BROADENING THE UTILIZATION OF CSMIP DATA: DOUBLE CONVOLUTION METHODOLOGY TOWARDS DEVELOPING INPUT MOTIONS FOR SITE RESPONSE AND NONLINEAR DEFORMATION ANALYSES

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Abstract

The double convolution methodology for the development of input motions for site response analyses and nonlinear deformation analyses is briefly presented. This methodology uses deep V_S profiles and random vibration theory to modify ground motions recordings from top-of-soil stations ("reference site") such that they are compatible with conditions at a neighboring location ("target site") and some selected depth (halfspace), while preventing numerical errors associated with the inverse nature of a deconvolution analysis. The methodology can be particularly useful for obtaining input ground motions for the forensic investigation of case histories or further modified to meet some design criteria and used for site response analyses and the subsequent determination of hazard at the surface for the seismic performance assessment of structures. The proposed approach is termed "double convolution" as it uses two site response analyses (SRAs) to compute a desired transfer function (TF). The methodology is briefly presented followed by a demonstration of its implementation in an open-access webtool.

Introduction

Ground surface seismic stations are dominant in most seismic networks around the world. Recordings from these stations are commonly used as input motions in site response analyses (SRAs) and 2- or 3-dimensional (2D or 3D hereafter) nonlinear deformation analyses (NDAs) employed for (1) the design of structures such as dams, bridges, and buildings; and (2) the study of case histories either towards validating numerical procedures or towards forensically investigating possible causes of failures (e.g., Pretell et al. 2021). For instance, Figure 1 presents a schematic of a typical scenario where input ground motions are needed for the evaluation of the seismic performance of a dam using NDAs. In this case, the target site and depth are the location of the dam and the depth of the halfspace, respectively.

Common approaches for developing input ground motions for the design of structures consist of two steps: (1) the selection of recordings based on a seismic scenario and site conditions consistent with the halfspace; and (2) the modification of the recordings to approximately match a spectral shape, a ground motion intensity measure, or meet some other criterion such that the resulting ground motions are consistent with the halfspace (e.g., Abrahamson 1992a, Hancock et al. 2006, Watson-Lamprey and Abrahamson 2006, Baker et al. 2011, Arteta and Abrahamson 2019, Mazzoni et al. 2020). The first step strongly depends on the candidate recordings available, which are often selected from recording stations (i.e., reference site in Figure 1) that have an inverse of the average slowness on the top 30 m (V_{S30}) higher than 760 m/s, i.e. rock sites (ASCE 2016). These stations are commonly referred to as "outcropping rock." Outcropping rock stations are not widely available in shallow crustal tectonic regions as they add up to only 3% of the ground motion recordings from the Center for Engineering Strong Motion Data (CESMD) as of June 2020. In the case of forensic studies, the ability to replicate the case history strongly depends on available seismic stations as candidate ground motions should be representative of the specific seismic scenario, at a specific location and depth. The limited number of ground motions recorded at outcropping rock sites leads practitioners and researchers to use ground surface motions recorded at soil sites, hereafter referred to as "ground surface recordings," with some modifications.

Several procedures are used for the development of input ground motions in the absence of recordings from rock stations. A common approach is deconvolution analysis, which is a type of 1D SRA that allows for the computation of ground motions that would have been recorded at some depth given ground motion recordings at the ground surface at the same site. Deconvolution can occasionally lead to numerical errors and spurious ground motions (Kramer 1996). Other approaches for the modification of ground surface recordings include the procedures proposed by Cabas and Rodriguez-Marek (2017) and Ntritsos et al. (2021), which respectively use V_S-κ_0 correction factors, and a four-step approach including deconvolution to account for differences between the target and reference (i.e., recording station) sites.

This paper presents a methodology for the modification of ground motion recordings from ground surface stations to be representative of conditions at some target depth and an example of its implementation in an open-access webtool. The ultimate goal of this work is to broaden the utilization of data from the Center for Engineering Strong Motion Data (CESMD) and ground surface stations in general. Specific results are expected to provide: (1) a robust yet practical methodology for the development of at-depth input ground motions based on ground surface recordings, and (2) a user-friendly web-based tool accompanied by a user guide and example applications.

