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GENERATION OF SPECTRUM-COMPATIBLE BI-DIRECTIONAL GROUND MOTION ACCELEROGRAMS FOR SEISMIC DESIGN OF BRIDGES

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Abstract

For the purpose of seismic performance verification of bridges in the process of seismic design, it is desirable to use spectrum-compatible bi-directional accelerograms with well-established multi-dimensional characteristics. In this paper, a method to generate spectrum-compatible bi-directional accelerograms is proposed, in which the complementary normal component wave computed by application of the Hilbert transform to standard accelerograms provided by design specifications is combined with the standard accelerograms. Generation of a set of bi-directional accelerograms by the proposed procedure based on standard accelerogram for Japanese highway bridge design code is demonstrated. It is shown that each orthogonal component of the generated bi-directional accelerogram is approximately compatible with the specified design spectrum, while the intensity of biaxial response spectrum is equivalent to that of the conventional unidirectional input, with respect to the unidirectional elastic response spectrum within the specified natural period range with a sufficient accuracy. Particular features of the effect of bi-directional input to structural model are examined with nonlinear dynamic response analysis of a simplified bridge model consisting of a superstructure, a seismic isolator and a seismic damper to show a typical feature of the effect of bi-directional input ground motions. The comparison reveals that the difference of the evaluated structural responses between the bi-directional and unidirectional input cases appears, and that the degree of the effect depends on the type of standard earthquake accelerograms corresponding to interplate-type earthquake and near-source earthquake ground motions.

Keywords: bi-directional input; bi-directional response; seismic performance assessment; Hilbert transform

1. Introduction

Earthquake ground motions are of multi-dimensional nature consisting of bi-directional motions in the horizontal components and unidirectional ones in the vertical component. The seismic response of structures induced by the ground motions also is three-dimensional and the horizontal bi-directional components of the ground motions are particularly important for the seismic performance assessment of the structures. However, in typical seismic design codes for highway bridges, in Japan [1] for example, seismic performance assessment is conducted by nonlinear time history analysis using unidirectional spectrum-matched accelerograms to excite in the longitudinal direction and in the transverse direction separately. This is mainly due to the fact that reliable bi-directional restoring force models of structural members applicable to the seismic performance assessment in design and construction practice are still on the developing stage. However, owing to research efforts by engineers and researchers in the development of modeling and assessing the bi-directional behavior of structures, numerical analysis of bi-directional structural response can be used if appropriate structural modeling is achieved.

In order to investigate the bi-directional seismic performance of structures, one of the viable options is to use ground motion accelerograms recorded during past earthquakes. However, the accelerograms of actual earthquakes do not match with the design spectrum to be used in seismic performance assessment. Although several methods to synthesize spectrum-matched bi-directional ground motions have been investigated in past research, the practical procedure of synthesis is not yet established. For example, Grant [2] developed a method to generate two horizontal ground motion components matched to the target response spectra with the use of weighted wavelets for spectral adjustment.

In this study, a procedure to synthesize spectrum-matched bi-directional accelerograms consisting of a spectrum-matched uni-directional accelerogram and its Hilbert transform, referred to as the complementary waves, as the orthogonal components applicable to seismic performance assessment is proposed. To discuss the implication of the accelerograms synthesized with the proposed method in the seismic performance assessment, the dynamic response of nonlinear elasto-plastic structures is investigated by numerical dynamic analysis of an idealized simple dynamic model.

2. Analysis of bi-directional accelerograms

As the preliminary of proposed method, the fundamental concepts to analyze the nature of bi-directional ground motion are described in this section.

2.1 Bi-axial response spectrum

Isotropic elastic single-mass models with various natural periods T and a damping ratio h=0.05 are assumed to be subjected to bi-directional ground motion acceleration $a_x(t)$, $a_y(t)$ in the x-y coordinate system, where t is the time, as shown in Fig.1. The bi-directional dynamic response of the single-mass system is computed by dynamic analysis using a numerical step-by-step time integration scheme. When the two components of the bi-directional structural response $d_x(T,\ t)$, $d_y(T,\ t)$ are plotted on the horizontal plane as a trajectory, the maximum radial distance of the trajectory from the origin can be expressed by

$$S_{Rd}(T) = \max_t \sqrt{d_x(T,t)^2 + d_y(T,t)^2} \tag{1}$$

This peak radial response $S_{Rd}(T)$ as a function of the natural period T of the structural model is referred to as the bi-axial response spectrum [3]. The concept of bi-axial response spectrum is an extension of the elastic response spectra in x and y components

$$S_{jd}(T) = \max_t \left| d_j(T,t) \right| \quad , \quad j = x, y \tag{2}$$

to the two-dimensional case. When the bi-axial response spectrum of the bi-directional ground motion is compatible with the target elastic response spectrum, the said bi-directional input ground motion is defined to be spectrum-matched in this study.

