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A simplified approach to account for directionality effects on 2D dynamic soil-structure interaction analysis

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ABSTRACT: In this study, a simplified approach to account for directionality effects on two-dimensional (2D) dynamic soil-structure interaction analyses (DSSI) is proposed. When an earthquake is recorded, the direction with the maximum intensities rarely corresponds with the orientation of accelerometers and, therefore, the maximum response of a system generally takes place at an intermediate unknown orientation. A straightforward approach is to perform DSSI analyses with a number of linear combinations of the horizontal as-recorded components to obtain the peak response parameters for each orientation. Nevertheless, DSSI analyses are computationally expensive especially when the nonlinear behavior of the soil is considered. Here, three hypotheses are evaluated for predicting the angle that generates the maximum response of a building. By determining this angle in advance, only one DSSI analysis would be required to obtain the maximum response of a system for a given earthquake. Here, a particular case is analyzed where a ground motion recorded at a rock outcrop is used to derive the input motion for a finite element model, including a soil deposit and a surface structure. A series of 2D dynamic finite element analyses were performed to assess the proposed approach where input motions were obtained from the linear combination of the horizontal as-recorded components of the 1976 Friuli earthquake. The obtained results show the importance of considering directionality effects in DSSI analyses. The maximum response of the system was reasonably captured with the orientation obtained through the simplified approach.

1 INTRODUCTION

Existing guidelines consider as-recorded components of an earthquake as input motions for 2D DSSI analyses (NIST GCR 12-917-21 2012). Earthquakes' ground-motion are recorded in three orthogonal components: two horizontal (normally N-S and E-W) and one vertical. However, the orientation of recording accelerometers rarely captures the maximum intensities and, therefore, the maximum response of a system generally takes place at an intermediate unknown orientation.

Figure 1 shows (a) the acceleration time histories, (b) the response spectra from the linear combination of the horizontal components (from 0° to 180° with increments of 1°, see Equation 1 below), and (c) the acceleration hodogram from the 1976 Friuli earthquake (Italy). It can be observed that the E-W component shows larger spectral accelerations (for most periods) compared to the N-S, but it lies below the envelope of the spectra from the rotated histories (RotD100, Boore 2010). This fact is known as part of the directionality effect of strong motion recordings, and it is nowadays considered in ground-motion prediction equations (GMPEs) (Pinzón et al. 2018a) or in the performance of structures (Vargas-Alzate et al. 2018, Pinzón et al. 2018b).

An approach to deal with this issue would be to perform DSSI analyses with a number of linear combinations of the two horizontal as-recorded components to obtain the peak