Approaches for developing input ground motions

Deconvolution analysis (Schnabel et al. 1972, Kramer 1996) is commonly used in engineering practice and research for the development of ground motions at depth based on a ground motion recorded at the ground surface (e.g., Mejia and Dawson 2006, Chiaradonna et al. 2018). It is a practical technique; however, it is also highly sensitive to the analysis input parameters such as the V_S profile (Cadet et al. 2011) and may run into numerical instabilities that impact the accuracy of the resulting ground motions (e.g., Roesset et al. 1995, Di Giulio et al. 2014). Common practices for preventing numerical issues when using deconvolution analysis include (1) scaling down the ground motion amplitudes such that only the ground motion fraction that can be explained by vertical propagation of waves is used (e.g., Silva 1988); (2) post-filtering of ground motions to remove any unreasonably high-frequency content (e.g., Silva 1988, Markham et al. 2015), and (3) using strain ratios and number of iterations different than the values traditionally used in equivalent linear SRAs (Bartlett et al. 2005). These approaches are either not implemented in most commercial programs or are developed based on observations specific to a single site and are thus of little use to the practicing engineer. In addition, oftentimes the site and depth of interest are not the seismic station and the sensor depth, but rather a neighboring location. Thus, a subsequent convolution analysis accompanied by scaling or other procedures may be required to adapt the deconvolved ground motion to the target location. Cabas and Rodriguez-Marek (2017) as well as Nritsos et al. (2021) have presented other approaches for dealing with this issue.

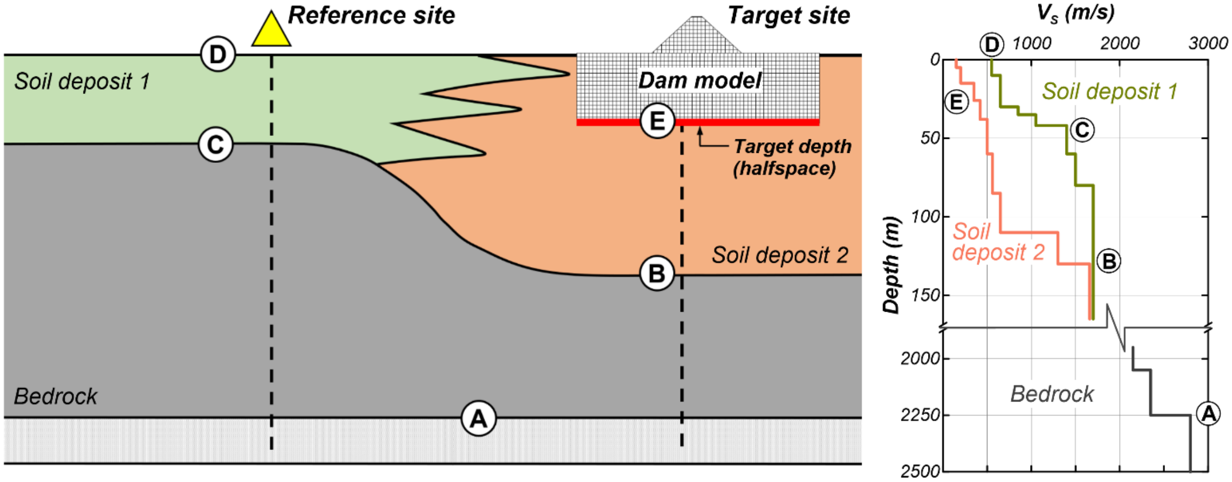


Figure 1. Schematic of a typical scenario where input ground motions for site response analyses (SRAs) or nonlinear deformation analyses (NDAs) at a target site can be developed based on a ground motion recorded at a reference site (seismic station).

Double convolution methodology for the development of input ground motions

The double convolution methodology allows for the development of ground motion recordings at a target site and depth (consistent with the conditions there) based on recordings from a ground surface station. Figure 1 shows a schematic of a project site with a neighboring seismic station where the approach can be used for the modification of ground motion recordings. In this schematic, input ground motions are developed for NDAs at the halfspace, location “E” at the “*target site*,” based on ground motion recordings from a neighboring top-of-soil station, location “D” at the “*reference site*.” Three additional locations need to be defined in Figure 1. Assuming that the target and the reference sites are sufficiently close, the geological conditions at these sites should become increasingly similar with depth, such that there are two locations, “B” and “C,” on a common geological horizon (see later Figure 3). Ongoing research is investigating several scenarios such that the range of acceptable closeness or distance between the reference and target sites can be determined. Thus, an earthquake generated at a deeper location should cause the same upgoing wavefield from an arbitrary location “A” to “B” and to “C.” In fact, the Vs profiles at the reference and target sites can stop at the depth corresponding to “B,” but herein a deeper location (“A”) is considered for simplicity in computing the profiles. Based on this reasoning and assuming that 1D wave propagation holds for kilometer-deep applications, random vibration theory (RVT)-based 1D SRAs (Hanks and McGuire, 1981; Boore, 2003; Rathje et al., 2005) can be conducted assuming an input motion at “A” to estimate the ground motions at “B,” “C,” “D,” and “E.” Then, the input ground motion at “E” can be estimated as:

$$\mathrm{FAS}_{\mathrm{E}}^{\mathrm{target}} = \frac{\mathrm{FAS}_{\mathrm{C}}}{\mathrm{FAS}_{\mathrm{D}}} \cdot \frac{\mathrm{FAS}_{\mathrm{E}}}{\mathrm{FAS}_{\mathrm{B}}} \cdot \mathrm{FAS}_{\mathrm{D}}^{\mathrm{rec}} \qquad (1)$$

where $\mathrm{FAS}_{\mathrm{E}}^{\mathrm{target}}$ is the Fourier amplitude spectrum (FAS) of the target input ground motion, $\mathrm{FAS}_{\mathrm{D}}^{\mathrm{rec}}$ is the ground motion recorded at the reference station, and $\mathrm{FAS}_{\mathrm{C}}$, $\mathrm{FAS}_{\mathrm{D}}$, $\mathrm{FAS}_{\mathrm{E}}$, and $\mathrm{FAS}_{\mathrm{B}}$ are computed using SRAs given an assumed input ground motion, $\mathrm{FAS}_{\mathrm{A}}$.For convenience, each ratio on the right-hand side of Equation (1) can be expressed as a TF:

$$\mathrm{FAS}_{\mathrm{E}}^{\mathrm{target}} = \mathrm{TF}_1 \cdot \mathrm{TF}_2 \cdot \mathrm{FAS}_{\mathrm{D}}^{\mathrm{rec}} \qquad (2)$$

where TF_1 modifies the ground motion recording at “D” to be compatible with the stiffer horizon at “C,” and TF2 propagates the ground motion from “B” (equivalent to “C”) to “E.” With TF_1 and TF_2 calculated, then the ground motion at location “E” is estimated by taking the inverse Fast Fourier Transform (iFFT) of $\mathrm{FAS}_{\mathrm{E}}$. Figure 2 illustrates a flow diagram for the double convolution methodology.

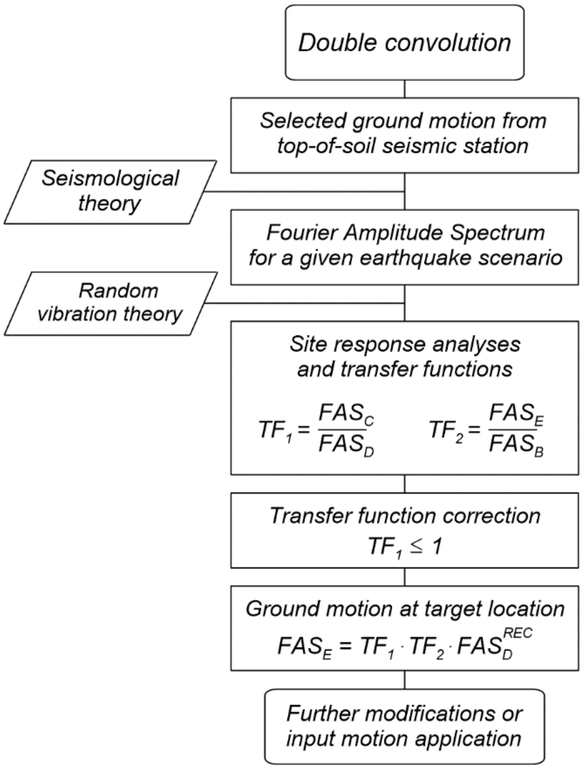


Figure 2. Methodology for the development of input ground motions for site response and nonlinear deformation analyses. Adapted from Pretell et al. (2019).