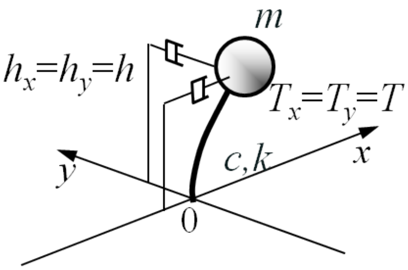


Fig. 1 – Bi-directional isotropic single-mass model

2.2 Complex polarization filter

Vidale [5] proposed the complex polarization filter to characterize the three-dimensional particle motion trajectory associated with earthquake ground motion due to the seismic wave propagation. In the application of the complex polarization filter, an indicator for the ellipticity of the trajectory is called the elliptical component of polarization, denoted by the symbol P_E. The elliptical component of polarization is computed with the following procedure. Let $a_x(t)$ and $a_y(t)$ be the components of the ground motion in the x and y directions at time t.

1. Determine the analytic signals $u(t)$ and $v(t)$ defined by Eq. 3.

$$\begin{aligned} u(t) &= a_x(t) + iH\left[a_x(t)\right] \\ v(t) &= a_y(t) + iH\left[a_y(t)\right] \end{aligned} \tag{3}$$

where i is the imaginary unit, $H[\ ]$ represents the Hilbert transform expressed by

$$H\left[x(t)\right] = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(u)}{t-u}du \tag{4}$$

2. At each time t, compute the complex covariance matrix $\mathbf{C}(t)$.

$$\mathbf{C}(t) = \begin{bmatrix} uu^* & uv^* \\ vu^* & vv^* \end{bmatrix}_t \tag{5}$$

where the superscript ‘*’ represents complex conjugate.

3. The matrix $\mathbf{C}(t)$ is Hermitian and its eigenvalues are nonnegative real values. Find the eigenvector χ_1 corresponding to the largest eigenvalue.

$$\chi_1(t) = \begin{Bmatrix} x_1(t) \\ y_1(t) \end{Bmatrix} \tag{6}$$

The eigenvector χ_1 is assumed to be normalized so that its norm equals to unity to satisfy $\left\|\chi_1(t)\right\| = \sqrt{x_1^*(t)\,x_1(t) + y_1^*(t)\,y_1(t)} = 1$.

4. Find $X(t)$ by

$$X(t) = \max_{\alpha}\sqrt{\left\{\mathrm{Re}\left(x_1(t)e^{i\alpha}\right)\right\}^2 + \left\{\mathrm{Re}\left(y_1(t)e^{i\alpha}\right)\right\}^2} \tag{7}$$

5. The elliptical component of polarization $P_E(t)$ is computed by

$$P_E(t) = \frac{\sqrt{1 - X(t)^2}}{X(t)} \tag{8}$$

The value of P_E is computed in the range between zero and unity. A linearly polarized motion and a circularly polarized motion correspond to P_E=0 and P_E=1, respectively, and the degree of ellipticity of the bi-directional motion is represented by the value of P_E, as shown in Fig. 2.

