

**Research Paper**

On the Inadequacy of JICA Seismic Site Response Estimation in Tehran: New Developed Shear Wave Velocity Profiles for the 1D Seismic Response Analysis in Tehran Sedimentary Basin

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Received: 270/08/2024

Revised: 21/10/2024

Accepted: 04/11/2024

Keywords:

Tehran basin, Array measurements, 1D site response

ABSTRACT

The amplification of ground motion at the surface is significantly influenced by soil properties, and constructing a reliable shear wave velocity model down to the seismic bedrock depth is indeed the key factor in determining a reliable seismic response. In Tehran, the previous site's seismic response analysis relied solely on very shallow geotechnical measurements up to the engineering bedrock. The results showed the negligible amplification in frequencies higher than 1 Hz that was very different with the results of experimental amplification ratios, obtained using the site to reference method on real earthquake data (Haghshenas, 2005). The latter indicated a high level of amplification for a broad range of frequencies. In present study, we recalculated simple one-dimensional seismic responses for Tehran, using the newly developed deep shear wave velocity models, developed by Soltani et al. (2025), to evaluate whether these models accurately represent the actual site amplification. The results indicate that the relative differences between newly 1D calculated transfer functions and experimental observation are less than 20%. However, in certain stations, mostly in the central part of the basin, these differences exceeded 20%, which can be attributed to the inherent multi-dimensional behavior of the Tehran basin.

How to cite the article:

Soltani, S., Haghshenas, E., Guillier, B. & Cornou, C. (2025). On the inadequacy of JICA seismic site response estimation in Tehran: new developed shear wave velocity profiles for the 1D seismic response analysis in Tehran sedimentary basin. *Journal of Seismology and Earthquake Engineering*, 27(3), 1-13. <https://doi.org/10.48303/jsee.2024.2039693.1122>



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1. Introduction

Soltani et al. (2025) construct a reliable shear wave velocity model down to the seismic bedrock depth for the Tehran sedimentary basin using an extensive geotechnical, geological, and geophysical survey including 197 downhole surveys, 585 ambient vibrations single station measurements, 33 ambient vibrations passive arrays, and 13 active arrays. The 1D shear wave velocity profiles (V_s) were defined at each array station using the joint inversion of Rayleigh waves dispersion curves (R_0 and R_1 , from passive and active arrays), the Rayleigh wave ellipticities (R_0 and R_1 , from arrays and single stations), the Love waves dispersion curves, the geotechnical information for the surficial layer as well as the resonance frequency of the soil, see Figure (1).

These extracted one-dimensional (1D) velocity profiles of Tehran are crucial in performing reliable ground motion simulations, understanding the spatial variability, and predicting soil amplification in each specific site. Typically, the initial stages of each site response analysis involve conducting a 1D analysis to evaluate (1D) site effects. In Tehran, such analyses were previously conducted by JICA (Japan International Cooperation Agency)

and CEST (Center for Earthquake Studies in Tehran) in 2000, as well as through a series of projects by IIEES (International Institute of Earthquake Engineering & Seismology) (Jafari et al., 2001a, b; 2004).

The majority of the 1D transfer functions computed in these studies exhibit low to moderate amplification, suggesting little or no amplification in most parts of the Tehran basin when considering representative soil profiles up to the engineering bedrock. The representative soil profiles used in these projects were mostly extracted based on shallow geotechnical data (N-SPT values) and surface geophysical surveys. However, these findings were totally in contrast with the experimental observation of soil amplification (e.g., Haghshenas, 2005; Haghshenas et al., 2008), which indicated a high level of amplification, reaching up to 8 in the south and southwest areas of the Tehran basin.

In this study, we aim to establish the new, authentic 1D site response model for Tehran basin by employing the newly developed velocity models that extend down to the seismic bedrock. Our goal is to identify the origin of observed differences in site amplification and emphasize

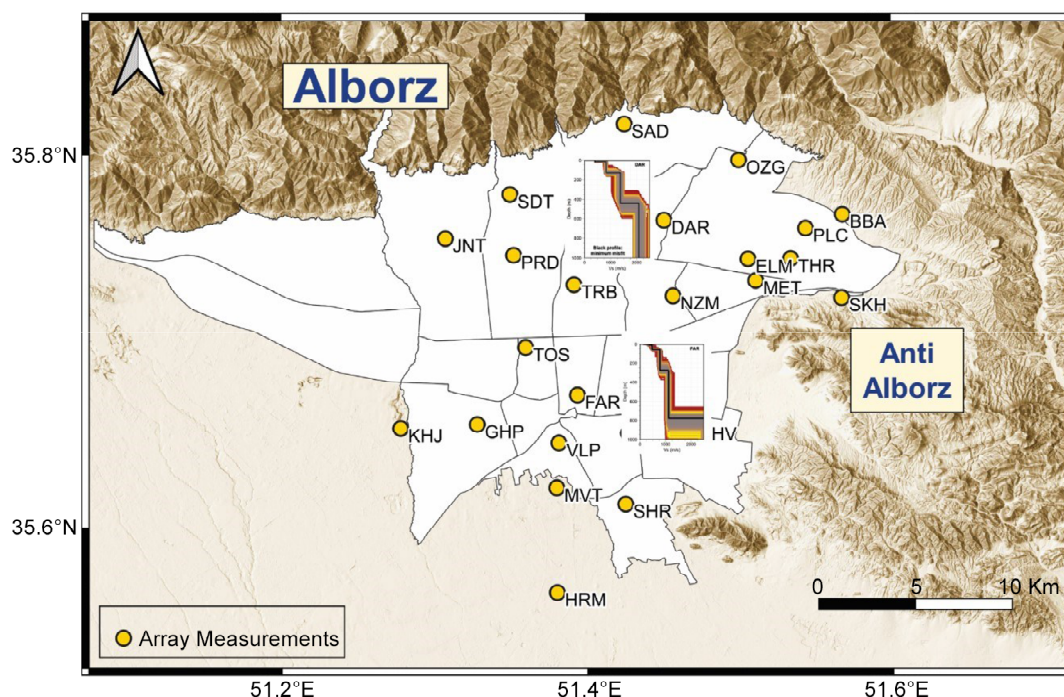


Figure 1. The location of microtremor array measurements, used for extracting the V_s profiles (see Soltani et al., 2025 for more details) and two representative 1D shear wave velocity profiles for the northern and southern regions of the basin. In the northern part, the bedrock depth typically extends to depths below 500 meters, while in the southern region, bedrock is found at depths ranging from 500 to 1000 meters.

the limitations of JICA study.

