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SENSITIVITY ANALYSIS FOR DERIVATION OF 1D V_S PROFILES USING INVERSE QUARTER-WAVELENGTH THEORY

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Abstract

It is possible to convert median response spectra estimated based on a selected Ground-motion Prediction Equation (GMPE) to its corresponding Fourier amplitude spectrum (FAS) by using the inverse vibration theory (IRVT). The IRVT uses extreme value statistics, properties of single-degree-of-freedom oscillator transfer functions, and spectral ratio correction to develop FAS that are compatible with input median response spectra. After obtaining a linear site amplification function in frequency domain corresponding to a specific site condition from analysis of FAS, the quarter-wavelength approximation (QWL) can be employed inversely and a 1D shear wave profile (V_S profile) as well as a host kappa value representative of the site condition and GMPE under consideration can be derived. kappa is the spectral-decay parameter which is often used to account for the reduction of the high-frequency amplitude of ground-motion caused by attenuation within the site profile. As part of the first step, when the IRVT is used to compute FAS, utilized peak-factor model and duration of motion model influences the results. Likewise, as part of the second step, when a linear site amplification function is derived based on FAS in hand, a reference V_S profile is employed that influences the linear site amplification function computed. And lastly as part of the third step, in computation of 1D V_S profile and host kappa value from linear site amplification function representing the site condition and the GMPE under consideration by employing the inverse quarter-wavelength theory, the density model utilized influences the computed V_S profile. Main objective of this study is to derive GMPE compatible V_S profiles and host kappa values for the recent Turkish GMPE of [1]. In doing so, different peak factor models; duration models; randomly generated reference V_S profiles and different density models were used. This allowed investigating the degree of effect of peak factor model, duration model, reference V_S profile and density model on computed 1D V_S profiles and host kappa values.

Keywords: Inverse Random Vibration Theory, Quarter-wavelength approximation, V_s profile, kappa.

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1 INTRODUCTION

[1] ground-motion prediction equation (GMPE) estimates the median and standard deviation of the ground motion as a function of source, path, and site parameters such as earthquake magnitude (i.e., moment magnitude, M_w), source-to-site distance (i.e., Joyner and Boore distance, R_{JB}), style of faulting, and local site conditions. This GMPE is based on abundant empirical ground-motion data from Turkey. [1] GMPE uses the nonlinear site function developed by [2] for the broader Europe to account for local site conditions. Local site conditions in this GMPE are characterized by the time-averaged shear-wave velocity over the top 30 m of the site profile (V_{S30}). Other parameters such as depth to a shear-wave velocity of 1.0 or 2.5 km/s horizon ($Z_{1.0}$ and $Z_{2.5}$) are not used hence effect of deeper part of the shear wave velocity (V_S) profile that controls long-period amplification and reflects basin effects are not taken into account. [1] study justify applicability of [2] site amplification model to the Turkish strong-motion data by carrying out detailed residual analyses. [1] reports no observable trends with changing V_{S30} values. In [3], the inverse quarter-wavelength (QWL) method proposed by [4] is used to estimate GMPE compatible host 1D V_S profiles and kappa values, κ for the [1] GMPE for different site conditions with corresponding V_{S30} values of 360 m/s, 490 m/s, 620 m/s and 760 m/s. In this manuscript, the study of [3] is extended and influence of peak-factor models, duration models, reference 1D V_S profiles and density models on computed 1D GMPE compatible V_S profiles and host kappa values are investigated.

2 INVERSE RANDOM VIBRATION THEORY

In this study, the inverse random vibration theory (IRVT) based method first proposed by [5] then modified by [6] is used to convert median response spectra estimated based on a selected GMPE to corresponding FAS. The IRVT uses extreme value statistics, properties of single-degree-of-freedom oscillator transfer functions, and spectral ratio correction to develop FAS that are compatible with input response spectra ([6]). The IRVT procedure approximates the Fourier amplitude [A(f_n)] at the oscillator natural frequency f_n as:

$$[A(f_n)]^2 \approx \frac{1}{f_n\left(\frac{\pi}{4\xi}-1\right)}\left(\frac{T_d}{2}\frac{Sa^2}{pf^2}-\int_0^{f_n}|A(f)|^2 df\right) \tag{1}$$

where ξ represents the critical damping ratio, Sa represents the spectral acceleration, pf represents the peak factor, and T_d represents the duration of the ground motion.

