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Assessment of site effects on soft clay deposits influenced by inclined deep hard strata in the southeastern zone of Mexico City

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ABSTRACT: As is well known, dynamic soil parameters for a specific site can be determined by field tests, provided that the boundaries between soil layers with different stiffness are horizontal. In some sites, however, the boundaries between strata are inclined or nearly vertical, especially in cases involving lava flows. This situation is significant when firm soil or rock deposits are buried beneath soft clay layers, such as in the southeastern part of Mexico City. In such cases, it becomes challenging to identify the dominant period of the site and shear wave velocity profile. This paper presents results from numerical simulations showing that irregular amplifications in the seismic response at the ground surface are caused by the reflection and refraction of seismic waves at inclined contacts of soil layers. Recommendations are offered to account for this phenomenon when interpreting the measurements of ambient vibration used to determine the dominant period of a site.

KEYWORDS: seismic site effects, inclined deep deposits, numerical analysis.

1 INTRODUCTION

This article aims to offer insights and recommendations to help interpret Nakamura-type field tests for estimating the dominant vibration period (T_d) of sites where the contact between soft soil and hard soil is inclined. This will allow for better interpretation of field test results to determine soil shear wave velocity profiles.

The article presents six criteria for calculating T_d. These criteria have evolved since the 1930s. The data used for these criteria comes from numerical modelling results obtained using the finite element method for a typical case in an area with a soft clay formation thickness of 20.0 meters or less. A brief description of the criteria used is provided below.

Historically, ground surface movements in horizontally layered soil deposits were calculated using the propagation of shear waves from rock formations. Jacobsen (1930) proposes a solution to this problem using the shear beam method, since the movements induced at the base by seismic excitation are considered to generate shear deformation in the soil only.

Soil amplification (of alluvial deposits) calculated with the shear beam solution assumes that the soil behaves linearly viscoelastically; that the soil stiffness is constant with depth; and that the movement at the base is horizontal, harmonic, and simple. Calculating the surface response of a finite-depth soil deposit to horizontal motion involves solving the motion equation, Kanai (1952, 1961) and Herrera and Rosenblueth (1965):

$$\rho \frac{\partial^2 u}{\partial t^2} + c\frac{\partial u}{\partial t} - \frac{\partial}{\partial z}\left[G(z)\frac{\partial u}{\partial t}\right] = -\rho a_g \tag{1}$$

where: ρ: soil mass density, c: viscous damping, $G(z)$: shear rigidity modulus at depth z, u: relative displacement, z: depth from the deposit surface, t: time, a_g: horizontal acceleration at the deposit base.

Another solution for the vertical propagation of plane waves in a viscoelastic soil layer uses the Voigt model (a spring connected in parallel to a viscous damper) and the following equation of motion:

$$\rho \frac{\partial^2 u}{\partial t^2} + G\frac{\partial^2 u}{\partial z^2} - \mu\frac{\partial^3 u}{\partial z^2 \partial t} = 0 \tag{2}$$

where: G: shear rigidity modulus, μ: soil viscosity.

These two equations derive methods that assume soil behaves like a viscoelastic material with constant stiffness and viscous damping for small deformations. However, it should be noted that soil behaviour is nonlinear. Hardin and Drnevich (1972) show through experimentation that a hyperbolic function can approximate soil behaviour. Based on the nonlinear stress-strain behavior of Ramberg-Osgood and equations of state and motion for dynamic soil parameters that vary with depth but remain constant at certain depths, Streeter *et al*. (1973) solve the one-dimensional shear wave propagation problem.

In studies of wave propagation to estimate the response of a soil deposit to seismic activity, the scheme of equivalent linear is often employed. This scheme accounts for the degradation of soil stiffness due to seismic-induced soil deformation.

Another method for calculating the seismic response of a stratified deposit is the concentrated-mass solution, which approximates the nonlinear behaviour of soil using a bilinear hysteretic model. The motion equation is solved using a stepwise procedure.

On the other hand, the Nakamura method uses a field test where monitors and measures ambient noise or vibration.

Seismic signals produced by focused point sources are coherent and have a finite duration. The relationship between phases is defined by response spectrum or Fourier spectrum. Seismic noise, on the other hand, is a continuous signal produced by many different and unrelated sources, Chávez-García and Montalva (2014).

