

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

Renmin Pretell<sup>(1)</sup>, Sumeet K. Sinha<sup>(1)</sup>, Katerina Ziotopoulou<sup>(1)</sup>, Jennie A. Watson-Lamprey<sup>(2)</sup>, and  
Dimitrios Zekkos<sup>(3)</sup>

<sup>(1)</sup> Department of Civil and Environmental Engineering, University of California, Davis

<sup>(2)</sup> Slate Geotechnical Consultants

<sup>(3)</sup> Department of Civil and Environmental Engineering, University of California, Berkeley

**Abstract**

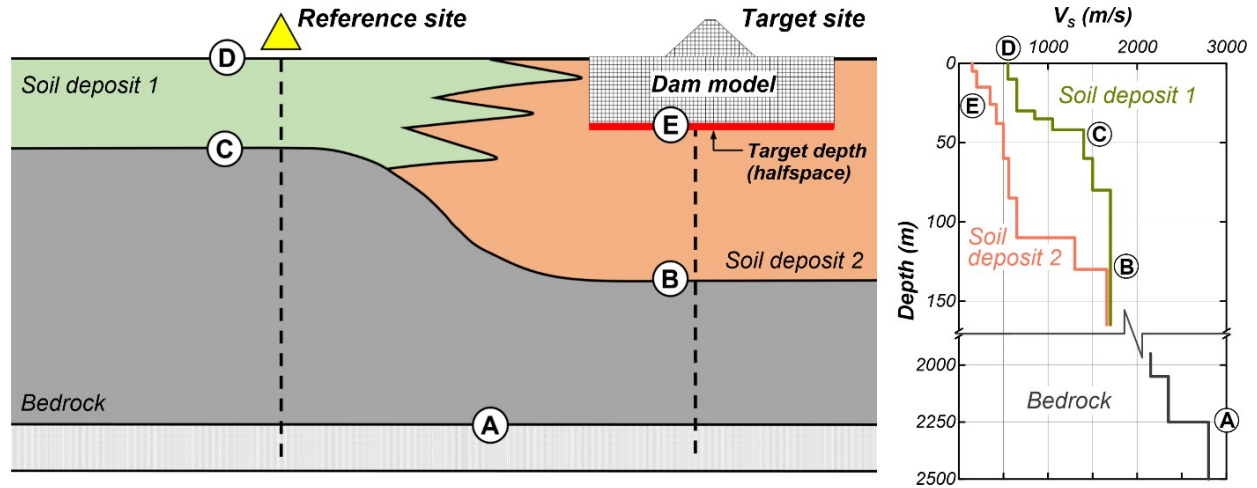
The double convolution methodology for the development of input motions for site response analyses and nonlinear deformation analyses is presented, and challenges associated with its development and implementation are discussed. This methodology uses deep VS profiles and random vibration theory to modify ground motions recorded on soil sites such that they are compatible with conditions at a selected depth within a deposit. This selected depth is commonly the base of a numerical domain for a 1D or 2D response analysis, i.e. halfspace. Ongoing efforts in the development of this methodology focus on constraining the ground motions' high-frequency content, where unrealistic amplification may be estimated. Two approaches for addressing this issue are presented using examples in California.

**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 (VS30) higher than 760 m/s, i.e. rock sites

(ASCE2016). 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.



**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).

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  $V_S - \square 0$  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 describes an ongoing investigation towards the development and implementation of the double convolution methodology, initially presented by Pretell et al. (2019). Pretell et al. (2019) presented a two-stage procedure for the development of input motions for SRAs and NDAs: (1) modification of ground motion recordings from ground surface stations to be representative of conditions at some target depth; and (2) incorporation of ground motion incoherency (e.g., Abrahamson 1992b) for the analysis of elongated geosystems. In this work, attention is placed on the first stage, hereafter referred to as “double convolution methodology.” First, previously proposed approaches are described and differences and commonalities with the

double convolution methodology are highlighted. Second, sites in California considered for the ongoing investigation are presented, and 5 km-deep VS profiles are developed based on shallow measurements (e.g., suspension logging tests) and velocity models from the Unified Community Velocity Model, UCVM (Small et al. 2017). Lastly, challenges associated with the development of the double convolution methodology and potential solutions are presented within the context of examples in California.

The ultimate goal of this investigation 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; (2) a user-friendly web-based tool accompanied by a user guide and example applications; (3) readily available modified groundmotion recordings at depths of potential interest within California sites, obtained during the development of this investigation; (4) newly measured VS profiles that will enrich the current database and allow for future research efforts; and (5) feedback to the Strong Motion Instrumentation Program (SMIP) regarding the utility of the available data.

### **Approaches for developing input ground motions**

#### **Deconvolution**

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 VS 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 et al. 1988); (2) post-filtering of ground motions to remove any unreasonably high-frequency content (e.g., Silva et al. 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.