While it is generally straightforward to convert an FAS to a corresponding response spectrum using random vibration theory, converting a response spectrum to a corresponding FAS using IRVT is not so simple. The fact that a spectral acceleration at a given period is influenced by a range of frequencies in the FAS making it impossible to relate the spectral acceleration at a given period merely to its FAS counterpart at the same period complicates the calculation of the Fourier amplitude [A(f_n)]. This problem is addressed in [6] using the properties of single-degree-of-freedom transfer functions that are narrow banded for lightly damped systems going to zero for frequencies greater than the natural frequency, f_n. This property limits the frequency range that contributes to the spectral acceleration at a certain period. The fact that the peak factor pf, which is needed to estimate the FAS cannot be determined a priori introduces another complication to the calculation of the Fourier amplitude [A(f_n)]. [6] suggests first assuming a peak factor value to develop an initial estimate of the FAS and then updating this assumed value using the generated FAS in later iterations.

As part of the IRVT procedure, Equation 1 is successively applied from lower frequencies to higher frequencies allowing for the calculation of the integral term in Equation 1. As the last step of the IRVT procedure, [6] suggests modifying the derived FAS based on the spectral ratio of the target to calculated response spectra. This correction process ensures a better match between the target response spectrum and the calculated response spectrum based on the IRVT-generated FAS.

In this study, the IRVT-generated FAS of response spectra that are computed by employing the recent Turkish GMPE of [1] is used for two purposes: (1) as the required input for the inverse QWL method which is outlined in the subsequent section, (2) as the required input for the calculation of host κ values by following the [7] approach.

For the calculation of host κ values, [7] suggests firstly computing response spectra at short distances for rock type site condition by employing a GMPE. Scenarios with short distances are suggested in order to minimize the impact of anelastic attenuation on the high-frequency part of the response spectrum and FAS. Scenarios with high V_{S30} values are suggested in order to avoid over-whelming κ with soil damping. In the [7] approach, response spectra are then converted to their corresponding FAS by employing the IRVT procedure summarized above. [7] suggests estimating κ values based on slope of FAS after converting FAS to log-linear space by following the [8] approach. According to [8], FAS in log-linear space follows the function $A_o \exp(-\pi\kappa f)$ between frequencies f_1 and f_2, where f_1 and f_2 are selected based on visual inspection such that ln(A[f]) versus f relationship is linear in the selected range. The [7] approach assumes that the crustal amplification function corresponding to the subsurface profile is constant in the frequency range used to estimate κ and that the FAS at high frequency is only controlled by κ. If the crustal amplification is not near constant at high frequencies, then [7] recommends that FAS is divided by the crustal amplification before estimating κ from the slope of the FAS.

3 INVERSE QWL METHOD

The QWL approximation to linear site amplification was first introduced by [9]. This method is based on computing the FAS linear site amplification at a particular frequency, A[f(z)] based on Equation 2: the square root of the ratio between the local seismic impedance (shear-wave velocity times density) and the seismic impedance at the source depth. Frequently, it is used to estimate linear site amplification given a reference V_S profile. Equation 2 is applicable for shear-waves with zero angle of incidence with respect to the vertical direction. ρ_R and V_{SR} represent the density and shear-wave velocity at the source depth. The local shear-wave velocity and density are averaged over a depth corresponding to one quarter of a wave-length for the frequency under consideration. Based on the work of [10], ρ_R and V_{SR} are adopted as 2.8 g/cm3 and 3.7 km/s, respectively, in this study. The linear relationship between density and V_S is employed as given in Equation 4, which is based on [11].

$$A[f(z)] = \sqrt{\frac{\rho_R V_{SR}}{\overline{\rho(z)}\,\overline{V_S(z)}}} \quad (2)$$

$$\overline{V_S(z)} = z \times 4f(z) \quad (3)$$

$$\rho = 1.742 + 0.2875V_S \quad (4)$$

The inverse QWL method proposed by [4], which enables development of a 1D V_S profile given a linear site amplification function in FAS domain, is also based on Equations 2 and 3. For a given FAS linear site amplification function, when the approach outlined below is applied sequentially from high to low frequencies, the corresponding 1D V_S profile can be computed from shallow to deeper layers:

Step 1: Express Equation 2 only in terms of V_S after substituting Equation 4 into Equation 2. For the highest frequency and shallowest layer: $\overline{V_S(z)} = V_s$ and $\overline{\rho(z)} = \rho$. Using the FAS linear site amplification corresponding to the largest available frequency, V_S for the shallowest layer can be derived based on Equation 2.