In this paper, the criteria used to calculate the predominant period (T_d) are:

1: Modified shear beam relation:

$$T_d = 4\sum_{i=1}^{n}\left(\frac{h_i}{v_{si}}\right) \tag{3}$$

where h_i y v_{si} are the thickness and shear wave velocity of each one of the clay layers i, and n is the total number of clay layers. Also, $H_0 = \sum h_i$, total thickness of the clay formation. In addition, v_{sa} is the average shear wave velocity throughout the clay deposit.

2: At sites with a high contrast in stiffness between soft soils and hard deep deposits, the ground vibration frequency obtained from the H_S/V_S spectral ratio correlates with the total thickness of the sediments at the site (H_0). In general, frequency and thickness are related by a nonlinear empirical function. In terms of T_d results, Lermo *et al.* (2019) indicate:

$$H_0 = a\,T_d^b = 21.72\,T_d^{1.04} \tag{4}$$

where a and b are parameters of the potential curve. Lermo *et al.* propose: $a = 21.72, b = 1.04$.

3: The period corresponding to the maximum peak of the response spectrum of the horizontal component of the signal, as calculated on the surface.

4: The period corresponding to the maximum peak of the transfer ratio, which is calculated as the SB ratio:

$$SB = PSA_{surface}/PSA_{seismo-base} \tag{5}$$

where $PSA_{surface}$ and $PSA_{seismo-base}$ are the Pseudo-Spectral Acceleration (PSA) of the horizontal component of the signal calculated at the surface and in the basement (hard soil), respectively.

5: Nakamura (1989, 2000) procedure: the period corresponds to the maximum peak of the spectral ratio (H_S/V_S):

$$S(f) = \frac{H_S}{V_S}\cdot\frac{1}{\frac{H_B}{V_B}} = R_S\cdot\left(\frac{1}{R_B}\right) \tag{6}$$

where R_S and R_S are the H/V spectral ratios at the surface and in the basement, respectively. Also, H_S, V_S, H_B, V_B are the Fourier spectra of the horizontal (H) and vertical (V) waves at a point on the surface (S) and at a point in the basement (B), respectively. Based on observations, it is known that H_B/V_B spectra for rock is approximately 1.0 ($R_B \approx 1.0$), because the amplitudes of the vertical and horizontal components of microtremors are similar at the rock base over a wide frequency interval where the strata are firm.

6: As an alternative to the Nakamura procedure, H_S and V_S are obtained from response spectra.

2 STUDY APPROACH AND CONSIDERATIONS

Considerations for calculating the dominant period with the criteria described and with the surface acceleration calculated with numerical modelling:

- Surface acceleration is calculated using wave propagation analysis in the time domain with the finite element method.
- The stratigraphy is typical of alluvial lake deposits in Mexico City. The clay formation overlies deep, hard deposits or an inclined basement (Auvinet *et al.*, 2017, 2019, 2021). The maximum thickness of the clay formation is 20.0 meters.
- The basement's inclination is due to possible flow or spillage from volcanic eruptions covered by lacustrine and alluvial deposits.
- The average shear wave velocity is 76.8 m/s, weighted by the thickness of each clay formation. Figure 1 shows the v_{si} profile determined by a suspension logging test, in the Colonia Del Mar, Tlahuac, site located southeast of Mexico City.
- Since the Nakamura procedure uses low-intensity waves, the incident wave used in this study is low intensity. This consideration helps avoid uncertainty in the surface wave response due to the nonlinear effects of soil behaviour. Also, the soil behaviour model is linearly elastic, and the soil dynamic parameters are not degraded due to the low intensity of the incident wave.
- To calculate the site response due to wave propagation, a bidirectional wave (horizontal and vertical) is applied to the bottom of the finite element numerical model. The applied wave is a synthetic earthquake scaled by a factor of 0.10 to represent a very low-intensity earthquake (Figure 2). The original earthquake was calculated using the Prodisis program (INEEL - CFE, 2015) for a return period of 475 years. The associated response spectrum shows that the peak in the corresponding 5% damped response spectrum is 25.5 cm/s², the dominant period associated is 0.16 s, and the peak ground acceleration (PGA) is 7.8 cm/s², Figure 3.
- The vertical component of acceleration is equal to the horizontal component.
- In numerical analysis, the soil damping is of the Rayleigh type.

