PRINT ISSN 1119-8362
Electronic ISSN 2659-1502

Full-text Available Online at
https://www.ajol.info/index.php/jasem
http://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 27 (5) 995-1001 May 2023

Determination of Elastic Properties of Soils around a Typical Erosion-Prone Area in Benin City, South-South Nigeria

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ABSTRACT: Soil properties play a crucial role in understanding the mechanisms of erosion and consequently developing appropriate mitigation strategies. The aim of this study is to determine the elastic parameters of soil in an erosion-prone area using the Multichannel Analysis of Surface Wave (MASW) method of geophysical exploration. The active method MASW was adopted for this study. Data were acquired using a 24-channel ABEM Terralock MATK-6 seismograph with geophones of frequency 14Hz. An 8 Kg hammer was used as a source to generate seismic energy. Data acquired were processed with SeisImager2D refraction software developed by Geometric Earth Science Ltd and 2-D shear wave (Vs) and P-wave (Vp) velocities were generated alongside 2-D profiles of Shear Modulus, Young's Modulus, Bulk Modulus, and Poison's Ratio. The result of this study reveals soft to medium-stiff saturated clay/dry sand/wet sand and medium-stiff to stiff saturated clays/dry sand/wet sand with shear wave velocity values ranging from 84 m/s to 504 m/s. The bulk modulus, shear modulus, poison's ratio, and Young's modulus range from 3.4 GPa to 5.9 GPa, 20 kPa to 440 kPa, 0.448 to 0.498, and 50 kPa to 1.05 GPa respectively.

DOI: **https://dx.doi.org/10.4314/jasem.v27i5.17**

Cite this paper as: AIGBOGUN, C. O; EGBO, D. O; AIREN, O. J. (2023). Determination of Elastic Properties of Soils around a Typical Erosion-Prone Area in Benin City, South-South Nigeria. *J. Appl. Sci. Environ. Manage.* 27 (5) 995-1001

Dates: Received: 17 February 2023; Revised: 08 April 2023; Accepted: 16 April 2023
Published: 30 May 2023

Keywords: Geomaterial; Soil Stiffness; SeisImager; Shear Modulus

The global rise in human population has a direct influence on infrastructure development. In infrastructure development and construction such as high-rise buildings, highways, power-plant stations, airport pavements, foundations, and underground structures, soil engineering properties play an important role. Accordingly, sufficient planning is a necessity for the construction of these infrastructures for long-term purposes, reduction of economic loss, and loss of lives resulting from failed structures (Oladotun et al., 2019). Inadequate knowledge of the geotechnical geophysical characteristics of soil causes structural collapse and soil failure (Alemayehu et al., 2022). In the range of elastic soil behavior, the soil's Young's modulus is the ratio of stress over strain along the same axis. It is an elastic parameter of soil that measures its stiffness. Generally, soil consistency and packing affect soil stiffness and elastic modulus. Seismic velocities and density are combined to determine a geomaterial's elastic stiffness (Fjaer, 2019). Shear Modulus, Modulus, Poison's Ratio, and Bulk Modulus, are the elastic properties of a geomaterial, and these values offer helpful details on the geomaterial. In order to prevent resonance during operation, these dynamic qualities are crucial for designing the foundations of buildings on which vibrating equipment is mounted (Mcdowell, 1990). The engineering properties of soil have been conventionally investigated via a borehole and in-situ geotechnical approaches (Hamza and Bellis, 2008). One of the limitations of this approach to geotechnical site investigation is that the information obtained is localized and non-continuous.

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Geophysical methods and techniques provide an efficient, fast, and economical approach to complement the conventional geotechnical in-situ methods due to the non-invasiveness, spatial, and temporal approach (Ismail et al., 2019). Several geophysical methods have been employed successfully in the investigation and determination of soil engineering properties including Surface Waves methods and Electrical Resistivity Imaging. Through the determination of the bulk modulus and shear modulus, the compressional (Vp) and shear (Vs) wave velocities of geomaterials can be employed in geophysical exploration to determine the subsoil competency (Sjqgren et al., 1979; Dutta, 1984). Reduced porosity and moisture content in a compact subsoil leads to an increase in shear wave and compressional wave velocities. Numerous effective applications of the Multichannel Analysis of the Surface Wave (MASW) approach have been made in environmental and geotechnical engineering (Tábok et al., 2017). For the aim of VS profiling in the 1D or 2D format of the subsurface, this technique makes use of the dispersion property of surface waves. Alemayehu et al. (2022) used Multichannel Analysis of Surface Waves to characterize soils in Hawassa Town, Southern Ethiopia, by determining the shear wave velocity. Low Vs was seen in the 1D Vs profile and 2D cross-section at a shallow depth, and the investigation's findings indicated that the near-surface soils are composed of stiff soil and soft rocks. Oluwatobi and Adekunle, (2015) also employed the multichannel analysis of surface waves method in characterizing the geological and geotechnical properties of soil. Results from this site characterization show that shear-wave velocity values are in the range of 63-400 m/s with stiff soil to soft clay soil, bulk moduli (k) in the range of 3.22-3.98 GPa, and shear moduli (μ) ranging from 7.15-7.43 MPa depicting the relatively low strength of the subsurface materials. Hence, the objective of this paper is to determine the elastic parameters of soil in an erosion-prone area using the Multichannel Analysis of Surface Wave (MASW) method of geophysical exploration.