Step 2: V_S value of step 1 can be used together with largest available frequency to estimate depth z of the shallowest layer of the V_S profile based on Equation 3.

Step 3: For each subsequent frequency (f_i) in the given site amplification function sorted in descending order, the shear-wave velocity, $V_S(i)$ of the corresponding profile layer, i, can be analytically solved for using Equation 5.

$$0.2875\Delta tt V_S(i)^2 + 1.742\Delta tt V_S(i) + z(i-1)\overline{\rho(i-1)} - \frac{\rho_R V_{SR} tt(i)}{A(i)^2} = 0 \quad (5)$$

The travel time to depth i, tt(i), can be related to frequency based on Equation 6. The difference in travel time between subsequent layers, Δtt, can then be written as given in Equation 7. Equation 8 illustrates that depth of a layer, Δz, and Δtt can be related through $V_S(i)$. Using these basic definitions, it is possible to express time averaged shear-wave velocity and density for layer i as given in Equations 9 and 10. After substituting Equations 9 and 10 into Equation 2, it is possible to derive the quadratic function of Equation 5, in which the only unknown is $V_S(i)$.

$$tt(i) = 1/(4f_i) \quad (6)$$

$$\Delta tt = tt(i) - tt(i-1) \quad (7)$$

$$\Delta z = V_S(i)\Delta tt \quad (8)$$

$$\overline{V_S(i)} = \frac{z(i-1)+\Delta z}{tt(i)} \quad (9)$$

$$\overline{\rho(i)} = \frac{\left[z(i-1)\overline{\rho(i-1)} + \Delta z \rho(i)\right]}{z(i-1)+\Delta z} \quad (10)$$

4 APPLICATION OF THE INVERSE QWL METHOD TO RECENT TURKISH GMPE

The inverse QWL method of [4] as described in the previous section is employed to derive GMPE compatible V_S profiles for the recent Turkish GMPE of [1] that will be referred to as KAAH15 throughout the rest of this manuscript. Main objective of this work was to derive host V_S profiles and κ values for the KAAH15 GMPE for V_{S30}=760 m/s site condition and to study influence of peak factor model, duration model, reference V_S profile and density model on the computed 1D V_S profile. As linear site response in GMPEs does not distinguish between site amplification and small-strain damping (κ), GMPE-specific host V_S profiles and companion κ values are derived together for the studied V_{S30}=760 m/s site condition. This required slight modification of the inverse QWL method as proposed by [4]. This will be discussed below.

Firstly, median response spectra for strike-slip scenarios with M_w: 5, 6, and 7; R_{JB}: 5, 10, and 20 km; and V_{S30}: 760 and 1000 m/s are computed for Turkey by employing the KAAH15 GMPE. Nonlinear site response is disabled in the calculation of median response spectra to isolate the linear site response. As strike-slip scenarios are chosen, ground-motion recordings from Northwestern Turkey govern median response spectra of KAAH15 GMPE. The derived V_S profiles and κ values are, therefore, specifically applicable for this region of Turkey.

The IRVT method is used to convert median response spectra to corresponding FAS. In this study, the computer program pyrvt ([12]) is employed for the conversion of median response spectra to corresponding FAS. Duration, T_d, is calculated using the [13] significant duration model D5-75, [14] total duration model, [15] significant duration model D5-95. Increase of duration due to oscillatory response is also considered according to [16] and [17] models.

Another parameter necessary for this conversion is the peak factor, pk. In this study, the peak factor models of [18], [19], [20], [21] and [22] are used in conversion of response spectra to FAS. The [18] peak factor model is consistent with the [19] model the most; [20], [21] and [22] deviate from the [18] models in the high frequency range and are listed in order of increasing deviation. The peak factor calculations are known to have higher sensitivity to higher frequency values ([23]).