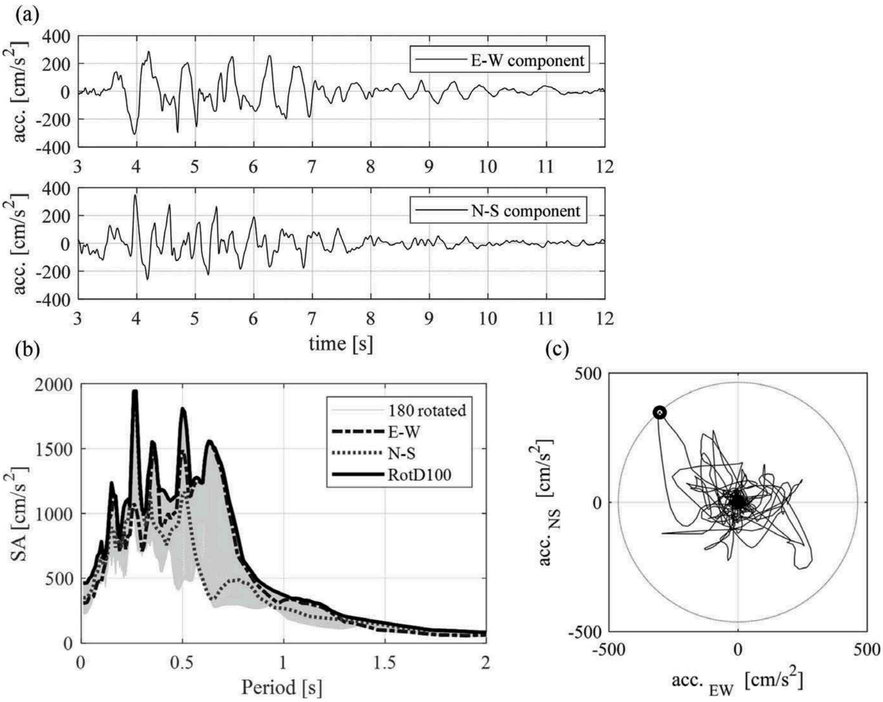

Figure 1. Friuli earthquake with moment magnitude (Mw) = 6.5, recorded at TLM1 station on May 6, 1976. (a) Ground motion horizontal components from Ambraseys et al. (2000) database, (b) response spectra from the as-recorded and rotated histories and the RotD100 response spectrum, and (c) acceleration hodogram.

response parameters. Nevertheless, DSSI analyses are computationally expensive especially when the nonlinear behavior of the soil is being considered.

A simplified approach is pursued in this study, where three hypotheses are evaluated to predict the angle that generates the maximum response of a building in a 2D DSSI analysis. These hypotheses are (1) the angle that generates the maximum Arias intensity of the signal (Arias 1970), (2) the angle where the maximum ground acceleration occurs, and (3) the angle that makes the response spectrum closest to RotD100. The main goal is to identify in advance the incidence angle that produces the maximum response of a system for a given earthquake and, therefore, to perform only one DSSI analysis including directionality effects.

Here, we address the specific problem where accelerograms recorded at a rock outcrop are employed to derive the input motion for a finite element model, including the soil deposit and a surface structure. To assess the proposed hypotheses, a series of 2D dynamic finite element analyses were performed using PLAXIS 2D (Brinkgreve et al. 2017). Input motions were derived from the linear combination of the horizontal as-recorded components of the 1976 Friuli earthquake (from 1° to 180° with increments of 2°). The structure at the surface is a 4-story steel frame building rigidly connected to a concrete raft foundation. The soil deposit corresponds to a 30 m deep medium to dense sandy layer, overlying a bedrock.

2 METHODOLOGY

2.1 *Complete Rotational Approach (CRA)*

In this method, a series of DSSI analyses are performed with the rotated horizontal ground motions of an accelerogram (the vertical component is neglected). Increments of 1° are usually employed in the range of 0° and 180°. Thus, 180 dynamic analyses per ground motion pairs need to be performed. In this way, the distribution of any output variable with respect to the incidence angle can be obtained allowing us to estimate the maximum response of a system for a given earthquake. The CRA can be summarized as follow:

- **STEP 1.** Soil-structure interaction (SSI) model
  2D modelling of the soil-building system.
- **STEP 2.** Seismic action
  Two as recorded orthogonal horizontal acceleration time histories are selected and rotated. The first calculation will be performed for one of the as recorded components, i.e. $\theta = 0$ (see Equation 1 below).
- **STEP 3.** DSSI analysis
  Perform the non-linear dynamic analysis for the selected seismic action.
- **STEP 4.** Repeat 2 and 3
  Steps 2 and 3 are repeated with increments of 1° in the range of 0° to 180°. Increments can be enlarged to reduce the number of analyses.

The rotated horizontal component $acc_{\mathrm{rot}}(t, \theta)$ is derived through the linear combination of the two as-recorded histories, as a function of the rotational angle θ, using the following equation:

$$acc_{\mathrm{rot}}(t,\theta) = acc_x(t,0)\cos\theta + acc_y(t,0)\sin\theta \tag{1}$$

where acc_x and acc_y are the two as-recorded horizontal components.

