Comparison of Invasive and Non-Invasive Methods in Site Response, Case Study: Soil Deposits of La Estrella

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Abstract. A great part of the Colombian territory is under medium to high seismic hazard due to the complex tectonic condition, which in turn affects, particularly, areas where the population density is highest. A response spectrum analysis of the ground is currently required by seismic design codes for site response analysis. For this, the shear wave velocity (Vs) profile must be established. The use of seismic invasive methods such as Down Hole or Cross Hole for the determination of the shear wave velocity (Vs), has been typically recommended. In recent years, significant progress has been made in non-invasive seismic methods such as MasW (Multichannel Analysis of Surface Waves) and ReMi (Refraction Microtremor), in order to estimate the Vs profile from surface waves analysis. Due to the accessibility and low cost, these methods represent a viable alternative to determine the profile of Vs. In this project, the seismic response of soil deposits was evaluated in the La Estrella municipality located in the south of The Aburrá Valley. One-dimensional (1D) models were simulated by characterizing the soil profile through the shear wave velocity with MasW and ReMi seismic tests. The results were compared with models based on shear wave characterization through Down Hole methods. The 1D response spectrums were determined with an equivalent linear model in DEEPSOIL and GTS NX software. The resulting spectra were compared through relative difference and correlation coefficient. Final results demonstrated that the spectra present low relative differences for long periods, moderate relative differences for moderate periods, and low to moderate relative differences for short periods. The general correlation coefficients were 0.6. This was evidence that non-invasive seismic methods allow an appropriate response spectrum analysis.

1. Introduction

Due to its geographical location, Colombia is one of the countries with the highest seismic activity. This is due to the interaction of four tectonic plates: South America, the Caribbean, Nazca, and Cocos. Furthermore, due to the climatic and topographic characteristics and social dynamics, the highest urban concentrations are located in areas of medium or high seismic hazard. An estimation with data from the 2018 census, and according to the seismic hazard zoning of Colombia \cite{1}, approximately 80\% of the Colombian population is located in areas of high or intermediate hazard, in addition, the cities of more than 300,000 inhabitants located in these areas concentrate more than 45\% of the whole population. To reduce the associated seismic risk, constructions in Colombia must guarantee their seismic resistance, implying, among other aspects, knowing the site response of the soils and their potential to amplify the waves generated by the earthquake.

The shear wave velocity (Vs) of the soil profile is one of the most important parameters in site response studies. The shear stiffness modulus ($G_0$) is calculated from the Vs profile and defines the
stress-deformation behavior of soil at shear stresses with low amplitudes. Furthermore, the response analyzes in the frequency domain are based on a closed solution of the equation of motion for the propagation of shear waves [2]. Therefore, in modeling, the response of the soil depends on and varies with the Vs values. Within the geotechnical study environment, it has been considered that the most reliable field tests for obtaining the Vs profile correspond to the Down Hole and Cross Hole tests, which in the present study are established as invasive tests.

The cost and time of execution of invasive tests in the characterization of the Vs profile are its main limitation [3]–[5]. As an alternative of lower cost and ease of execution, the MasW (Multichannel Analysis of Surface Waves) and ReMi (Refraction Microtremor) methods have developed, which are based on the analysis of surface waves to obtain Vs profiles [5] and correspond to non-invasive tests.

With non-invasive methods, it is possible to reduce the time and costs in obtaining Vs profiles; however, aspects have emerged that make these methods generate low confidence in geotechnical consultants. These aspects are related to the non-uniqueness of the solution, which limits the precision in identifying the positions of the layer boundaries and, therefore, generates variability in the results; and the lateral variability that affects the path of the waves and hence the values of Vs [3]–[6]. In response to the low reliability of non-invasive methods, studies have been carried out in which the reliability is evaluated, and results are compared between invasive and non-invasive tests.

Comina et al. [3] evaluated the reliability of non-invasive tests. They concluded that the non-uniqueness of the inversion does not significantly affect the precision and reliability of the estimation of the shear wave velocity in the first 30 m. (Vs30). Garofalo et al. [6] compared results of several non-invasive tests performed at the same site to identify the variation in the Vs profile and concluded that the overall variability could be considered small. Likewise, Garofalo et al. [4] and Darko et al. [5] compared Vs profiles obtained from invasive and non-invasive tests, and they conclude that Vs profiles estimated with each method are comparable. The comparison between invasive and non-invasive tests in the characterization of the Vs profile shows that they are comparable and accurate enough to apply non-invasive methods to determine the Vs profile.