For KAAH15, the ratio of FAS for each of the nine scenarios at a specific V_{S30} relative to the FAS of the same earthquake scenario with V_{S30} of 1000 m/s is computed. The FAS site response relative to V_{S30} of 1000 m/s is then computed by averaging those of the scenarios with M_w 6 and 7 and R_{JB} distance 5, 10, and 20 km. Relative FAS site response computed for the M_w 5 scenarios are not employed because they exhibit the largest deviation from the rest of the scenarios at high frequencies.

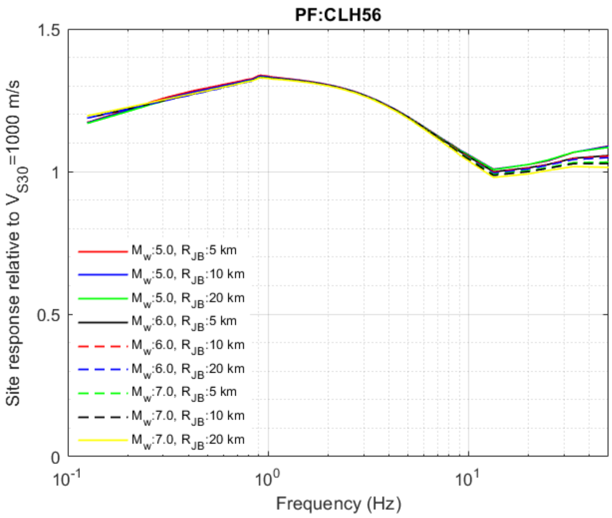
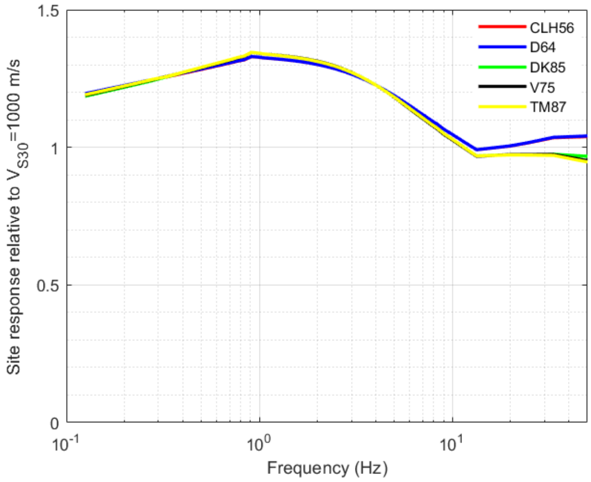


Figure 1: Linear site response in FAS domain relative to V_{S30} of 1000 m/s for KAAH15 ([1]) for scenarios with M_w 5, 6, and 7 and R_{JB} of 5, 10, and 20 km. The [18] peak factor model and [14] duration model are utilized.

Figure 1 illustrates the ratio of FAS for the nine scenarios corresponding to a V_{S30} value of 760 m/s relative to those at 1000 m/s for KAAH15. This ratio approximates the FAS linear site response of the GMPE relative to the selected reference site condition. Figure 1 indicates that the computed FAS site response relative to the reference site conditions is generally stable for the nine scenarios considered. In the high frequency range, deviations among the scenarios are observed for frequencies exceeding 25 Hz. This behavior of IRVT-based FAS is described as saturation of the response spectrum at high frequencies by [7] and linked to high regional κ values. To make sure that this behavior does not have any effect on the results: (1) the relative FAS site response is computed by averaging those of the scenarios with M_w 6 and 7 and distance of 5, 10, and 20 km, excluding those with M_w 5 as they exhibit the largest deviation from rest of the scenarios at high frequencies, (2) the relative FAS site response values corresponding to frequencies up to 20 Hz are used in the derivation of GMPE compatible host V_S profiles and κ values.