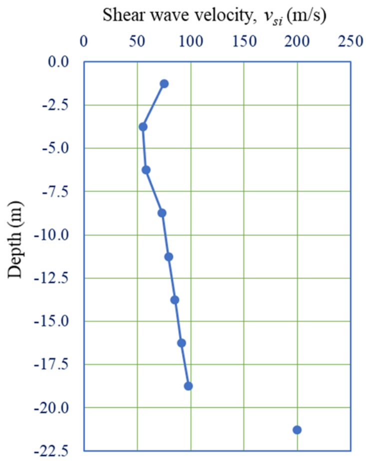


Figure 1. Shear wave velocity profile.

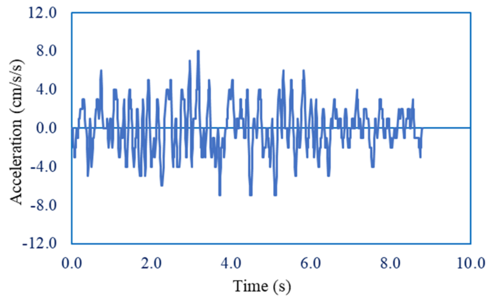


Figure 2. Input wave.

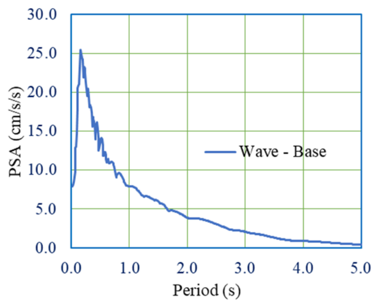


Figure 3. Response spectrum of the input wave.

3 CALIBRATION STAGE

The calibration of the analysis procedure includes calculating the surface response of a simple problem by numerical modelling and comparing the T_d values calculated by the indicated criteria. It also includes defining the Rayleigh soil viscosity parameters: α, β.

Input data and specific considerations:

- The clay formation is 20.0 meters thick, and the clay-hard soil contact is horizontal.

- In the wave propagation analysis, the applied acceleration histories are horizontal (*H*) and vertical (*V*), Figure 4.
- Figure 4 also shows the numerical model used in the propagation analysis, the point on the ground surface from which the wave response is calculated, and the stratigraphy used.

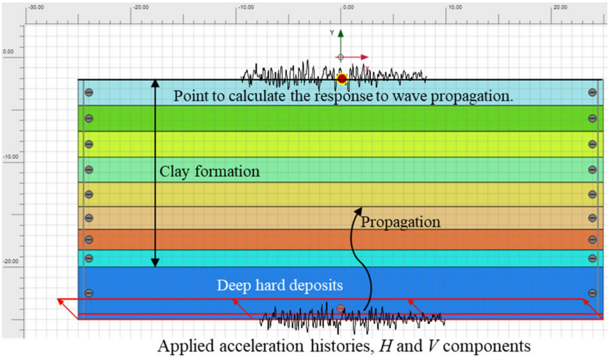


Figure 4. Numerical model to calculate the wave propagation.

Results:

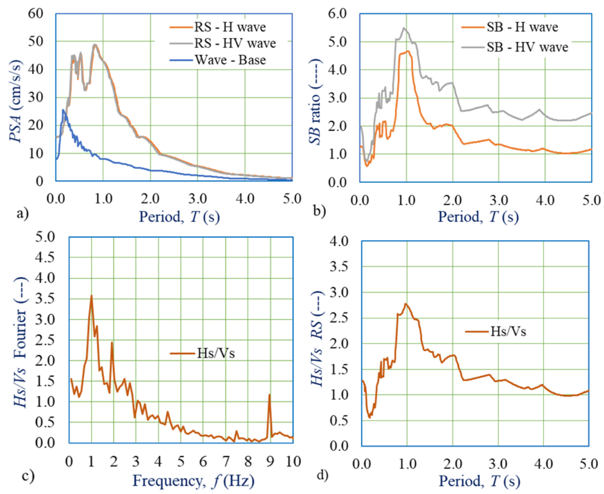
The dominant period (T_d) calculated with the indicated criteria and with the surface response calculated with numerical modelling varies between 0.84 s and 1.08 s (Table 1). These results are consistent with corresponding ones using the analytical method, EERA program (Bardet *et al*., 2000), where the dominant period associated with the maximum peak of the surface response spectrum is 1.05 s.

Table 1. Dominant period (T_d, in s) by the six considered criteria.