2. 1D Site Response

Local site conditions can amplify ground motion. Despite the fact that the wave propagation in layered earth can be very complicated, this simple fact can be interpreted by a very basic theory in 1D structures.

In a typical horizontally stratified sedimentary basin, where there is no velocity inversion or other anomalies, and ignoring the effects of scattering and attenuation, shear wave velocity and density are generally lower near the surface compared to greater depths. In such conditions, the wave energy ($\rho v_s \dot{u}^2$) requires a consistent flow throughout the medium. Consequently, when wave velocities (v_s) decrease in the near-surface, particle velocity ($\dot{u}$) must increase (Kramer, 1996). Similarly, for the near surface layers, the reflection theory force incline rays to touch horizontal interfaces in a quite vertical direction. Thus, given that the wave propagates in an almost vertical direction, multiple vertical refraction leads to what is known as the "1D site effect."

This simple theory forms the basis for the widespread use of 1D analysis among earthquake engineers to evaluate the effects of local site conditions. However, it is important to note that the 1D assumptions are valid if all interfaces extend infinitely in the horizontal direction, which is not the case in real scenarios, especially for those with strong 2D/3D structures like narrow valleys or the valleys with lateral heterogeneities (Zhu, 2018).

Despite these limitations, 1D site response still remains the most commonly used method for assessing site effects for engineering purposes because of low cost and relatively reliable results (Thompson et al., 2009, 2012; Rathje et al., 2010).

The 1D method in practice involves the use of transfer functions, which are the mathematical models that describe how the frequency content of an input signal is transformed as it propagates through a system (here: 1D soil profiles). Transfer functions determine how each frequency in the bedrock input motion is amplified or de-amplified by the soil profile. The transfers function in the frequency domain for the soft sediment visco-elastic

homogeneous layer overlaying rigid bedrock can be written as:

$$F(\omega) = \frac{1}{\cos K^* H} = \frac{1}{\cos \left(\frac{\omega H}{v_s^*} \right)} = \frac{1}{\sqrt{\cos^2 \left(\frac{\omega H}{v_s} \right) + \left[\xi \left(\frac{\omega H}{v_s} \right) \right]^2}} \quad (1)$$

where K^* is a complex wavenumber and H stands for layer thickness. For small damping ratios (ξ) at lower frequencies, the amplification of transfer function will reach a local maximum at $KH = \pi / 2 + n\pi$ which is called natural/fundamental frequency, f_0 (Kramer, 1996).

$$\omega_n \approx \frac{v_s}{H} (\pi / 2 + n\pi) \xrightarrow{n=0, 1, 2, \dots} \omega_0 \approx \frac{\pi v_s}{2H} \rightarrow f_0 = \frac{v_s}{4H} \quad (2)$$

With the same procedure, the amplification (A_0) of ground motion at f_0 can also be written by formula depending on the impedance contrast between the sediment layer and the bedrock as well as the damping factor of the sediment layer:

$$A_n = \frac{C}{1 + (2n+1)0.5\pi C\xi} \quad C = \frac{\rho_2 V_{s2}}{\rho_1 V_{s1}} \quad (3)$$

Based on the above formula, the two key site indicators (Fundamental frequency and site amplification) depends on the thickness and the shear wave velocity of soil profiles. Therefore, accurately determining these two values provides the most robust assessments of site amplification at the fundamental frequency.

3. Previous Study and Its Weaknesses

To provide a point of reference for 1D response analysis in Tehran basin, we compare the results of the JICA's 1D site response analysis with the findings from the experimental site effect study conducted by Haghshenas in 2005 at the same locations. The comparison reveals significant differences. Specifically, the 1D transfer functions from the JICA & CEST (2000) show no amplification below 1 Hz, which contradicts the 2005 study results that identified clear amplification,

particularly at very low frequencies (Figure 2). This discrepancy indeed highlights some specific weaknesses in the JICA study.

The main issue goes back to the fact that the JICA study used engineering bedrock rather than seismic bedrock depth. The engineering bedrock is generally defined in seismic codes as the depth at which shear wave velocity reaches a specific value (Di Giulio et al., 2021). This value varies among different seismic codes such as 760 m/s in

Iranian Standard No. 2800 (BHRC, 2014), 800 m/s for rock in EC8 (EC8, 2004) and 1500 m/s for hard rock in NEHRP (FEMA, 1997). In the JICA study, the engineering bedrock was associated with N-spt values of 100 for all various soil types (clay, clay and sand, sand, gravel). The shear wave velocity has been correlated to standard penetration test values (N-SPT) using the least square method with 580 m/s considered as engineering bedrock (Figure 3). It appears that the value selected by