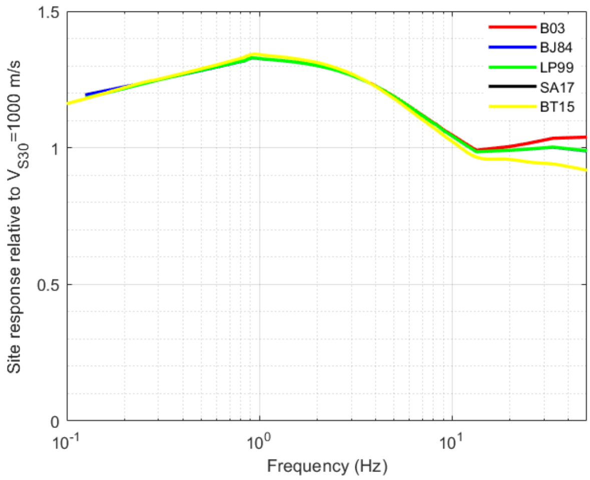


Figure 2: (a) Linear site response in FAS domain relative to V_{S30} of 1000 m/s for KAAH15 ([1]) by utilizing the CLH56 ([18]), D64 ([19]), DK85 ([20]), V75 ([21]) and TM87 ([22]) peak factor models with [14] duration model and (b) Linear site response in FAS domain relative to V_{S30} of 1000 m/s for KAAH15 ([1]) by utilizing the B03 ([14]), BJ84 ([16]), LP99 ([17]), SA17 ([13]), BT15 ([15]) duration models. In FAS computations together with all duration models listed, the CLH56 peak factor model was used; except for the BT15 duration model which was used together with the V75 peak factor model.

Figure 2a illustrates the average relative linear FAS site response functions for the KAAH15 for V_{S30} value of 760 m/s computed by utilizing five different peak factor models together with the [14] duration model. These functions represent the combined relative effects of linear site amplification and relative κ scaling.

The relative linear FAS site response functions given in Figure 3 are converted into total FAS site response functions by multiplying them with the FAS site amplification model of the corresponding reference Vs profile (i.e., for V_{S30} value of 1000 m/s for the KAAH15 GMPE) including corresponding kappa attenuation. In computation of a reference V_S profile for V_{S30} of 1000 m/s, the generic rock and generic very hard rock velocity models of [11] are used together with the interpolation method of [24] as V_S profiles specifically suggested for Turkey are not available especially up to required depths and required V_{S30} values. For the obtained reference V_S profile corresponding linear site amplification values are then calculated using the QWL method with zero angle of incidence by using the computer program site_amp ([25]). The host κ for the reference site condition is also calculated. The FAS of the nine scenarios with M_w 5, 6, and 7; R_{JB} distances of 5, 10 and 20 km and V_{S30} of 1000 m/s are used to calculate κ. The IRVT based approach suggested by [7], which is described above is followed for this purpose. The average κ value derived from studying FAS of these nine scenarios is 0.0376. The computed FAS site amplification model for the V_{S30} value of 1000 m/s is illustrated in Figure 3.

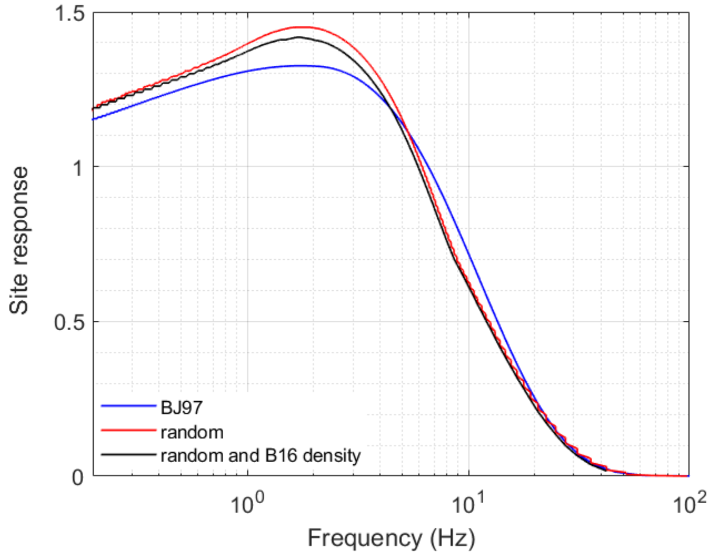


Figure 3: FAS site amplification models of reference V_S profiles (Both random and B16 based). For the KAAH15 ([1]) GMPE, the reference V_S profile corresponds to a V_{S30} value of 1000 m/s. Two separate density models are used in derivation of these amplification models: BJ97 and B16.