Wave	1	2	3	4	5	6
H	1.08	0.92	0.84	1.04	---	---
H, V	1.08	0.92	0.82	0.94	0.98	0.94

Symbology: criteria: 1: Shear beam relation, 2: Lermo (2019), 3: peak of the response spectrum, 4: peak of the transfer ratio (SB), 5: Nakamura, Fourier spectrum, 6: Nakamura, response spectra.

The data in Table 1 are based on the graphs shown in Figure 5, which include response spectra (*RS*), *SB* transfer ratio, Nakamura-based Fourier spectra (*Nk-F*), and Nakamura-based response spectra (*Nk-RS*).



Symbology: *PSA*: Pseudo-Spectral Acceleration, *SB*: transfer ratio Equation (5), *RS*: response spectrum, *H wave*: horizontal wave only, *H-V waves*: bidirectional wave (horizontal and vertical).

Figure 5. Results of wave propagation, case: horizontal basement, calibration stage.

Besides, the results shown were obtained with the Rayleigh damping parameters: $\alpha = 0.050$ and $\beta = 0.015$; hence, these parameters will be used in the next analyses.

4 CASE: HORIZONTAL STRATIGRAPHY, INCLINED BASEMENT

The dominant period (T_d) is calculated using the dynamic response at various points on the ground surface, which is determined by numerical modelling with the finite element method. For each calculation point, the strata and total thickness of the clay formation are known from the numerical models. A numerical model is developed for each basement inclination considered. The site surface response is then calculated using low-intensity bidirectional acceleration. The results are then compared to those obtained using the indicated criteria.

Input data and considerations:

- The basement inclination is oriented as shown in Figure 6. The inclination varies from zero (horizontal) to 2%, 4%, 8%, 16%, and 20% (or cm/m). Furthermore, the horizontal length of the inclination is 100.0 m. The clay strata are horizontal, so implicitly, there are no regional consolidation effects.
- By symbology, the direction of wave propagation is "in favor" of the basement inclination (Figure 6a) or "against" (Figure 6b).
- The thickness of the clay formation in the numerical model corresponds to the vertical profile at the point where the dynamic response is calculated. The thickness varies due to the basement inclination.
- For the profile with the greatest soil thickness (20.0 m), the average shear wave velocity is 76.8 m/s. The dominant period for the horizontal basement varies as indicated in Table 1.

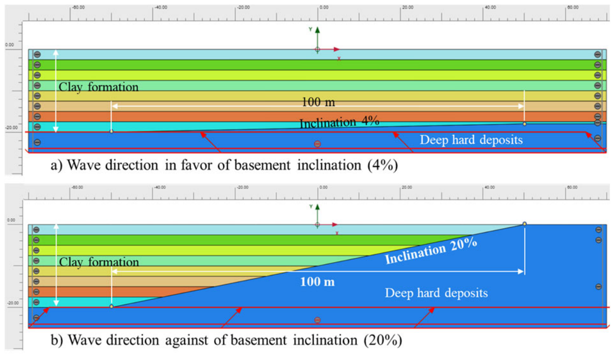


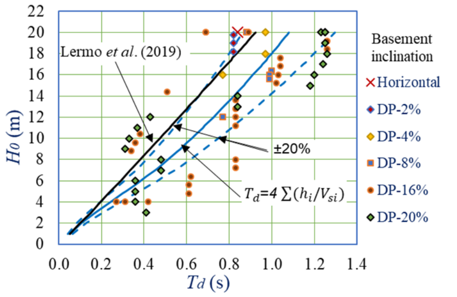
Figure 6. Numerical model of cases: inclined basement and horizontal clay strata, direction of wave propagation is a) in favor of, and b) against the basement inclination.

Results:

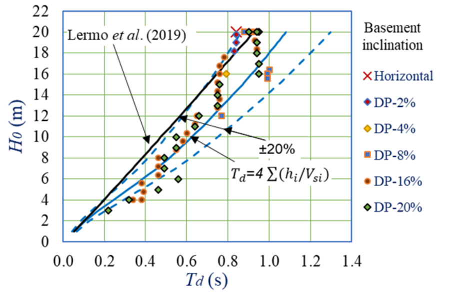
Figures 7-10 show the following:

- The figures show the T_d calculated using the indicated criteria and the thickness of the clay formation (H_0) obtained from the numerical model.
- For comparison, the blue and black curves in each graph are the T_d values calculated using the modified shear beam and Lermo relations, criteria 1 and 2, respectively. Additionally, curves calculated with ±20% of the modified shear beam relation (equation 3) are indicated as dashed blue lines in the same figures. These last two curves indicate a concentration interval relative to the modified shear beam ratio.
- Criterion 3: For T_d calculated with criterion 3, there are more points outside the concentration interval when the direction of the wave propagation is in favor of the

basement inclination (Figure 7). When this direction is against the basement inclination, there are more T_d values concentrated within the curves considered.