MATERIALS AND METHODS

Local Geologic Settings of Study Area: Edo State is situated in South-South Nigeria and it is an important sedimentary basin in Nigeria due to its nearness to the oil fields around the Niger Delta region. The area under study (Figure 1) falls within the Benin Formation of the Niger Delta Basin, located in the Southern part of Edo State. The area is underlain by sedimentary whose geology is characterized by deposits laid during tertiary and cretaceous periods. About 90% of sandstone and shale intercalations constitute sedimentary rock formation (Alile et al., 2011). The Formation describes the extensive reddish earth comprising loose ill-sorted sands which underlie the Recent-Quaternary Deposits of the Upper fringes of the Niger Delta (Ikhile, 2016).

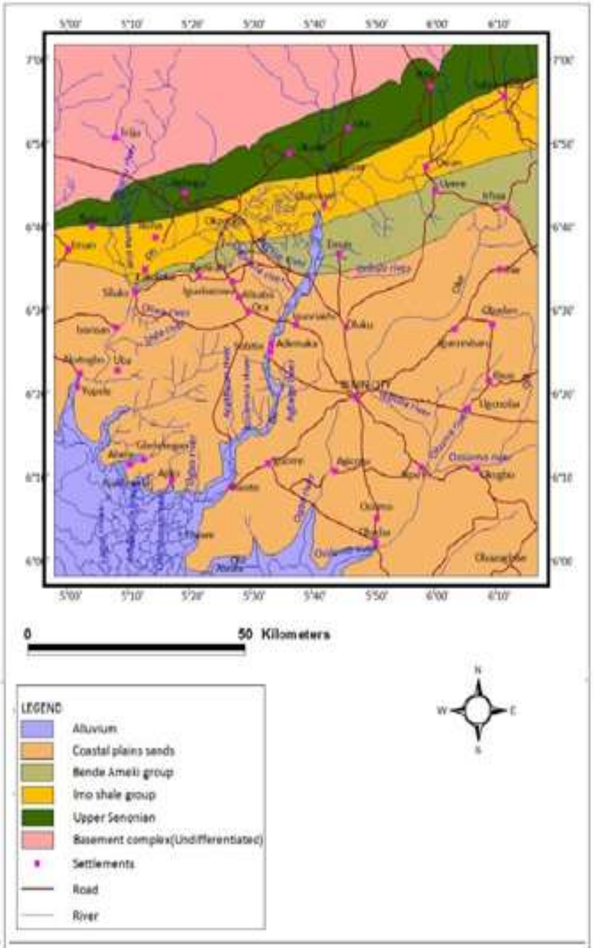

Fig 1: Geological Map of Benin City showing the study area (Olatunji *et al.,* 2014)

The survey area is located within longitudes 005° 40' 50.52" E to 005° 40'47.65" E, latitudes 06° 20' 40.64" N to 06° 20'35.95" N, and elevation of 43 to 38 m at Queen Ede gully erosion site situated in Ikpoba-Okha Local Government Area, Benin City. Data were acquired using a 24-channel ABEM Terralock MATK-6 seismograph using geophones of frequency 14Hz. The geophone array was monitored to ensure all geophones were correctly connected and coupled with the ground. An 8 Kg weight of hammer was employed to generate seismic energy by striking a ground-level metal plate. Energy generated at every point was stacked to improve the definition of the record. 1 second and 0.5 milliseconds were used as recording time and sampling intervals respectively. The system was prepared for the first shot record after the initial setup. Initializing the recording program and arming the trigger system initiates the recording sequence. When ready, the person in charge of swinging the hammer is signaled, and the survey is then started with a stroke of the hammer. The seismograph receives notice that the survey has started when the triggering mechanism responds. Signals are captured for a specified amount of time and at a specified interval. After the sounding is accepted, the setup is then moved to the next sounding. A total of 2 traverses were recorded during this survey.

Multichannel Analysis of Surface Wave (MASW): The MASW method utilizes the principle of wave physics to measure, analyze and map shallow subsurface structures. According to Hooke's law, the strain $\boldsymbol{\epsilon}$, that an object experiences is related to the stress σ, imposed on the object (Callister and William 2001).

$$\boldsymbol{\sigma = \epsilon E} \qquad 1$$

Where E is the elastic modulus when no permanent deformation is experienced. Wave propagation depends on the capacity to elastically deform particles inside a given media.