The total FAS site response functions computed for V_{S30} value of 760 m/s by multiplying the relative linear FAS site response functions of Figure 2 with the FAS site amplification model of reference V_S profile (Figure 3) are given in Figure 4.

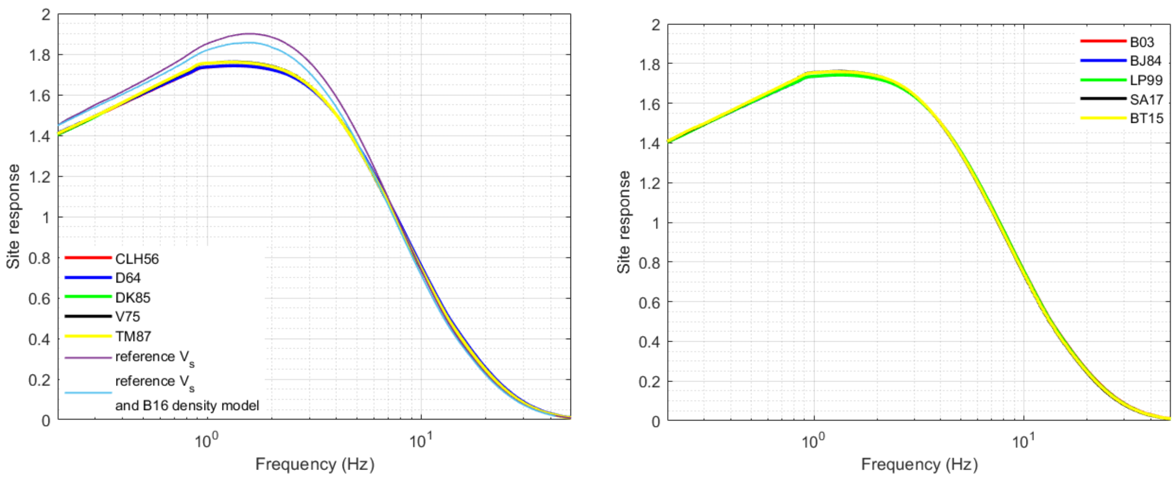


Figure 4: Total linear site response in FAS domain for KAAH15 ([1]) and for V_{S30} value of 760 m/s (a) by utilizing the CLH56 ([18]), D64 ([19]), DK85 ([20]), V75 ([21]) and TM87 ([22]) peak factor models with [14] duration model and (b) by utilizing the B03 ([14]), BJ84 ([16]), LP99 ([17]), SA17 ([13]), BT15 ([15]) duration models.

As mentioned above, relative FAS site responses computed for different scenarios deviate from one another for frequencies exceeding 20 Hz. To eliminate effect of these deviations on computed V_S profiles FAS site response functions are not used for frequency values exceeding 20 Hz. However, the frequency range of 20-100 Hz is necessary for derivation of host V_S profiles. As a solution of this problem, [4] suggests representing the top 30m of the Vs profile with a power function and obtains the analytical model of total FAS site response as given in Equation 11, which is applicable for the top 30m. Selecting a frequency range such as f_{30}-100 Hz, f_{30} representing the frequency corresponding to a 30m depth of a profile and fitting Equation 11 for estimation of unknown parameters b and κ in this range, allows estimation of κ values for different peak factor and duration models considered as well as computation of total FAS site response for frequencies in the range 20-100 Hz. Estimated κ values in this manner represent GMPE compatible host κ values and are listed in Table 1 for V_{S30} value of 760 m/s.

$$SR(f) = \left[\frac{\rho_R V_{SR} 0.03^b / V_{S30}}{\left(1.742 - \frac{V_{S30} * 0.2875 * \left(4f * \frac{0.03^b}{V_{S30}}\right)^{\frac{b}{b-1}}}{0.03^b * (b^2 - 1)}\right) * (\frac{4f * 0.03^b}{V_{S30}})^{b/(b-1)}} \right]^{1/2} * \exp(-\pi\kappa f) \quad (11)$$

Peak-factor and duration models	**κ (s)**
pf: CLH56, d: B03	0.0393
pf: D64, d: B03	0.0393
pf: DK85, d: B03	0.0397
pf: V75, d: B03	0.0398
pf: TM87, d: B03	0.0399
pf: V75, d: BT15	0.0398
pf: CLH56, d: SA17	0.0400
pf: CLH56, d: LP99	0.0394
pf: CLH56, d: BJ84	0.0394
pf: CLH56, d: B03 random V_S profile	0.0385
pf: CLH56, d: B03 random V_S profile and B16 density model	0.0400

Table 1: Derived host κ (s) values for the KAAH15 ([1]) for V_{S30} of 760.