In the present study, the seismic response of soil deposits in the La Estrella municipality, located south of the Aburrá Valley, was evaluated. Non-invasive MasW and ReMi tests were carried out to estimate the Vs profile. Then, one-dimensional (1D) models were simulated to obtain the site response on the ground using the equivalent linear model in DEEPSOIL and GTS NX software. The results were compared with seismic response models based on the characterization of shear waves using the invasive Down Hole method, carried out in the Aburrá Valley seismic microzoning study [7], [8].

2. Basic concepts

Idealizing an infinite medium, in which a stress wave travels and passes through a differential element, the one-dimensional wave equation of motion is deduced, which is defined as [9]:

\[
\frac{\partial^2 u}{\partial t^2} = V^2 \frac{\partial^2 u}{\partial x^2}
\]  

(1)

Where V represents the velocity of propagation of the wave, \( u \) is the displacement in the \( x \)-direction, and \( t \) the time. In equation (1), it is observed that the velocity propagation of the wave depends only on the properties of the material (stiffness and density) and is independent of the amplitude of the wave. The solution of equation (1) can be written in the form [9]:

\[
u(x, t) = f(vt - x) + g(vt + x)
\]  

(2)
Where \( f \) and \( g \) can be any arbitrary function of \((vt - x)\) or \((vt + x)\) that satisfies equation (1). In equation (2), it is observed that \( f \) remains constant as \( x \) increases with time (at the velocity \( V \)), and \( g \) remains constant as \( x \) decreases with time. Therefore, the solution of equation (2) describes a displacement wave \([f(vt - x)]\) traveling with velocity \( V \) in the positive \( x \)-direction and another wave \([g(vt + x)]\) traveling with the same velocity in the negative \( x \)-direction. This implies that the shapes of the waves do not change with position or time. If an infinite medium is subjected to harmonic stress in steady-state \( \sigma(t) = \sigma_0 \cos \omega t \), where \( \sigma_0 \) is the amplitude of the stress wave, and \( \omega \) is the circular frequency of the applied load, the solution can be expressed using the wavenumber, \( k = \omega / V \), in the form [9]:

\[
(x, t) = A \cos(\omega t - kx) + B \cos(\omega t + kx)
\]  

(3)

The first and second terms described in equation (3) correspond to harmonic waves that propagate in the positive and negative \( x \)-direction, respectively. The wavenumber is related to the wavelength, \( \lambda \), of the motion by:

\[
\lambda = V \bar{T} = \frac{V}{f} = \frac{2\pi}{\omega} V = \frac{2\pi}{k}
\]  

(4)

Where \( \bar{T} \) is the period of the applied load and \( \bar{f} = 1/\bar{T} \). In equation (4), it is observed that, at a given frequency, the wavelength increases with the velocity of wave propagation increases. The transfer function can be understood as a filter that acts on the input signal to produce an output signal with different characteristics. The transfer function depends on the soil deposit and rock base features. The transfer function starts from the solution of the wave motion equation, equation (1), for the elastic rock base case. For a soil deposit that is divided into layers with different stiffness and damping characteristics, the transfer function is defined as [9]:

\[
F_{ij}(\omega) = \frac{a_i(\omega) + b_i(\omega)}{a_j(\omega) + b_j(\omega)}
\]  

(5)

Equation (5) indicates that the movement in any layer of a soil deposit can be determined from the movement in any other layer; if the movement at any point in the soil profile is known, the movement can be calculated at another point.

