Madrid, O. A., Hayashida, T. (2024), Estimation of vs30 distribution in the Metropolitan Area of San Salvador,
Synopsis of IISEE-GRIPS Master's Thesis, Bulletin of IISEE, 59.

ESTIMATION OF VS30 DISTRIBUTION IN THE METROPOLITAN AREA OF SAN SALVADOR

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ABSTRACT

El Salvador, situated in the Pacific subduction zone between the Caribbean and Cocos plates and positioned along a volcanic chain, is susceptible to frequent and destructive earthquakes. Historical seismic events have substantially damaged buildings in the country, emphasizing the critical need for robust disaster mitigation strategies. This study aims to develop a Vs30 distribution map for the metropolitan area of San Salvador (AMSS) as a fundamental tool for disaster preparedness. Vs30 represents the average shear-wave velocity in the upper 30 m of the ground and is a crucial parameter for assessing seismic site amplification. VS30 was estimated using two methodologies: one using topographic data derived from digital elevation models (DEM) and the other using an empirical formula based on peak amplitude and frequency of the horizontal-to-vertical spectral ratios (EHVSRs) from historical strong ground motion records. Results indicated a notable correlation between Vs30 values obtained from topographic data and local geology. Furthermore, a comparison of Vs30 values from both methodologies revealed substantial similarities, suggesting that the amplified EHVSRs can effectively approximate the Vs30 distribution. To enhance the estimation accuracy of Vs30 and strengthen the correlation, future research should incorporate direct ground investigation techniques such as standard penetration tests (SPT), borehole data, and microtremor array measurements. These direct measurements will facilitate the refinement of empirical equations to better align with the specific soil characteristics of the AMSS, ultimately leading to more precise Vs30 values and improved disaster mitigation strategies.

Keywords: Vs30 distribution, EHVRs, topography, seismic site effects.

1. INTRODUCTION

El Salvador, situated in a region of intense seismic activity due to the subduction of the Cocos plate beneath the Caribbean plate, volcanism, and geological faults, faces significant seismic hazards. The Metropolitan Area of San Salvador (AMSS) is located in the Central Graben and experiences frequent shallow crustal earthquakes. The most amount of El Salvador's population resides in the AMSS, and understanding the seismic hazards is crucial for future earthquake preparedness.

Despite large intraplate earthquakes along the subduction zone, shallow moderate-sized earthquakes in volcanic zones have also caused significant destruction. The earthquake on December 12, 1862 (Mw=8.1), October 10, 1986 (Mw=5.4), and January 13, 2001 (Mw=7.7), as well as the subsequent February 13, 2001 earthquake (Mw=6.6), resulted in numerous casualties and extensive damage. The Ministry of Environment and Natural Resources (MARN) reported 944 deaths and the damage of nearly 280,307 houses due to the 2001 earthquakes, with significant damage caused by ground shaking and induced landslides in Santa Tecla City.

San Salvador is located on the active Central American volcanic chain, a prominent geologic feature stretching roughly 1100 km from Guatemala to Costa Rica (Simkin et al., 1981). This volcanic chain is distributed along the convergent plate boundary where the Cocos Plate dives northeasterly beneath the Caribbean Plate along the Middle America Trench (Burbach et al., 1984). While most seismic activity in Central America concentrates on this thrust zone, significant earthquakes also occur

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along the volcanic chain. Harlow and White (1985) proposed a "forearc sliver model" to explain this concentration. In this model, oblique plate convergence (convergence at an angle) creates minor but consequential right-lateral motion (east-west movement) along the volcanic chain, triggering earthquakes (Harlow et al., 1993).

Figure 1 shows geological Map of AMSS. El Salvador boasts a remarkably young geological landscape. Approximately 75% of the national territory is composed of Tertiary-aged rocks, with a predominance of Pliocene formations. Pleistocene deposits cover an additional 25% of the land area. In contrast, Cretaceous marine sedimentary rocks contribute minimally, encompassing only around 5% of the total geological makeup. Volcanic activity has played a dominant role in shaping El Salvador's geology. The vast majority of the country's rocks are volcanic in origin, with only a limited presence of marine sediments from the Cretaceous period. Additionally, intrusive igneous rocks, likely formed during the Miocene epoch, have been identified in specific locations.