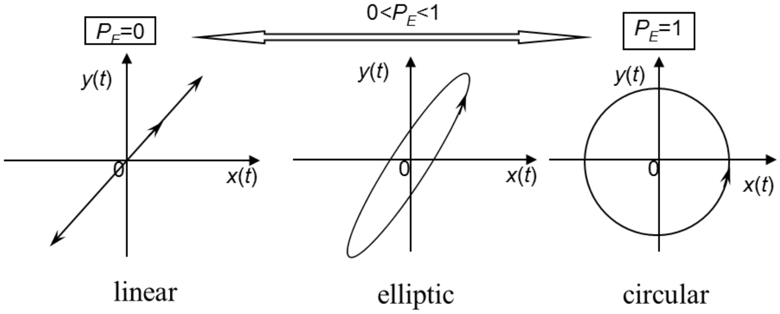


Fig. 2 – Concept of elliptical component of polarization

3. Complementary orthogonal component wave

The deviation of the bi-axial response spectrum from the conventional elastic response spectrum of each component was found to be minimized when the horizontal particle trajectory of the bi-directional input becomes closer to the circular shape, as a result of investigation using numerical dynamic analysis. Since the condition for circular trajectory can be quantitatively determined by the complex polarization analysis, the following procedure is proposed to generate bi-directional input with minimum deviation of the bi-axial response spectrum from the elastic response spectrum of a given unidirectional accelerogram.

The x and y components of a bi-directional input are denoted by $a_x(t)$ and $a_y(t)$, respectively. Let us consider a problem to determine $a_y(t)$ such that the bi-directional input satisfy

$$P_E(t) = 1 \tag{9}$$

when $a_x(t)$ is provided as a given reference accelerogram. The accelerogram $a_y(t)$ that satisfies this condition shall be referred to as the *complementary orthogonal component wave* of $a_x(t)$.

It is assumed that the matrix $\mathbf{C}(t)$ in Eq.5 can be represented by the values of the instantaneous values the bi-directional input at time t, without applying moving average or other smoothing techniques. In such a case, the following expression is obtained.

$$\mathbf{C}(t) = \begin{Bmatrix} u(t) \\ v(t) \end{Bmatrix} \begin{Bmatrix} u^*(t) & v^*(t) \end{Bmatrix} \tag{10}$$

In this case, the eigenvector $\boldsymbol{\chi}_1$ is given by

$$\boldsymbol{\chi}_1(t) = \beta \begin{Bmatrix} u(t) \\ v(t) \end{Bmatrix} \qquad \text{where} \quad \beta = \frac{1}{\sqrt{|u|^2 + |v|^2}} \tag{11}$$

From Eq.8, the condition for $X(t)$ to satisfy Eq.9 is

$$X(t) = \frac{1}{\sqrt{2}} \tag{12}$$

This condition is satisfied if the following relationship holds.

$$v(t) = \pm i\, u(t) \tag{13}$$

In this case, $u(t)$ and $v(t)$ are located at two points on a circle around the origin on the complex number plane, in the directions from the origin perpendicular to each other. Therefore, it can be shown that substitution of $x_1(t)=\beta\, u(t)$ and $y_1(t)=\beta\, v(t)$ into Eq.7 results in Eq.12. With the use of the definition of $u(t)$ and $v(t)$ given by Eq.3, Eq.13 implies

$$a_y(t) + i\,H\left[a_y(t)\right] = \pm\, H\left[a_x(t)\right] \mp i a_x(t) \tag{14}$$

and this relationship holds if

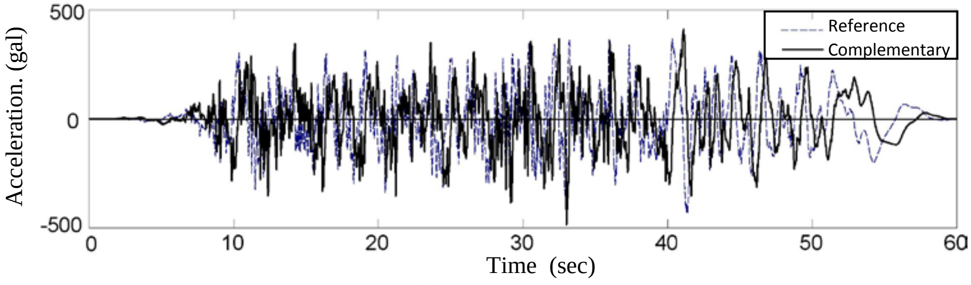
$$a_y(t) = \pm\, H\left[a_x(t)\right] \tag{15}$$

For convenience, $a_y(t)$ given by Eq.15 with the positive sign is defined as the complementary orthogonal component wave of $a_x(t)$, i.e. the complementary orthogonal component wave is the Hilbert transform of the reference wave.