The equivalent linear model approximation consists of modifying the Kelvin-Voigt model in order to consider some types of soil non-linearity. The non-linear and hysteresis behavior (stress-deformation of the soil) is approximated, during cyclical loads, by equivalent linear properties of the soil. The hysteresis curve can be described in two ways as follows: 1) by the curve itself and 2) by parameters that describe the general shape of the curve. In general, the slope and amplitude of the hysteresis curve are considered the most important features. The inclination of the curve depends on the stiffness of the soil that can be described at any point during the loading process by the tangent shear modulus \( G_{tan} \), however, since \( G_{tan} \) varies depending on the load cycle, it is necessary to represent the inclination of the curve with an average value, which can be approximated with the value of the secant shear modulus \( G_{sec} \):

\[
G_{sec} = \frac{\tau_c}{\gamma_c}
\]  

(6)

Where \( \tau_c \) and \( \gamma_c \) are the shear stress and the amplitude of the shear strain respectively. \( G_{sec} \) describes the slope of the hysteresis curve, then the shear modulus of linear equivalent \( G \) can be defined. The amplitude of the hysteresis curve is related to the area as a measure of the dissipation of energy, which can be described by the damping ratio:
\[ \xi = \frac{W_D}{4\pi W_s} = \frac{1}{2\pi} \frac{A_{\text{curve}}}{G_{\text{sec}} \gamma^2} \]  

(7)

Where \( W_D \) is the dissipated energy, \( W_s \) is the maximum strain energy, and \( A_{\text{curve}} \) is the area of the hysteresis curve. The \( G_{\text{sec}} \) and \( \xi \) parameters refer to the equivalent linear parameters of the material. Within the equivalent linear model, for the analysis of the response of the soil, these parameters are used to represent the behavior of the soil.

The secant shear modulus of soil varies with the amplitude of cyclic strain. At low strain amplitudes, \( G_{\text{sec}} \) is high; however, \( G_{\text{sec}} \) decreases as the strain amplitude increases. \( G_{\text{max}} \) represents the highest value of the shear modulus, which corresponds to the slope generated from the origin. At large amplitudes of cyclic deformation, the ratio of the modulus \( G_{\text{sec}}/G_{\text{max}} \) is less than 1. The variation of the ratio between the shear modulus and the shear strain is observed in Figure 1 (a). The shear modulus degradation curve represents the hysteresis curve for various shear strain amplitudes.

![Figure 1. Dynamic curves.](image)

The damping ratio of the soil represents the width of the hysteresis curve for several shear strain amplitudes. Similarly, the curve represents the dissipation of energy, which varies in relation to the soil type. The typical shape of the damping curve is shown in Figure 1 (b). The non-linear behavior of the soil can be represented with equivalent linear properties (stiffness and damping degradation curve). Since the calculated deformation level depends on the values of the equivalent linear properties, an iterative procedure is required to ensure that the properties used in the analysis are compatible with the calculated deformation levels in all layers. The iteration for the equivalent linear approximation consists of estimating values of \( G \) and \( \xi \) of the curves presented in Figure 1 (a) and Figure 1 (b) until reaching a convergence value. Even though the complete convergence is not absolutely guaranteed, differences of less than 5% to 10% are accepted and generally achieved in three to five iterations.

Surface wave analysis aims to estimate the shear wave velocity profile by solving an inverse model problem based on an experimental dispersion curve. Surface wave analysis is typically implemented with three sequential steps: seismic data acquisition (seisograms), processing (dispersion curve estimation), and inversion (model parameter optimization). Time histories of ground motion (seismic records) measured at a fixed number of points on the ground surface are the experimental data. The acquisition is carried out with seismic survey equipment, made up of a seismograph and a series of geophones, between 12 and 24, which are located on the ground to record the wave front. The acquisition of seismic information can be made actively or passively.

The field data is processed to recover an experimental dispersion curve. Several processing techniques can be adopted for seismic analysis data set; most of them work in the spectral domain. The most common procedures are transformation-based methods such as: frequency-wave number (\( f-k \)) or frequency-slowness (\( f-p \)) for active source data and \( f-k \) analysis for passive data. The inversion process aims to find the best subsurface model whose direct response has well agreement with the experimental
data, based on a proper definition of the adjustment function that is minimized in investment. Typically, for surface wave analysis, the fit function is a norm of the distance between the experimental and the theoretical scattering curves associated with a given subsurface velocity model. The shear wave velocity profile is obtained as the set of model parameters that best fit the associated theoretical dispersion curve and the experimental dispersion curve. The solution can be generated from local or global search methods.

3. Materials and methods
To compare the response from the invasive and non-invasive tests, the following steps were followed:

1. Characterization of the site by means of down hole tests
2. Site characterization by MasW and ReMi tests
3. 1D modeling and comparison of model results.