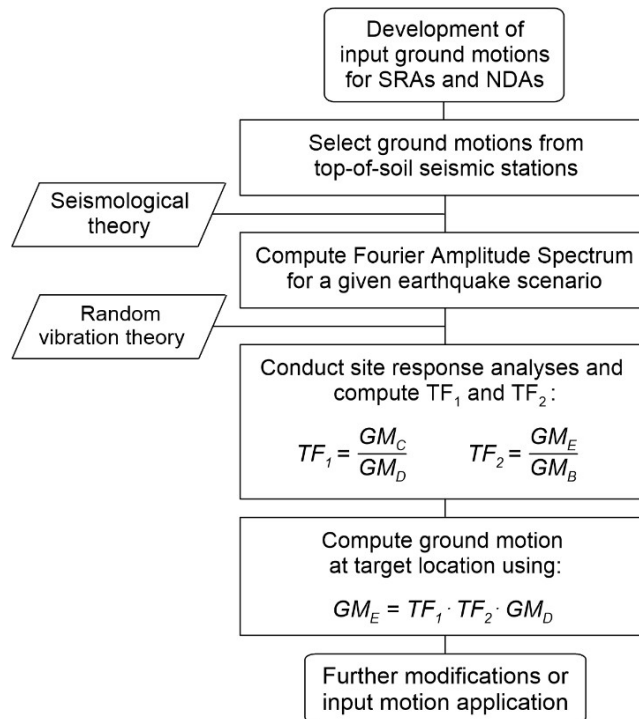
#### **VS- $\square_0$ correction by Cabas and Rodriguez-Marek (2017)**

Cabas and Rodriguez-Marek (2017) proposed a VS- $\square_0$  correction factor to modify ground surface recordings and make them consistent with conditions at some target depth, where  $\square_0$  is the distance-independent component of the high-frequency decay parameter (Anderson and Hough 1984). This approach captures both impedance and attenuation effects through the respective use



$$\underbrace{GM_E}_{\text{Target}} = TF_1 \cdot TF_2 \cdot \underbrace{GM_D}_{\text{Reference}}$$

Where  $TF_1$  is computed as the ratio of results from two convolution analyses, from “A” to “C” and from “A” to “D.”  $TF_2$  allows for the subsequent convolution to a target depth, e.g. a selected halfspace, and is computed similarly to  $TF_1$ . The input ground motion at location “A” can be developed as a Fourier Amplitude spectrum using seismological theory (e.g., Brune 1970, 1971, Boore 2003a), finite fault seismological simulations (e.g., Beresnev and Atkinson 1998), or another preferred method. This ground motion is then propagated upwards using random vibration theory (RVT). Once  $TF_1$  and  $TF_2$  are computed, the ground motion at location “E” can be estimated using the inverse Fast Fourier Transform (iFFT) of the product of these TFs and the reference ground motion recording. Note that  $TF_1$  is equivalent to the TF used for deconvolution analysis, and  $TF_2$  is equivalent to conducting a subsequent convolution analysis using the deconvolved time history as input motion. In applications that only require deconvolving a ground motion recording at the reference site,  $TF_2 = 1$ . However, in most applications the deconvolved ground motions need to be further modified (e.g., linear scaling) to account for source, path, and site effects (e.g., Chiaradonna et al. 2018). Figure 2 presents a flow chart of the double convolution methodology.



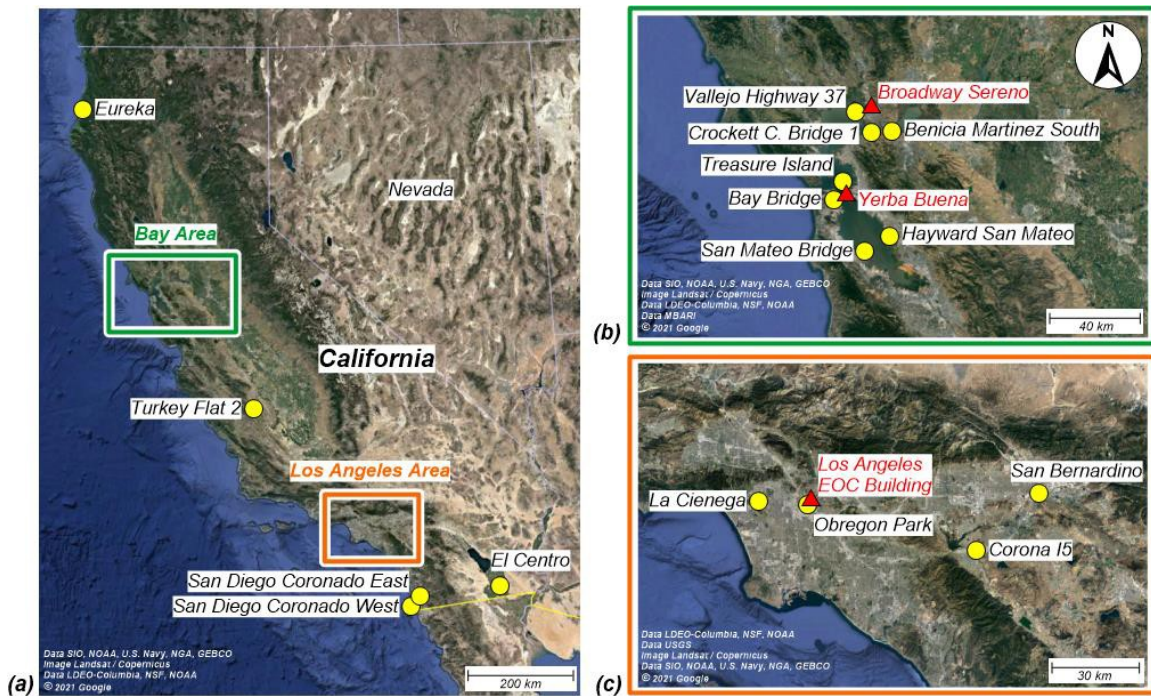
**Figure 2.** Proposed methodology for the development of input ground motions for site response and nonlinear deformation analyses. Adapted from Pretell et al. (2019).