As a result, relationships between several output variables (e.g. roof displacement or base shear) can be obtained as functions of the rotation angle θ. However, this method entails high computational costs, and it would be of practical interest to develop a simplified approach allowing the determination of peak parameters with fewer computational resources.

2.2 *Simplified Rotational Approach (SRA)*

Here, a simplified approach is sought for the prediction of the orientation producing the peak response of the system. By deriving this angle in advance, only one DSSI analysis is required for a given earthquake compared to the 180 analyses needed in the former approach (if increments of 1° are employed). Three different hypotheses are evaluated: (1) the angle that generates the maximum Arias intensity of the signal (Arias 1970), (2) the angle where the maximum ground acceleration (PGA) occurs, and (3) the angle that makes the response spectrum closest to the RotD100 spectrum.

2.2.1 *Arias Intensity (AI)*

The Arias Intensity (AI) is a measure of the severity of a ground motion and represents the total energy per unit weight stored by a set of undamped simple oscillators through an earthquake (Arias 1970). The AI for a given rotated motion is defined in the following way:

$$\mathrm{AI}(\vartheta) = \frac{\pi}{2g}\int_0^{t_r} acc_{rot}{}^2(t,\vartheta)\mathrm{dt} \tag{2}$$

where g is the acceleration due to gravity and t_{f} is the total duration of the record.

The AI is estimated for each rotated signal. According to this hypothesis, the rotation angle producing the maximum AI will generate the maximum response of the system.

2.2.2 *Peak Ground Acceleration (PGA)*

As seen in the hodogram (Figure 1c), the acceleration direction of a ground motion varies in the horizontal plane. Therefore, for a given time, the maximum acceleration generally occurs at an orientation different from those of the recording accelerometer. By deriving the peak ground acceleration for each of the rotated motions, a PGA as a function of the rotation angle can be defined ($\mathrm{PGA}_{\mathrm{rot}}$), computed in the following way:

$$\text{PGA}_{\text{rot}}(\theta) = \max[|acc_{\text{rot}}(t, \theta)|] \text{for } \theta[0180] \tag{3}$$

According to this hypothesis, the rotation angle producing the maximum PGA_{rot} will generate the maximum response of the system.

2.2.3 *Maximum response spectrum*

The aim is to find the angle that generates spectral accelerations closest to the RotD100 spectrum within a given range of vibration periods, related with the fundamental period of the system. The two acceleration components are combined using Equation 1 with increments of 1° in the range of 0 and 180°. Because the response spectrum is defined as the maximum absolute amplitude of a single degree of freedom damped oscillator, this measure has a periodicity of 180°. The spectrum for a given rotated motion (SA_{rot}) is estimated as shown in Equation 4. The RotD100 spectrum represents the envelope of the 180 spectra from the rotated motions (Figure 2).

$$SA_{\text{rot}}(T, \xi, \theta) = \max\left(|u_{\text{rot}}(t, T, \xi, \theta)|\right)_{\text{for}t} \tag{4}$$

where $\ddot{u}_{\text{rot}}$ is the acceleration response of the oscillator, T is the vibration period, and the damping ratio Then, the angle that generates the $\text{RotI100T}_1\text{T}_2$ spectrum is estimated, defined as the response spectrum of an acceleration time series of a given rotation angle θ that minimizes a penalty function, defined in Equation 5, between periods T_1 and T_2. In other words, the $\text{RotI100T}_1\text{T}_2$ is the spectrum from a given rotated motion closest to the RotD100 spectrum in the considered range of periods. The present hypothesis assumes that the rotation angle corresponding to the $\text{RotI100T}_1\text{T}_2$ spectrum will produce the maximum response of the system.

$$penalty(\theta) = \frac{1^{N_{per}}}{N_{per}} \sum_{i=1}^{h} \left[\frac{SA_{rot}(Ti, \xi, \theta)}{SA_{RotD100}(Ti, \xi)} - 1 \right]^2 \tag{5}$$

where N_{per} is the number of sample periods between T_1 and T_2.