3.1. Characterization of the site by means of down hole tests
In this study, a previously documented case study was selected, where invasive seismic tests and modeling of the seismic response were carried out [7]. The description of the case study is presented in Chapter 4. The seismic hazard for the municipalities of Aburrá Valley was taken from the seismic microzoning study [7]. Based on this, the spectrum of seismic hazard for a return period of 475 years at the municipality of La Estrella was determined (Figure 2). The uniform seismic hazard spectrum for La Estrella was taken as a target spectrum which in turns, was used to scale the excitatory signals. For the project, the seismic records presented in the seismic microzoning [7] were used for a hazard level of 475 years. Table 1 shows the seismic records’ characteristics, and Figure 2 shows the response spectra of the seismic records called BOCAT, BN1, and ECA.

The dynamic soil parameters were obtained from the shear modulus and the damping ratio degradation curves defined previously and presented in [7]. Figure 3 shows the dynamic curves obtained for the debris flow deposits. Degradation curves included three curves explained as follows; 1) the curve with the black hatching corresponds to the minimum band; 2) the curve with the red hatching corresponds to the middle band; and 3) the curve with the orange hatching corresponds to the maximum band. For site response analysis, models were carried out with each of the bands. The minimum, average, and maximum bands were used to consider the uncertainty of the dynamic characterization of the debris flow deposits.

3.2. Site characterization by MasW and ReMi tests
Non-invasive surface seismic tests of the MasW and ReMi types were carried out at the site. The basic instrumentation for the execution of the tests consisted of a vibration source, a trigger system, a series of geophones, and a data acquisition system to process the electrical signals collected by the geophone. For the MasW seismic test, an 8 kg hammer, the GEA24 seismograph with 24 channels, 4.5 Hz vertical geophones, and the Gea 24 software were used for data acquisition. In the ReMi test, the same equipment as MasW tests was used, but readings were taken of environmental ground vibrations. The information was recorded in .SEG2 format for further processing. Figure 5 shows the non-invasive exploration line. The methodology for the analysis of surface waves corresponded to the acquisition, processing, and inversion of the data obtained; each activity is described below.

- **Seismic data acquisition.** A linear arrangement of a 60 m length with equidistant geophones was made for the active test, the wave field was recorded with time windows of 2000 ms, sampling frequencies of 4000 Hz, and numbers of shots greater than 10 at each point. For the passive test, the same arrangement used for the active test was used, recording of the environmental vibration with time windows between 30 sec and 15 min., samplings at intervals of 5 sec and 10 sec, and constant samplings
for 5 min, 10 min, and 15 min with a sampling frequency of 250 Hz. The information was recorded and stored for further processing.

- **Processing.** The data collected in the field were processed with the ZondST2D algorithm to obtain the experimental dispersion curve. The processing of the active and passive signals was carried out with the surface wave analysis modules for the MasW and ReMi methods. ZondST2D generates 2D representations of the wavefield spectrum in the domain of velocity phase-frequency (v-f) and wave number-frequency (k-f). In addition, ZondST2D allows the extraction of the dispersion curve manually or semi-automated.

- **Inversion.** The experimental dispersion curve was adjusted by means of a global search process, where the error was identified, and the profile (model) of shear wave velocity was estimated by the record obtained.

The dispersion curve was obtained for each of the records of the MasW and ReMi tests. From the inversion process, the experimental dispersion curve was adjusted through a global search process, where the error was identified. The shear wave velocity profile (model) obtained by recording was estimated. To consider the uncertainty in the characterization of the non-invasive Vs profile, with the mean value and standard deviation of the data, ten (10) random profiles were generated, named A1 to A10, which are presented in Figure 4 (a). With the Vs profiles shown in Figure 4 (a), evaluation was made of the site response with non-invasive tests. In Figure 4 (b), the invasive Vs profile is presented, defined for the La Estrella slope deposits, and taken from the seismic harmonization study [8]. Regarding with the invasive Vs profile, random profiles named A1 to A10 with the standard deviation of the data were generated.

