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Methodology for the development of input motions for nonlinear deformation analyses

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ABSTRACT: Nonlinear deformation analyses (NDAs) are widely used in engineering practice to evaluate the seismic performance of geosystems. Results from an NDA strongly depend amongst many factors (e.g. numerical platform, soil model, site characterization, etc.) on the input motions. Unrealistic input motions may overly dominate the response of the soil-structure system, and thus overshadow all other components of an analysis, especially when it is performed in the framework of a validation exercise. A practical methodology for the development of input motions for NDAs of geosystems based on ground motion recordings is proposed. This methodology has three main features: (1) capability to properly modify surface ground motion recordings for use in dynamic analyses; (2) accounting of the spatial variation of seismic waves in the input ground motions; and (3) incorporation of the uncertainty related to site-specific characterization. Input motions developed using the proposed methodology are expected to be more compatible with site-specific conditions and to be used to capture a range of possible geosystems' dynamic responses.

1 INTRODUCTION

The selection of input ground motions for design varies depending on the application (e.g. Rathje et al. 2010). Different protocols have been published over the years, each one targeting at providing guidelines for the selection of ground motions for: (1) the seismic design of buildings, (2) the response-history analysis of low- and medium-rise buildings, (3) the performance-based nonlinear response-history analysis of buildings, and (4) the design or evaluation of nuclear power plants. However, these guidelines lack a framework for the selection of input ground motions particularly for geotechnical earthquake engineering applications.

Within the framework of geotechnical earthquake engineering, input ground motions are utilized in nonlinear deformation analyses (NDAs) towards two main goals: (1) to study the behavior of geosystems under seismic loads leading up to design; and (2) to study the behavior of geosystems subjected to past earthquake events (e.g. case histories studies and validation studies). Although there are generally no constraints for the selection of ground motions in the former case, apart from an overall target fit to a spectrum, only a small number of input motions can typically be used in the latter, limited to the recordings of the event of interest. Additionally, NDAs require input motions compatible with an in-depth location, aligned with the bottom boundary of the numerical grid, rather than free field conditions. These requirements, in combination with the lack of data and the uncertainties involved in the field of seismology, make the selection and the if-need-be modification (i.e. development) of input ground motions for NDAs a challenging task.

Common practices for the development and assignment of input ground motions in NDAs vary depending on the type of available recording(s) (Figure 1): (1) *within* motions; (2) *outcropping* motions; and (3) *free surface* motions. Within and outcropping motions can be directly used in NDAs in combination with an appropriate boundary condition (e.g. Kwok et al. 2007), while free surface motions need to undergo a deconvolution analysis (e.g. Mejia & Dawson 2006) and be

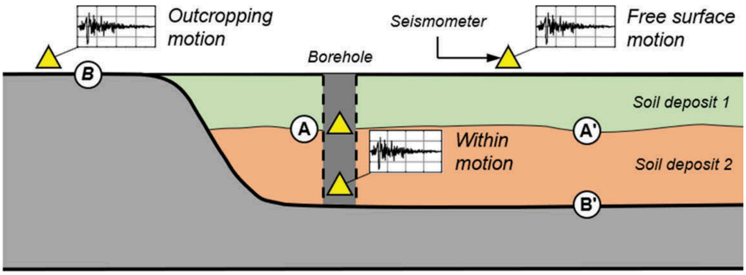

Figure 1 . Types of ground motion recordings based on seismic station locations.

subsequently assigned as within ones. All three approaches carry uncertainties and limitations: (a) Results from deconvolution analyses may inadvertently lead to numerical errors and the procedure is thus frequently not recommended; (b) for all three cases the spatial variation of ground motions is typically neglected, and a single ground motion is applied at the base of NDAs. Whereas this simplification is reasonable for small scales, it might not be realistic for extended geosystems (e.g. dams, levees, buried lifelines, etc.); (c) uncertainties associated to input motions may overly dominate the responses from NDAs and thus overshadow all engineering efforts put into the implementation of other components of the analyses. This has been pointed out by various researchers (e.g. Bray & Travasarou 2007, Bradley 2011) who have concluded that input ground motions are the biggest source of uncertainty in NDAs. Conversely, the uncertainty associated to the development of input ground motions is rarely quantified.