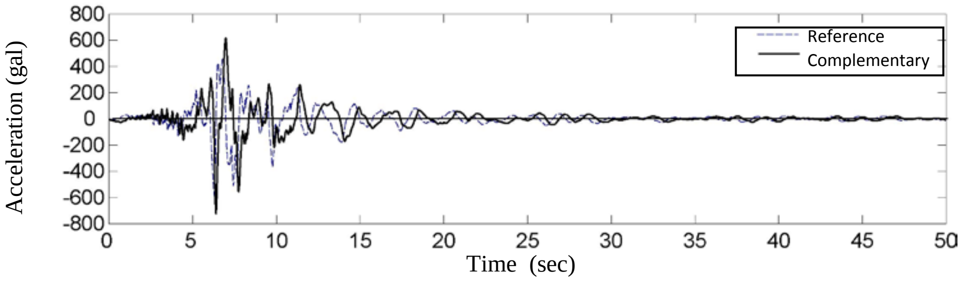
The Hilbert transform is a linear transformation of time series to add $\pi/2$ phase shift, while the amplitudes of all the frequency components are maintained [5]. Therefore, the Fourier amplitude spectra of the reference accelerogram $a_x(t)$ and of the complementary accelerogram $a_y(t)$ are identical. Although this fact does not guarantee that the elastic response spectra of the reference accelerogram and the complementary accelerogram are exactly identical, the elastic response spectrum of the latter can be expected to be approximately identical to that of the former. Assuming the situation that a unidirectional accelerogram compatible to the elastic design spectrum provided for the seismic performance assessment required in the structural design is use as the reference accelerogram $a_x(t)$, its complementary accelerogram $a_y(t)$ also approximately satisfies the compatibility to the elastic design spectrum. Therefore, the bi-directional accelerogram consisting of the reference and complementary waves can be used as an idealized bi-directional input ground motion compatible with the specified elastic design spectrum, which can be generated with a simple numerical procedure.

4. Example of generated bi-directional accelerograms

Examples of bi-directional input created by the proposed procedure are shown in this section. Two accelerograms provided in Japanese highway design code [1] are chosen as the reference unidirectional design-spectrum compatible ground motions: sample accelerogram No.1 for 'Level-2' 'Type-I' earthquake for soil condition III (denoted by I-III-1) and sample accelerograms No.1 for 'Level-2' 'Type-II' earthquake for soil condition III (denoted by II-III-1). The characters of the design earthquake ground motions I-III-1 and II-III-1