The one-dimensional response with the equivalent linear model was evaluated for the Vs profiles of non-invasive tests (Figure 4 (a)) and invasive tests (Figure 4 (b)). For each invasive / non-invasive Vs profile, response models were performed, with each scaled signals and each dynamic curves for the debris flow deposit (minimum, average, and maximum band). For each excitatory signal, 33 site response models were made, 11 with the minimum band, 11 with the middle band, and 11 with the maximum band. Each defined Vs profile was also considered for both invasive and non-invasive profiles. All of these cases permit to consider variation and uncertainty in characterizing the Vs profile and the dynamic curves. Each model presented corresponds to the results of the response of each excitatory signal and for each band of the dynamic curve, for which 34 site response models are presented, including the mean of the model results.

3.3. 1D modeling an Comparison of model results
To calculate the one-dimensional response, the DEEPSOIL and GTS NX software were used. In GTS NX the one-dimensional response was evaluated with the free field analysis module. Response spectra with the invasive / non-invasive Vs profile were calculated with each software. To compare the surface response between the spectra generated with the invasive and non-invasive Vs profile, the relative difference between spectra was defined and calculated as:

$$\delta S_a = \frac{\sum_{i=1}^{N} |\ln (S_{at}(T_i)) - \ln (S_{aNi}(T_i))|}{N} \times 100$$  \hspace{1cm} (8)

Where $S_{at}$ corresponds to the spectral acceleration value calculated from the invasive Vs profile and $S_{aNi}$ corresponds to the spectral acceleration value calculated from the non-invasive Vs profile at period $T_i$. For the analysis of the difference between spectra, the periods were divided into the short period (0.0 - 0.2 s), medium period (0.2 - 2.0 s) and long period (2.0 - 10.0 s) [10]. In addition, to review the relationship between the response spectra, the correlation coefficient was calculated, which is defined as:
\[
\delta = \frac{\sum_{i=1}^{N}[(X_i - \bar{X}) \times (Y_i - \bar{Y})]}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2 \times \sqrt{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}}}
\] (9)

Where \(\bar{X}\) and \(\bar{Y}\) is the mean of the values of \(X\) and \(Y\). The correlation coefficient takes values between -1 and 1. As defined in [11], there is a good fit when \(r > 0.6\), and there is a poor fit when \(r < 0.6\).

**Table 1.** Characteristics of seismic records.

| Seismic Record | BOCAT | BN1 | ECA |
|----------------|-------|-----|-----|
| Code           | BOCAT | BN1 910422 | ECA 990820 |
| Date           | 25/01/1999 | 22/04/1991 | 28/08/1999 |
| Station        | Bocatoma - Pereira | BN1 | ECA (Esc. Católica Active) |
| Magnitude (Mw) | 6.2 | 7.7 | 6.5 |
| Origin process | Local | Local | Subduction |
| Soil type      | Soft | Soft | Soft |
| Epicentral Dist. (Km) | 14 | 114 | 105 |
| Hypocentral Dist (km) | 42 | 114 | 107 |
| Site condition | Free field | Base building | Free field |

![Figure 2. Uniform hazard spectrum and excitatory signals.](image)

![Figure 3. Dynamic curves. (a) stiffness degradation and (b) damping ratio.](image)

### 4. Case de study

The study area is located in the municipality of La Estrella, southwest of the Aburrá Valley, in the Villa Mira urbanization, approximately 16.0 km from the city of Medellin. **Figure 5** shows the location of the study area.
Figure 4. Vs profile (a) non-invasive Vs profile and (b) invasive Vs profile.

Figure 5. Location of the study area.
In the study area, there is a geological formation of slope deposits, defined in the seismic microzoning [7] as La Estrella debris flows (Qft / e). This formation corresponds to non-lithified deposits made up of clasts and matrices. The clasts are generally fresh, subangular to sub-rounded, embedded in a silty clay matrix. The selection of the deposit is very poor, varying the diameter of the clasts from meters to centimeters, composed of diabase.

According to drilling carried out in the study area [7], the slope deposit is divided into a weathered debris flow, located between the ground surface and 19.0 m depth, characterized by a greenish-gray, yellowish-brown, and dark brown silty clay matrix, with fine gravels, which embeds rock blocks up to 0.5 m in diameter, angular in shape, weathered towards the edges and of diabasic composition. From 19.0 m depth to 32.0 m depth, a fresh debris deposit consists mainly of rock blocks (diabase, porphyries, and basalts), up to 0.7 m in diameter, angular in shape, and fresh. The matrix is greenish-gray silty clay. Figure 5 shows the geological map associated with the study area.