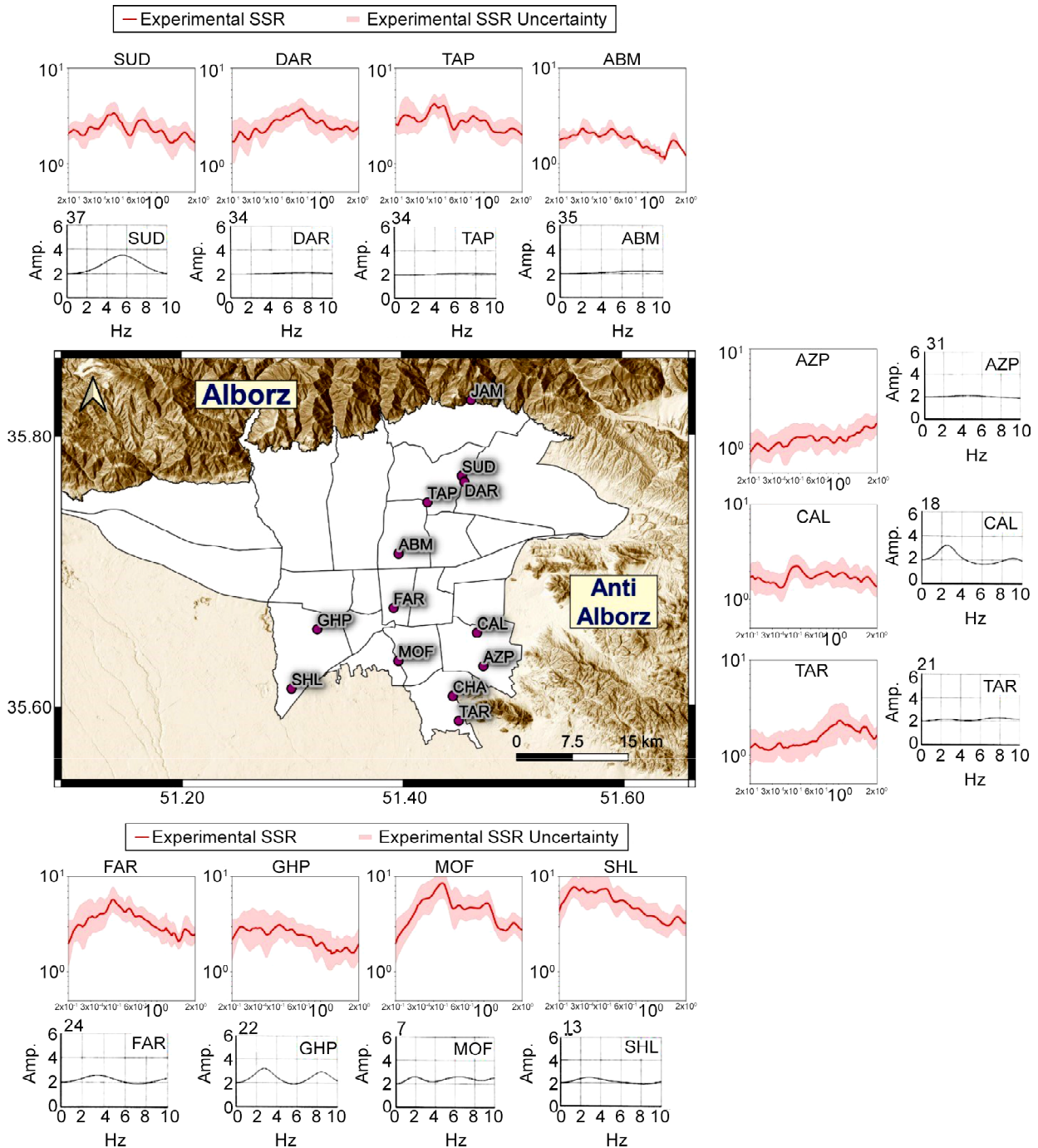


Figure 2. Temporary network station location and the corresponding JICA and CEST (2000) 1D transfer function (black curves) and Haghsheenas (2005) SSR amplification functions (red curves). CHA and JAM are the reference stations and the SSR amplification functions are shown in log-log plot.

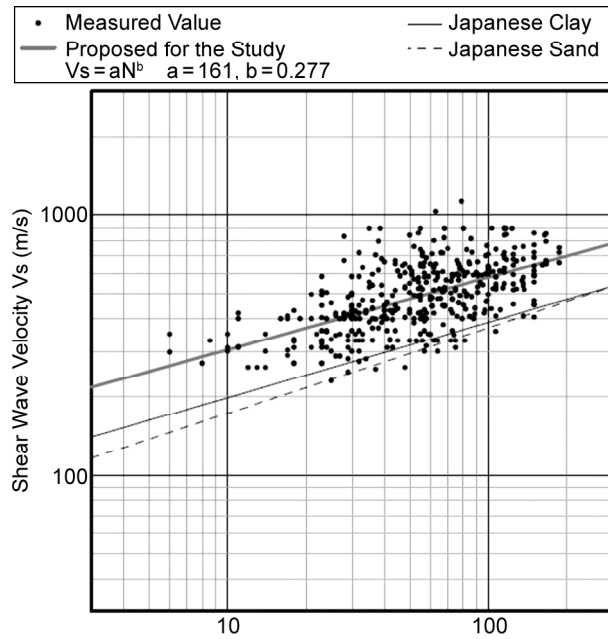


Figure 3. The relation between the N-spt and the shear wave velocity values at measured downholes (From JICA and CEST, 2000).

JICA is relatively small, even below the typical engineering bedrock values specified in Iranian building codes. This value is particularly not valid for the region with stiff soil conditions, such as Tehran basin.

In this regard, Poggi et al. (2017) found that common proxies such as V_{s30} , V_{sz} , $V_{(eng. \text{ bedrock})}$ are not the most effective proxies for site characterization in high-velocity sites. Similarly, Bergamo et al. (2021) demonstrated that the two sites with the same V_{s30} in Switzerland and Japan, but with different depth-to-bedrock values, exhibit different site amplification patterns. These observations indicate that the JICA, which did not account these critical depth conditions, was unable to provide reliable results for site amplification

in Tehran.

4. 1D Site Response Analysis in Tehran

The new 1D site response simulation in Tehran was conducted using the PSVSH Fortran code, which calculates the response of a horizontally layered structure to incident plane waves with arbitrary incidence angle and types (Bard & Cornou, 2000). The code can compute the 1D site response at the surface as well as other depth-specified receivers. The input files include the input signal, soil column characteristic and computational parameters.

In contrast to JICA study, SH plane waves with a 0° incidence angle replaced the synthesized earthquake as an input signal. In this case, the signal was generated as a Gaussian pulse, as narrow as possible, to approximate a Dirac function given the f_{max} value. This approximation will be valid for distant events. That means the SH plane waves act like the regional earthquakes when the earthquakes are far enough and the ray paths reach layer interfaces vertically. This approach is also acceptable when results are not compared in the time domain. Other important computational parameters are briefly described in Table (1).

4.1. Extracting Velocity Profiles

The first step of simulation involves defining a single shear wave velocity profile for each site. Since each inversion provides a set of velocity profiles for each site, different authors have employed various approaches to account for the uncertainties in these profiles. For example, Di Giulio et al. (2012) used a specific number of

Table 1. The short description for computational parameters used for PSVSH code.

