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AN INVESTIGATION OF THE RELATIONSHIP BETWEEN STANDARD PENETRATION TEST AND SHEAR WAVE VELOCITY FOR UNSATURATED SOILS (A CASE STUDY OF THE EARTHQUAKE PRONE AREA OF THE ALBERTINE GRABEN)

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ABSTRACT

When an earthquake occurs, seismic waves radiate away from the source and travel rapidly through the earth’s crust. When these waves reach the ground surface, they cause shaking that may last from a few seconds to minutes. The nature and distribution of earthquake damage is strongly influenced by the response of soils to dynamic loading. This response is controlled to a large extent by the dynamic soil properties such as stiffness, damping, Poisson’s ratio and density. The prediction of ground shaking at soil sites requires knowledge of the soil expressed in terms of shear wave velocity (V_s). It is preferable to measure V_s by in situ wave propagation tests. However, it is often not economically feasible to conduct these tests at all locations. On the other hand the Standard Penetration Test (SPT) is the most common in situ site geotechnical test which is carried out in most site investigations. Hence a reliable correlation between V_s and SPT would be of considerable advantage, reducing the cost of site investigations. This paper presents, therefore, the development of an empirical relationship between V_s and SPT N-value for the soils of Kasemene Oil exploration area located in Buliisa District in Uganda. As part of an attempt to mitigate the effects of earthquakes in the area, a model is needed to predict V_s required for site response analysis. The effect of correcting V_s and SPT N-values on the model was evaluated and the model was also compared with published models. The process involved correlating 273 data pairs of V_s and SPT N-values which were measured at the same depth. The extensive Vs measurement was carried out using the Multichannel Analysis of Surface Waves (MASW) technique. The SPT N-value data was measured from boreholes drilled within the boundaries of the MASW survey lines. Results show that the relationship between V_s and SPT N-value depends on the effective overburden stress, and that ignoring the influence of effective overburden stress creates bias in the model. It was also found out that none of the published models fitted the data well and there is tremendous difference in the V_s values predicted by these models. The model exhibits good prediction performance and can be used to predict shear wave velocity for soils within the study area or for areas with a similar soil type.

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INTRODUCTION

Oil exploration is currently taking place in an earthquake prone area of the Albertine Graben located in the Western Rift valley in Uganda. This region lies in the seismic zone I as per the seismic hazard zoning of Uganda. This is a very seismically active region since it has experienced several severe earthquakes of surface wave magnitudes $M_s \geq 6$ in recent times (Mavonga and Durrheim, 2009; Twesigomwe, 1997). Such strong earthquakes are considered severe (Kramer, 1996) and result into loss of life and damage to infrastructure. For example, the Toro event of 20th March 1966 (M_s=6.1) led to the death of 160, 1300 people injured and 7000 buildings destroyed and the Kisomoro event of 5th February 1994 (Ms=6.0) in which 8 people were killed (Midzi et al., 1999). Since the oil industry requires a large amount of infrastructural facilities such as roads, offshore structures, pipelines, buildings, refinery, heavy machinery which is operational at all times, there is need for such infrastructure facilities to be earthquake resistant.

The risk of loss of life and damage to infrastructure due to earthquakes can be mitigated by carrying out a detailed dynamic analysis and design of the built environment taking seismicity into consideration. Such an analysis requires among others the seismic shear wave velocity (V_s) as an input parameter (Kramer, 1996; Thaker and Rao, 2011). It is preferable to measure V_s by in situ wave propagation tests; however, it is often not economically feasible to conduct these tests at all locations. On the other hand, the Standard Penetration Test (SPT) is commonly used in most site investigations. Hence a reliable correlation between V_s and the Standard Penetration Test blow count (SPT N-value) would be of considerable advantage, reducing the cost of site investigations. Many such models for the relationship between V_s and SPT N-Value have been developed in other parts of the world (Andrus et al., 2004; Athanasopoulos, 1995; Hanumantharao and Ramana, 2008; Imai and Tonouchi, 1982; Maheswari et al., 2008; Ohta et al., 1972; Seed and Idriss, 1981; Thaker and Rao, 2011). However, most of these relationships are location specific and consider uncorrected SPT N-values. Many of the previous models reported in the literature have been developed for saturated soils. Models for unsaturated soils have rarely been reported in the literature. In tropical equatorial regions, civil engineering systems are mostly developed or founded in unsaturated soils above the water table. The behaviour of unsaturated soils is more complex and not fully understood. Such soils have more than two phases and the pore pressure is negative relative to the atmospheric pressure (Standing, 2012). In this study, an attempt was made to develop a reliable correlation between V_s and SPT N-value for unsaturated soils of Kasemene area located in Buliisa Sub-county in Buliisa District, along the shores of Lake Albert in Uganda. This area was selected because of its significant importance to the oil industry and also due to the availability of site-specific geophysical and geotechnical data provided by Tullow Oil.

