $|x_0|/c$. Further, c and $S_T(\omega)$ are the horizontal speed of the propagating wave and the observed one-sided power spectrum, respectively. Function $A()$ is called coherency, and by referring to a previous study (Ishii,1981), it can be assumed to be written as

$$A(|\omega||x_0|/c) = \exp\{-\alpha|\omega||x_0|/(2\pi c)\}, \tag{14}$$

where α denotes the degree of distortion of time history due to propagation, or the distortion coefficient (Kawakami and Sato,1983; Kawakami, 1989,1990). By definition, a zero value for α is free of distortion, whereas a large value for α greatly decreases the correlation between the two time histories.

Cross-spectrum of Space-time Variation

Multiplying both sides of (13) by $\Delta\omega$, the relationship between line cross- and power spectra can be given by

$$S_{XT}(x_0, \omega_n)\,\Delta\omega = S_T(\omega_n)\,\Delta\omega \cdot \exp\{-\alpha|\omega_n||x_0|/(2\pi c)\}\exp(-i\,\omega_n x_0/c). \tag{15}$$

Then, substituting (12) into (15), the cross-spectrum of space-time variation yields

$$S_{XT}(x_0, \omega_n)\,\Delta\omega = \frac{(a_n^2 + b_n^2)}{2} \cdot \exp\{-\alpha\,|\omega_n||x_0|/(2\pi c)\}\exp(-i\,\omega_n x_0/c). \tag{16}$$

An assumed corresponding cross-correlation function can also be obtained by the inverse Fourier transformation of the two-sided cross-spectrum.

$$\begin{aligned} R^0_{XT}(x_0, \tau) &= \frac{1}{2}\int_{-\infty}^{\infty} S_{XT}(x_0, \omega)\exp(i\,\omega\tau)\,d\omega \\ &= \frac{1}{2}\sum_{n=1}^{N}(a_n^2 + b_n^2)\exp\{-\alpha|\omega_n||x_0|/(2\pi c)\} \cdot \cos\{\omega_n(\tau - x_0/c)\}. \end{aligned} \tag{17}$$

Space-time Variation Including Observed Record

Regarding condition B, first process $U_1(t)$ has been chosen from m processes $U_i(t)\quad(i = 1, \ldots, m)$ in (2),

$$U_1(t) = \sum_{n=1}^{N}|H_{11}(\omega_n)\sqrt{\Delta\omega}|\,\sqrt{2}\cos\{\omega_n t + \theta_{11}(n) + \phi_{1n}\}, \tag{18}$$

and it has been matched with the observed record.

In the above equation, terms $|H_{11}(\omega_n)\sqrt{\Delta\omega}|$ and $\theta_{11}(n)$ can be estimated as follows. From (4) and (5),

$$S_{11}(\omega_n)\,\Delta\omega = H^*_{11}(\omega_n)\,\sqrt{\Delta\omega} \cdot H_{11}(\omega_n)\,\sqrt{\Delta\omega}, \tag{19}$$

$$S_{11}(\omega_n)\,\Delta\omega = S_{XT}(0, \omega_n)\,\Delta\omega = S_T(\omega_n)\,\Delta\omega. \tag{20}$$

Substituting (12) into (19) and (20) and ensuring that $S_T(\omega_n)\Delta\omega$ is not a negative value, one derives

$$R_e[H_{11}(\omega_n)\,\sqrt{\Delta\omega}] = \sqrt{(a_n^2 + b_n^2)/2}, \tag{21}$$

$$I_m[H_{11}(\omega_n)\,\sqrt{\Delta\omega}] = 0. \tag{22}$$

Therefore,

$$|H_{11}(\omega_n)\,\sqrt{\Delta\omega}| = \sqrt{(a_n^2 + b_n^2)/2}, \tag{23}$$

$$\theta_{11}(n) = 0. \tag{24}$$

Finally, time history $U_1(t)$ yields

$$U_1(t) = \sum_{n=1}^{N}\sqrt{a_n^2 + b_n^2}\cos(\omega_n t + \phi_{1n}). \tag{25}$$

However, the Fourier series of the observed record given by (7) can be rewritten as

$$F(t) = \sum_{n=1}^{N} A_n \cdot \cos(\omega_n t + \beta_n), \tag{26}$$

where

$$A_n = \sqrt{a_n^2 + b_n^2}, \tag{27}$$

$$\beta_n = \tan^{-1}(-b_n/a_n). \tag{28}$$

From a comparison between (25) and (26), ϕ_{1n} in (18) can be established as

$$\phi_{1n} = \beta_n = \tan^{-1}(-b_n/a_n). \tag{29}$$

After all, if ϕ_{1n} in (29) is used, simulated time history $U_1(t)$ in (2) is the same as the observed one.

