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MICROZONATION MAP OF SEISMIC SITE CONDITION AND AMPLIFICATION OF GREATER ACCRA REGION, GHANA

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ABSTRACT

The capital city of Ghana, Accra, is located within the most seismically active region of the country. This study seeks to assess the seismic site condition and amplification based on the shear wave velocity for the regional capital by the topography as a proxy method. Point slope measurements are extracted and subjected to seismic site condition correlation of the NEHRP for stable regions. The correlative seismic site condition within a limiting slope boundary corresponding to a specific soil class is obtained using regression analysis. We first analyzed available single-point microtremor measurements to know the fundamental soil frequency for the study area, after which some inversion parameters based on diffusion assumption were considered concerning the soil frequencies to understand the terrain within the study area. The inversion outcome could not support the actual representation of soil layers since it did not include dispersion curves to aid in generating profiles with relatable soil layers. The obtained Vs30 is then further subjected to the linear site amplification equation for stable regions by Stewart et al. Scaling ground condition for linear soil response over an average oscillator period of 0.4 to 2 seconds. An interpolation using the inverse distance weight method was applied to the calculated seismic site conditions and the site amplification data sets to generate a representative map at a square kilometer area raster. A comparison will then be made between the global seismic site condition map to understand the changes and possible similarities. The newly generated map could serve as an improved first-order approximation of Vs30 for the capital region.

Keywords: Microtremor, Topographic slope, Seismic site condition (Vs30), Amplification.

1. INTRODUCTION

Seismic microzonation is the procedure of estimating the response of soil layers under earthquake excitation and thus the variation of ground characteristics on the ground surface about displacement, velocity or acceleration. Site amplification or excitation increases the intensity of ground vibration and response due to local geological conditions depending on soil properties that differ significantly in local geological environments. The local soil is a filter that influences the seismic waves from the subsurface bedrock to the ground surface. Good seismic-resistant design of structures would thereby be resistant to the ground amplification intensity during earthquakes.

Several research works establish the southern part of Ghana as the most seismically active zone, though the country is far from the global tectonically active region. Kutu et al. (2013) establish that the seismicity of southern Ghana, as known in past and present, is due to tectonic fault activities of the St. Paul's and Romanche transform-fracture zone systems offshore Ghana.

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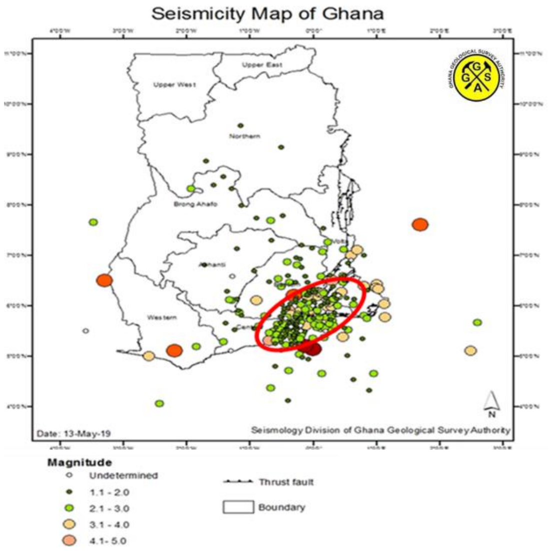

Figure 1. Seismicity Map of Ghana indicating records of earthquakes both past and present

The probabilistic seismic hazard study by Ahulu et al. (2017) also cemented the reactivation scenario with explanations of work done in six critical cities in the south on generating a 10% probability of exceedance of peak ground acceleration in 50 years. Findings from Ahulu et al. highlight that the highest level of seismic hazard in Ghana is within the capital city, Accra and Tema, the industrial city of Ghana, with peak ground acceleration of about 0.2g, diminishing with distance away from the south. Amponsah et al. (2008) computed the seismic ground motion along four profiles across geological ground conditions to access the hazard zones and extract engineering parameters helpful in designing, using a deterministic hybrid approach.

Movement along the Transform fault and Fracture zone continuously causes ongoing seismicity in southern Ghana hence the recent reoccurring of tremors within the south. Assessment of seismic hazards and microzonation of the capital region of Ghana will enable us to correlate the potential seismic areas with relatable exposures to ground shaking hazards, mainly earthquakes

2. DATA

The relief contour elevation data set of the Greater Accra Region from the Geoscientific Information System Division of the Ghana Geological Survey Authority will be subjected to data processing using the ArcGIS pro Software. Also available for comparison is the ground conditions map relative to the geology and stratigraphic map of the capital region. Single point microtremor measurements were carried out sporadically from May to June 2019 within the study area using the 4.5-hertz Trillium 120PA broadband seismometer, which will also serve as query data for estimating the average shear wave velocity. Finally, an extracted global seismic site condition map will be used as supplementary data for comparison and improvement.