GENERAL GEOLOGY OF THE STUDY AREA

The study was carried out in Kasemene oil exploration area located in Buliisa Sub-county in Buliisa District, along the shores of Lake Albert in Uganda. This area is 23 km^2 in size stretching from the shores of Lake Albert up to the tentative Central Processing Facility (CPF) area. The Graben where the study area is located stretches from the border between Uganda and South Sudan in the north to Lake Edward in the south. It covers a total North-South distance of over 500km with a variable width averaging 45km (Lirong et al., 2004a). The Albertine graben has been characterized as a Cenozoic rift basin formed and developed on the Precambrian orogenic belts of the African craton during the Late Tertiary due to North-South rift propagation (Abeinomugisha and Kasande, 2012; Lirong et al., 2004a; Lirong et al., 2004b). This area has experienced several tectonic events of both extension and compression regimes coupled with climate and lake level fluctuations. Stratigraphically the Graben is covered by thick fluvial-lacustrine rift valley sediments of Pliocene-Pleistocene age of approximately 6km as shown in Fig.1 (MacDonald, 1966). The sediments are predominantly sandstones, siltstones, claystones and shales. The sandstones and siltstones are mostly of high porosity and permeability (Ochan and Amusugut, 2012).

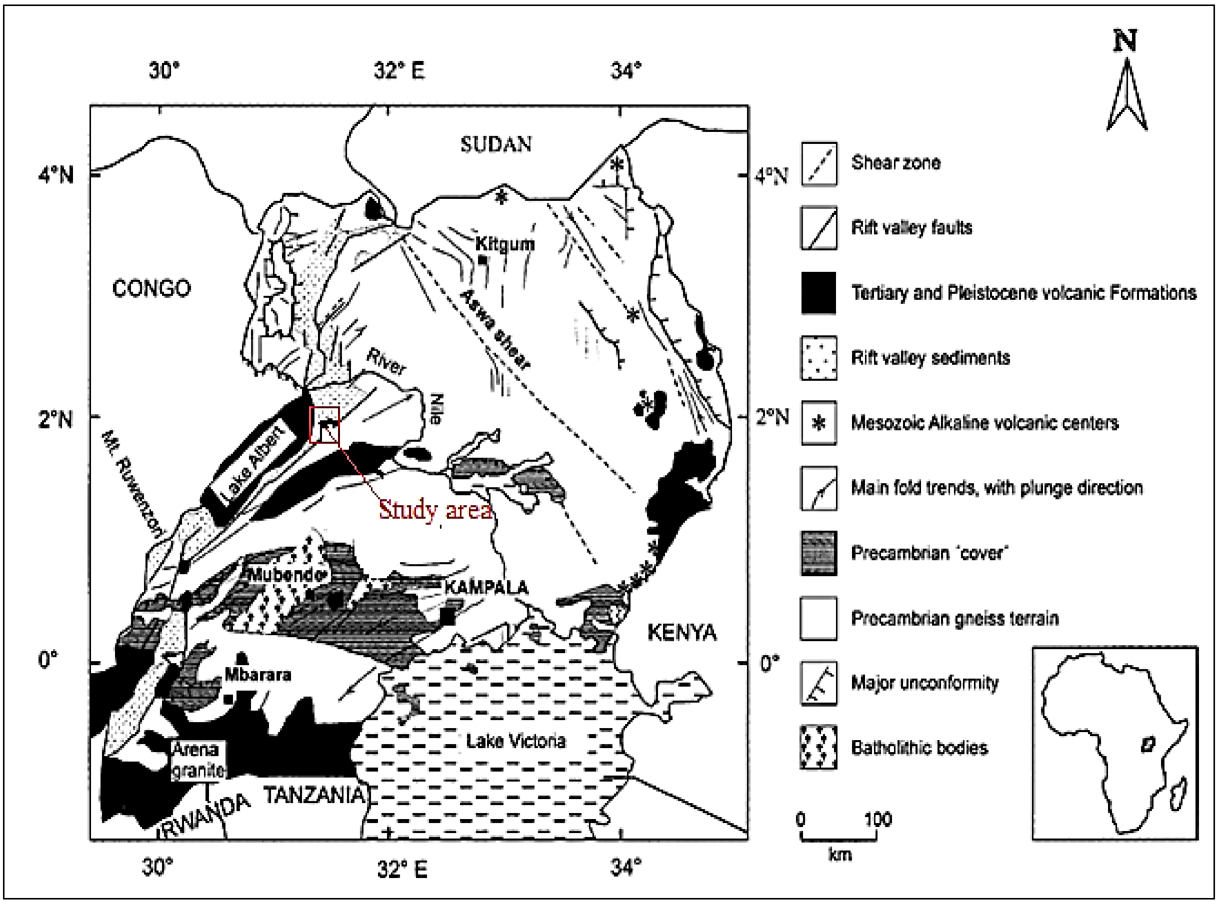


Figure 1. Simplified geological map of Uganda showing the location of the study area and some structural features (modified after MacDonald (1966))