Important Inputs	Description
$n_f = 2048$	Number of points in frequencies domain, for which the transfer function is to be computed
$f_{min} = 0$	Starting frequency in Hz for the computation of transfer function.
$F_{max} = 20$	Maximum frequency in Hz for the computation of transfer function
Teta = 0	Incidence angle in degrees, Measured respect to the vertical axis.
Mode = 3	Mode = 1, 2 or 3 corresponds to incident P, SV or SH waves.
$nr = 1$	Number of receivers at which the response is to be computed.
$zr = 0$	Depth of the j^{th} receiver.
Inputacc = 0	Integer parameter indicating the type of input signal in the time domain. Inputacc = 0, the input signal is automatically computed by the program.

profiles (100) with the lowest misfit values, while Teague et al. (2018) randomly selected a specific number of profiles from the 1000 models with the lowest misfits.

In our study, we compared the effect of using 100 and 1000 lowest misfit profiles on the variation of f_0 and A_0 to choose the best velocity profile with the minimum misfit.

Figure (4) shows the result of the test with 100 (panel A) and 1000 (panel D) velocity profiles with the lowest misfit. For panel A, the fundamental frequency of transfer function (f_0) ranges from 0.98 to 1.04 Hz, while the amplitude (A_0) ranges from 1.88 to 2.03. Further analysis of 1000 velocity profiles (Panel D) reveals that the f_0 range extended from 0.96 to 1.05 Hz, while A_0 range spans from 1.77 to 2.07.

Given that the computed values for f_0 and A_0 for the velocity profile with the lowest misfit are 0.99 and 1.97, respectively. It can be inferred that the minimum misfit value provides a reasonable estimate of f_0 and A_0 , serving as a potential average.

Other simulation parameters are defined based on certain assumptions. To have compressional wave velocity we used a V_p/V_s ratio as 2, since this ratio typically falls within the range of 1.5 to 2.0 in sediments. Given the soil stiffness

in Tehran, we selected the ratio of 2.0.

Additionally, we adopted a constant density value of 2000 g/cm³, which is estimated based on specific measurements of moisture content and the density of clayey or sandy soil in Tehran by JICA & CEST (2000).

Finally, since wave attenuation in the Tehran basin not yet been reliably computed or is particularly reliable for crustal structure, it cannot be accurately used for predicting wave attenuation in sediments. Therefore, we considered simplified Q_s and Q_p parameters which is estimated relative to the quality factors using the well-established rule-of-thumb equation presented by Aki and Richards (1980).

$$Q_s = V_s / SC_{Q(\text{Svaling factor})} \quad (4)$$

$$Q_s = \frac{V_s}{10} \text{ and } Q_p = 2 / Q_s \quad (5)$$

For the bedrock velocity, the value cannot be defined solely on inversion results because the minimum frequency of the computed dispersion curves in Tehran is higher than the fundamental frequency associated with the sediment-bedrock interface in the basin. In this regard, Okada (2003) studied dispersion curves in a deep basin of Tokachi plain (Hokkaido, Japan) and found that in order to

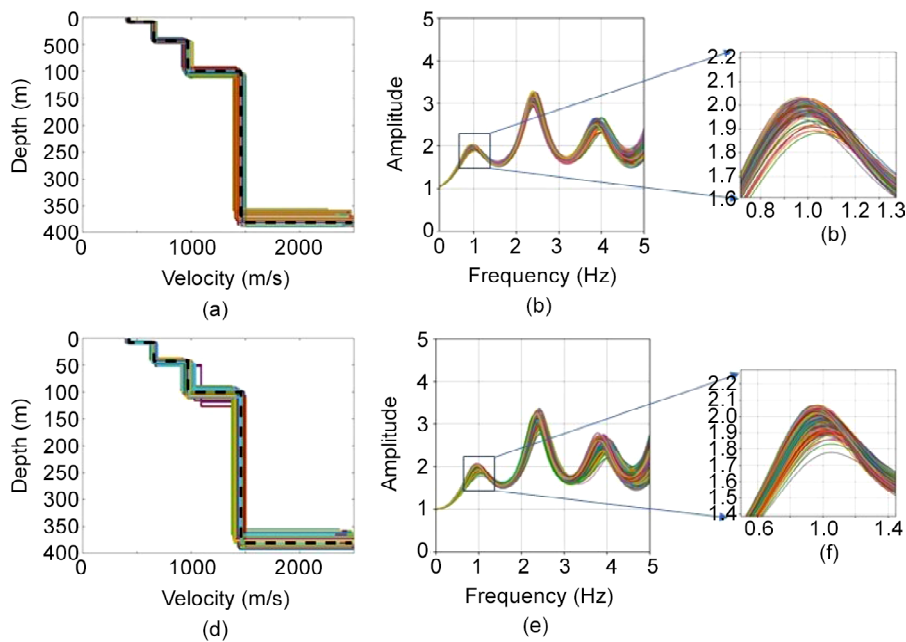


Figure 4. (a) Shear wave velocity profile for the 100 lowest misfit values. Black dash line represents the minimum misfit profile. (b) Transfer function for these 100 lowest misfit values. (c) Zoom to extract f_0 and A_0 . (d) Shear wave velocity profile for the 1000 lowest misfit values for NAM site. Black dash line represents the minimum misfit profile. (e) Transfer function for these 1000 lowest misfit values. (f) Zoom to extract f_0 and A_0 .

accurately estimate the bedrock velocity using microtremors, dispersion curves would need to be calculated down to natural frequencies below 0.2 Hz in that basin.

Since assessing bedrock velocity is crucial for the final simulation, as it can affect strongly the amplification values through impedance contrast, we extracted this value from previous studies on crustal structures in Tehran basin. For example, Abbassi et al. (2010) created a simplified model for the crustal velocity structure in the southern edge of the central Alborz, based on local earthquake travel time inversion and joint inversion of receiver functions and Rayleigh waves. Their model indicated a $v_p = 5.4$ km/s down to the depth of three kilometers. Based on their model, the v_s for bedrock velocity can be estimated 3.05 km/s.