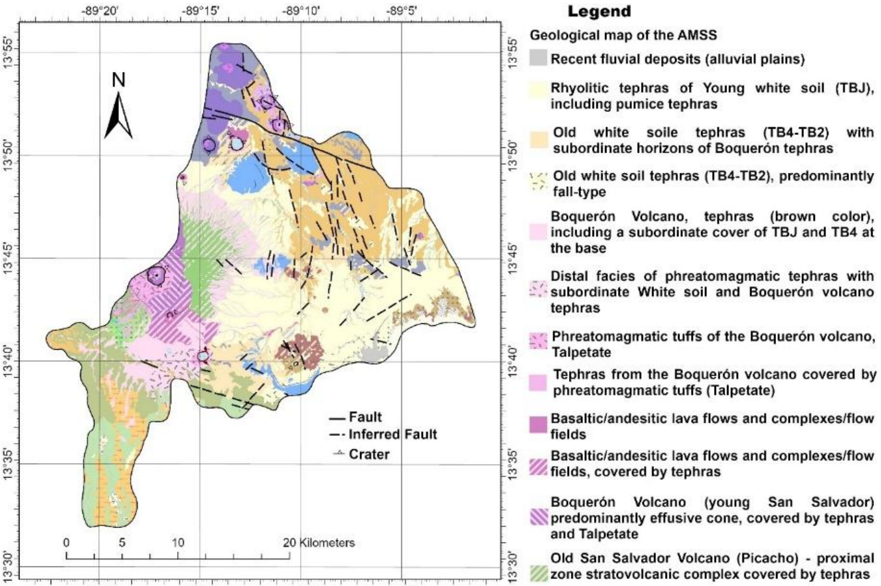

Figure 1. Geological Map of the Metropolitan Area of San Salvador translated form OPAMSS Geological Map.

The average shear-wave velocity in the top 30 meters (Vs30) is a critical parameter in earthquake engineering. It characterizes how soil and sediments respond to ground shaking during an earthquake. Vs30 is a key factor in determining ground motion amplification at a specific site. Vs30 is widely used to predict ground motion, assess seismic hazards, and develop seismic building codes. Currently, there is no direct data available that provides specific Vs30 values, and soil classifications are not yet tied to a defined Vs30 range. The only available Vs30 distribution, provided by the USGS, is a rough and low-quality estimation. This gap underscores the need for more precise measurements and standards, especially as the building code is being updated. Accurate Vs30 values are essential for these revisions, as they play a crucial role in seismic hazard assessments and ensuring building safety.

This study examines the relationship between topography, Vs30, and how we can estimate Vs30 using empirical equations and seismic records.

2. DATA

For our analysis of strong ground motion records, we utilized strong ground motion data at 33 stations from the Ministry of Environment and Natural Resources (MARN) of 38 past earthquakes with Mw >= 4.3, including local earthquakes and subduction zone earthquakes between 1976 and 2021 (Figure 2).

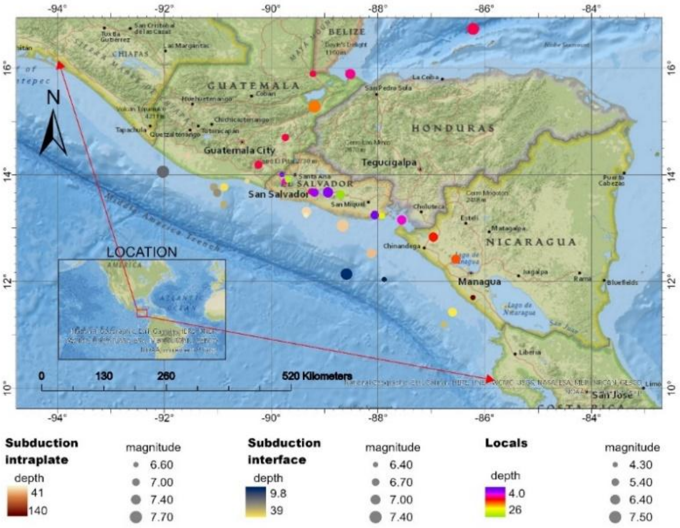

Figure 2. Location of 38 earthquakes used in this study.