3 FINITE ELEMENT MODEL

Two finite element models have been developed to evaluate the directionality effects using the CRA and the SRA. The first one is the 4-story steel building depicted in Figure 3a with W16X89 and W14X68 columns and beam sections respectively. Connections between elements are fully restrained (ANSI/AISC 358 2010). The fundamental period of the building is 1.0 s.

In the second model, a soil layer is included to assess the influence of the SSI. The surface structure is the same than the first model, but it is founded on a 0.3 m thick concrete raft

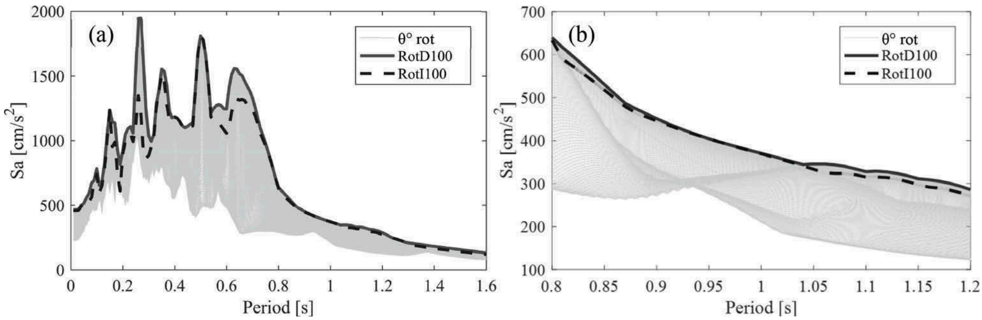

Figure 2. Response spectra from the rotated motions, the RotD100 spectrum, and the $\text{RotI100T}_1\text{T}_2$ spectrum [with (a) T_1=0.01 s and T_2=1.6 s and (b) T_1=0.8 s and T_2=1.2 s] from 1976 Friuli earthquake.

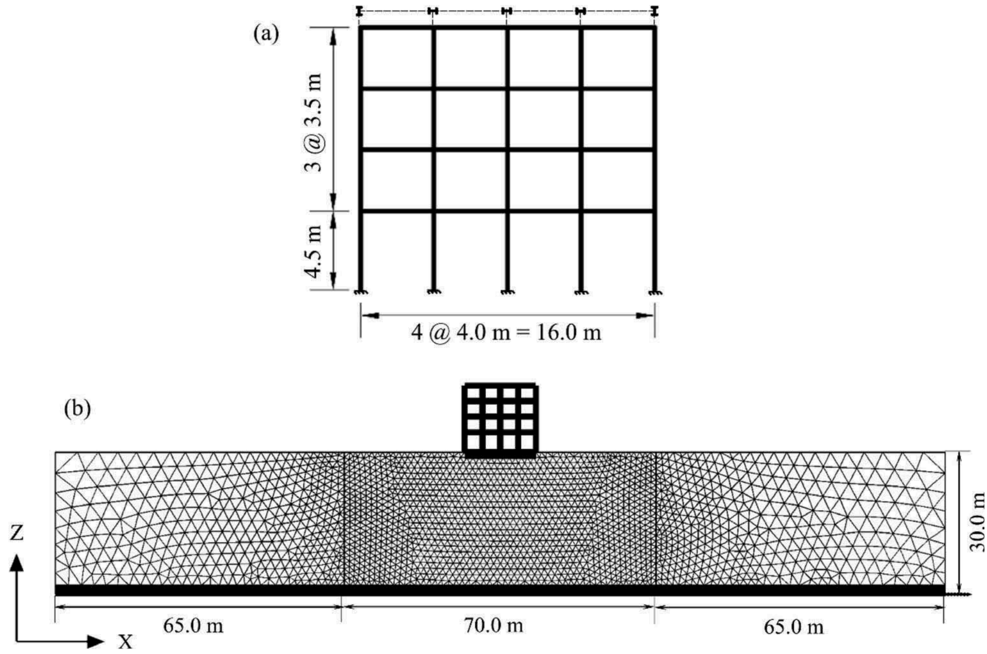

Figure 3. (a) Building and (b) soil-building finite element models.