In previous studies on methods for unconditional simulations of space-time variation, all values of ϕ_{in} ($i = 1, ..., m$, $n = 1, ..., N$) have been simulated as mutually independent and uniformly distributed random variables. However, in this study, ϕ_{1n} ($n = 1, ..., N$) have been determined by (29) to satisfy condition B, and remaining members ϕ_{in} (i=2, ..., m, n=1, ..., N) have been simulated as mutually independent and uniformly distributed random variables.

Summary of Algorithm of Developed Method

The developed simulation method for space-time variation including the one observed record can be summarized as follows:

i) Calculate Fourier coefficients, a_n and b_n, by expanding the observed record into a Fourier series as shown by (7).
ii) Choose site location x_i where the time history should be simulated as the ith random process.
iii) Assume a cross-spectrum by using (16), after estimating horizontal speed of propagating wave c and distortion coefficient α.
iv) Factor the cross-spectral matrix into two triangular matrices as shown by (4), and estimate $|H_{ip}(\omega_n)\sqrt{\Delta\omega}|$ and $\theta_{ip}(n)$.
v) Calculate $\phi_{1n}(n = 1, ..., N)$ by using (29).
vi) Generate mutually independent and uniformly distributed random variables for values of ϕ_{in} ($i = 2, ..., m$, $n = 1, ..., N$).
vii) Calculate space-time variation by using (2).

SIMULATION USING IMPERIAL VALLEY EARTHQUAKE RECORD

In this section, numerical results are presented using records taken from the El Centro site during the Imperial Valley earthquake (May 18, 1940). These records are frequently used for the dynamic analysis of structures. The maximum acceleration of the NS component is 341.7 cm/s^2. The displacement time history estimated from the numerical integration of the acceleration record has also been open to the public as shown by Fig.2 (Hudson *et al.*, 1971), and the maximum value of displacement is 10.9 cm. During simulation, the first 48 sec of the record was used, and the first to the 29th Fourier coefficients were calculated.

Wave horizontally propagating speed c and distortion coefficient α have respectively been assumed as 1,000 m/s and $0.2 \times 2\pi$. The value of the distortion coefficient was determined based on Ishii's study (1981). Here, the corresponding cross-correlation function given by (17) has been assumed as shown by Fig.3(a). The thick line at $x_0 = 0$ in Fig.3(a) indicates the auto-correlation function of observed time history.

Time histories have been simulated at 31 points that are distributed over -6 to $+6$ km with an equal distance between adjacent points of 0.4 km. Among time histories $U_i(t)$ ($i = 1, ..., 31$), subscript $i = 1$ in $U_i(t)$ denotes the recording point at $x = 0$, and even and odd numbers of i ($2 \leq i \leq 31$) denote simulating points located at positive and negative sides of $x = 0$, respectively. The distance between the simulating point and recording point $x = 0$ increases with increasing subscript i.

Figure.4(a) shows space-time variation simulated by following the algorithm summarized previously. It should be noted that the simulated time history at point i=1 ($x = 0$) indicated by the thick line in Fig.4(a) is completely identical with the observed record shown in Fig.2, therefore satisfying Condition B. Figure.4(b) shows cross-correlation functions, in the space and time domain of $-24 < \tau < +24$sec and $-6 < x_0 < +6$km, calculated from the simulated space-time variation sample in Fig.4(a).

In Fig.4(b), it should be noticed that the cross-correlation function of this simulated sample is nearly, but not exactly, equal to the assumed one shown in Fig.3(a). However, their ensemble average should be identical with the assumed cross-correlation function. To verify this, simulations were conducted one hundred times and the ensemble average was calculated. The results are shown in Fig.3(b), and it can be noticed that they are identical to those in Fig.3(a).