The input motion at “A” is defined using seismological models (e.g., Brune 1970, 1971; Boore, 2003), finite fault simulations (e.g., Beresnev and Atkinson, 1998), or any other method, and different attention is required depending on the application. In the case of modifying weak ground motions that do not yield any level of soil nonlinearity, any input ground motion can be used if linear elastic 1D SRAs are conducted for the double convolution approach. In the case of modifying strong ground motions that lead to a moderate level of soil nonlinearity (i.e., shear strains lower than 0.1% based on Kaklamanos et al., 2013), then the input motion should be defined based on the characteristics of the specific recording’s earthquake event (e.g., magnitude and distance) and calibrated to yield a FAS at “D” that is like the recorded ground motion. The accuracy in the input ground motion allows to properly capture any softening that the soil underwent during the earthquake. RVT is recommended herein as it does not require time histories and thus ease the input motion definition at "A."

Simplifications and extensions of the double convolution approach can be included depending on specific needs and site conditions. In cases where the ground motion recordings are needed at some depth at the reference site (i.e., from "D" to "C" in Figure 1), then $TF_2 = 1$. In cases where input ground motions are needed for forensic analyses and the target and reference stations are relatively far apart (with this still being under investigation), then the resulting ground motion can be further modified to account for differences in path effects (e.g., Chiaradonna et al., 2018; Ntritsos et al., 2021). Similarly, in cases where the input ground motions are required for engineering design, then the ground motions resulting from double convolution can be further modified to match a design spectrum (e.g., Hancock et al., 2006; Watson-Lamprey and Abrahamson, 2006; Baker et al., 2011; Kalkan and Chopra, 2010; Kwong and Chopra, 2015; Arteta and Abrahamson, 2019; Mazzoni et al., 2020), or to generate a suite of incoherent ground motions (Abrahamson, 1992b, 1993; Zerva, 2009) for the analysis of geographically distributed geosystems.

The double convolution methodology is different from previously proposed approaches. This methodology provides (1) a robust and practical technique for the modification of ground surface recordings to make them compatible with conditions at some target site and depth; (2) the ability to account for moderate soil nonlinearities such as those handled by equivalent linear SRAs, i.e., maximum shear strains lower than 0.1% (Kaklamanos et al. 2013); and (3) the potential for efficient propagation of uncertainties. The double convolution approach uses deep V_S profiles to account for site effects within high-V_S materials, which are typically considered negligible and might lead to underestimation of the seismic response (Steidl et al. 1996). The interested reader is directed to Pretell et al. (2021) for more information on the deep V_s profiles and some of the challenges involved in the process. The proposed methodology uses 1D linear elastic or equivalent linear SRAs along with RVT, and thus carries the same limitations as these tools, e.g., omission of ground motion lengthening effects and changes in ground motion phase due to wave propagation.

Web-based application tool

An open-access web application tool is being developed to make the double convolution methodology accessible and usable by the broader community of practicing engineers and researchers. This tool will facilitate the generation of input motions for SRAs, NDAs, and similar applications. The web tool provides a user-friendly and intuitive graphical user interface (GUI) for taking the input parameters of the model: reference and target site profile characteristics, target depths for the development of input ground motions, and the recorded earthquake motion at the ground surface. These input data are then synthesized to generate time histories of accelerations that can be used as input ground motions for SRAs, NDAs, and other similar applications. The web tool is developed using React (Facebook Inc. 2021), Flask (Pallets Projects 2021), and pystrata (Kottke et al. 2022). Figure 3 shows the web application architecture and request-response cycle. React is used to build the front end, i.e., the application's user interface (UI). Flask is used to build the back-end server to receive, send, and process the requests made by the user. Finally, any analysis involved in the double convolution methodology is performed in the back end using python and the pystrata implementation (Kottke 2019). The web tool will be made available online and accessible to the public. In addition, a user manual with analysis guidelines and example applications will be provided to assist the users in using the tool. Its capabilities and intuitive and user-friendly GUI are expected to be of valuable use to the geotechnical engineering practice and academia in providing a practical yet robust approach for developing ground motions. Figure 4 illustrates the interface of the web application tool with the tabs “Reference Site,” “Target Site,” “Ground Motion,” “Analysis Parameters” for receiving input parameters, and the “Results” tab for showing the synthesized input ground motions after performing the double convolution analysis.