This paper implements a practical methodology for developing horizontal input ground motions for NDAs. This methodology offers an alternative to deconvolution analysis for the modification of free surface motions and addresses the oversight of spatial variability of ground motions and uncertainties. The proposed methodology aims to enhance ground motion characterization procedures for the evaluation of extended geosystems subjected to earthquake events, i.e. the study of case histories and the validation of numerical modeling tools against them.

2 COMMON PRACTICES FOR THE DEVELOPMENT OF INPUT GROUND MOTIONS

Developing input motions for NDAs at a "*study site*" refers to the process of using motions recorded at a "*reference site*". Depending on the location of the latter (Figure 1) three types are defined:

2.1 *Within ground motions*

Within ground motions are motions recorded at various depths in vertical downhole arrays. Such recordings are widely used in research to study wave propagation through vertical profiles towards validation of site response analysis techniques or the evaluation of incoherence (e.g. Abrahamson 1992, Zerva 2009). Within motions provide valuable information at a specific site and depth, however their usability in analyses at different locations is limited and thus they are rarely utilized in practice. Within ground motions can be used without modification in NDAs at different sites at the same depth as recorded, if soil conditions are similar (locations A and A' in Figure 1). In NDAs, within ground motions must be used along with a rigid base boundary condition (Kwok et al. 2007), which implies that dissipation of energy is not allowed.

2.2 *Outcropping ground motions*

Outcropping ground motions are motions recorded on the ground surface at sites with high enough impedance to behave linearly under strong ground motions (i.e. rock outcrops). These recordings can be used as in-depth input motions within soil deposit sites at depths of similar impedance (B and B' in Figure 1). This location is referred to as the elastic half space (EHS) and the selection of its location is a topic of extensive ongoing research.

The key assumption behind the use of outcropping recordings as input motions is that the reflection of upward-propagating waves at outcrops takes place with no amplification or deamplification. The upward-propagating wave is then assumed to be identical at different neighboring locations sharing the same medium (grey zone along boundary BB' Figure 1). Thus, the selection of outcropping recordings for NDAs relies on the similarity between any two sites: the *reference site* and the EHS at the *study site*. The identification of the EHS should be supported by geology, i.e. it is recommended that the outcropping station and the EHS belong to the same geological formation or share geological features (particularly stiffness). Failure to choose an appropriate *reference site* may lead to errors in site response analyses (e.g. Cabas et al. 2014). Due to the lack of recorded outcropping ground motions, the effects of shallow softer layers (e.g. weathered rock) are often overlooked and recordings considered to correspond to be actual outcropping sites.

2.3 *Free surface ground motions*

Free surface ground motions are motions recorded at surfaces of soil deposits without a restriction on impedance and are commonly modified through deconvolution analysis and used in NDAs. Deconvolution is an inverse equivalent linear procedure, where a recorded free surface ground motion is utilized to calculate the motion that would have been recorded at depth. Advantages over other approaches (e.g. generation of stochastic time histories), include: (1) its implementation in several software, e.g. Shake2000 (Ordonez 2012), DeepSoil (Hashash et al. 2017), and Strata (Kottke et al. 2018); (2) its need for minimum site characterization, i.e. most importantly a shear wave velocity profile; and (3) its computational efficiency. Engineering practice and research (e.g. Markham et al. 2015, Chiaradonna et al. 2018) has widely adopted deconvolution due to its usability. Deconvolving ground motions may, however, inadvertently lead to numerical errors and a biased response with its issues being similar to issues pertaining to equivalent linear one-dimensional site response analyses:

- It cannot be performed if the equivalent linear conditions have been greatly violated by nonlinearities in which case judgement needs to be exercised;
- It implicitly assumes that recorded ground motions result from vertically-propagated waves only. Contributions from higher-frequency surface waves, as well as inclined trapped, and reflected waves generated by basin and topographic effects are missed. Typically, such contributions lead to higher surface accelerations. The oversight of this fact can lead to ground motions with unreasonably high accelerations (see example application). Silva (1988) studied the coherency between observed and theoretical vertically-propagated surface motions at the Richmond Field Station and concluded that only about 75% of the power of a surface recording can be modeled through vertical propagation of waves, and suggested that 87% of a pre-filtered (low-pass filter at 15 Hz) free surface recording be initially used for deconvolution analysis. These findings have been taken as recommendations and extrapolated to different sites, but results are only applicable to the Richmond Field Station;
- The transfer function used depends on the soil properties between the surface and the depth of interest at the *reference site*, thus deconvolved ground motions carry the signature of that site and should generally not be used at locations with different shallow material properties;
- Due to its iterative nature, more than one deconvolved motions may be estimated from a recorded free surface ground motion depending on the number of iterations chosen, especially when large strains are involved, i.e. there is no unique solution (Kramer 1996).

3 PROPOSED METHODOLOGY FOR THE DEVELOPMENT OF INPUT MOTIONS

A methodology is presented for the development of input motions for NDAs based on ground motion recordings, and it has three main capabilities: (1) development of input motions from free surface recordings without using deconvolution analysis; (2) incorporation of ground motion spatial variation; and (3) consideration of uncertainties related to seismic site response analysis. The methodology process is illustrated in Figure 2 and has two main stages each or both used depending on the applicable scenario: (1) modification of recording ground motions to be compatible with soil conditions at the base of the NDA model; and (2) generation of incoherent ground motions to account for the spatial variability. Uncertainties associated to site and ground motion characterization utilized in these two stages are accounted for throughout the process.

3.1 *Modification of recorded ground motions*

Ground motion recordings need to be modified to be compatible with in-depth conditions. In this section all locations are shown in Figure 3. Common practices for within and outcropping ground motion recordings have been adopted and a new practice is developed for the scenario when free surface records at a *reference site* (D) are used to develop input ground motions for the base of an NDA analysis at a *study site* (E). The similarity in shear wave velocities up a depth of about 150 m (B) allows the development of input ground motions for analyses within the soil deposit 2.

The procedure is based on two premises: (1) two ground motions generated by the same earthquake and propagated to the surface from the same location and through the same soil profile derive similar transfer functions; and (2) nearby locations, with similar soil profiles at depth (geologically and in terms of impedance) but different shallow materials, will have common ground motions up to the depth of similar conditions (B and C). Based on these two assumptions, the ground motion at the base of an NDA model (E) can be computed from a free surface ground motion (D) and two transfer functions, TF_1 and TF_2 obtained from the propagation of an earthquake similar to the recorded one. The Fourier amplitude spectrum of this ground motion is calculated using seismological theory and the point source model (or generated separately and directly input), implemented in the software Strata v0.6.3 (Kottke et al. 2018) at a deep location, "A". Random Vibration Theory (RVT) is utilized to propagate this ground motion to the surface and compute TF_1 and TF_2, required to modify free surface ground motions. The use of seismological source models and RVT has two main advantages: (1) a ground motion similar to the recorded earthquake at the seismic station can be simulated as opposed to arbitrarily selecting a recorded ground motion; and (2) there is no need for time series to perform site response analysis.

Let GM_C, GM_D, GM_E, and GM_B denote the ground motions in frequency domain at locations "C", "D", "E", and "B" respectively. Thus, $TF_1=GM_C/GM_D$ and converts the free surface motion "D" to obtain the motion at the soil-rock contact at the *reference site* "C", location at which ground motions are expected to be reasonably similar to those at depth in the *study site* (B). Similarly, $TF_2=GM_E/GM_B$ and converts the ground motion "B" at depth (common between the *reference* and the *study sites*) into a ground motion at a shallower depth at the *study site*. Therefore, for the input ground motion at point "E" based on the free surface recording:

$$GM_{E(study)} = \frac{GM_C}{GM_D} \cdot \frac{GM_E}{GM_B} . GM_{D(reference)} = TF_1 \cdot TF_2 \cdot GM_{D(reference)} \tag{1}$$

where the product $TF_1 \ldots TF_2$ serves as scaling factor to modify a free surface recording to obtain an input motion at a depth of interest. Note that GM_B and GM_C in Equation (1) are equivalent and could be canceled out, however, it is useful to keep this relation so that each TF