METHODOLOGY

Seismic Survey

A seismic survey was carried out by conducting Multichannel Analysis of Surface Waves (MASW) tests at 110 locations over the entire study area. The procedure and data processing steps of MASW survey which were followed in this study are as explained by Park et al.(1999). The MASW method has been found to be effective in determination of the shear wave velocity (Maheswari et al., 2008) required for site response analysis. This method was used because it is non-invasive and it gives a high Signal-to-Noise ratio (S/N) during both the data acquisition and processing stages. In this study, a 24 channel engineering seismograph Geode model from OYO Corporation with external portable computer was used for acquiring wave form data. MASW tests were carried out by spreading multiple geophones for estimating one dimension (1D) and two dimensional (2D) shear wave velocity profiles. Twenty four geophones of 4.5-Hz capacity were used with a spacing of 6m between them and these were located on a straight line on the ground surface. A sledge hammer of 10kg with a switch, 68mm thick metallic plate and a trigger cable were used to generate the wave. The distance between the source and the nearest geophone was fixed to 3.0 m and the source was shifted in 6m intervals. The spread had a capacity of 10 Hz.

Rayleigh wave data were generated and recorded at all shot points. Data for each shot were digitally recorded and saved in the equipment. The acquired data from the engineering seismograph was then transferred for analysis. The analysis involved generation of V_s profiles of either 1D or 2D format using a simple three-step procedure: preparation of a multichannel record, dispersion curve analysis and inversion. The first step in the analysis was the making of the file list in which all waveform files and source receiver configurations were mentioned. The next step was to extract all pairs which had Common Mid Point (CMP) from all traces and to calculate their cross relation CMP gathers. Cross relation CMP gather files were saved as pseudo shot gather files for each CMP location. Then dispersion curves were generated by converting the data into a frequency domain for each cross correlation CMP gathers and then checked. Generation of a dispersion curve was one of the most critical steps for generating accurate V_s profiles.

Dispersion curves were displayed as phase velocity versus frequency plots. This model was established by calculating the phase velocity from the linear slope of each component of the swept frequency record. The 1D shear wave velocity profiles were calculated using the dispersion curves obtained from waveform data by non linear least square method. Then, by placing each 1D V_s profile at a surface corresponding to the middle of the survey line, 2D V_s map was constructed. That is, multiple V_s profiles obtained were then used for a 2D interpolation to create the final map.

Geotechnical Characteristics of Kasemene Area

A geotechnical investigation was conducted involving drilling of boreholes within the study area. The locations of the boreholes were selected to ensure that they were evenly distributed over the entire study area and within at most 6m from the nearest MASW survey line. Drilling was carried out immediately after conducting seismic surveys and it was done in two phases. In the first phase, fourteen boreholes for infrastructure facilities were drilled up to a maximum depth of 20m using a "Dando 2000™" cable percussion rig. These boreholes were drilled along the shores of Lake Albert, in the tentative Central Processing Facility (CPF) area and at banks of the dry Sambya River bed situated South East of the CPF area. The second phase comprised of drilling fourteen boreholes up to a depth of 6m at the existing and proposed oil well pads using 'Dando Terrier™' percussion drilling rig. Two boreholes were drilled on each pad. Disturbed samples were collected at intervals of 0.6 to 1.5 m depth using a split spoon sampler. The SPT test was carried out in each borehole in accordance with BS 5930:1990. Based on the recovered samples, drilling logs were prepared and the recovered samples were transported to the laboratory to conduct index property tests.

The soils in the study area were interpreted up to 20m depth using data from 28 boreholes. Fig.2 summarises typical soil profiles for boreholes drilled in the CPF area and Sambya Bed River. The uppermost layer is comprised of pure sand (deposited sand) varying from the ground surface to a maximum depth of 4.5m. The sand layer increases in thickness towards the escarpment. Beyond this depth, the area is covered by sand mixed with significant amounts of clay and some silt. Laboratory test results show that the material beyond this depth is of consistent composition with the majority of samples plotting as sandy cohesive deposits on a gradation chart. Out of 69 samples tested, only 7 samples had percentage passing 75μm sieve greater than 50%. The sand is however mixed with significant percentages of clay and some silt. There is a general tendency of the fines content to increase with depth across the entire study area. Majority of the samples plotted above the A-line of the plasticity chart indicating that the fine grained portion of the soil underlying the study area behaves as clay of varying plasticity and falls in the classification "clay of intermediate to high plasticity" on the plasticity chart. Bulk density values of the material were high and are ranging from 1.430 to 1.892 Mg/m^3. This was attributed to the sand being mixed with significant amounts of cohesive material.