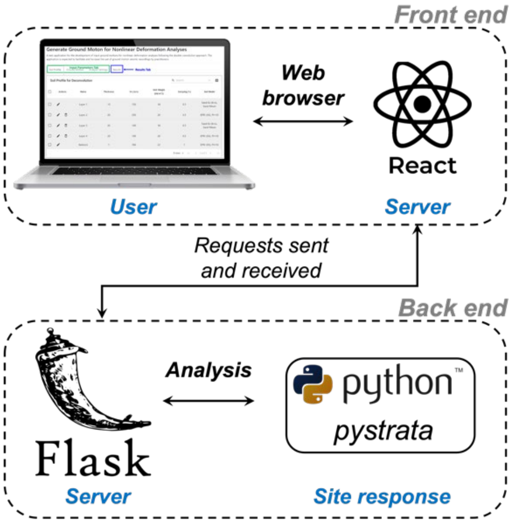
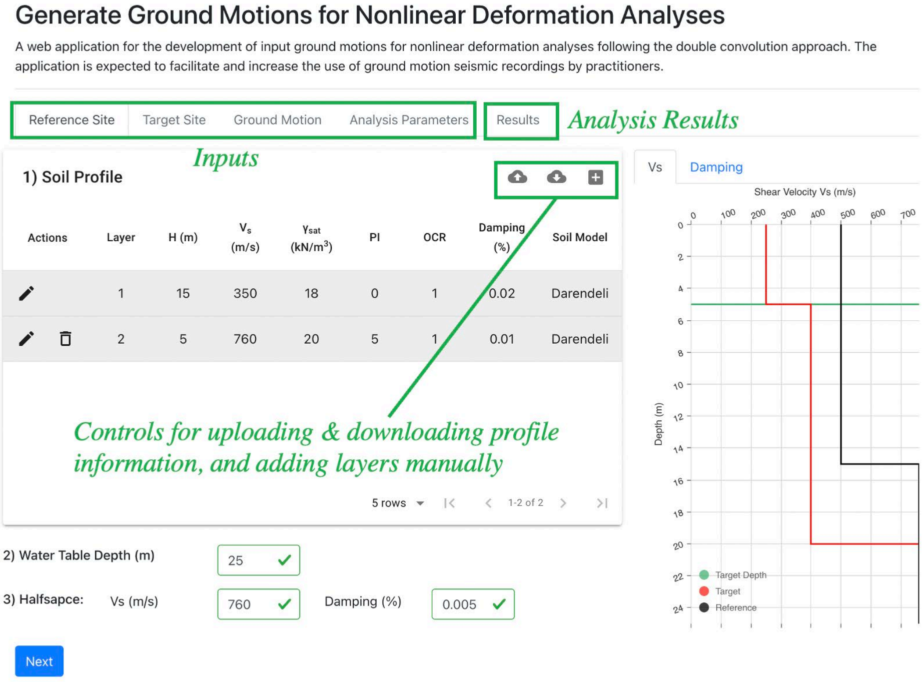


Figure 3. Web application tool architecture and request response-cycle.



Generate Ground Motions for Nonlinear Deformation Analyses

A web application for the development of input ground motions for nonlinear deformation analyses following the double convolution approach. The application is expected to facilitate and increase the use of ground motion seismic recordings by practitioners.

1) Soil Profile

Actions	Layer	H (m)	V_s (m/s)	γ_{sat} (kN/m^3)	PI	OCR	Damping (%)	Soil Model
	1	15	350	18	0	1	0.02	Darendeli
	2	5	760	20	5	1	0.01	Darendeli