The other velocity models calculated for Alborz region below 5 km depth are shown in Table (2).

4.2. Transfer Functions Calculation at Array Stations

Once the velocity profiles characteristics were accurately defined, the next step involved the calculating of 1D transfer functions.

In the first step, the transfer functions were calculated for each of the 33 velocity profiles that were obtained from the best misfit profile (Figure 5). However, since the velocity profile does not accurately represent the bedrock velocity, we used a value of 3000 m/s, derived from literature review (Table 2). As examples, the results of the calculated transfer function are illustrated for two selected stations, also in Figure (5).

It is now important to compare the similarity between the transfer functions of the 1D models and the observed H/V measurements on noise recordings in Tehran (Soltani et al., 2025). This comparison is essential to determine whether the 1D analysis accurately represents the real site

Table 2. Velocity models calculated for Alborz region below 5 km depth.

Reference	V_s (km/s)	V_p (km/s)	Reference	V_s (km/s)	V_p (km/s)
Priestley et al., 1994	-	5.6	Shirzad et al., 2018	3~3.2	-
Tatar et al., 2007	3.2	5.6	Rezaei Far & Kissling, 2018	-	5.9
Abbassi et al., 2010	3.05	5.4	Maheri Peyrov et al., 2020	-	5.3
Nemati et al., 2013	-	6.0	SoltaniMoghadam et al., 2019	-	5.35
Shomali & Shirzad, 2015	2.9	-			

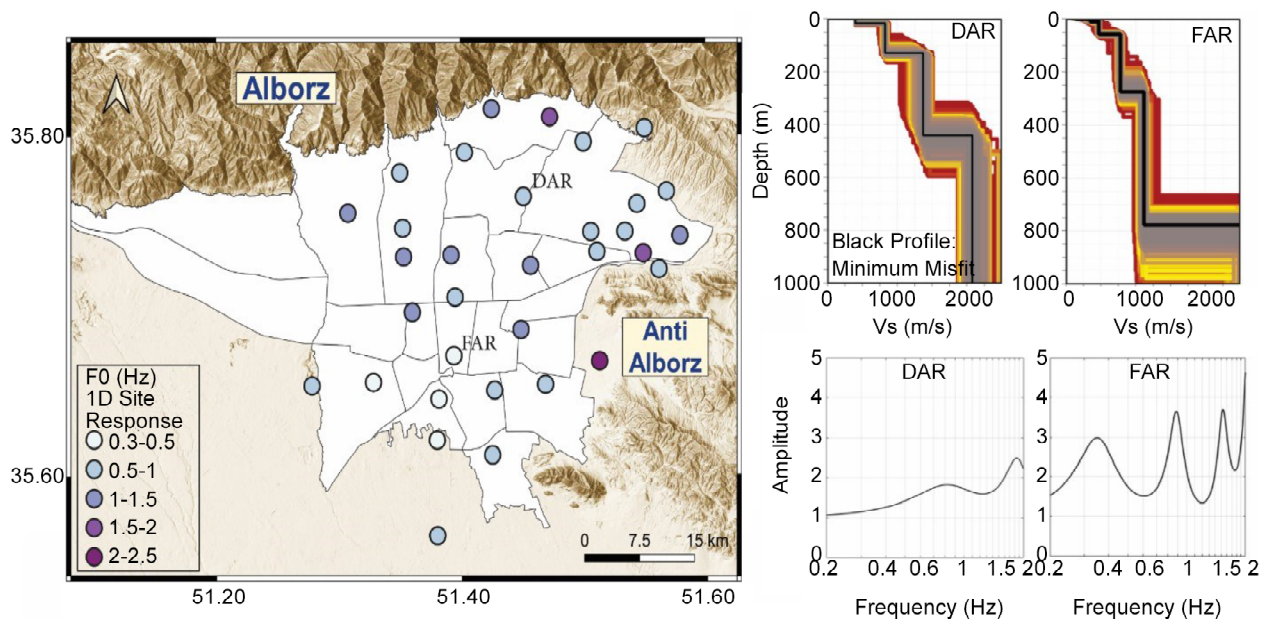


Figure 5. Transfer functions were calculated for each of the 33 velocity profiles with two samples of calculated transfer functions for two sites in north (DAR) and south (FAR) of Tehran. The best profile with the minimum misfit is indicated in black on the inversion results (top two graphs), along with the corresponding theoretical transfer functions (bottom two graphs) for each soil profile.

amplification or not. The H/V values were obtained from the average of the H/V curves for each array station, including their corresponding error bars, which were visually estimated from these curves (Soltani et al., 2025).

Figure (6) illustrates the H/V f_0 (black square) with observed error (light orange) and the measured transfer function f_0 (green square). For the seven stations where average f_0 cannot be extract from H/V curves, only 1D transfer function values are represented are (red dash-dot line stations).

These results indicate that the relative errors between the transfer function and observed H/V values for four stations (JNT, TOS, PRZ, and NZM) exceeded 20% with differences in fundamental frequency (f_0) greater than 0.15 Hz. For other stations, although the errors are present, they are still considered acceptable as they fall within the range of the error bars.

Various factors could contribute to this observation. The main reason might be the intrinsic limitation of 1D modeling, which is unable to provide an accurate representation of the experimental results. Another possible factor relates to 3D effects in this region due to the thickness of alluvial deposits and strong lateral discontinuities associated with faulting and folding, which lead to multidimensional site effects, as discussed by Soltani et al. (2025).

Moreover, as mentioned in Haghsheenas (2005), the H/V results should be interpreting with caution in the Tehran basin, mostly attributed to the existence of low levels of energy of arrival ambient noises. For the mentioned stations, the extracted H/V amplitude from experimental data is equal to or less than 2 with a broad peak. These

kinds of H/V curves, called low amplitude curves, were observed mainly in the center of the city (close to JNT, TOS, PRZ, and NZM stations). Using these kinds of curves to estimate the bedrock depth can lead to minor errors and may result in a slight underestimation of the bedrock depth and the corresponding 1D transfer function fundamental frequency.