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 VS profiles to account for site effects within high-VS materials, which are typically considered negligible and might lead to underestimation of the seismic response (Steidl et al. 1996). 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.

### Development of double convolution for sites in California

The double convolution methodology is used to develop ground motions at selected depths based on ground surface recordings from the CESMD, located in California. Sixteen geotechnical array sites from the CESMD are selected across California, three of them are paired with a neighboring ground surface site (Figure 3, Tables 1 and 2). The downhole recordings of geotechnical array sites allow for the partial evaluation of the performance of the proposed methodology, i.e. the estimation of TF1. Meanwhile, the paired sensors allow for a full evaluation of the proposed methodology. The selection of neighboring sites reduces the differences in source, path, and site effects between sites, thus reasonably improving the quality of the evaluation.



**Figure 3.** Seismic stations selected for the application of the double convolution methodology: (a) locations in California, (b) locations in the Bay Area, and (c) locations in Los Angeles Area.

### Ground motion recordings

The ground motion recordings from CESMD, collected and processed by Afshari et al. (2019), are used in this study. To examine the effect of soil nonlinearity and based on a  $I_T$ -based criterion, ground motions are separated into weak and strong ground motions and with linear

elastic and equivalent linear SRAs used, respectively. Ground motions that yield shear strain index ( $I_\gamma$ ) values lower than 0.01% are considered weak and appropriate for linear elastic SRAs (Kaklamanos et al. 2013), where  $I_\gamma$  was proposed by Idriss (2011) and is defined as:

$$I_\gamma = \frac{PGV}{V_{S30}} \times 100\%$$

Where  $I_\gamma$  is in percentage, and PGV is the peak ground velocity at surface in the same units as  $V_{S30}$ . Ground motions yielding  $I_\gamma$  values between 0.01 and 0.1% are considered strong and equivalent linear SRAs more appropriate for their propagation.

**Table 1.** Geotechnical array sites to be considered in this investigation.

MEDID	Station	Sensor depth <sup>1</sup> (m)	$V_S$ shallow(field test)	$V_S$ deep (UCVM <sup>2</sup> )	$V_S$ shallow-based $V_{S30}$ (m/s)
68323	Benicia Martinez	35	Suspension logging	cs173h	588
68206	Crockett Carquinez Bridge 1	45.7	Suspension logging	cs173h	350
1794	El Centro	195	Suspension logging	cvms5	200
58798	Hayward San Mateo	91	Suspension logging	cencal	184
24703	La Cienega	100	Suspension logging	cvmsi	254
24400	Obregon Park	69.5	Suspension logging	cvmsi	450
23792	San Bernardino	35	Suspension logging	cvmsi	268
58961	San Francisco Bay Bridge	40	Suspension logging	cencal	383
58642	Treasure Island	122	Suspension logging	In progress	159
36520	Turkey Flat 2	23	SASW	cs173h	Not applicable
68310	Vallejo Highway 37	44.7	Suspension logging	cs173h	527

<sup>1</sup> Sensor depth considered for this study.

<sup>2</sup> Acronyms/abbreviations presented in Table 3.

**Table 2.** Ground surface stations for the application of double convolution methodology.

CSMEDID	Station	$V_S$ shallow (field test)	$V_S$ deep (UCVM <sup>4</sup> )	$V_S$ shallow-based $V_{S30}$ (m/s)	Neighboring downhole station	
					Site name	Distance (km)
58163	Yerba Buena	Downhole <sup>2</sup>	cencal	Not available <sup>3</sup>	Treasure Island	2.25
24723	LA EOC Building <sup>1</sup>	Downhole <sup>2</sup>	In progress	Not available <sup>3</sup>	Obregon Park	1.50
68294	Broadway and Sereno	Not available	In progress	Not available	Vallejo Hwy. 37	2.29

<sup>1</sup> Los Angeles County of Emergency Office Center Building.

<sup>2</sup>  $V_S$  profiles measured 220 and 580 m from the Yerba Buena and LA EOC Building stations, respectively.

<sup>3</sup> Measured  $V_S$  profile shallower than 30 m.

<sup>4</sup> Acronyms/abbreviations presented in Table 3.

**Site characterization**

The site characterization of the selected CESMD sites is conducted for linear elastic and equivalent linear applications. The characterization consists of the following: (1) development of deep  $V_S$  profiles based on shallow measurements and velocity models, (2) small-strain damping profiles, (3) soil unit weight profiles, and (4) equivalent linear properties. The following section describes the criteria and assumptions considered for the selection of these input parameters.

***Shear wave velocity ( $V_S$ ) profiles***

Shear wave velocity ( $V_S$ ) profiles for the selected sites are developed as the combination of relatively shallow site-specific measurements and deep profiles based on  $V_S$  models from the UCVM (Small et al. 2017) as presented in Figure 4. Shallow  $V_S$  profiles are collected from various studies: Gibbs et al. (1992, 2000), Nigbor and Swift (2001), Boore (2003b), Gibbs et al. (2003), Thompson et al. (2010), and Petralogix (2017), with most of these integrated into the database by Afshari et al. (2019). In addition, 5 km-deep  $V_S$  profiles are sampled from velocity models included in the UCVM. The sample spacing ranges from 1 to 10 m, with finer sampling at the top of the profile. The shallow and deep  $V_S$  profiles are combined to obtain a detailed  $V_S$  profile near the ground surface while reaching a significant depth to estimate the site response.