2) Water Table Depth (m): 25

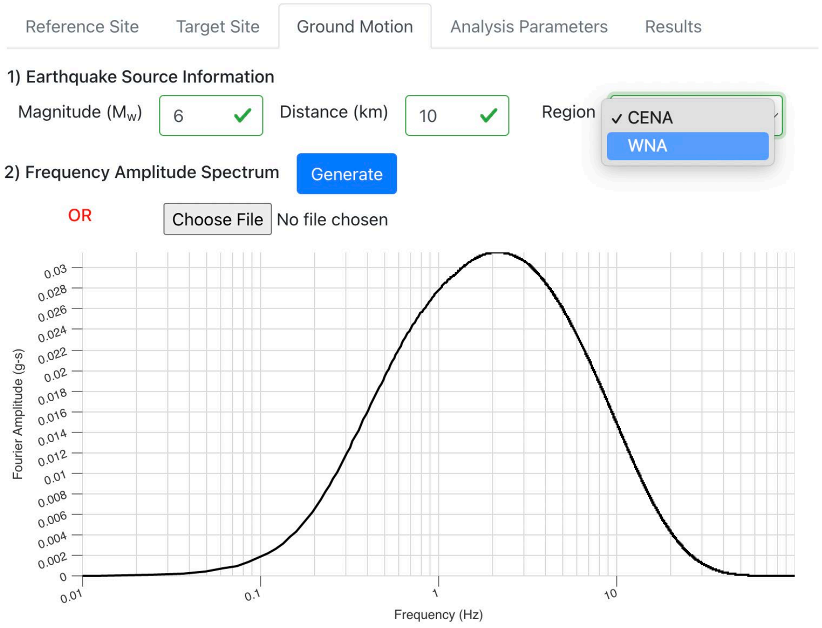
3) Halfsapce: Vs (m/s): 760 Damping (%): 0.005

Figure 4. Web application interface for inputting reference and target soil profile

Features and Simple Example

Some currently implemented features of the webtool are:

1) Interactive plots of shear wave velocity and damping profiles for target and reference site.
2) Performs both linear elastic and equivalent linear analyses. These options are available under the "*Analysis Parameters*" tab. (Figure 7)
3) Ability to download and upload the soil profile data for reference and target site (see annotations of Figure 4).
4) The Fourier Amplitude Spectrum (FAS) of the ground motion can be generated from the Earthquake-Source model or can be provided as a separate file under the "*Ground Motion*" tab (Figure 5).
5) Results from the 1-D site response analysis include plots of (a) Transfer Functions and (b) maximum shear strain profiles (Figure 8).
6) For generating input motions from the obtained transfer functions: the user can either select a suite of motions (provided in the tool) or upload their own motion file. Results from the motion analysis include: (a) time-history, (b) Fourier Amplitude, and (c) Response spectrum plots. (Figure 9)
7) Tooltips (graphical user interface elements in which, when hovering over a screen element or component, a text box displays information about that element) are also currently being implemented at multiple locations of the tool in order to assist users more efficiently.
8) Allows downloading of the generated input motion from the analysis. The user can again choose another ground motion and correspondingly generate the input motion for the NDA analysis. (Figure 9)


1) Earthquake Source Information

Magnitude (M_w): 6 ✓

Distance (km): 10 ✓

Region: ✓ CENA / WNA

2) Frequency Amplitude Spectrum

Figure 5. Options for specifying input motion.

Figure 5 illustrates a simple scenario to demonstrate how the web tool may be used. For simplicity Point A is considered the common horizon of upward traveling waves. Here, the goal is to find the motion at point C (target site) subject to knowing the motion at point B (top-of-soil recording at reference site). All shear wave velocities are considered uniform.