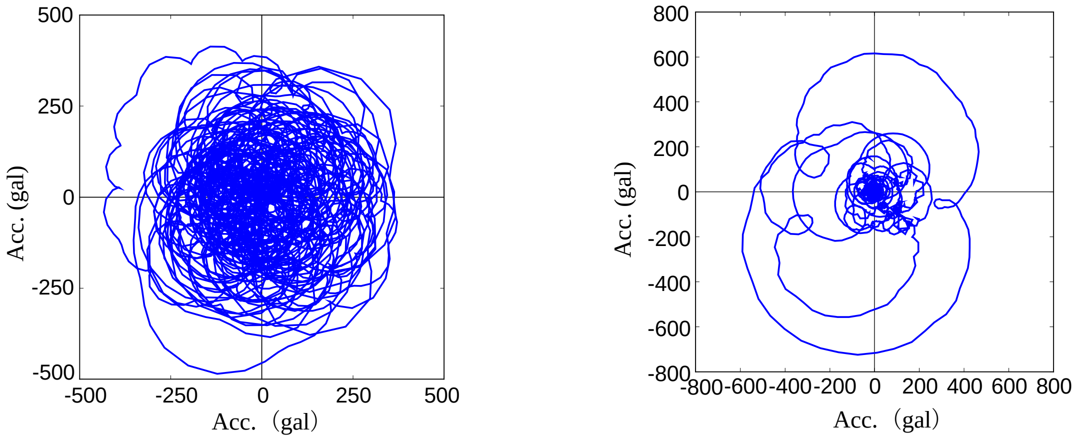
(a) Case I-III-1



(b) Case II-III-1

Fig. 3 – Reference and complementary accelerograms

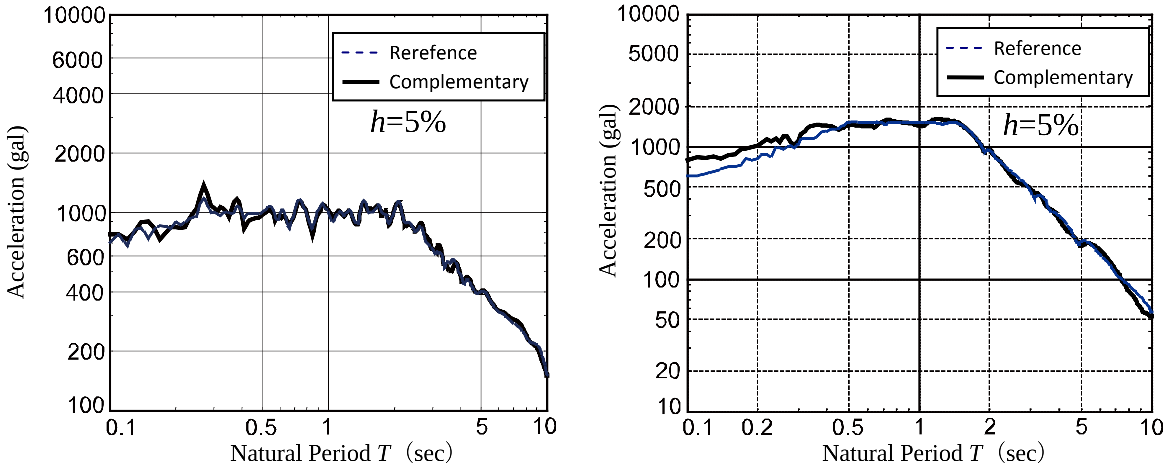
correspond to a near-source MCE with a moderate magnitude event, and a MCE assuming far-field seismic fault with a large magnitude event, respectively, on the soft soil condition. The reference and complementary accelerograms for the two cases are shown in Fig.3. Trajectories of the generated bi-directional ground motions using the reference accelerogram as the *x*-component and the complementary accelerogram as the *y*-component are shown in Fig.4.



(a) Case I-III-1 (b) Case II-III-1

Fig. 4 – Trajectories of generated bi-directional ground motions

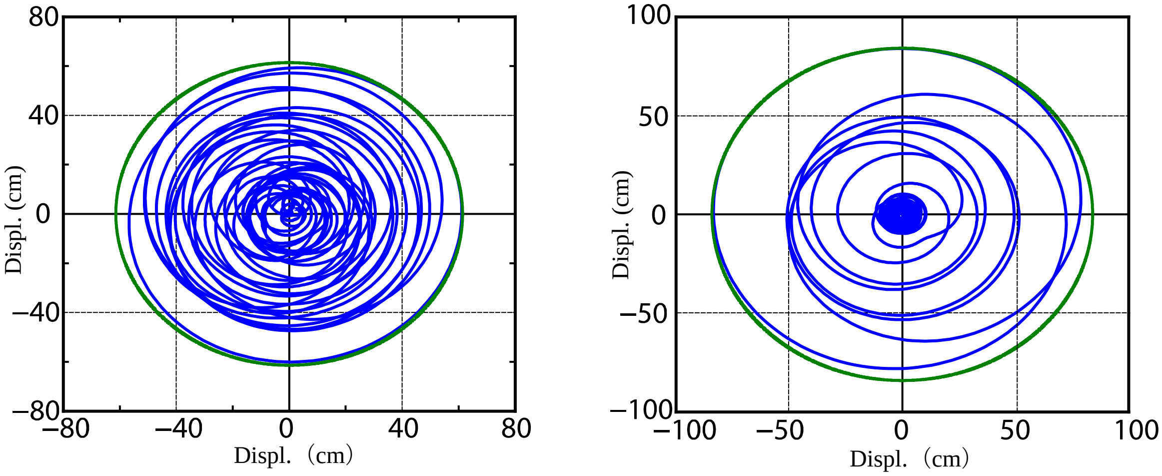
Plots of the response spectra comparing the reference accelerogram and the complementary accelerogram are shown in Fig.5. In both cases, the response spectra of the two accelerogram components are almost in good agreement, with the exception of the short-period range for Case II-III-1. This result indicates the validity of the hypothesis that the response spectrum of the complementary acclerogram and that of the reference accelerogram are approximately idential.