**Table 3.** Velocity models from the SCEC UCVM evaluated for the selection of deep  $V_S$  profiles.

Model name	Abbreviation	Comment <sup>1</sup>	Reference
Modified Hadley-Kanamori 1D	1D	Southern California region, $V_P$ -base estimation of $V_S$ .	Hauksson (2010)
Northridge region 1D	bbp1D	Northridge region, based on profiles from the Southern California Earthquake Center sites.	Graves and Pitarka (2010)
Central California velocity model, CCA06	cca	Based on full 3D tomographic inversions.	En-Jui Lee
USGS Bay Area velocity model v0.8.3	cencal	3D velocity model defined on regular mesh.	Brocher et al. (2006)
Southern California velocity model, CVM-H v15.1	cvmh	Southern California 3D velocity model defined on regular mesh. Developed by SCEC and the Harvard Structural Geology Group.	Süss and Shaw (2003), Shaw et al. (2015)
Southern California velocity model CVM-S4	cvms	Southern California 3D velocity model defined as rule-based system. Developed by the SCEC, Caltech, and USGS groups.	Kohler et al. (2003)
Southern California velocity model, CVM-S4.26	cvms5	Based on CVM-S4 as starting model but improved using 3D tomography and 26 iterative updates.	Lee et al. (2014)
Southern California velocity model, CVM-S4.26.M01	cvmsi	Based on the CVM-S4.26 but preserving some of the geotechnical information in the original CVM-S4 that was lost during tomography improvements.	Lee et al. (2014)



CyberShake v17.3 Central California Velocity	cs173	Tiled from CCA06, CenCal, and CVM-S4.26.M01.	SCEC (2018a)
CyberShake v17.3 Central California Velocity	cs173h	Similar to the above but includes the San Joaquin and Santa Maria Basins and data from Harvard's group.	SCEC (2018b)

<sup>1</sup> Based on Small et al. 2017, Shi and Asimaki 2018, SCECpedia, and github.com/SCECcode/UCVM.

The aforementioned sources of VS often provide multiple alternative profiles. Shallow VS profiles generally consist of measurements from P-S suspension logging tests, and non-invasive methods such as the spectral analysis of surface waves (SASW). From these, P S suspension logging is preferred as it is an invasive method and thus provides high resolution regardless of depth (Passeri 2019). The deep VS profiles are obtained using all of the models presented in Table 3 when available for the location of the sites. Most models include a geotechnical layer, GTL (Elyet al. 2010) that consists of a soft layer in the top 350 m generated based on VS30, and the CVM- H15.1.0 VS at 350 m. The GTL helps with accounting for the soft sediments near the ground surface, but it assumes a smooth increase in VS and thus misses the presence of sharp impedance contrasts that affect site response (Shi and Assimaki 2018), and occasional inconsistencies in the geometry of the Los Angeles basin (Taborda et al. 2016). Therefore, shallow VS profiles are entirely used to replace the top portion of the UCVM profiles at all the selected locations.

Deep VS profiles are selected based on how well the shallower portion compares to the shallow VS profiles from site-specific measurements. No shifting of depth or VS scaling is applied to the deep VS profiles in the selection process. Taborda et al. (2016) conducted a validation study to evaluate the CVM-S4, CVM-S4.26, CVM-H, and CVM-H with GTL models in their ability to lead to accurate ground motion predictions for 30 events recorded in Los Angeles. The authors concluded that the CVM-S4, CVM-S4.26.M01 models (Table 3) consistently yielded the most accurate results. Based on this finding, deep VS profiles from the CVM-S4 and CVM-S4.26.M01 models are preferred when multiple profiles are equally adequate. The selection and construction of VS profiles represent a source of epistemic uncertainty that will be further studied, and newly measured VS profiles incorporated in future stages of this investigation.