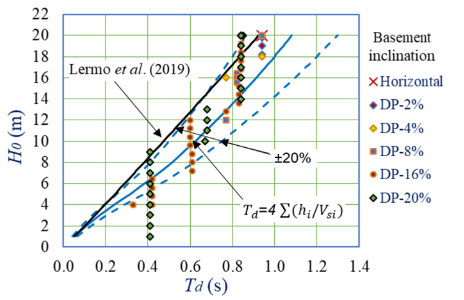
a) Direction of wave propagation in favor of basement inclination



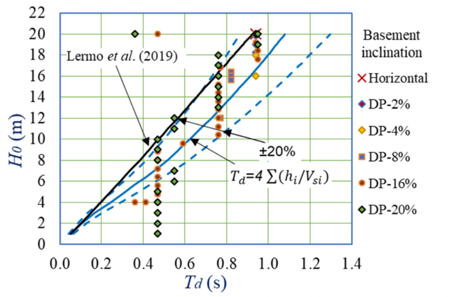
b) Direction of wave propagation against of basement inclination

Figure 7. Variation of T_d calculated with the peak value of the response spectrum (criterion 3) of surface horizontal component (H_s).

- Criterion 4: Here, the T_d values are constants in intervals of H_0, and practically independent of the direction of wave propagation (Figure 8). When the direction of wave propagation is against the basement inclination and for the maximum thickness considered (20.0 m), the T_d values deviate from the trend. This is possibly due to the refraction and reflection effects of the incident wave.



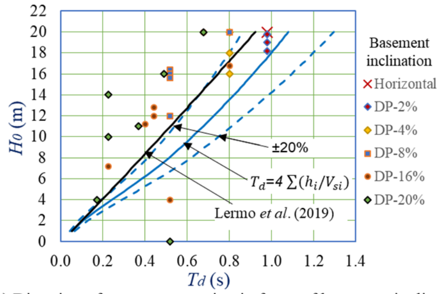
a) Direction of wave propagation in favor of basement inclination



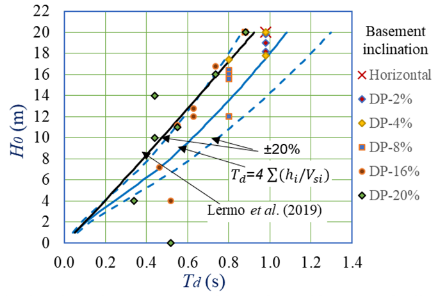
b) Direction of wave propagation against of basement inclination

Figure 8. Variation of the T_d values calculated with the peak value of the SB transfer ratio (Equation (5), criterion 4) of the surface horizontal component (H_s).

- Criterion 5: For T_d calculated with criterion 5 (Figure 9), the dispersion of the T_d is significant with respect to the reference curves, especially when the direction of wave propagation is in favor of the basement inclination. Also, greater dispersion occurs when basement inclinations are 8%, 16%, and 20%. The T_d values are underestimated.



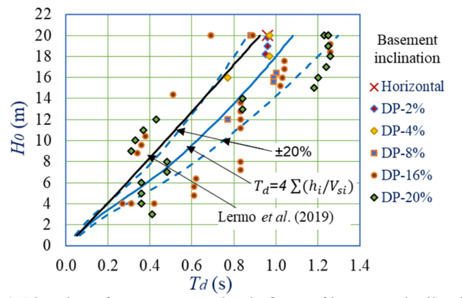
a) Direction of wave propagation in favor of basement inclination



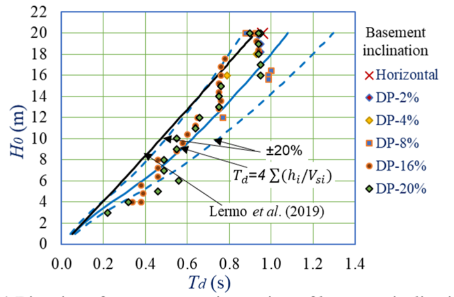
b) Direction of wave propagation against of basement inclination

Figure 9. Variation of T_d calculated with the Nakamura procedure based on Fourier spectra, criterion 5.