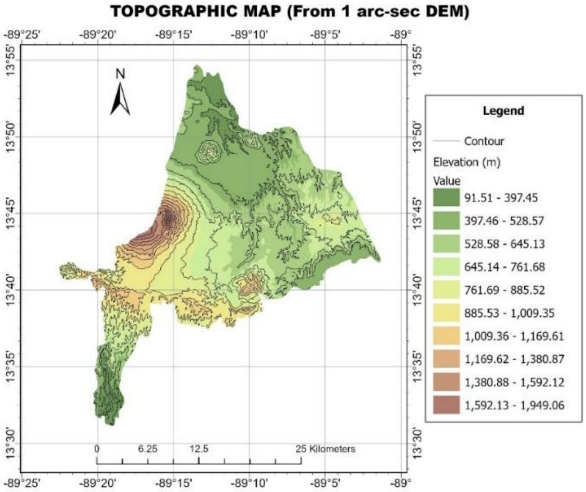

Figure 3. topographic map creating starting from one arc-sec DEM

To characterize the topography of the study area, this research utilizes the Forest and Buildings removed Copernicus DEM (FABDEM). FABDEM is a global elevation map derived from the Copernicus GLO-30 Digital Elevation Model (DEM) with a significant advantage: it removes biases caused by building and tree heights. This allows for a more accurate representation of the bare earth surface topography. The data has a high resolution of 1 arc second grid spacing, which translates to approximately 30 meters at the equator, providing detailed information for our analysis. Also has been use the HydroSHEDS Core Data 3 arc-sec DEM.

3. METHODOLOGY

3.1. EHVRs calculation

This study outlines the process of deriving Engineering Horizontal-to-Vertical Response Spectra (EHVRs) from strong ground motion data. The analysis converts time-domain waveforms of the three ground motion components (NS, EW, UD) into frequency-domain spectra using the Fast Fourier Transform (FFT). These spectra are then squared to obtain power spectra.

To enhance data quality, the power spectra are smoothed using the Konno & Ohmachi (1998) filter with a bandwidth of 20. This process improves the clarity of spectral features. Subsequently, EHVRs are calculated by dividing the smoothed horizontal spectra (NS and EW) by the vertical spectrum (UD), using the following equation equation:

$$EHVRs = \frac{\sqrt{P_{NS(f)}^2 + P_{EW(f)}^2}}{P_{UD(f)}} \tag{1}$$

Where P denotes the power spectrum, **EW** is the amplitude on the horizontal component from east to west, **NS** is the amplitude on the horizontal component from north to south, and **UD** is the amplitude on the vertical component from up to down.

Generally, the computed EHVRs exhibit consistent patterns. However, in certain cases, significant discrepancies (up to a factor of two) can occur around the peak frequency. These variations might indicate the influence of complex site conditions, such as 2D or 3D topography or irregularities within the subsurface basin structure.

3.2. Estimation of Vs30 using topographic data

Given the absence of a simple mathematical relationship between slope and Vs30, a discrete approach was adopted. Vs30 values were characterized based on the National Earthquake Hazards Reduction Program (NEHRP) boundaries (FEMA A, 1994), which were further divided for finer resolution. Topographic slopes were then assigned to the median Vs30 value from the corresponding subdivided NEHRP category. The combined roles of slope and elevation in predicting Vs30 were analyzed using multiple linear regression. While slope and elevation often correlated well, elevation alone was a less reliable predictor of Vs30 due to extensive low-slope areas at various elevations. Consequently, using slope as the sole variable provided a stronger correlation with Vs30.