3. METHODOLOGY

We will extract point attributes from the global seismic site condition map with the corresponding the average shear wave velocity in the upper thirty meters of soil depth (Vs30) regionally to ascertain our study's regional perspective of ground response. The Vs30 regional point extraction will be compared to the intended Vs30s to understand the influences of relatable topographic measurements on the regional Vs30 map from the USGS. The USGS site condition extracted data set and the estimated seismic site condition data set will be subjected to the average PGV amplification model to understand and compare the ground behavior. A seismic site condition and a site amplification map representing the average PGV of the study area will be generated using these two data sets, USGS Data Set and the estimated seismic site condition data set.

3.1. Planar Method

The slope of the study area was determined based on the planar method adopted in the ArcGIS Pro software. The slope is defined as the rate of changes of the surface in the horizontal (*dz/dx*) and vertical (*dz/dy*) directions from the center cell or point elevation to each adjacent cell or point elevation multiplied by a shortened description of the result from 180 divided by π.

$$slope(°) = \tan^{-1}\left(\sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}\right) \times 57.26578 \tag{1}$$

3.2. Slope Based Seismic Site Condition (Vs30) Method

The estimated topographic slope at any point is grouped within the subdivided slope range limits used by the National Earthquake Hazard Reduction Program (NEHRP) to classify the ground conditions into soil classes based on regression analysis using the equation below:

$$Estimated\ V_s30\ (\text{m/s}) = (Slope\ (\text{Rad}) \times M) + Intercept(C) \tag{2}$$

M is considered the gradient of the regression equation within the limits of a known NEHRP slope class.

3.3. Microtremor Horizontal to Vertical Spectrum Ratio

As proposed in several studies, the horizontal to vertical spectrum ratio (HVSR) in three directions of a single-point measurement is very useful in determining the ground frequency of a location. It is also a vigorous means of estimating the site's fundamental frequency. The proposed equation for calculating the HVSR is as follows:

$$HVSR = \frac{\sqrt{F_{\text{NS}}(\omega)^2 + F_{\text{EW}}(\omega)^2}}{F_{\text{UD}}(\omega)} \tag{3}$$

Where $F_{\text{NS}}(\omega)^2$, $F_{\text{EW}}(\omega)^2$ and $F_{\text{UD}}(\omega)$ are the respective Fourier amplitude spectra of the north-south, east-west, and up-down parameters of the site record, the frequency that corresponds to the peak spectrum transfer ratio relates to the fundamental frequency for each site location (Nakamura, 1989).

3.4. Inversion of HVSR Measurements of Rayleigh Waves with Clear Peaks

Using the diffuse field theory, we will perform our single-point measurement inversion of the HVSR. With the hypothesis of a diffuse seismic field (noise), agreeing with Sanchez-Sesma et al. (2011), the HVSR can be considered like the imaginary part of the Green's function on a horizontally layered medium. Considering a diffuse seismic field of microtremors, the HVSR is as expressed in the equation below as directional energy densities:

$$[\,H\,/\,V\,]\,(\omega) = \sqrt{\frac{E_1(x,\omega) + E_2(x,\omega)}{E_3(x,\omega)}} \tag{4}$$

The directional energy densities, E_1, E_2 and E_3, referring to the horizontal and vertical degrees of freedom at the point x is like the expression of equation (3). Generating the HVSR with the imaginary part of the Green's function (GF) as an unknown parameter, as in equation below for a horizontally layered structural design made of isotropic elastic layers. Where the G_{11} $(\mathbf{x},\mathbf{x},\omega)$ is the displacement GF in the direction 1 at a point x due to the application of a unit point force in the same direction applied at the same point.

$$[\,H\,/\,V\,]\,(\omega) = \sqrt{\frac{\text{Im}[G_{11}\ (\mathbf{x},\mathbf{x},\omega)] + \text{Im}[G_{22}\ \ (\mathbf{x},\mathbf{x},\omega)]}{\text{Im}[G_{33}\ \ (\mathbf{x},\mathbf{x},\omega)]}} \tag{5}$$

3.5. Site Amplification Map.

In this study an alternative site amplification model by Stewart et al. (2017) based on Vs30 as the sole predictive variable for site response will be used to enable us to generate an ergodic site amplification map from Vs30 values concerning stable crustal regions. The simulated model becomes very compatible with the soil site class categories adopted in the NEHRP, with soil class boundary dependent on the limits of Vs30. The soil class boundary of this model is related to the assumed model used in the Building Code Ghana for site class classification or condition.