Based on the inverse QWL approach of [4] and IRVT approach of [7], the estimated κ values are not κ_0 (i.e. κ estimated at zero epicentral distance) but κ_1 (i.e. average κ estimated for scenarios at short distances) instead. [4] studied the relationship between short-distance kappa, κ_1 and zero-distance kappa, κ_0 for Western United States and reached the conclusion that κ_0 is smaller than κ_1 with a constant shift of 0.005s for different scenarios considered.

The modified total FAS site response obtained by following above explained approximation in the frequency range of 20-100 Hz is then divided by the κ operator term to obtain the FAS linear site amplification for different site conditions considered. The inverse QWL approach is applied to the FAS linear site amplification obtained to derive the GMPE specific host V_S profiles for V_{S30} value of 760 m/s. The derived V_S profiles are constrained to attain the V_S value of 2500 m/s at depths consistent with the [26] suggested depth-to-bedrock model (Z2.5).

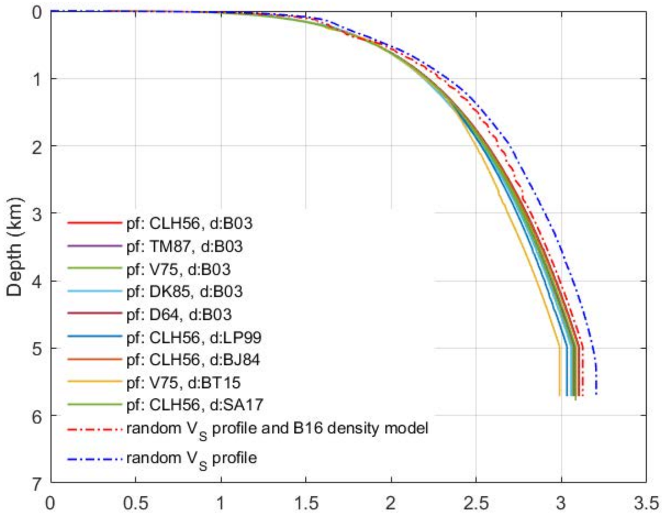


Figure 5. GMPE compatible host V_S profiles for KAAH15 corresponding to V_{S30}= 760 m/s.

In order to observe sensitivity of computed 1D Vs profile and host kappa value to adopted density model, using peak factor model of CLH56 and duration model of B03, density model of [24] is used instead of [11]. Also, in order to observe sensitivity of computed 1D Vs profile and host kappa value to adopted reference V_S profile for V_{S30} value of 1000 m/s, a reference V_S profile is randomly generated as 4 power law functions such that in the top 30m depth average value is 1000 m/s, at 0.443km V_S value is 2500 m/s (default $Z_{2.5}$ value of NGAWest2 for Western United States) and 3500 m/s is not exceeded for deeper layers (velocity at the source). Results are shown in Figure 5 and Table 1.

5 CONCLUSIONS

In this study, GMPE compatible 1D host V_S profiles and κ value are derived for Turkey. [1] GMPE is selected to represent regional ground-motion attenuation for Turkey. GMPE compatible V_S profiles are derived for site condition with V_{S30} value of 760 m/s up to 6km depth. Host κ values are also computed for site condition with V_{S30} values of 760 and 1000 m/s. In doing so, the peak factor models suggested by [18], [19], [20], [21] and [22]; the duration models suggested by [13], [14], [15], [16] and [17]; randomly generated reference V_S profiles and density models suggested by [11] and [24] were used. This allowed investigating the degree of effect of peak factor model, duration model, reference V_S profile and density model on computed 1D V_S profiles and host κ values. Results indicate that computed 1D V_S profiles and host κ values are quite stable and adopted reference V_S profile influences the computed 1D V_S profiles and host κ values the most.

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