Finally, for all other stations, none of the sites presents a difference between f_0^{HV} and f_0^{TF} greater than 20%. This suggests that the use of 1D modeling based on the new 1D velocity models can provide fairly reliable results in the Tehran basin, with acceptable levels of error (Figure 7).

4.3. Transfer Function Calculation Using Simplified Model

Since we can only extract specific shear wave velocity profiles for the array measurement locations, establishing 1D models for each arbitrary location across the basin is essential to obtain comprehensive results. This will also allow us to compare the results with H/V data from all available single-station measurements (159 reliable H/V curves from 585 measurements). To accomplish this, we need to retrieve these 1D models through some parametric simplification:

According to the inversion results and based on Tehran geology, the majority of retrieved velocity profiles consisted in three layers. In all profiles, it is possible to omit the very soft layer without significantly impacting the results in the low-frequency band, as the empirical observations in Tehran consistently show peak frequencies below 2 Hz (Haghsheenas, 2005). This is supported by the fact

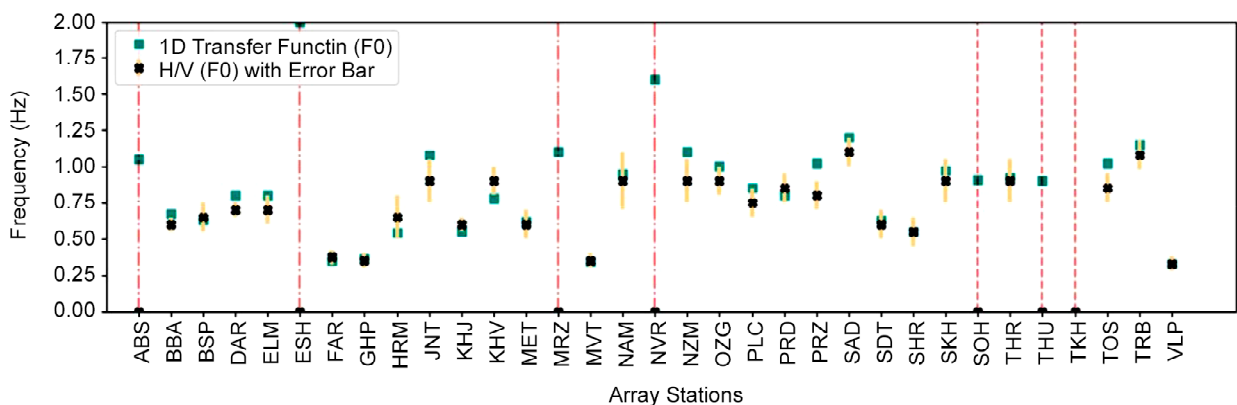


Figure 6. Fundamental frequencies (f_0) extracted from array stations (black x) with estimated error (orange bars) and the calculated f_0 (green square) from 1D transfer function. The red dashed lines represent the arrays without f_0 coming from H/V curves.

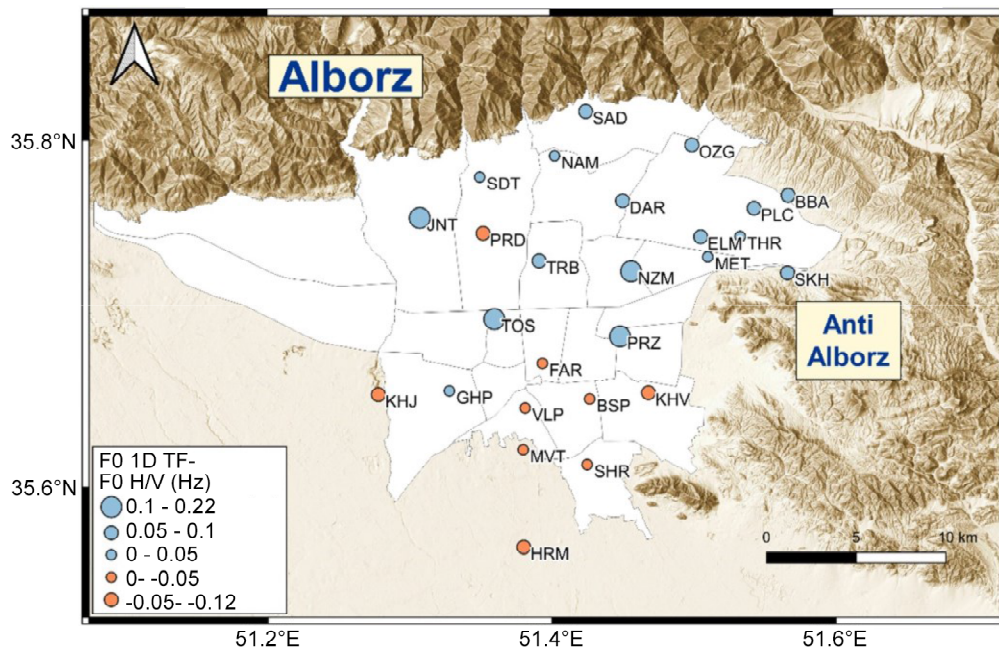


Figure 7. Tehran map showing the absolute difference between f_0 from the transfer functions and the f_0 extracted from the H/V curves at array stations.