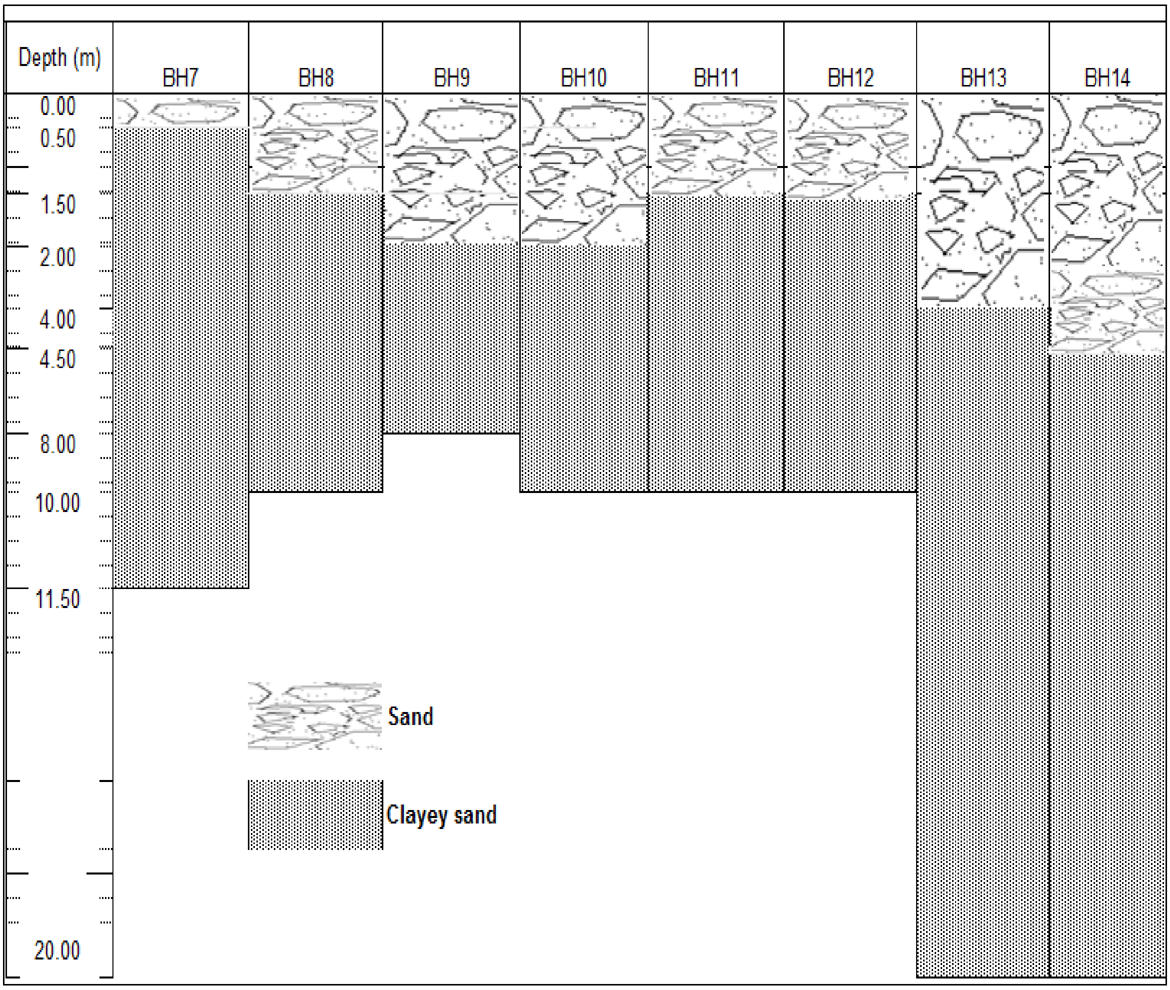


Figure 2. Soil profiles for boreholes in the CPF area (BH7, 8, 9, 10) and Sambya River (BH13, 14)

STATISTICAL REGRESSION

Shear wave velocity can be measured directly in the field by conducting a seismic survey. However, it is not always economically feasible to conduct these surveys at all locations. Numerous relationships between V_s and SPT N-values are reported in the literature. The N values for most of these relationships, including Anbazhagan et al. (2012), are typically not corrected for overburden effective stress. They are sometimes corrected for hammer energy, rod length and sampler inside diameter. It is therefore impossible to know whether bias is introduced by hammer efficiency, non-standard samplers or overburden pressure. SPT practices and measurements vary significantly due to differences in equipment and procedures around the world. Therefore the amount of energy delivered to the sampler might be different depending on the type of machine used and the place where testing is carried out.

There, however, still exist disagreements among researchers on whether to use the uncorrected or corrected SPT N-values. Hasancebi and Ulusay (2007) for example used energy corrected SPT N-values in their model, and found that it had a low correlation coefficient. Maheswari et al. (2010), however, reported that the corrected and uncorrected SPT N-values predicted Vs with equal accuracy. Majority of the published models are often expressed in the form of a power regression function given by Eq. (1) as shown in Table.1. A and B are regression constants which depend on the correlation coefficient. Generally, as A increases B decreases for the same strata (Imai and Tonouchi, 1982). Early efforts to develop these kind of models utilized laboratory results, but as field measurements of V_s became more common and reliable, such models became more refined (Brandenberg et al., 2010).

$$V_S = AN^B \tag{1}$$

The model in this paper addresses the shortcoming in the existing literature by considering the overburden correction factor. The V_s and energy corrected SPT N-value (N_{60}) are often correlated with relative density for sands using Eq.(2), (Youd, 2001). This factor was not directly applied to V_s and N_{60}, but rather incorporated through the β2 parameter which provided a measure of the relative overburden scaling between V_s and N_{60} that minimizes residuals with respect to effective overburden stress (σ'_v) simultaneously with N_{60}. The alternative approach would have involved estimating n and m values for each soil sample as shown in Eq. (2) and regressing on V_s and N_{60} as shown by Andrus et al. (2004). However, n and m could not be accurately estimated for the data set, since these parameters depend on a number of factors including: plasticity, cementation, and soil type, to mention but a few.