(Figure 3b). The soil deposit is characterized as a 30 m deep medium to dense sandy layer, overlying a bedrock. The lateral extension of the model was considered large enough so that any unwanted wave reflections, occurring at the lateral free-field boundary conditions, are damped before reaching the zone were the SSI effects are relevant. The input-motions were applied at the base of the model through a compliant base (Joyner and Chen 1969) with minimum flection of the downward propagating waves. An elasto-plastic constitutive model (Brinkgreve et al. 2007) was employed to account for the nonlinear response of the soil. The model includes features like small-strain stiffness degradation, a hyperbolic hardening law, and a Mohr-Coulomb type limit surface. Both finite element models have been developed and analyzed using the PLAXIS 2D software (Brinkgreve et al. 2017).

As mentioned before, input motions were derived from the linear combination of the horizontal as-recorded components of the 1976 Friuli earthquake, recorded at TLM1 station (1° to 180° rotation angles with 2° increments). The station is located at a rock outcrop, which is assumed to correspond to the base rock of the soil's deposit. 90 analyses for each finite element model were performed in the case of the CRA. The main monitored variable was the roof displacement relative to the base of the building.

4 RESULTS

Results obtained through the CRA are depicted in Figure 4. Figure 4a shows the AI as a function of the rotation angle, where the maximum value is attained for an incidence angle of 153°. A quite similar result of 154° was obtained for the $SA_{rot}/SA_{RotD100}$ ratio (Figure 4c; gray lines represent the ratio for different periods between T_1 and T_2 and the black line is the average). The period range used was T_1=0.8 s and T_2=1.2 s, i.e. ±0.2 the fundamental period of the building. A somewhat smaller angle of 132° was derived using the PGA_{rot}.

The results obtained with the CRA are compared with those from the SRA. Figure 5 shows the maximum relative roof displacement as a function of the rotation angle, obtained through the CRA, for both models: (a) building and (b) soil-building. The values obtained with the SRA are also depicted in the figure. The SRA using the AI and the $SA_{rot}/SA_{RotD100}$ hypotheses