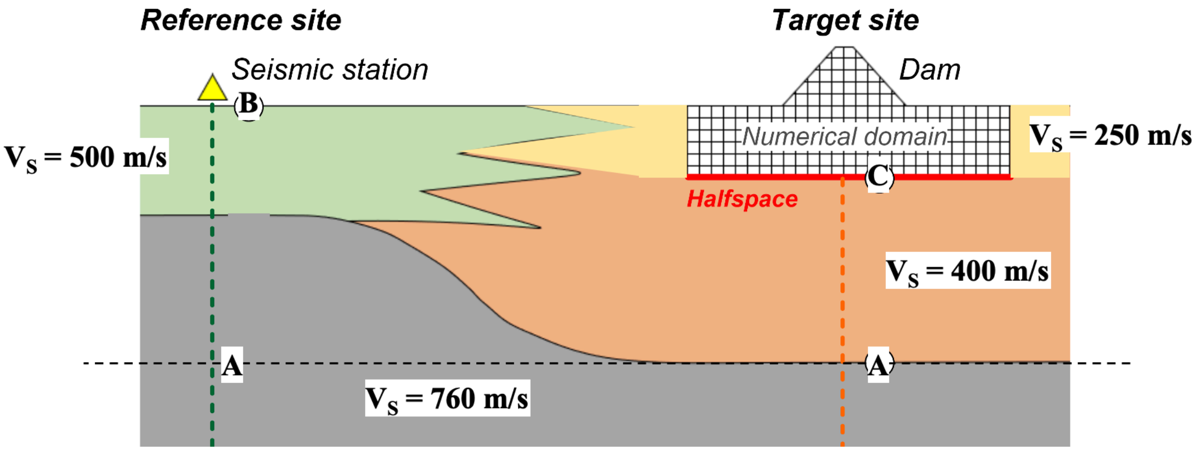
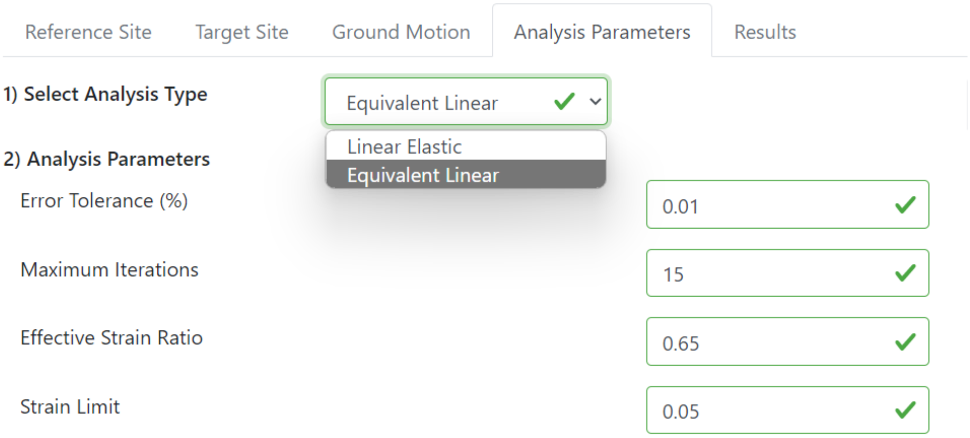


Figure 6. Example profile. The points are renamed relative to Figure 1 and the common deep horizon is at A considering that the target site is not very deep.

The model is generated by tabbing through the available menus starting from specifying the two sites and the depth of interest at the target site. Options include specifying the depth of the water table (assuming constant across) and the stiffness of the halfspace in terms of shear wave velocity. Figure 5 illustrates the options for specifying the Motion at Point B. Figure 7 shows the available options under the "Analysis Parameters" tab for the Equivalent Linear method. Once the user enters those, the analysis automatically commences. When done, results are automatically presented under the Results tab (Figures 8 and 9). The user has the option of downloading the developed motion. An planned addition is to add the ability to run multiple scenarios so uncertainties can be tracked.



1) Select Analysis Type: Equivalent Linear

2) Analysis Parameters

Error Tolerance (%): 0.01

Maximum Iterations: 15

Effective Strain Ratio: 0.65

Strain Limit: 0.05

Figure 7. Web application interface for specifying analysis parameters.