3.3. Estimation of Vs30 using EHVR peak frequency and amplitude

The effectiveness of the EHVSR as a parameter for describing site response was evaluated by comparing EHVSR to Vs30 and assessing their correlation and usefulness. The calculated EHVSRs from strong ground motion data were used for this comparison. A uniform method was employed to derive the peak frequency (Fpeak) and peak amplitude (Apeak) from the averaged H/V response spectra of each site. These H/V peak parameters were categorized and analyzed alongside Vs30 values with a regional focus.

Several empirical relationships and models have been proposed to establish a direct correlation between the peak frequency and amplitude of EHVSR and Vs30. In this study, the empirical equations (Eqs. 2–4) proposed by Hadi Ghofrani and Gail M. Atkinson in 2014 were used. This approach allowed for a systematic comparison and analysis of the site response parameters, providing insights into the effectiveness of HVSR in describing site response in relation to Vs30.

For Fpeak > 1Hz.

$$log(V_{S30}) = 2.35(\pm 0.01) + 0.38(\pm 0.02)\log(f_{peak}) \qquad (2)$$

If fpeak =1 Hz, we cannot infer Vs30. Therefore, for Fpeak < 1, the following relation between Apeak and Vs30. Was used.

$$log(V_{S30}) = 2.88(\pm 0.01) - 0.64(\pm 0.03)\log(A_{peak}) \qquad (3)$$

Using Fpeak and Apeak as predictor variables, Vs30 was estimated Vs30 as follows:

$$log(V_{S30}) = 2.63(\pm 0.02) + 0.30(\pm 0.01)\log(f_{peak}) - 0.47(\pm 0.03)\log(A_{peak}) \qquad (4)$$

where the values withing parenthesis represent the uncertainty, for this study it was use the central value, which is mean that the uncertainty was not taking in consideration, $\boldsymbol{f_{peak}}$ is the frequency where the peak amplitude is observed, $\boldsymbol{A_{peak}}$ is the maximum amplitude.

4. RESULTS AND DISCUSSION

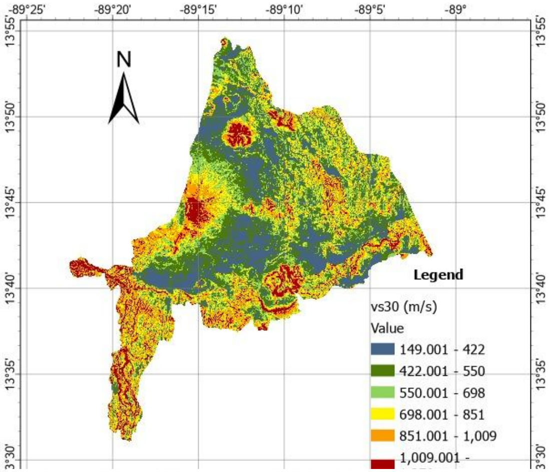

Figure 4. Vs30 distribution created from one arc-sec DEM.

The relationship between slope and Vs30 distribution is closely linked to soil stiffness; areas with high slopes typically correspond to stiffer soils, resulting in higher Vs30 values. Steeper terrains often have more compact and consolidated materials and exhibit higher shear wave velocity. In contrast, regions with low Vs30 values usually have softer soils, primarily sediments. These sediments have less consolidation, leading to lower Vs30 values. Therefore, the slope of the terrain can be a significant indicator of soil stiffness and its Vs30 distribution.

Figure 5 shows the frequency distribution at each station over geological map of the AMSS. Those *Fpeaks* were used for the calculation of Vs30 value show in Table 1, where also is compare with the Vs30 value at each station using the value calculated with the topographic data (Figure 4). The estimated Vs30 values should be validated against direct measurements (e.g., borehole data, geotechnical methods, and microtremor array). This validation allowed for adjustments to the equations used, ensuring that they were adapted to the specific conditions of the study area and yielded accurate results, and the best relationship between different methodologies can be established.