$$\left(\frac{P_a}{\sigma'_V}\right)^m \overline{V}_S = A\left(\frac{P_a}{V'_V}\right)^n N_{60}^B \tag{2}$$

This study utilized data from a set of 28 boreholes and 26 MASW survey lines which were located within the vicinity of the boreholes (i.e. within a maximum of 6m width). A total of 273 data pairs for V_s and SPT N-values which were measured at the same depth were generated and grouped for the regression analysis. The effective stress term (σ'_v) was included in the regression to inherently define the relative scaling of n and m for the data set. In the development of this relationship, both the shear wave velocity and the SPT N-value were corrected for effective overburden stress using the formula shown in Eq.(2) (Youd, 2001), which is often modified as shown in Eq.(3) for ease of application; where β_0=In (A), β_1=B, β_2=n-m and ε is a random error term which is normally distributed with zero mean (Hines et al., 2004).

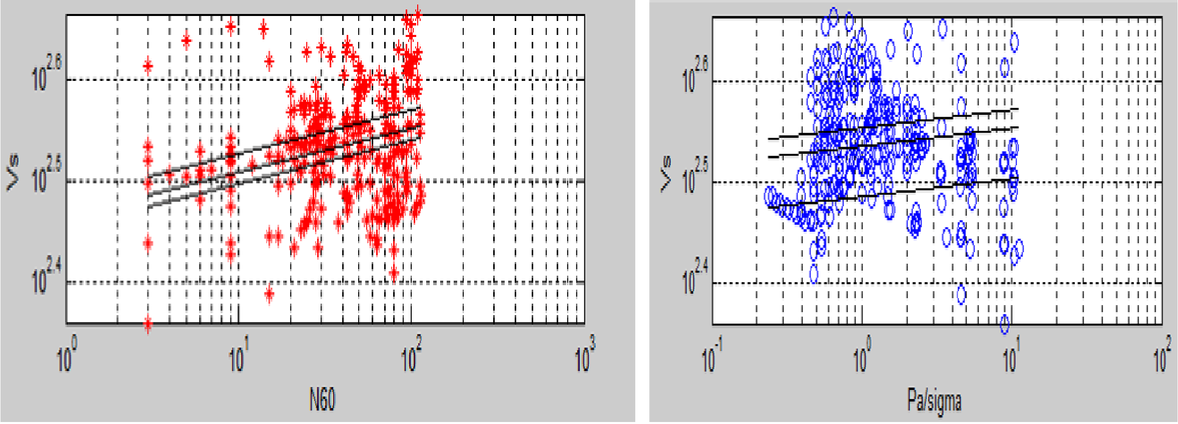
$$\ln \overline{V}_S = \beta_0 + \beta_1 \ln N_{60} + \beta_2 . \ln\left(\frac{P_a}{\sigma'_V}\right) + \varepsilon \tag{3}$$

As is the common practice, the model was solved using the method of ordinary least square regression to obtain the β-parameters and the resulting regression model is given in Eq.(4). The correlation coefficient for the study area relationship is R^2=0.873. The model was evaluated by checking for the goodness of fit and testing for the significance of the regression and it was found to be adequate.

$$\ln \overline{V}_S = 5.6764 + 0.0436 \ln N_{60} + 0.0181 \ln\left(\frac{P_a}{\sigma'_V}\right) \tag{4}$$

Influence of N_{60} and Overburden Effective Stress

Trend lines were fitted on the experimental data as shown in Fig.3. These were useful for identifying the relative influence of N_{60} and Pa/σ'_v, respectively, on the model. These lines correspond to the minimum, median and maximum values for N_{60} and Pa/σ'_v drawn to assist in comparing their relative influence on the V_s prediction. The model between V_s with either N_{60} and Pa/σ'_v was examined by observing how closely spaced the trend lines are within a given plot. As it can be seen the trend lines were closer to each other in the plot of V_s against N_{60} than in the plot of V_s against Pa/σ'_v as shown in Fig.3. This demonstrated that N_{60} exerts a stronger influence on the model than Pa/σ'_v indicating that, in the range of common engineering interest, V_s was more strongly related to blow count than to overburden stress. Brandenberg (2010) found out that for sand, V_s is more significantly related to Pa/σ'v than to N_{60} and that the relationship becomes smaller for silt and is lowest for clay. In this research the regression was developed for clayey sand. This probably explains why V_s was more related to N_{60} than to Pa/σ'_v. However, it was demonstrated that V_s is related to Pa/σ'_v and ignoring it creates bias in the correlation.