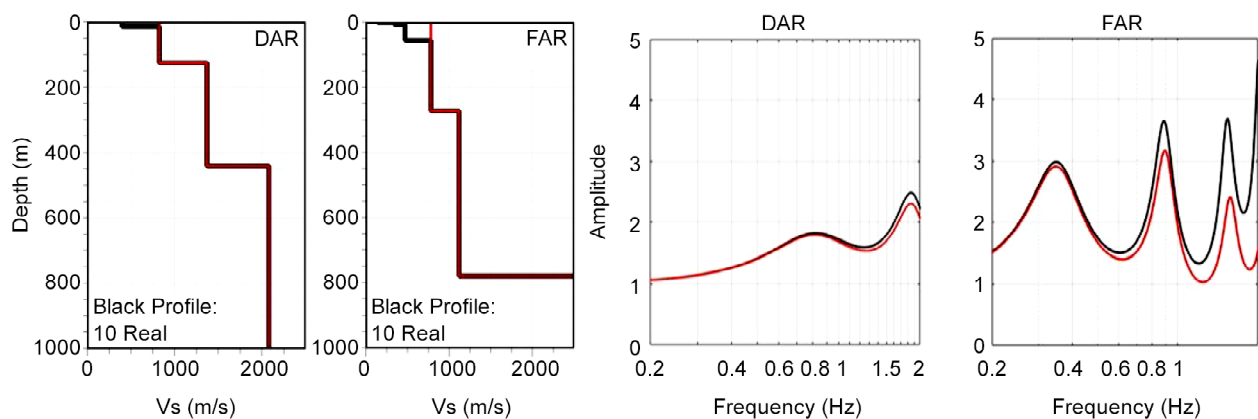


Figure 8. Comparison of the transfer function calculated for real best extracted 3 layers profiles (black profiles in 2 left graphs) and simple 2 layers models ((red profiles in 2 left graphs, omitting the thin shallow low velocity layers) for two sites in north (DAR) and south (FAR) of Tehran. The corresponding theoretical transfer functions are shown in black and red curves on 2 right graphs).

that the wavelengths of the seismic waves, are long and therefore, they should not be affected by the properties of very shallow subsurface layers. This simplification makes possible to reduce and simplify the layers from three or more layers into two layers; one soft layer and one stiff/hard layer; without changing the results while decreasing the complexity of model. The results simply show that this simplification has almost no effect on the frequency and amplitude content of the first frequency peak because of the small thickness of the first layer for all 1D soil profiles (Figure 8).

The next simplification step is to define the one average shear wave velocity for each layer. This is

done by averaging the shear wave velocities for both soft and hard/stiff layers across the array sites (Figure 9). We compute an average velocity per layer from the 33 sites (red and blue plain lines) fixing an error at ± 200 m/s for the soft layer (red dashed lines) and at ± 250 m/s for the stiff/hard layer (blue dashed lines). The average shear wave velocity for the soft layer is 835.45 m/s, while for the hard layer, it is 1272.84 m/s.

Once the average shear wave velocity is calculated, we can proceed with the 1D models for each location by using the average shear wave velocity and the thicknesses at that location. The thicknesses were determined by extracting values

from interpolations of one-dimensional shear wave velocity profiles using a Kriging linear interpolation scheme (sediment-sediment and sediment-bedrock interfaces interpolation). An example of one simplified model are shown in Table (3).

It should be noted that, using these simplified 1D

model and transfer function led to some changes in f_0 . For example, at the FAR station located in south, the new f_0 retrieved from the simplified model is greater than the f_0 in the first site response analysis since it has relative larger velocity variation compare to real profile (Figure 10).

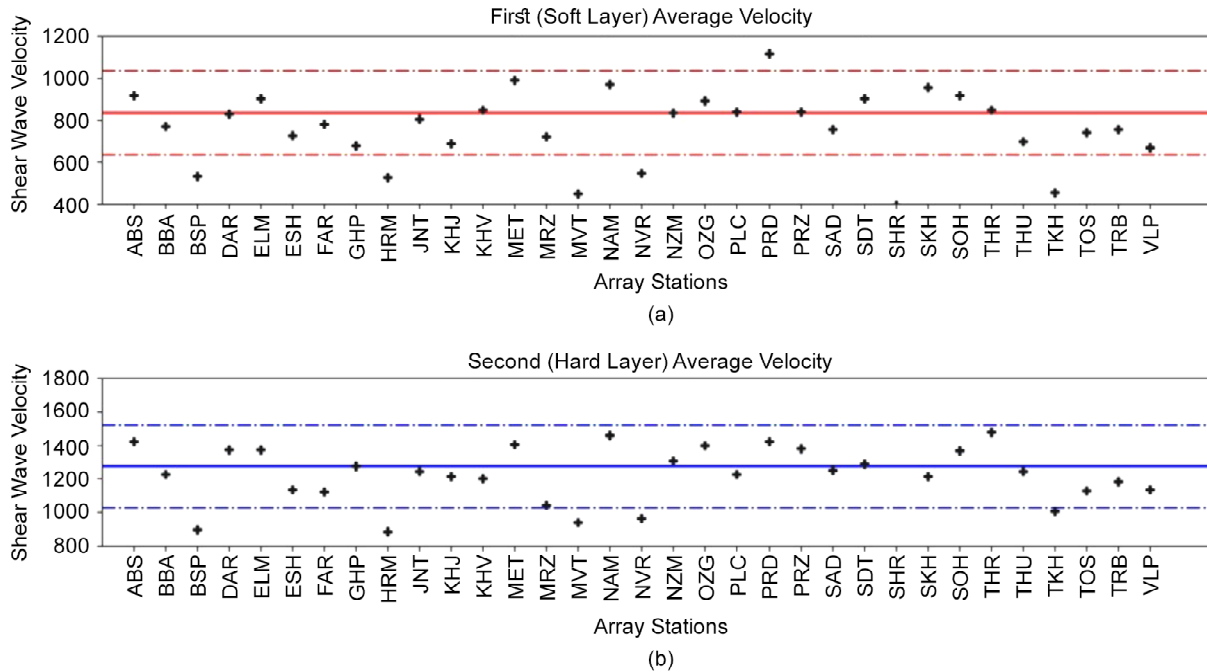


Figure 9. Velocity simplification for the soft layer (a) and the stiff layer (b). The black crosses represent the layer velocity in each of the 33 sites. The red or blue plain lines represent the average velocity from the 33 sites. For the soft layer (a) the dashed lines represent ± 200 m/s and for the hard layer (b) the dashed lines represent ± 250 m/s.

Table 3. Example of simplified model. The thickness of first and second layer extracted from sediment-sediment and sediment-bedrock interpolated map. (See: Soltani et al., 2024 for more information). The Vs for each layer extracted from the averaging velocity process. The value for Vs in bedrock is fixed to 3000 m/s from literature review.