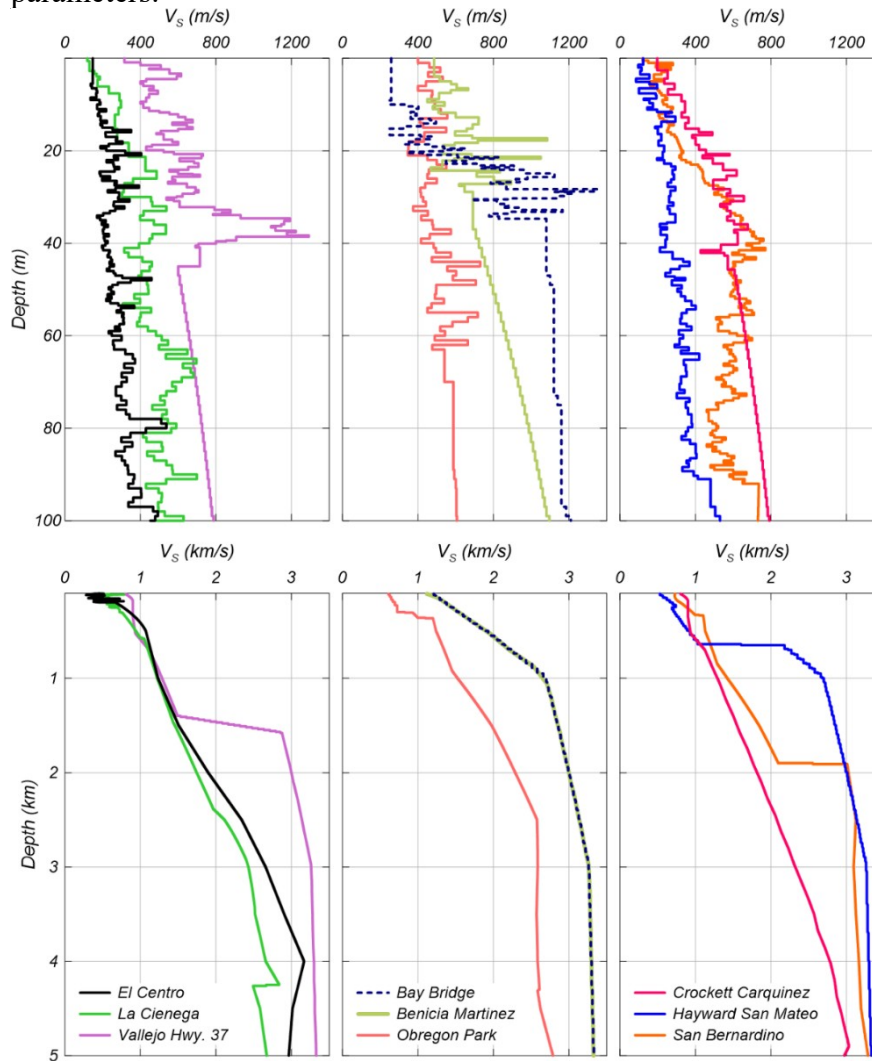
***Other material properties***

Other material properties consist of the small-strain damping, equivalent linear properties for soils, and unit weight. These properties are estimated based on correlations and typical values. Small-strain damping is computed based on quality factors (Q) estimated as a function of VS based on a relation proposed by Campbell (2009) for sites in California:

$$\frac{D}{min} = \frac{1}{2 \cdot Q} ; \quad \text{and} \quad Q = 7.17 + 0.0276 \cdot V_s$$

Where  $V_S$  is in m/s and  $D_{min}$  in decimal.

Equivalent linear properties are assigned to soil materials ( $V_S \leq 760$  m/s), whereas linear elastic behavior is assumed for rock-like materials ( $V_S > 760$  m/s). The Darendeli (2001) model is used to model the nonlinear behavior of all soils. This model is selected to account for the dependency of soil's behavior on the effective vertical stress. Different plasticity indexes (PIs) are assigned to soil materials based on the overall characteristic of the soil unit as described in the available boring logs or geological information included in database by Afshari et al. (2019) and other available studies listed in previous section. Granular soils (i.e., sands and gravels) are assigned a  $PI = 0$ , and fine soils are assigned a  $PI = 15$  as a reasonable representative estimate. Finally, a unit weight of  $18 \text{ kN/m}^3$  is assumed for all soils, whereas a unit weight of  $22 \text{ kN/m}^3$  is assumed for all rock-like materials. The ability of the double convolution methodology for efficiently propagating uncertainties allows for the future incorporation of alternative selected parameters.



**Figure 4.** Combined shallow ( $V_S$  measurement-based) and deep (UCVM-based)  $V_S$  profiles for various seismic stations selected for the modification of ground motions using the double convolution methodology. *Note: Grouping of profiles for visual purposes only.*

## Challenges associated with the development of the double convolution methodology

Key aspects challenging the development and validation of the double convolution methodology towards being robust and reasonably accurate, mainly consist of three issues: (1) an unrealistic amplification of the ground motion high-frequency range observed in computed ground motions; (2) inaccuracies inherent in 1D SRAs and uncertainty in the estimated response due to using different computer programs (Meite et al. 2020); and (3) the aleatory variability and epistemic uncertainty, mainly associated with VS. Herein, the focus is placed on the first issue, and alternative procedures for handling it are presented. The second and third issues have been previously studied in the context of convolution SRAs by various researchers, e.g., Toro (1995), Bonilla et al. (2002), Kaklamanos et al. (2013), Zalachoris and Rathje (2015), Griffiths et al. (2016), Kaklamanos and Bradley (2018), Meite et al. (2020), and Stewart and Afshari (2020), among others.

### *Unrealistic amplification of ground motions' high-frequency content*

The double convolution approach relies on two TFs: TF1 is used to modify the ground surface ground motion such that it is compatible with conditions at depth, and TF2 propagates that ground motion upwards to the base of the numerical domain (Figure 1) or a target depth. Often, an unrealistically high amplification is observed in the TF1's high-frequency range. This problem is also one of the common sources of errors in deconvolution analyses and the VS- $\kappa 0$  correction factor approach by Cabas and Rodriguez-Marek (2017). This section describes two potential solutions within the context of linear elastic SRAs and two examples in California.