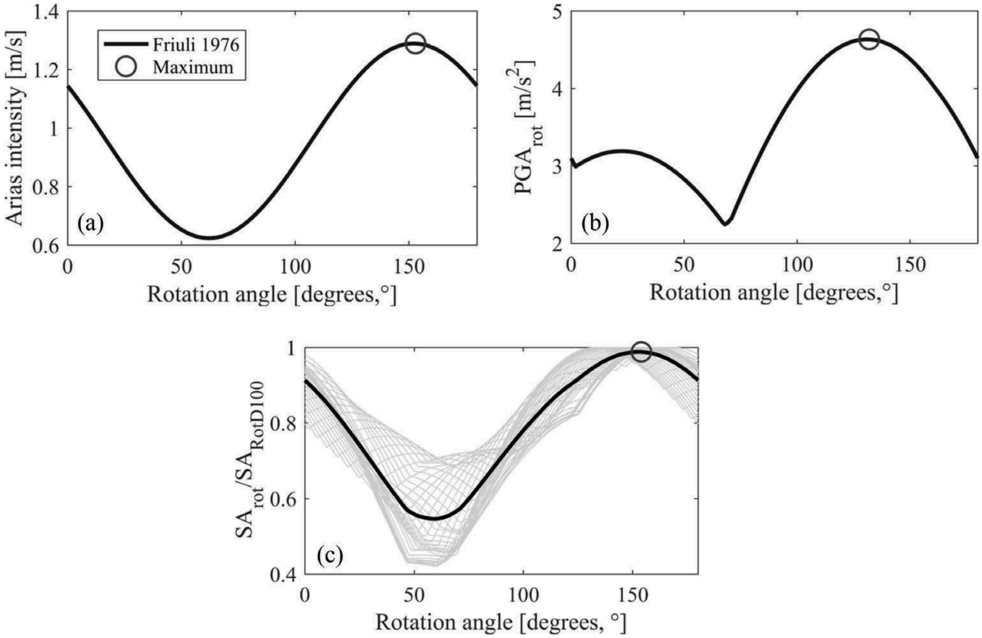

Figure 4. (a) Arias intensity, (b) peak ground acceleration, and (c) $SA_{rot}/SA_{RotD100}$ spectral ratios as a function of the rotation angle for the 1976 Friuli earthquake.

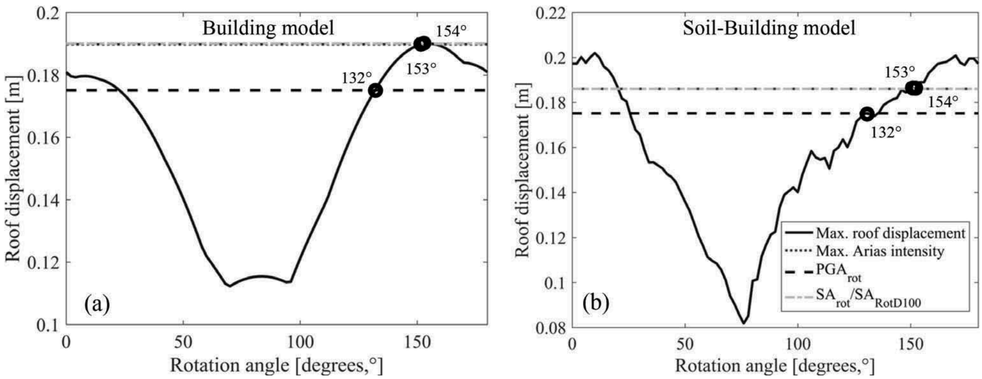

Figure 5. Comparison of the maximum roof displacements obtained for the (a) building and (b) soil-building models using the CRA (continuous line) and the SRA.

captured adequately the angle where the maximum response of the building occurs (in terms of roof displacements). Values more distant are obtained with the PGA_{rot} hypothesis.

In the case of the soil-building model, none of the three hypotheses of the SRA captured adequately the angle of the maximum response. Since they were derived only from the input time-histories, which are applied at the base of the model, they overlook site effects that might modify the motion when propagating through the soil's deposit. For this reason, free-field calculations were included in the SRA. They correspond to finite element models of the soil's deposit, without any surface structure, where the incidence angles of the SRA are computed from the time-histories recorded at the top of the soil layer. Although this entails conducting free-field finite element analyses for each rotation angle, they require significantly less computational resources compared to the full DSSI analysis (Figure 3b) since only a slender column of soil, with special lateral boundary conditions, is required (Mánica et al. 2014). Free-field