Thickness	V_p (m/s)	V_s (m/s)	Density (Kg/m ³)	Q_p	Q_s
57	1670	835	2000	167	83
247	2545	1272	2000	254	127
0	5200	3000	2000	500	250

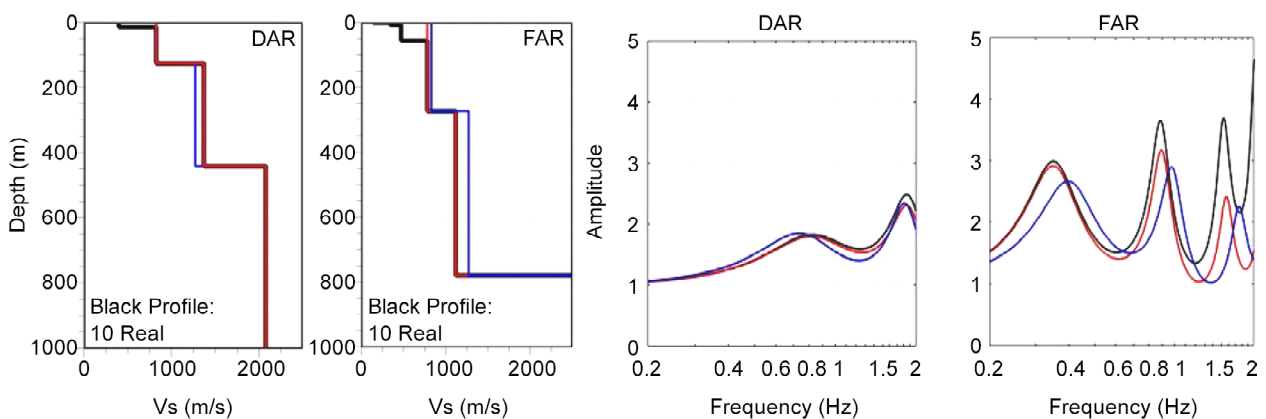


Figure 10.: Best extracted profile (in black), 2 layers profile (in red) and the simplified profile (in blue) for two sites in north (DAR) and south (FAR) of Tehran (the 2 graphs at left) and the corresponding theoretical transfer functions calculated for them (the 2 graphs at right).

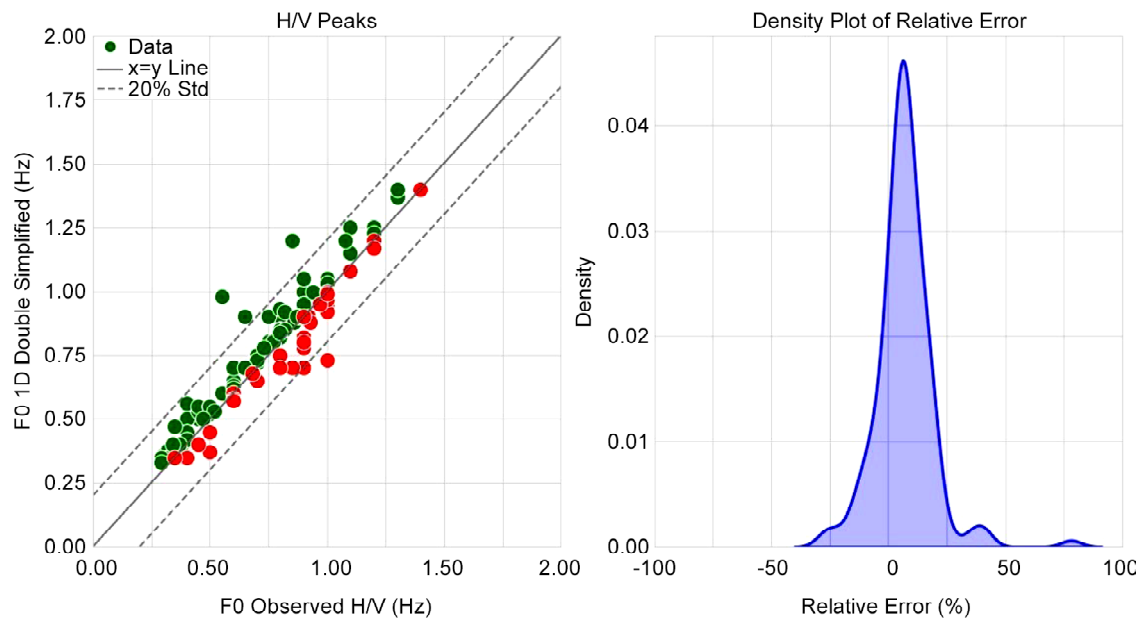


Figure 11. The location of microtremor array measurements, used for extracting the V_s profiles (see Soltani et al., 2024 for more details) and two representative 1D shear wave velocity profiles for the northern and southern regions of the basin. In the northern part, the bedrock depth typically extends to depths below 500 meters, while in the southern region, bedrock is found at depths ranging from 500 to 1000 meters.

However, for the majority of array stations, this epistemic error is considered acceptable (below 0.5 Hz). The largest errors from averaging and simplification occur only at a few stations in the south, such as FAR.

Finally, with the simplified models for the entire Tehran basin, we can calculate 1D simplified transfer functions for every location such as H/V measurement. Figure (11) show the distribution of observed H/V peaks in Tehran and their corresponding f_0 values obtained from 1D simplified models. An analysis of these results reveals that the peak density function concerning relative errors remains below 20%, with a median error of about 9%.

5. Conclusion

In this paper, we have highlighted the shortcomings of the JICA study in Tehran, which has been used as a reference for many risk assessment studies in the Tehran basin, by comparing it with the actual amplification values in Tehran. The main weakness lies in the use of engineering rather than seismic bedrock profiles, which prompted us to seek a solution.

To address this issue, we incorporated new velocity profiles acquired for Tehran (Soltani et al., 2025) that reach to the seismic bedrock in

order to compute seismic responses. Our analysis of seismic responses for simplified models, clearly demonstrated that the new profiles yield significantly more accurate results compared to the JICA model when compared to experimental H/V ratios in Tehran. However, it is worth noting that in certain stations mostly in the central and southern areas of Tehran, there appears to be an underestimation. This underestimation could be attributed to the presence of multi-dimensional site effects, as noted in previous studies such as Haghshenas (2005). Nonetheless, the present simple 1D models were able to provide reasonably accurate estimates for the fundamental frequency of the soil, at very low computational costs, with an average error of less than 20%.

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