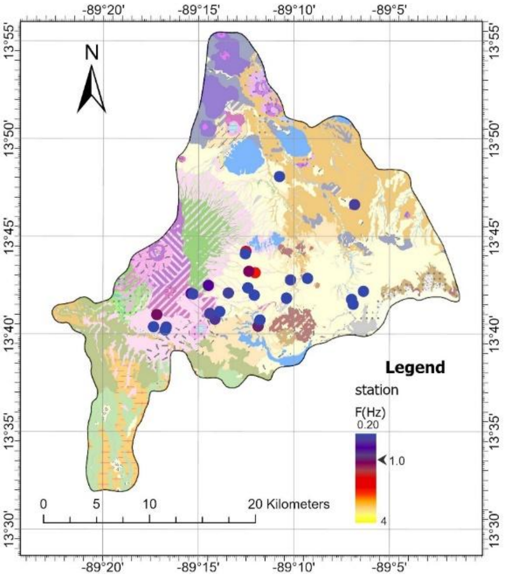

Figure 5. Frequency distribution at each station location over geological map.

Table 1. Comparison of Vs30 value using both methodologies, topographic (1. 3 and 9 arc-sec) and EHVSRs data.

No	**ID**	**Vs30 1Arcsec (m/s)**	**Vs30 3Arcsec (m/s)**	**Vs30 9Arcsec (m/s)**	**Vs30 .Eq 4 (m/s)**	**Vs30 .Eq 3 (m/s)**	**Vs30 .Eq 2 (m/s)**
1	AEIL	349	383	305	152	362	-
2	AI	292	353	378	140	390	-
3	APOP	325	345	302	158	361	-
4	BA	346	418	348	97	233	-
5	CAIM	614	551	409	93	223	-
7	CLUB	572	536	455	116	259	-
8	CLUC	557	510	495	173	305	-
9	CPRF	389	420	399	340	-	379
11	CRBP	526	361	356	221	-	299
12	CRW	506	478	352	187	326	-
13	DB	370	453	452	136	326	-
14	EX	337	412	372	109	274	-
17	IV	345	357	384	253	-	266
18	MAGT	402	403	373	233	-	262

5. CONCLUSIONS

The suitability of using HVSRs for estimating shear wave velocity (VS30) and the calculation starting from topographic data of AMSS was investigated. Results indicated that 73% of seismic stations exhibited peak frequencies below 1 Hz, with a majority (54%) situated on rhyolitic tephra (young white soil) with tuff. The remaining seismic stations (27%) exhibited peak frequencies between 1 and 4 Hz. Vs30 values derived from EHVSR peak amplitude and frequency demonstrated a closer correlation with those obtained from topographic data compared with those calculated using Eqs. 3 and 4, important to mention that, calculating Vs30 using Strong ground motion is mor accurate and direct way than using topographic data.

Both Vs30 and EHVSR results were crucial for mitigating earthquake hazards. These were particularly valuable for generating seismic amplification maps, which highlighted areas susceptible to stronger ground shaking during earthquakes. Moreover, understanding the predominant ground amplification frequencies can improve the designing of earthquake-resistant structures. By ensuring that the building's natural frequency diverges from the ground's amplification frequency, engineers can minimize the risk of resonance during seismic events and enhance the safety and resilience of structures in earthquake-prone regions. However, direct ground investigation methods such as standard penetration tests (SPTs), borehole data, and microtremor array measurements are essential for robust validation. These in situ measurements will facilitate the refinement of empirical equations to better account for the unique soil characteristics of San Salvador, leading to more accurate Vs30 estimations and improved disaster mitigation strategies.

ACKNOWLEDGEMENTS

This research was conducted during the individual study period of the training course "Seismology, Earthquake Engineering and Tsunami Disaster Mitigation" by the Building Research Institute, JICA, and GRIPS. I want to express my sincere gratitude to Dr. T. Hayashida, Senior Research Scientist at the International Institute of Seismology and Earthquake Engineering (IISEE), for his invaluable guidance and support throughout my study. I want to express my profound gratitude to my family for their continuous encouragement and support. I would also like to thank my classmates and friends from the Seismology, Tsunami, and Earthquake Engineering course for sharing their valuable time and experiences with me.

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