(a) V_s versus N_{60} (b) V_s versus Pa/σ'$_v$

Figure 3. V_s versus N_{60} with trend lines corresponding to the minimum, median and maximum for Pa/σ'$_v$ and N_{60}

Effect of Ignoring Overburden Factor

In order to demonstrate the effect of ignoring the effective overburden stress term in the regression, Eq.(1) was transformed into Eq.(5) by taking logarithms and it was solved using ordinary least squares regression. The resulting regression model is shown in Eq.(6) and the residuals were plotted against N_{60} and effective overburden stress as shown in Fig.4. Results show that there was no bias with respect to N_{60}, which is indicated by a very low regression coefficient of $5\text{x}10^{-5}$. On the other hand, there was significant bias with respect to overburden effective stress which was indicated by a slightly higher regression coefficient of 0.041 showing that there was a tendency of the residuals to increase with effective overburden stress. This finding demonstrated that similar bias might be present in publications which correlate V_s directly with N_{60} without considering the influence of effective overburden stress. This may be the reason why most models in literature differ so significantly from each other. Such relationships can only be used in situations where the overburden effective stress influence is deemed so low. The model shown in Eq.(7) is of the form given in Eq.(1) developed neglecting the effect of effective overburden stress.

$$\ln \overline{V}_S = \beta_0' + \beta_1' \ln(N_{60}) + \varepsilon' \tag{5}$$

$$\ln \overline{V_S} = 0.57189 + 0.0322 \ln(N_{60}) \tag{6}$$

$$V_s = 304.56 N_{60}^{0.0322} \tag{7}$$

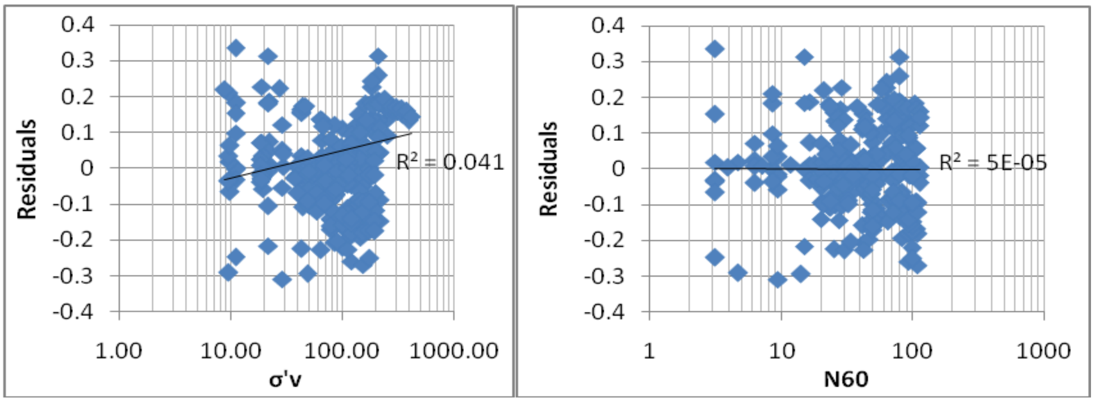


Figure 4. Residuals for regressions that neglect the influence of Pa/σ$_V$ on relation between V_s and N_{60}

Effect of Using Uncorrected SPT N-value

To demonstrate the bias caused by using the uncorrected SPT N-values, the regression analysis was carried out between the weighted shear wave velocity and N shown in Eq.(8). Eq.(8) was obtained by taking logarithms of the terms in Eq.(1). Eq.(8) was then solved using ordinary least squares regression method resulting into a model shown in Eq.(9). The resulting residuals were plotted against N_{60} and results show that there is no bias with respect to N_{60}. This finding demonstrated that for the soils in the study area, correction for equipment and borehole variations may not be necessary. The relation shown in Eq.(10) is of the form given in Eq.(1) which was developed ignoring correction for equipment and borehole variations.

$$\ln\overline{V_S} = \beta_0^{''} + \beta_1^{''}\ln N + \varepsilon \qquad (8)$$

$$\ln\overline{V_S} = 0.57416 + 0.0270\ln(N) \qquad (9)$$

$$V_S = 311.51N^{0.0270} \qquad (10)$$

Comparison with Published Relations

Given the soil non-linearity and the fact that the soils in the study area consist of mainly sand in the upper layer and clayey sand in the lower layer, this study therefore only considered published models which were developed for sand, clayey sand and all soil types as shown in Table.1. These models are all of the form given in Eq.(1) apart from the relation developed for soils in the study area. The models vary significantly from each other in terms of the regression constants. This could be attributed to the fact that these models are developed for different locations and soils.

The published models were fitted to the experimental data as shown in Fig.5 in an attempt to establish if they can be used to predict shear wave velocity in the study area. Some of the models predicted shear wave velocities at medium SPT N-values fairly well, but gave poor predictions at lower and higher SPT N-values. Models such as Kalteziotis et al. (1992), Kiku et al (2001), Andrus et al. (2004) and Shibata (1970) were outside of the lower bound of the research data indicating that they would under predict shear wave velocity for soils in the study area. Anbazhagan et al. (2012), Seed and Idriss (1981), Hanumantharao and Ramana (2008), Seed et al. (1983), Athanosopoulos (1995) and Ohsaki and Iwasaki (1973) fairly predicted the shear wave velocity at low SPT N-values but overestimated the shear wave velocities as the SPT N-values increased.