- Criterion 6: For T_d calculated with criterion 6 (Figure 10), the dispersion of the T_d is the lowest of all the criteria used with respect to the reference curves. There is less dispersion when the direction of wave propagation is against the basement inclination.



a) Direction of wave propagation in favor of basement inclination



b) Direction of wave propagation against of basement inclination

Figure 10. Variation of T_d calculated with the Nakamura procedure based on response spectra, criterion 6.

The base data for calculating the dominant period with these criteria are shown in Figure 11, which includes response spectra (RS), SB transfer ratio, Fourier spectra of Nakamura procedure (Nk-F), and response spectra of alternative Nakamura procedure (Nk-RS).

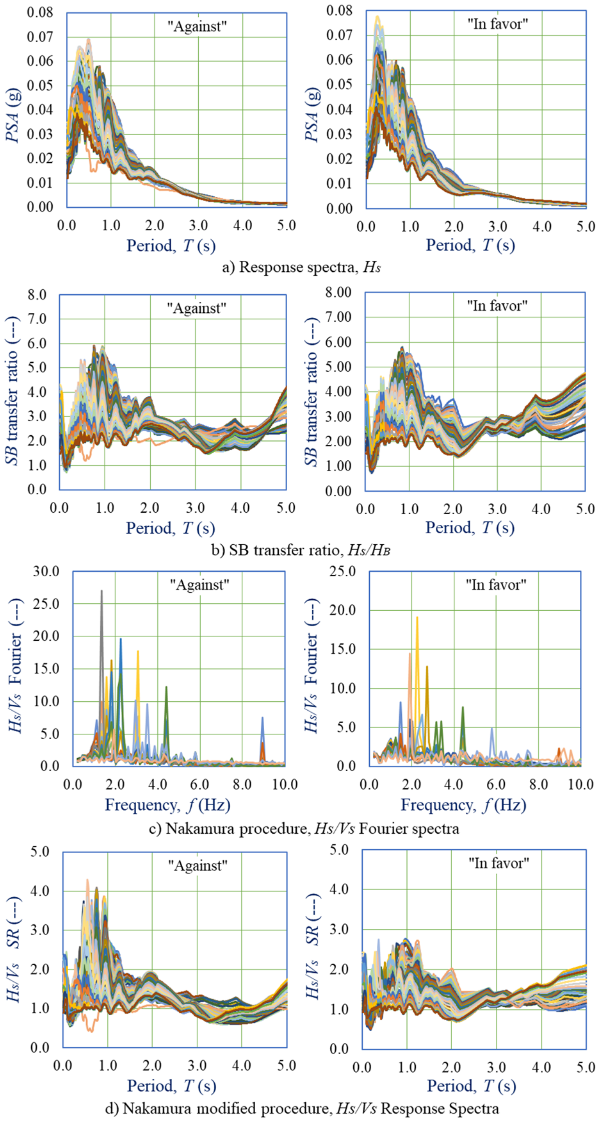


Figure 11. A graphic representation of the database calculated with numerical modelling of wave propagation.