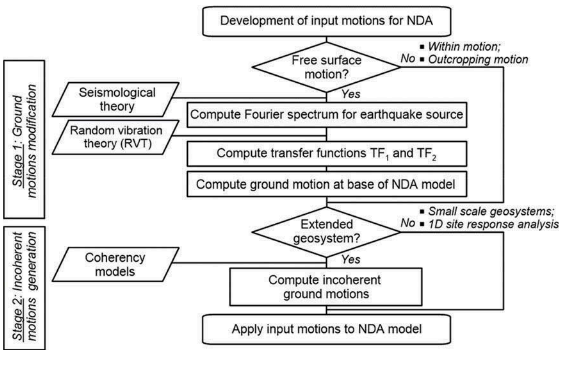

Figure 2 . Flow chart of methodology for the development of input ground motions for NDAs.

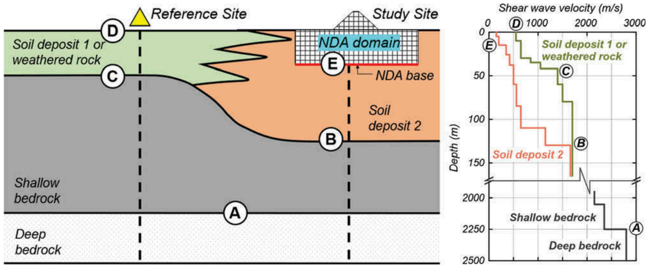

Figure 3 . Scheme of a typical case where input ground motions for NDAs are needed.

can be computed directly from independent site response analyses. By using TFs from convolution analyses, this procedure offers a more robust alternative than deconvolution to modify free surface recordings.

3.2 *Incoherent ground motions*

NDA models vary in length, ranging from small (e.g. shallow foundations) to large scale simulations (e.g. dams). The latter often involve the implementation of NDA models of several hundreds of meters long. Over these large distances, it is expected that phase variations of the ground motion will take place, producing incoherent ground motions with different phases and amplitudes. Thus, using a single motion at the base of an NDA domain (Figure 3) is not a realistic assumption.

Incoherent ground motions result due to four factors (Zerva 2009): (1) wave passage effect, which refers to the difference in arrival time of inclined plane waves to impinge a site (Figure 4, where t denotes the time delay between the arrival of waves 3 and "n"); (2) extended source effect, which is the delay in waves transmitted to the ground surface from different locations of a fault as its rupture propagates; (3) scattering effect, explaining changes in the direction of propagation due to the presence of defects in the medium; and (4) attenuation effect, related to the decrease in wave amplitude as they travel away from the source. Out of these factors, the attenuation effect may not be significant within the scale of most man-made structures. Spatial variation of earthquake ground motions and its effects on concrete structures have been widely studied in the past (e.g. Abrahamson 1985, Hao et al. 1989, Der Kiureghian 1996), however little research has been conducted for geotechnical engineering applications (e.g. pipelines).

The coherency, $\gamma_{jk}(\omega)$, between two ground motion records '*j*' and '*k*', can be calculated as:

$$\gamma_{jk}(\omega) = \frac{S_{jk}(\omega)}{\sqrt{S_{jj}(\omega)S_{kk}(\omega)}} \tag{2}$$

where $S_{jk}(\omega)$ is the smoothed cross-spectrum between the two records, defined as the Fourier transform of the cross-covariance function, and $S_{jk}(\omega)$ and $S_{jk}(\omega)$ are the power spectral density functions of the records *j* and *k*, and ω is the circular frequency. The lagged coherency is defined as the absolute value of the coherency and is the phase variation between two signals. Unlike phase variability, variations in amplitude have not been widely studied and no explicit models for amplitude variability have been proposed (Zerva 2009).