Models such as Maheshwari et al. (2010), Imai and Tonouchi (1982), Thaker and Rao (2011), Imai (1977), Ohta et al. (1972), Imai and Yoshimura (1970), Ohta and Goto (1978) and Hasancebi and Ulusay (2007) were low shear wave velocity predictors at lower SPT N-values and fair predictors at SPT N-values greater than 20 blows/300mm. These latter models were tested using the available data from boreholes 8 and 10 in CPF area and MASW survey lines 13 and 62 respectively. Shear wave velocity profiles were constructed as shown in Fig.6. The shear wave velocity profiles of these relationships were farther apart from the experimental profile implying that these relationships are poor predictors of shear wave velocity for soils in the study area. Therefore none of the above models should be used to predict shear wave velocities for the soils in the study area apart from the study area model.

Table 1. Relationships used in the comparison (Adopted from [$] Hanumantharao and Ramana, (2008); [~]Thaker and Rao, (2004) and *Anbazhagan and Sitharam, (2012))

Author (s)	Correlation	Soil	Country
Research Model	$\ln \overline{V}_S = 5.6764 + 0.0436 \ln N_{60} + 0.0181 \ln\left(\frac{P_a}{\sigma'_v}\right)$	**All**	**Uganda**
[$]Imai and Yoshimura (1970)	$V_s=76.0N^{0.39}$	All	Japan
[$]Ohsaki and Iwasaki (1973)	$V_s=82.0N^{0.39}$	All	Japan
[$]Imai et al., (1975)	$V_s=90.0N^{0.34}$	All	Japan
[$]Imai (1977)	$V_s=91.0N^{0.34}$	All	Japan
[$]Ohta and Goto (1978)	$V_s=85.3N^{0.35}$	All	Japan
[$]Ohta et al., (1972)	$V_s=87N^{0.36}$	Sand	Japan
[$]Jafari et al., (1997)	$V_s=22.0N^{0.85}$	All	Iran
[$]Athanasopoulos (1995)	$V_s=107.6N^{0.36}$	All	Greece
[$]Kalteziotis et al., (1992)	$V_s=76.2N^{0.24}$	All	Greece
[$]Imai and Tonouchi (1982)	$V_s=97.0N^{0.31}$	All	Japan
[$]Yokota et al., (1991)	$V_s=121.0N^{0.27}$	All	Japan
Seed and Idriss (1981)	$V_s=61.0N^{0.50}$	All	USA
[$]Seed et al., (1983)	$V_s=56.4N^{0.50}$	Sand	USA
*Anbazhagan and Sitharam (2006)	$V_s=50.0N^{0.41}$	All	India
[~]Kiku et al., (2001)	$V_s=68.3N^{0.292}$	All	Japan
[~]Hasancebi and Ulusay (2007)	$V_s=90.0N^{0.308}$	All	Turkey
[~]Maheshwari et al., (2010)	$V_s=95.64N^{0.301}$	All	India
[$]Hanumantharao and Ramana (2008)	$V_s=82.6N^{0.43}$	All	India
[~]Thaker and Rao (2011)	$V_s=59.72N^{0.42}$	All	India
[$]Andru et al., (2004)	$V_s=87.8N^{0.25}$	All	USA
[$]Lee (1990)	$V_s=57.0N^{0.49}$	Sands	USA
[$]Shibata (1970)	$V_s=32.0N^{0.50}$	Sands	Japan
[$]Chein et al., (2000)	$V_s=22.0N^{0.76}$	Silty sand	Taiwan
[$]JRA (1980)	$V_s=80.0N^{0.33}$	Sands	Japan