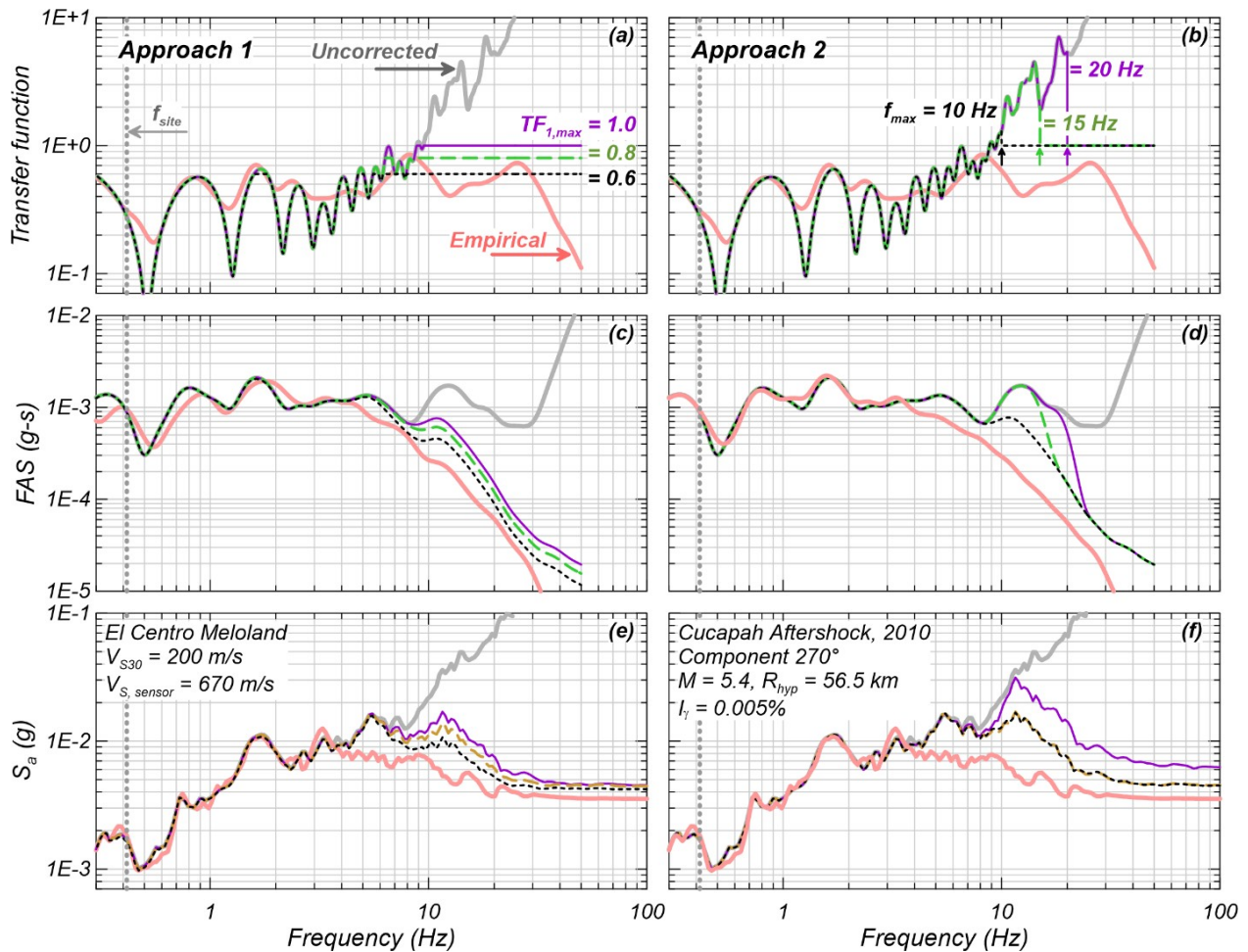
Events recorded at The El Centro and Obregon Park geotechnical array sites are used in this section. In this exercise, the reference and target sites are the same, and thus  $TF_2 = 1$ . One-dimensional SRAs are conducted using pySRA (Kottke 2019) and the acceleration response spectra are computed using pyRotD (Kottke 2018). A single acausal-filtered ground motion recording from the database by Afshari et al. (2019) is used per site. Recordings from the deepest sensors are used such that the widest possible frequency band is used. In this evaluation, downhole recordings (i.e., within ground motions) are used and thus appropriate wavefield assumptions are made in the analyses to get results that are comparable with the empirical data.

Results from the double convolution approach are presented in Figures 5 and 6 up to a maximum usable frequency of approximately 50 Hz, common to all the recordings used. Figures 5a and 6a present the empirical  $TF_1$ , computed as the ratio of the ground motion recorded at depth and the ground surface recording and smoothed using the technique proposed by Konno and Ohmachi (1998). The theoretical equivalent TFs are also presented. The uncorrected TF is obtained by following the procedure presented in Figure 2, while the two alternative TFs are obtained from using two approaches for constraining unrealistic high amplifications:

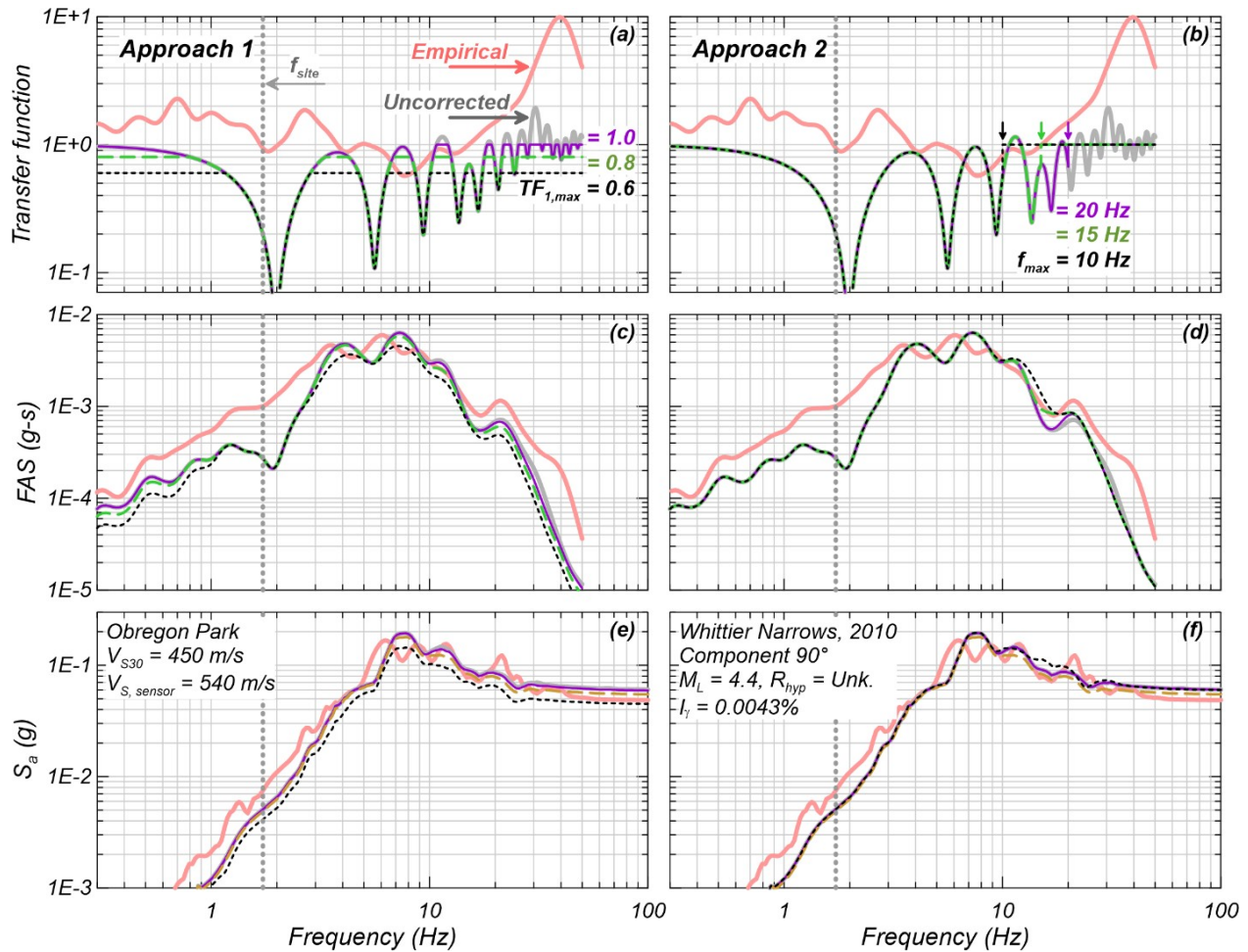
(1) establishing a TF cap ( $TF_{1,max}$ ) and (2) constraining the contribution of TF within a frequency range up to a maximum value,  $f_{max}$ , for the computation of ground motions at depth. Figures 5c to 5f, and 6c to 6f present the resulting Fourier amplitude spectra (FAS) and acceleration response spectra resulting from the use of all the previously described TFs. Cutoff values for these two approaches,  $TF_{1,max} = 0.6, 0.8, \text{ and } 1.0$  (Figures 5a and 6a), and  $f_{max} = 10, 15, \text{ and } 20$  Hz (Figures

5b and 6b), are selected guided by empirical observations, and a greater body of results not presented herein for brevity. In the case of El Centro, the empirical TF varies consistently under the value of 1, whereas the uncorrected  $TF_1$  progressively increases from 0.8 Hz to values higher than 10 at 25 Hz (Figures 5a and 5b). On the other hand, a different behavior is observed for Obregon Park, in which the empirical TF increases from 1 at 15 Hz to values up to 10 at 40 Hz, whereas the uncorrected  $TF_1$  remains under values of 2 (Figures 6a and 6b).

The performance of the investigated approaches, judged based on the similarity to the empirical TFs, FAS, and response spectra, vary significantly for the El Centro site, whereas they are very similar in all the cases for Obregon Park. The wide range of variability of results for El Centro are mainly caused by the  $TF_1$  trend to increase in the high-frequency range, contrary to what the empirical  $TF_1$  shows. Also,  $TF_1$  estimated using Approach 1 constrains more the TF's higher values (Figure 5a) and thus has a better estimate of the FAS and response spectra is achieved (Figures 5c and 5e), compared to Approach 2. A low  $TF_{1,max} = 0.6$  leads to a TF more similar to the empirical from 8 to 30 Hz (Figure 5a). Similar trends are observed in terms of FAS and spectral accelerations (Figures 5c and 5e). Results for the event at Obregon Park indicate a more similar performance between both approaches and amongst the different  $TF_{1,max}$  and  $f_{max}$  values (Figures 6c to 6f). In this case, a  $TF_{1,max} = 1$  leads to the most accurate FAS and spectral accelerations at low and high frequencies (Figures 6c and 6d), although with some underprediction, and overpredictions between 6 and 8 Hz. A  $f_{max} = 10$  Hz yields better predictions. The difference between the responses of these sites challenges the robustness of the double convolution approach, given that a single value for  $TF_{1,max}$  and  $f_{max}$  might not be appropriate in all cases. Future advances of the double convolution methodology will focus on the development of a robust approach, based on either the first approach or a combination of both approaches, for constraining unrealistically high amplifications while reasonably preventing or aggravating the degree of underpredictions. Recommendations will be made for forward predictions, including those conducted at non-downhole sites, which are of interest for most applications.