The proposed methodology generates a suite of equally spaced incoherent time series of acceleration based on a seed motion. The seed motion is the input motion representative of conditions at the base of the NDA model (either the within or outcropping recordings, or the modified free surface ground motion) and is modified by adding a stochastic component to the phase angle and shifting the phase due to wave passage effects. Incoherent motions are generated based on a separation distance through an iterative procedure to match a coherency model (Abrahamson 1992).

3.3 *Incorporation of uncertainties*

A number of seismological and geotechnical parameters are involved in the development of input ground motions for NDAs. Uncertainties are unavoidable due to limitations of current

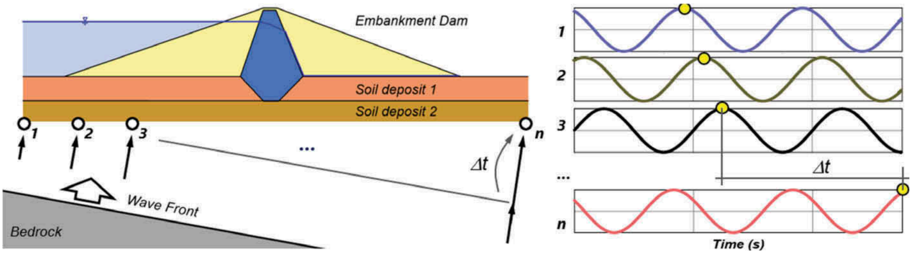

Figure 4 . Incoherent ground motions impinging the foundation of an earth dam.

measurement techniques, the spatial variability of soils, the lack of data, or simply the limitations of knowledge to fully characterize natural phenomena. These uncertainties might lead to a single ground motion developed with the proposed methodology (or any other preferred practice) deviating from what is more accurate for a *study site*. Thus, it is highly recommended to develop multiple equally-possible input ground motion realizations as opposed to a 'best' one. The main sources of uncertainty related to the proposed methodology are:

- Shear wave velocity profiles: outside of research there is currently no established technique to quantify the uncertainty associated to shear wave velocity measurements (in shear wave velocity and thickness of layers);
- Equivalent linear properties of the soils involve a high level of uncertainty. A good understanding of the site conditions is required to select a suite of appropriate dynamic properties;
- Incoherent ground motions are generated based on a coherency model and a stochastic component. Thus, more models should be considered to account for this uncertainty;
- Seismological parameters; there is uncertainty associated to some of the seismological parameters used to reproduce the earthquake of interest, e.g. stress drop and site attenuation.

Ranges of potential values (e.g. based on a standard deviation) for the aforementioned parameters and others if appropriate, must be considered for the computation of transfer functions as described in Section 3.1. For example, the software Strata has the capability to incorporate uncertainties related to soil properties through the generation of multiple profiles through Monte Carlo simulations. Uncertainty associated to seismological parameters could also be included through different input motions. Finally, multiple suites of incoherent ground motions should be generated for each input ground motion previously computed (i.e., for each seed motion).

4 EXAMPLE APPLICATION

Input ground motions are developed for the evaluation of the Balboa Blvd. case history (*study site*) located within the San Fernando Valley (Los Angeles, USA). The site underwent significant ground deformation during the M6.7 Northridge earthquake in 1994. This event has been recorded at several sites, including the Rinaldi Receiving Station (RRS), which is a free surface *reference site* located approximately 2 km away from the *study site*. The Balboa Blvd., due to its length of about 600 m (Figure 5a), can be viewed as an extended geosystem. Given the available recording and dimensions of the *study site*, it is suited for the application of the proposed methodology.

A suite of 11 equally spaced (every 50 m) incoherent motions are developed at a depth of 15 m. Shear wave velocity profiles for the study and reference sites were obtained using the Unified Community Velocity Model (Small et al. 2017). As the two sites are close, the V_s profiles from UCVM were the same (Figure 5b), which eliminates the need for TF_2. Uncertainty associated with shear wave velocity was accounted by considering a range of □20% in Strata. Seismological parameters for the Northridge earthquake were utilized and the transfer function TF_1 was calculated based on RVT. Subsequently, multiple input motions were computed. Figures 5c and d compare time history of accelerations and Fourier spectra respectively of the computed modified ground motions against a deconvolved, which presents unreasonably high accelerations.