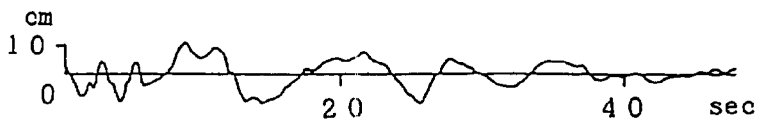
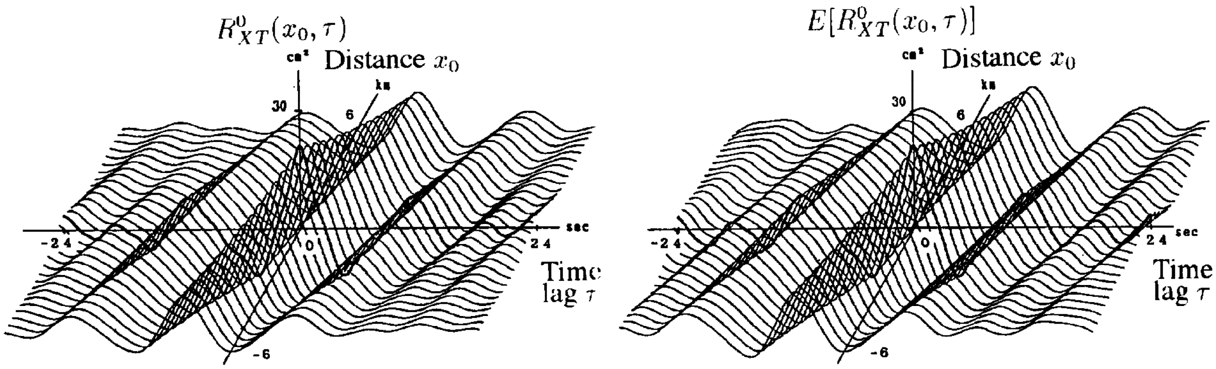
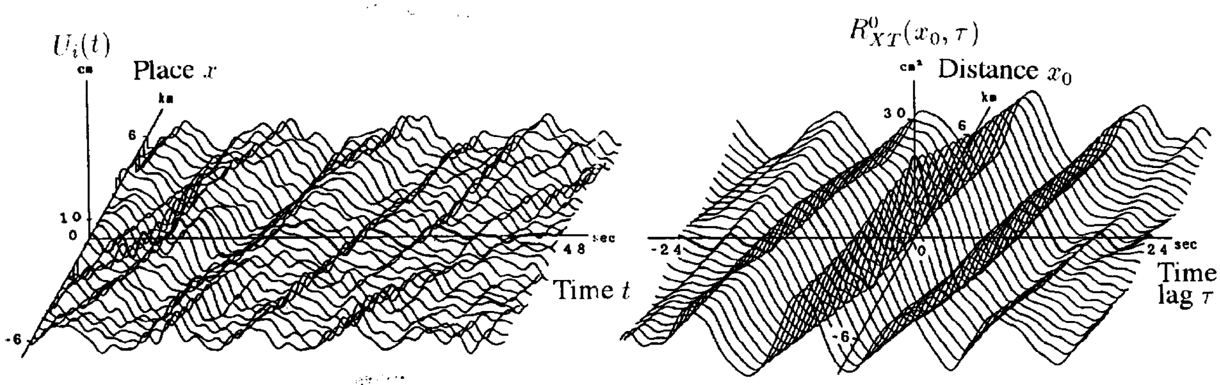


Fig.2. Observed wave during Imperial Valley earthquake (1940)



(a) (b)

Fig.3 (a) Assumed cross-correlation function and (b) ensemble average from 100 samples



(a) (b)

Fig.4 (a) Simulated space-time variation and (b) its cross-correlation function

In this section, several examples of the application of the method developed in the previous section have been demonstrated, and the effects of parameters used have been illustrated. However, the values of parameters are only based on a few previous studies. To utilize simulated space-time variation in the design of structures, the values of these parameters should be investigated in more detail by using a number of seismic array records observed under various ground conditions.

CONCLUSIONS

In designing underground structures to withstand earthquakes, the estimation of space-time variations around the structure is an important problem to be solved. The objective of this paper has been to simulate space-time variations that include observed records.

In this paper, conditions A and B have been considered, and a new method has been developed to simulate space-time variation based on the theory of multiply-correlated random processes. In the case study, the Imperial Valley earthquake record was used, and cross-correlation functions have been assumed so that seismic waves propagate in the positive direction and correlation decreases with wave propagation. Under these assumptions, space-time variation has been simulated and the following conclusions have been derived:

1) Simulated space-time variation includes the observed record;
2) The auto- or cross-correlation function of the simulated space-time variation sample is nearly equal to the assumed one; and
3) Ensemble average of the auto- or cross-correlation function of the simulated space-time variation samples is exactly equal to the assumed one.

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