**Figure 5.** Two different approaches for constraining the high-frequency content in transfer function 1 ( $TF_1$ ) and the effect on Fourier amplitudes and spectral accelerations ( $S_a$ ). Figures (a), (c), and (e): Approach 1, TF cap ( $TF_{1,max}$ ) across all frequencies. Figures (b), (d), and (f): Approach 2, TF considered up to a maximum frequency ( $f_{max}$ ). El Centro site; downhole sensor depth = 195 m. Note: Site's fundamental frequency,  $f_{site}$ , computed as the average  $V_S$  divided by 4 times the depth to the sensor.



**Figure 6.** Two different approaches for constraining the high-frequency content in transfer function 1 ( $TF_1$ ) and the effect on Fourier amplitudes and spectral accelerations ( $S_a$ ). Figures (a), (c), and (e): Approach 1, TF cap ( $TF_{1,max}$ ) across all frequencies. Figures (b), (d), and (f): Approach 2, TF considered up to a maximum frequency ( $f_{max}$ ). Obregon Park site; downhole sensor depth = 69.5 m. *Note: Site’s fundamental frequency,  $f_{site}$ , computed as the average  $V_S$  divided by 4 times the depth to the sensor.*

### Web-based application tool

A 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. Figure 7 illustrates the interface of the web application tool with the tabs “Soil profile,” “Ground motion,” “Analysis,” for receiving input parameters, and the “Results” tab for showing the synthesized input ground

motions after performing the double convolution analysis. In addition, the ability to download a summary of the input parameters locally and the results will be implemented.

### DOUBLE CONVOLUTION METHODOLOGY

Soil Profile   Ground Motion   Analysis   **Results** ← *Results tab*

Target Site *Input parameters tab* +

<input type="checkbox"/>	Actions	Name	Thickness (m)	Vs (m/s)	Unit Weight (kN/m <sup>3</sup> )	Damping (%)	Model
<input type="checkbox"/>		Sand	5	150	18	0.5	Seed and Idriss (mean)
<input type="checkbox"/>		Sandy clay	10	250	18	0.5	EPRI (PI=15)
<input type="checkbox"/>		Gravelly Sand	20	350	20	0.5	Seed and Idriss (mean)
<input type="checkbox"/>		Bedrock	0	760	22	0.2	-

5 rows |< < 1-4 of 4 > >|

Figure 7. Web application interface for the target site’s input data.

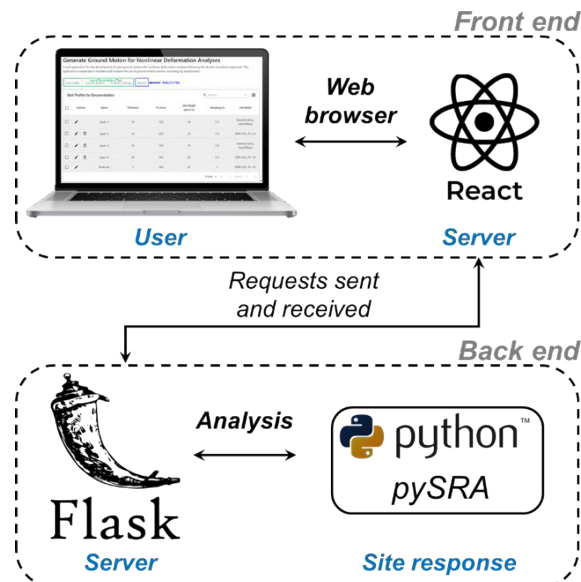


Figure 8. Web application tool architecture and request response-cycle.

The web tool is developed using React (Facebook Inc. 2021), Flask (Pallets Projects 2021), and pySRA (Kottke 2019). Figure 8 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 pySRA implementation (Kottke 2019).

The fully developed web tool will be ultimately 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.

### Final remarks

This paper 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.

Challenges encountered in the development of the double convolution methodology can be separated into three parts: (1) the unrealistic amplification of the ground motions' high-frequency content often obtained in computed ground motions, (2) the inaccuracies inherent to 1D SRAs and the uncertainty associated with site response computer programs; and (3) the aleatory variability and epistemic uncertainty associated with VS and other parameters. The first part challenges the robustness of the approach, whereas the second and third parts challenge the precision of the results and the validation of the methodology. Empirical observations from California sites and an investigation of two approaches for handling the unrealistic amplifications of the ground motions' high-frequency content indicate that selecting a transfer function cap,  $TF_{1,max}$ , can be an effectiveness measure. Further statistical evaluation of the empirical data is needed to determine an appropriate  $TF_{1,max}$  for the high-frequency range. The proposed methodology is limited to cases of moderate to low nonlinearity (i.e., shear strains lower than 0.1%), it does not account for changes in phase or duration due to wave propagation, and the resulting ground motions might need further adjustments depending on site-to-source distance of the target and reference sites, or any other case-specific needs.

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; (2) a user-friendly web-based tool accompanied by a user guide and example applications; (3) readily available modified ground motion recordings at depths



of potential interest within California sites, obtained during the development of this investigation; (4) measured  $V_s$  profiles that will enrich the current seismic station database and allow for future research efforts; and (5) the double convolution methodology will ultimately lead to the overall broadening of the utilization of data from the Center for Engineering Strong Motion Data (CESMD) and ground surface stations in general.

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