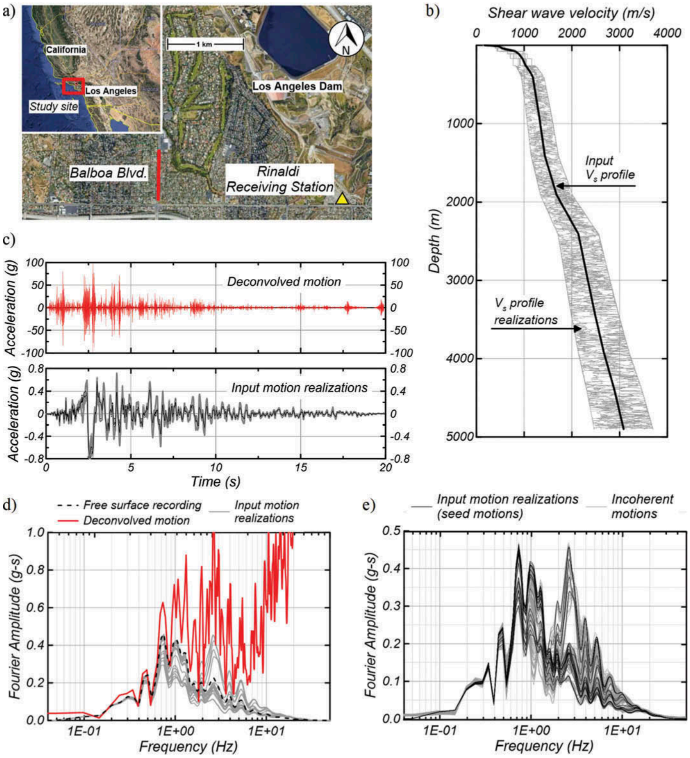

Figure 5 . Location of the study and the *reference sites*; b) Shear wave velocity profile; c) Time histories of accel-erations; d) Fourier spectra comparison; e) Fourier spectra of 20 suites of input motion realizations.

Finally, each possible ground motion was utilized as a seed to generate a suite of incoherent motions to be applied along the base of the NDA for the Balboa Blvd. site. Figure 5e shows the Fourier spectra of amplitudes for these motions.

5 SUMMARY AND CONCLUSIONS

Common practices for the selection and assignment of input motions for NDAs were reviewed, and associated applications, assumptions, and limitations were summarized.

A practical methodology was proposed for developing input motions for NDAs based on ground motion recordings. This methodology adopts common practices for the application of within and outcropping recordings and describes a procedure for the modification of free surface recordings, consisting of the application of transfer functions computed from site response analyses based on seismological theory and RVT. Spatial variation of ground motions is incorporated by generating a series of incoherent ground motions compatible with coherency models from the literature and based on a separation distance. Uncertainties related to site response analysis were listed and recommended to be accounted for in the process. The proposed methodology facilitates the development of more realistic input motions compatible with site specific conditions and accounting for uncertainties associated with seismic site response analysis. It overcomes limitations of common practices and offers a robust alternative to modify free surface recordings. The adopted approach leads to the development of multiple equally-possible input motion realizations as opposed to a single "best" one, thus capturing the range of geosystems' dynamic responses. The methodology can also be used to compute ground motions for 1D site response analysis if incoherent ground motions are not needed. The procedure is meant for relatively neighboring locations. If similar seismological and geotechnical environments are encountered at distal sites, then additional modifications are required to account for attenuation effects (e.g. with GMPEs).

This methodology works within the framework of the equivalent linear analysis and thus has similar limitations. Recordings from reference sites with very low shear wave velocity profile or that have experienced extreme nonlinearities (e.g. ground failure) during shaking are not recommended for developing input motions. Modification of free surface recordings requires transfer functions computed from 1D site response analyses, which do not account for contributions from surface, inclined and trapped waves; thus, amplitudes of such transfer functions might be systematically underestimated. This issue is believed to be minor compared to the uncertainties related to the selection of subsurface parameters. Currently ongoing sensitivity analyses are expected to identify the ranges of uncertainties of the various parameters and their effect on the final motion.

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