The linear model has two main measurable parameters, the Vs30 scaling term (F_V) and the amplification at Vs30 reference condition of outcrop map where Vs=3000m/s.(F_{760}) as a modifier. Due to the unavailability of ground motion intensities,F_{760} is said to be negligible.

$$F_{lin} = F_V(Vs30, T) + F_{760}(T) \tag{6}$$

The trilinear log to log scale Vs30 scaling model is shown below as:

$$F_V = \begin{cases} c * \ln\left(\dfrac{V_1}{V_{ref}}\right), & Vs30 \leq V_1 \\ c * \ln\left(\dfrac{Vs30}{V_{ref}}\right), & V_1 < Vs30 \leq V_2 \\ c * \ln\left(\dfrac{V_2}{V_{ref}}\right) + \dfrac{c}{2} * \ln\left(\dfrac{Vs30}{V_2}\right), & Vs30 > V_2 \end{cases} \tag{7}$$

Where c is the average slope in the log-log space for the central portions between the corner velocities V_1 and V_2 as indicated in the coefficient to the period graph based on the electronic supplement provided by Stewart et al. (2017). V_{ref} represents the velocity at which F_V =0 thus it is taken as 760 m/s. All these coefficients are dependent oscillator periods.

4. RESULTS AND DISCUSSION

4.1. The microtremor measurements

The values estimated correspond well with results from Amponsah et al. (2008) within the geology polygon constraints, though it could not indicate the layer difference with depth. Most of the available measurements showed no clear peaks, with some showing no peaks. The flatness of most of these measurements gave an initial impression of stiffness within the study area with just about a few with two or more peaks. With the few available clear peaks, the estimated results are as below. The absence of the Rayleigh dispersion curve in performing the joint inversion modelling proved the HVSR data to be undependable due to the constraining parameters being prone to increasing ambiguity.

Using the equation used in the building code, CEN (2004), we evaluated the Vs30 on the clear peaked HVSR curves. Regarding this outcome, the southern area could be classified as Soil Type D with a Vs30 range between 180m/s and 360m/s using the NEHRP classification and C with a similar Vs30 range regarding the country’s building code.

4.2. The Topography Proxy Method

This method proves that physical soil properties that influence shear modulus are equally a vital influence on shear properties. In general, void space and effective mean stress dominate shear modulus changes since density variations tend to be smaller in soils. This explains the good correlation between the lower shear wave velocity and lower slope topography. The study also proved the influence of the shear wave velocity on stiff interlocking geological units like rocks, based on hardness and fracture spacing, given that they are more resistive to erosion: a steeper slope and higher shear wave velocity.

Estimating the shear wave velocity by regression analysis showed good distribution over the slope range within the study area and correlated well with the global Vs30 by the USGS. The estimated Vs30 ranged between 100 m/s in the low-lying flat surface within the southern part towards the east of Greater Accra to about 1530m/s towards the north of the study area and the western, northeast, and southwest topographic relief trends. Estimated Vs30 within some parts of the study area was lower than that of the global Vs30 by the USGS, with some regions having higher estimations than the worldwide map.