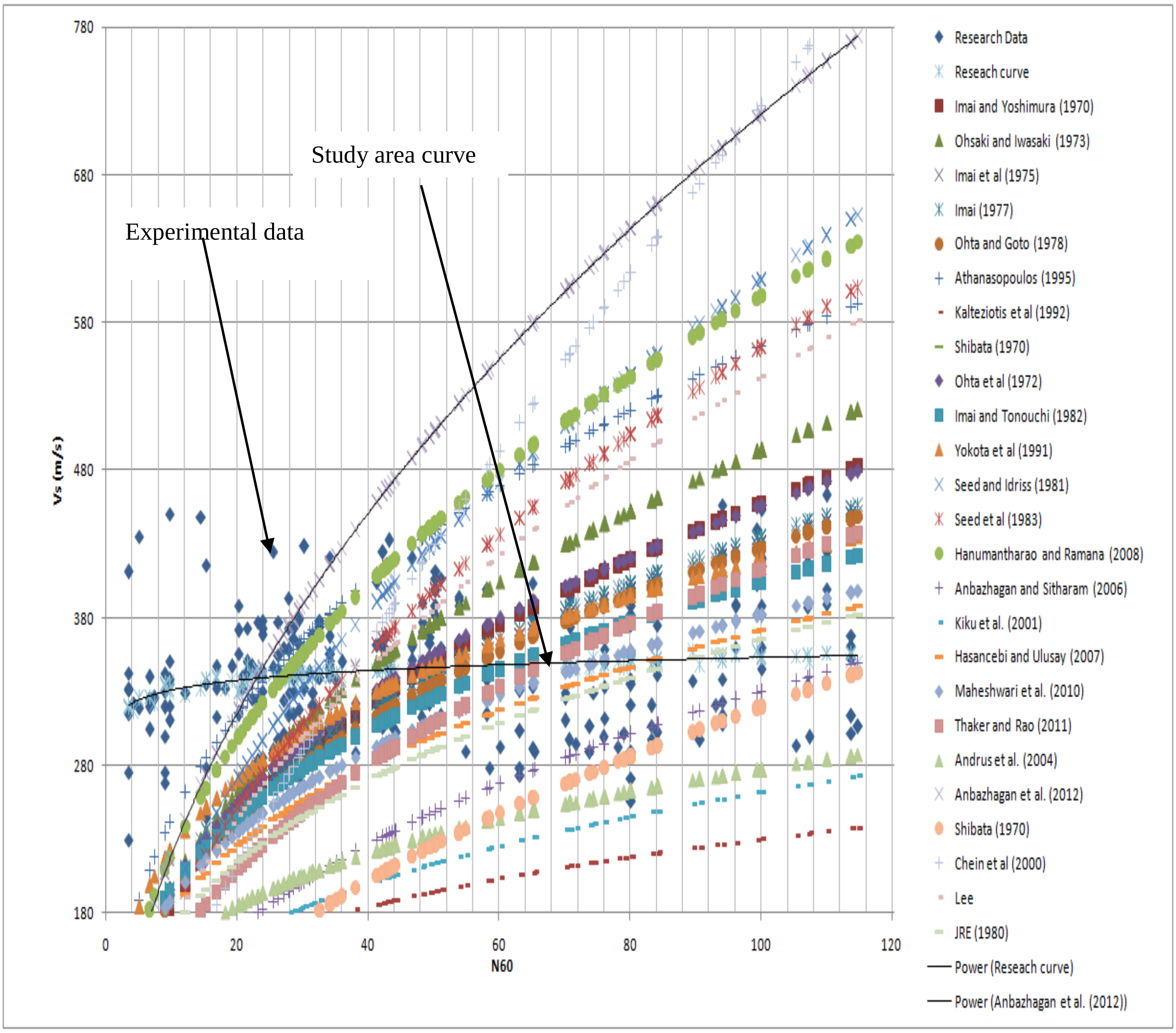
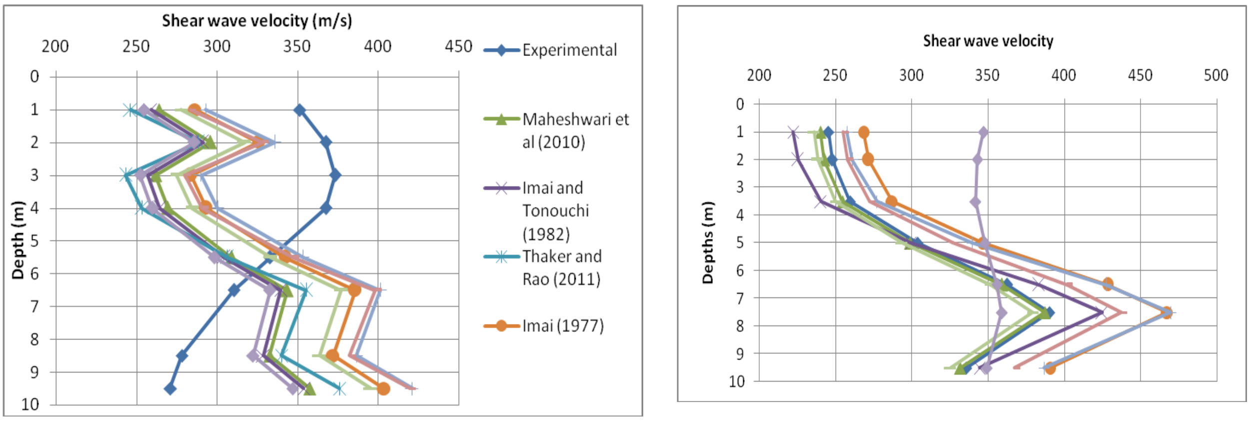


Figure 5. A comparison with the Existing correlations from literature superposed on data set used in this study



Borehole 8 and MASW 13

Borehole 10 and MASW 62

Figure 6. Comparison of shear wave velocity profiles

CONCLUSION

A relationship between shear wave velocity and STP N-values for the soils in Kasemene area in the Albertine region near Lake Albert was developed. The study revealed that ignoring the influence of effective overburden stress in the correlation may introduce bias in the model. There was high variability among published models and this was attributed to the fact that these models were developed from different regions and for different soils types. None of the published models fitted the data well and they cannot therefore be used to predict shear wave velocity in the study area.

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