(a) Case I-III-1 (b) Case II-III-1

Fig. 5 – Comparison of response spectra

Bi-directional responses of 2-dimentional isotropic linear elastic single-mass oscillators under the generated bi-directional input excitation are computed. As the representative results, plots of displacement response trajectories of an isotropic single-mass isolator of a natural period of T =1.5 sec subjected to the two bi-directional inputs Case I-III-1 and Case II-III-1 are shown Fig. 6. The maximum response amplitudes obtained by the uni-directional input given by the reference accelerogram are indicated by the radius of the circles drawn with green lines. These plots indicates that the generated bi-directional input shows preferable properties for seismic performance assessment purpose, that strength of the bi-directional input is regarded as uniform for all directions, and that the maximum resultant bi-directional response and the maximum response by the uni-directional reference input are in good agreement.



(a) Case I-III-1 (b) Case II-III-1

Fig.6 – Response trajectories of an isotropic single-mass isolator (T =1.5sec) subjected to bi-directional inputs generated by the proposed method

5. Nonlinear response to bi-directional inputs created by the proposed method

The effect of the use of bi-directional input generated by the proposed procedure on the bi-directional response of nonlinear elasto-plastic structural system models is investigated by numerical dynamic analysis. The Multi-Shear-Spring (MSS) model with eight bilinear springs is used to represent the bi-directional elasto-plastic behavior of seimic isolators with energy dissipation capabilities, and a friction element to express the seismic dampers of friction-type attached between the superstructure of a mass of 900 t and the substructure, as shown in Fig. 7. Three initial natural period is selected to be 1.9 sec at the displacement amplitude of 500 mm. The load of the damper is assume to be 0.2 times the weight of the superstructure, and the initial length is 400 mm. The rotation of the damper axis due to the translational displacement of the superstrucre is considered in the analysis.

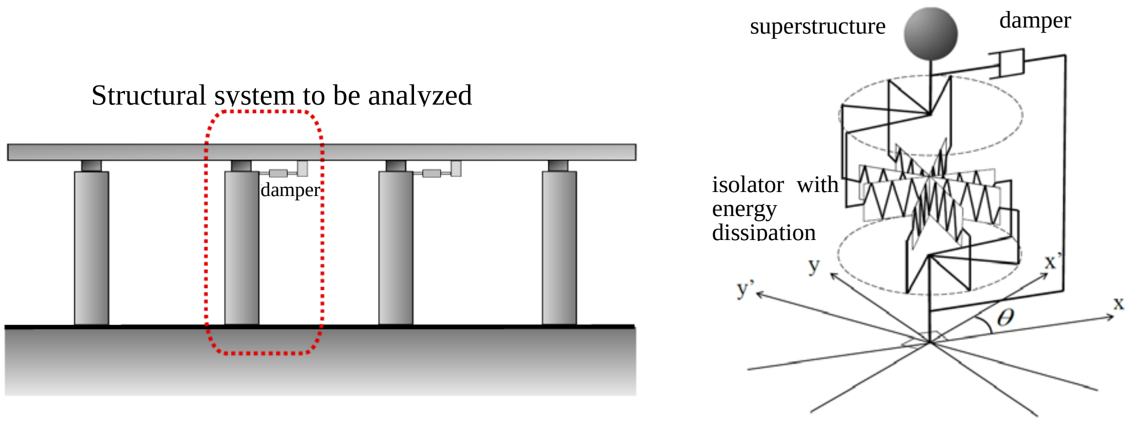
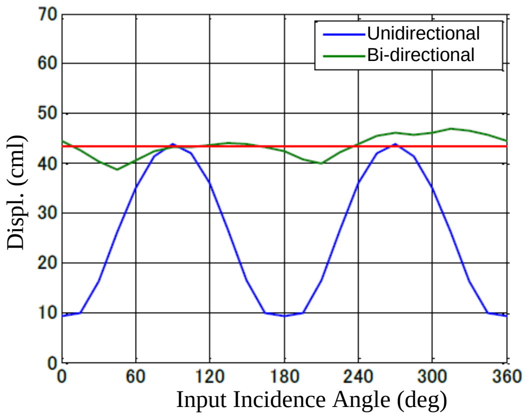
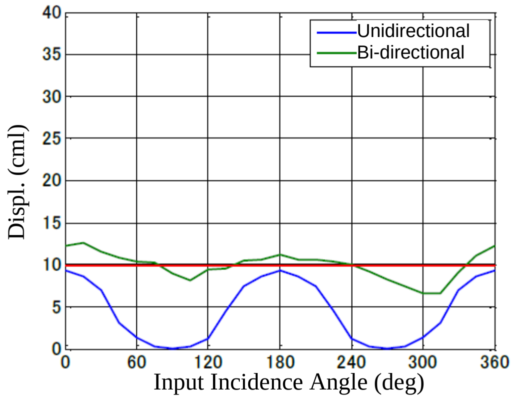