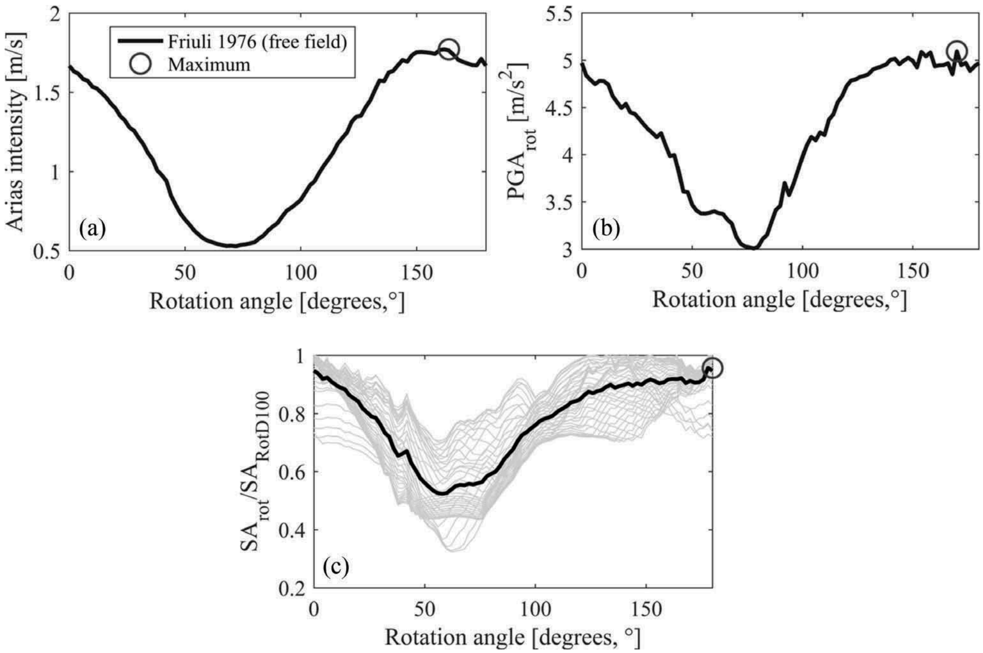

Figure 6. (a) Arias intensity, (b) peak ground acceleration, and (c) $SA_{Rot}/SA_{RotD100}$ spectral ratios as a function of the rotation angle for the 1976 Friuli earthquake derived from the time histories computed on the top of the free-field analyses.

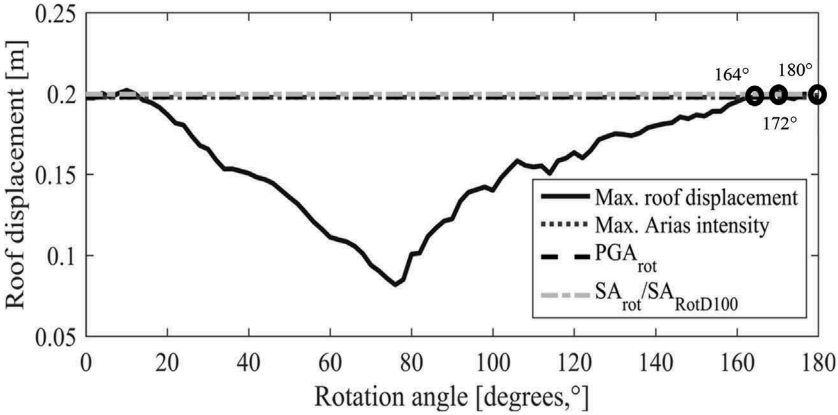

Figure 7. Comparison of the maximum roof displacements obtained for the soil-building model using the CRA (continuous line) and the SRA combined with free-field calculations.

calculations are generally performed using frequency-domain methodologies to reduce calculation times where nonlinearity is introduced through iterative procedures (Schnabel et al. 1972). However, the full elastoplastic model employed prevents the use of frequency-domain methods to assess the free field response.

The obtained results combining the SRA and the free-field calculations are shown in Figure 6. The angles obtained for the AI, PGA_{rot}, and $SA_{rot}/SA_{RotD100}$ hypothesis were 164°, 172°, and 180° respectively; they are all larger than those obtained only from the input time-histories. In Figure 7, they are compared with the results of the full DSSI analysis. In this case, the peak roof displacement was reasonably captured with the three hypotheses of the SRA.

5 CONCLUSIONS

Obtained results show the importance of considering directionality effects in DSSI analyses. They suggest that peak parameters of a system, including directionality effects, might be obtained from a single DSSI analysis decreasing calculation times considerably. Nevertheless, site effects must be incorporated, at least in this particular case were the input motion was recorded at a rock outcrop which is assumed to correspond to the rock base of the soil's deposit. These site effects might be included through free-field computations. The proposed hypotheses of the SRA must be validated through additional analyses with different characteristics such as diverse ground motion records; building structural typologies, shapes, and heights; and soil's deposits with different properties.

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