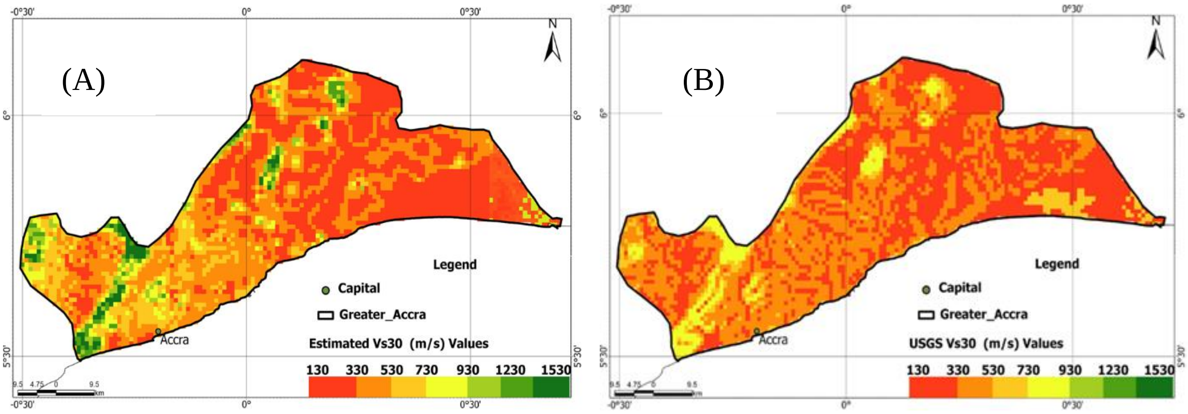

Figure 2. Map of estimated Vs30 (m/s) (A) and USGSVs30 (B) maps for Greater Accra Region. The values range between 130 to 1530 m/s for the Estimated map and 180 to 900 m/s for the USGS map.

4.3. The Vs30 Site Amplification.

With coefficients estimated from a given electronic supplement for the linear amplification model, without considering the non-linear component, a relational Vs30-based site amplification map for the Greater Accra region is developed. The total amplification is the sum of the Vs30-scaling term and the F_{760} term, representing the amplification at Vs30=760m/s site condition relative to the 3000m/s reference condition. Generally, building codes use F_V factors at an average period ranging from 0.4 to 2.0 s as a moderate site amplification. When used, the cap Fv factor is a modifier for ground motions in generating hazard maps with site conditions referenced at 760m/s for Vs30.

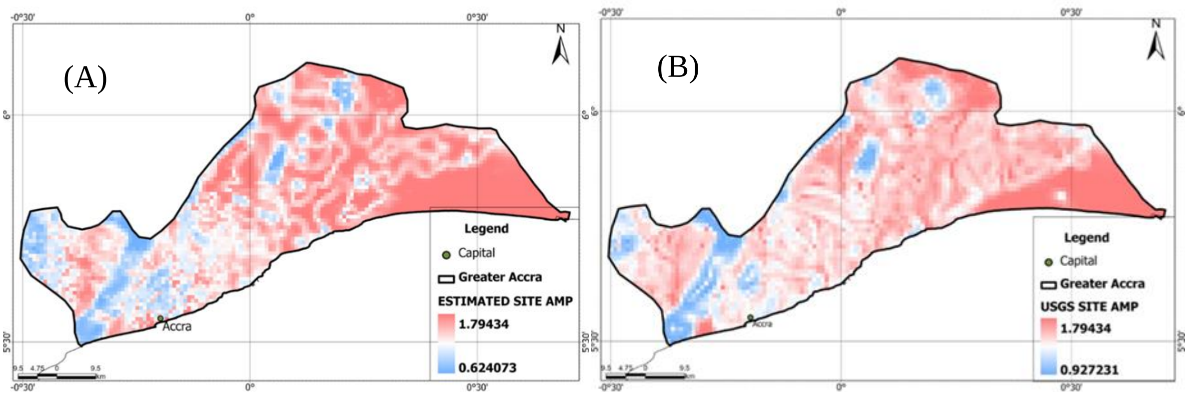

Figure 3. Final site amplification map generated based on estimated Vs30 (A) and USGS Vs30 (B), from slope map. Ranging between 1.794 to 0.624 and 1.794 to 0. 927.respectively.

Finally, a site amplification factor map about Vs30 is generated from the site amplification model equation (7) above. The developed map using the model above shows some relations with the highest and minimum amplifications at 1.79 and 0.62, respectively, relating to high topographic reliefs and flat-lying areas in the study area. About sixty per cent of the study area shows site amplifications relating to the high amplification levels, with about forty per cent showing minimal amplification. The increased amplification signals attest to the continuous record of seismicity in an area like Weija.

5. CONCLUSIONS

The map generated was characterized by different site values of Vs30 estimations ranging between a minimum of 100 m/s and 1530 m/s. The newly estimated Vs30, compared to the globally determined Vs30 map for the study area, showed some similarities and differences, which further proves the update expected for this study due to developmental changes within the study area.

We then tried to estimate Vs30 from available single-point microtremor measurements within the study area. Results from this evaluation were non-relatable due to unavailable parameters in delineating layer thickness and assuming that the ground condition is homogeneous.

We then evaluated the region's site amplification map based on the estimated Vs30 and the extracted Vs30 from the global Vs30 map using the Vs30 scaling method over an average oscillator period from 0.4 to 2 seconds. The final map gives a surface distribution of the PGV amplification factor over the study area, comparing the estimated and USGS values. The estimated site amplification and seismic site condition maps are better representation maps that relate well to the capital city's ground motion and land condition. The maps will serve as a guide to improving the land use management practices of stakeholder institutions.

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