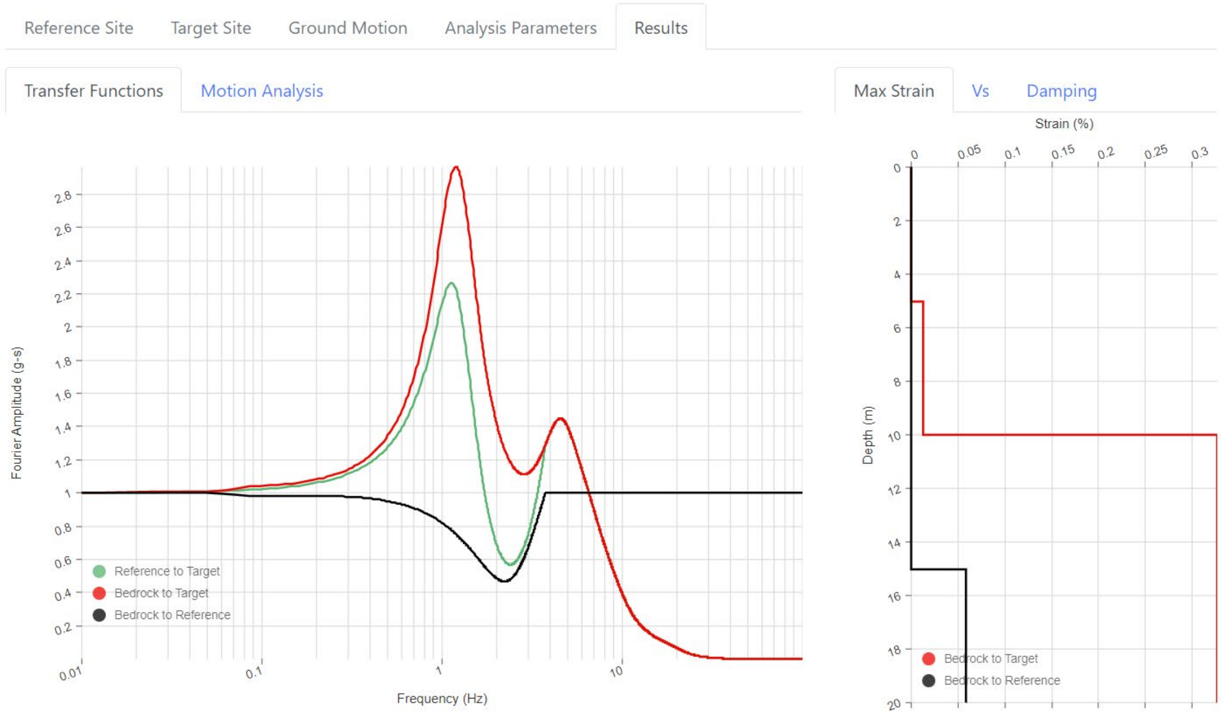


Figure 8. Results on transfer functions (see earlier descriptions) between the different locations of interest and the maximum shear strain profiles obtained from the site-response analysis

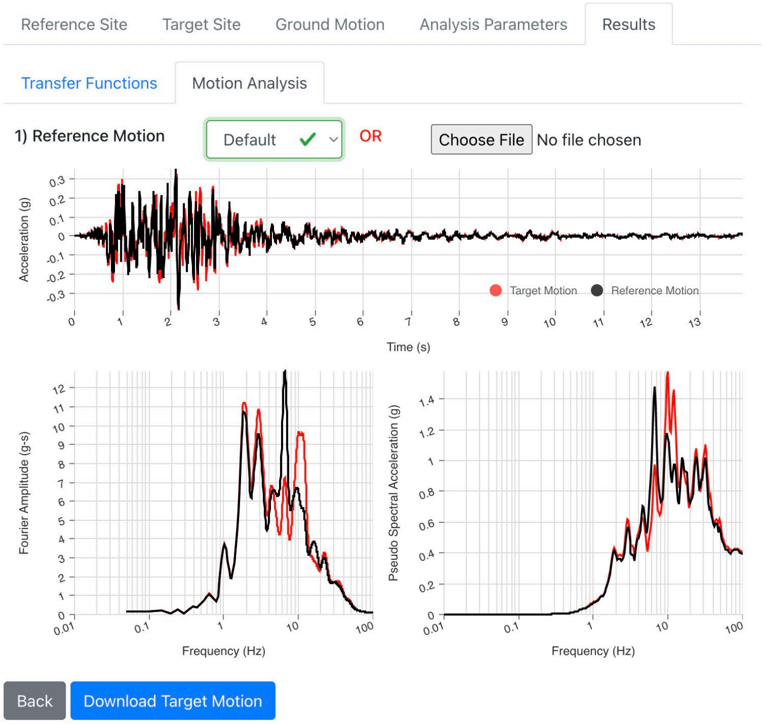

1) Reference Motion: Default

Figure 9. Motion analysis under Results. Results are presented in terms of accelerations time history, Fourier Amplitude Spectra, and Pseudospectral Accelerations.

Final Remarks

This paper briefly presented the double convolution methodology for the development of input ground motions primarily for the performance of site response analyses (SRAs) and nonlinear deformation analyses (NDAs) towards the design of structures or the forensic investigation of case histories. The double convolution methodology utilizes ground surface recordings, which dominate most seismic networks in the world. Advantages of the double convolution methodology as compared to commonly used and previously proposed approaches are: (1) its robustness in computing ground motions at a target depth based on ground surface recordings, (2) its implementation in a user-friendly interface to eventually facilitate the use of the proposed methodology in engineering practice and research, (3) the ability to account for moderate soil nonlinearities, and (4) the potential for efficient propagation of uncertainties.

The double convolution methodology addresses a problem of practical importance. Expected outcomes of this investigation include: (1) a robust yet practical methodology for the development of input ground motions, and (2) a user-friendly web-based tool accompanied by a user guide and example applications. The paper presented the webtool interface that is currently under development and a workflow alongside with the results it yields.

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