Fig. 7 – Nonlinear bi-directionalsingle-mass model of a bridge with seismic dampers

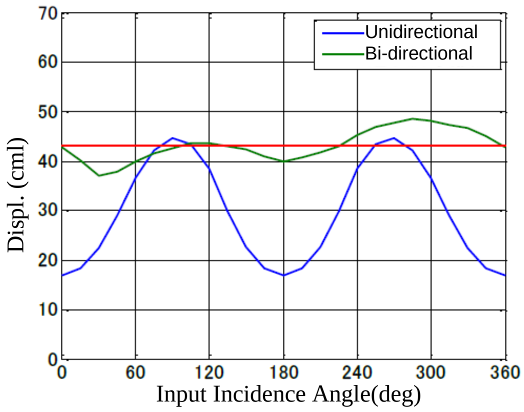


(a) Maximum displacement of isolator

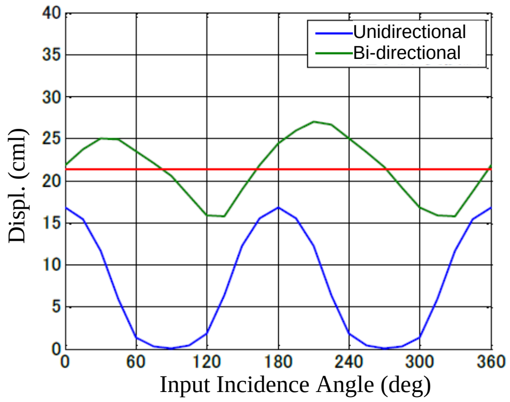


(b) Maximum displacement of damper

Fig. 8 – Response and incidence (Case I-III-1)



(a) Maximum displacement of isolator



(b) Maximum displacement of damper

Fig. 9 – Response and incidence (Case II-III-1)

The bridge response for the unidirectional input using the reference accelerogram and that for the proposed bi-directional input are compared. The dynamic analysis was carried out with various incidence angles of both types of input in the range between zero and 360 degrees, and the relationship between the obtained maximum response values and the incidence angle is plotted in Figs. 8 and 9 for Case I-III-1 and Case II-III-1, respectively. The particular responses plotted in these plots are the maximum resultant bi-directional displacements and the maximum damper displacements.

For Case I-III-1, no significant variation of the maximum response with respect to the incidence angle is observed in the plot of Fig. 8, and the average of the assessed displacement, indicated with a red line, is almost identical to the assessment using the unidirectional input. This observation is an indication of the validity of the proposed input in terms of consistency with the conventional seismic performance assessment method. On the other hand, the maximum response of the damper displacement in Case II-III-1 exhibits considerable variation with respect to the incidence angle, as well as a significant increase of possble maximum response from the assessment using the unidirectional input, as can be seen in Fig.9a. Careful attention is required for the assessment of some types of response quantities as the damper displacment which are sensetive to the bi-directional nature of the input for the near-source earthquake ground motions with a great level of nonstationarity.

6. Conclusion

In this study, a procedure to synthesize spectrum-matched bi-directional accelerograms with the use of complementary orthogonal component wave concept is proposed. In order to examine the character of the accelerograms synthesized by this procedure and significance in the seismic performance assessment of structures, the response of a bi-directional nonlinear elasto-plastic system models to the synthesized accelerograms is investigated. It is found that careful attention is required for the assessment of some types of response quantities as the damper displacment which are sensetive to the bi-directional nature of the input for the near-source earthquake ground motions with a great level of nonstationarity.

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