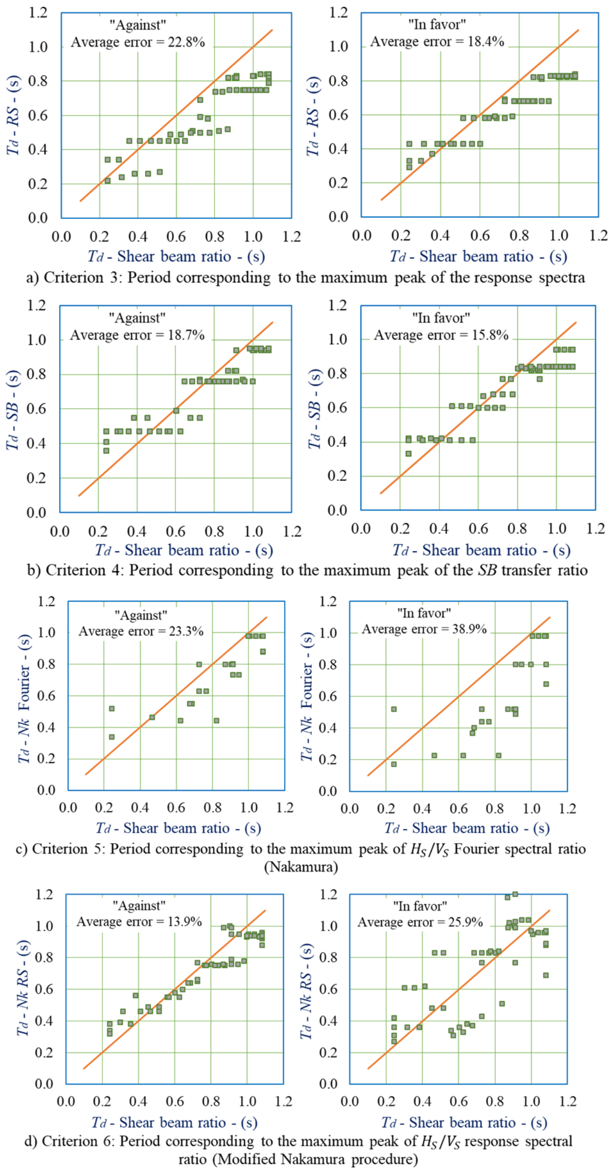


Figure 12. Variation of the T_d values considering as reference to the shear beam ratio (criterion 1).

Table 2. Relative error (in %) of the dominant period (T_d) calculated with the criteria 3, 4, 5, 6 respect to criterion 1.

Wave	3	4	5	6
Against	22.8	18.7	**23.3**	**13.9**
In favor	18.4	15.8	**38.9**	24.1

Symbology: criteria: 1: Shear beam relation, 3: peak of the response spectra, 4: peak of the transfer ratio (SB), 5: Nakamura, Fourier spectra, 6: Nakamura, response spectra.

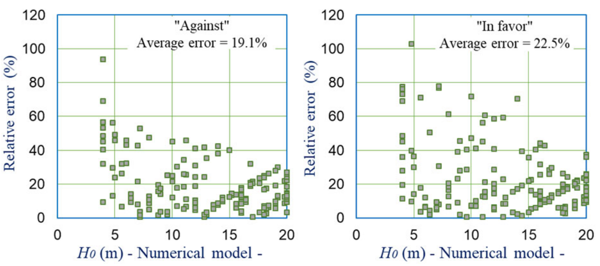


Figure 13. Relative errors (in %) for all cases analyzed using the shear beam ratio (criterion 1) as a reference.

5 INTERPRETATION OF RESULTS

In the case of calibration with horizontal basement, the T_d values calculated using the criteria define an interval that varies between 0.82 and 1.08s. It should be noted that the criteria define a T_d interval and that the results are derived from only one type of input signal; in other words, the study does not evaluate the variation in T_d as a function of the input signal frequency (Table 1).

Using the shear beam ratio of criterion (1) as a reference, Figure 12 and Table 2 show: criterion 6 shows the highest convergence with the least relative error of 13.9% and criterion 5 shows the lowest convergence with the largest relative error of 38.9%. Likewise, the second-best convergence is with criterion 4, the relative error is 15.8%. The relative errors indicated are average values.

The errors relative to criterion 1 are greater when the thickness of the soft soil (H_0) is smaller (Figure 13).

6 CONCLUSIONS

An assessment of site effects on soft clay deposits generated by inclined deep hard deposits, strata observed in the southeastern zone of Mexico City, was presented.

Based on calibration analyses, which used several criteria to evaluate the dominant vibration period of a site with soft soil, a horizontal basement, and a single signal, it is evident that considering an interval of dominant periods is convenient. This has several implications, including for structural analyses of buildings and infrastructure, as well as for the definition of the type of earthquake to use in dynamic interaction analyses to determine the possible resonance.

The numerical experiment on bidirectional wave propagation at a site with inclined basement revealed that the basement inclination and the direction of wave propagation, relative to the basement inclination, significantly influence the calculation of the dominant period of a site. These two characteristics must be considered in prospecting studies and ambient vibration measurements to improve the accuracy of the dominant period calculation.

For the type of wave and the basement inclination data used in this study, the standard Nakamura procedure, using Fourier spectra, showed less accuracy compared to the alternative Nakamura procedure based on response spectra.

In the present study, it was observed that, on the surface, in small areas near both limits of the basement inclination, the response to vibration is more irregular compared to the inclination body, possibly due to the reflection and refraction of the induced waves.

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