5. Results and discussions
Several models were developed to evaluate the effect of various variables on soil amplification. Initially, the DEEPSOIL software was used, generating model D1 corresponding to the spectrum performed with invasive tests and model D2 to the spectrum performed with non-invasive tests. Subsequently, the GTS NX software was used, and models G1 and G2 were generated, corresponding to the spectra performed with invasive and non-invasive tests, respectively (see Figure 6).

According to the results, it is identified that for models D1 and D2, the spectral shape of the response is similar, with maximum acceleration values between 1.19 to 1.2 (g) respectively, in which a natural period of the soil is obtained between 0.22 to 0.25 sec. For models G1 and G2, the spectral shape varies in periods less than 0.1 sec and presents maximum acceleration values between 1.1 to 1.3 (g), respectively. A natural period of the soil between 0.22 to 0.24 sec is obtained.

Table 2 shows the relative difference between the calculated response spectra. In general, the maximum difference is 14.9% between models D1-G2 at long periods. The minimum difference is presented in the comparison between models D1-D2 and G1-G4 at long periods. Table 3 shows the correlation coefficient, for all the models in the long periods; coefficients greater than 0.6 were roughly observed, indicating an important correlation between the compared spectra for these periods. For the medium periods, the average coefficient is 0.7, and for the short periods, the average value is 0.51.

Comparing the 1D surface response spectra, relative differences between 0% and 14.9% are presented. In addition, correlation coefficients are obtained for long periods from 0.53 to 1.0 with mean values of 1.0; for medium periods between 0 to 1.0, with mean values from 0.65 to 0.83; and for short periods, a variation of the correlation coefficient between 0.26 to 0.91, with mean values from 0.35 to 0.65, between the response spectra calculated with the invasive Vs profile and the non-invasive Vs profile.

6. Conclusions
The results show that one-dimensional models elaborated with data from non-invasive tests such as MasW and ReMi, present similar results to the models elaborated with data from invasive tests such as down hole. This enhances the ease and low cost of executing these tests for amplification studies required for seismic microzonation processes and the design of significant civil works.

According to the results of the comparison of the 1D models, in general, low relative differences are obtained for the long periods, and correlation coefficients on average greater than 0.6, which indicate a significant agreement between the data. The relative difference is low for the medium periods, between 0.2% to 11%, with correlation coefficients in general greater than 0.6. The difference between the
spectra is generally low for the short periods, between 2.5% to 13.7%, with correlation coefficients an average of 0.51.

Figure 6. Response spectra with invasive and non-invasive Vs profiles.

Table 2. Relative difference.

| Period | Short | Medium | Long |
|--------|-------|--------|------|
|        | Min   | Med    | Max  |
| D1     | 2.5%  | 5.4%   | 7.9% |
|        | 0.2%  | 1.0%   | 4.5% |
|        | 0.0%  | 0.1%   | 0.3% |
| D2     | 2.7%  | 5.9%   | 11.4%|
|        | 0.1%  | 1.2%   | 10.4%|
|        | 0.0%  | 0.1%   | 0.3% |
| G1     | 3.1%  | 9.1%   | 13.7%|
|        | 0.3%  | 2.8%   | 11.0%|
|        | 0.3%  | 4.2%   | 14.9%|
| D2     | 2.8%  | 5.9%   | 9.0% |
|        | 0.2%  | 2.2%   | 5.9% |
|        | 0.2%  | 4.1%   | 14.6%|

Table 3. Correlation coefficient.

| Period | Short | Medium | Long |
|--------|-------|--------|------|
|        | Min   | Med    | Max  |
| D1     | 0.35  | 0.35   | 0.58 |
|        | 0.05  | 0.83   | 1.00 |
|        | 1.00  | 1.00   | 1.00 |
| D2     | 0.33  | 0.65   | 0.86 |
|        | 0.0002| 0.76   | 1.00 |
|        | 1.00  | 1.00   | 1.00 |
| G1     | 0.38  | 0.52   | 0.67 |
|        | 0.02  | 0.67   | 1.00 |
|        | 0.53  | 0.99   | 1.00 |
| D2     | 0.26  | 0.52   | 0.91 |
|        | 0.005 | 0.65   | 1.00 |
|        | 0.53  | 0.99   | 1.00 |

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