Dynamic soil characteristics including shear wave velocity, bulk modulus, Poisson's ratio, Young's modulus, and shear modulus are used to measure the degree of stiffness of the subsurface. The shear wave velocity (Vs) and P-wave velocity (Vp) are related by the equation (Adewoyin *et al.*, 2017).

$$Vp = 1.7Vs \qquad 2$$

The Hookean elastic equation can be used to derive these values using compressional and shear wave velocities as the input parameters, which are often obtained through low-strain dynamic tests like MASW (Bayo et al., 2021). Young's Modulus **E**, describes the soil's resistance to tensile or compressive stresses which defines elastic stiffness as a key property required in engineering designs. This is given by

$$E = \frac{\rho V_S^2(3V_P^2 - 4V_S^2)}{V_P^2 - V_S^2} \qquad 3$$

The resistance of the soul to compression is given by K (Bulk Modulus)

$$K = \rho(V_P^2 - \frac{4}{3}V_S^2) \qquad 4$$

Poison's Ratio **V**, describes the soil's tendency to change in width per unit width change in length as it is stretched or compressed

$$V = \frac{V_P^2 - 2V_S^2)}{2(V_P^2 - V_S^2)} \qquad 5$$

Shear Modulus **μ** describes the soil's resistance to shear stress

$$\mu = \rho V_S^2 \qquad 6$$

Despite several studies, no detailed investigation using MASW has been carried out in the study area, especially in 2-D format. The objective of this study is to ascertain the elastic properties of soil by generating the Shear Wave (V_s) velocity structures of the subsurface in 2-D and estimate the dynamic elastic moduli of the subsurface thereby determining stiffness around the study area.

Data acquired were processed using SeisImager2D refraction software. This begins by using the Pickwin module to accurately pick the first breaks corresponding to the geophones in the profile. With this, the time-distance curve is generated for the profile based on the profile length, shooting locations, geophone spacing, and the first arrival times. Secondly, by selecting the frequency domain (5 to 40Hz), the dispersion curve is developed. To eliminate noisy picks both on the low and high-frequency ends of the curves, the dispersion curve is edited. The final 2-D S-wave velocity profile is displayed after the initial shear wave velocity model is set up with depth and the appropriate number of iterations for the data inversion to settle on the best match of the initial model with the observed data. Our final velocity-depth profiles have root mean square errors (RMSE) that are fewer than 5%. The elastic parameters were then generated accordingly. The visual output of the unprocessed record of the shot is shown in Figure 2.

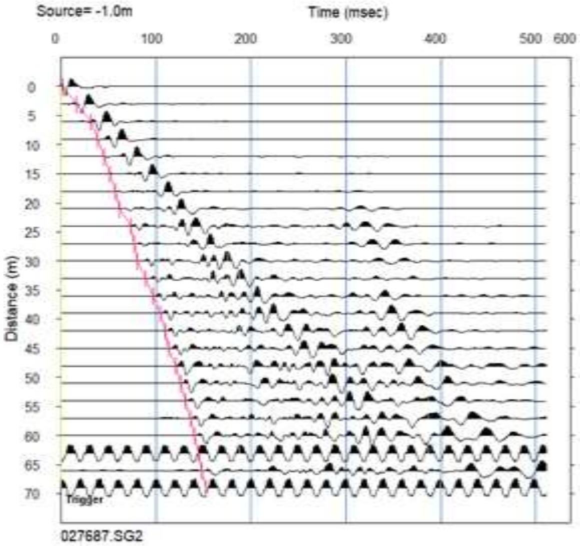

Fig 2: Visual Output of Acquired Unprocessed Record of MASW Shot

Table 1: Site Classification of Shear Wave Velocity by NEHRP (Park, (2013)

NEHRP Site Classification	Average Shear Wave Velocity (Vs) (m/s)
Special Study	Less than 100
Soft	100 to 200
Medium Stiff	200 to 375
Stiff	375 to 700
Rock	Greater than 700

RESULTS AND DISCUSSION

The results obtained from the investigation with the respective soil elastic properties are presented in figures 3(a-f) and 4(a-f). The inverted shear velocity model of Traverse One (Figure 3a) revealing to the distance and depth of about 138 m and 37 m respectively color-coded from 108 m/s to 504 m/s.

From the ground surface to the depth of 20 m across the section, the shear wave velocities are in the range of about 108 - 323 m/s which may imply soft to medium saturated shales and clays/ dry sand/ wet sand with pockets of relatively high shear velocity of range 395 m/s to 440 m/s within the later distances of 42 m to 66 m and 93 m to 102 m while past this zone to the depth of about 37 m lies medium to stiff saturated shales and clays/ dry sand/ wet sand with shear wave velocity ranging of about 323 m/s to 504 m/s.

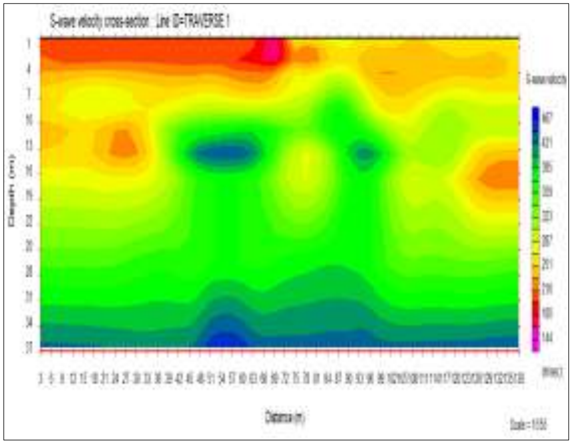

Fig 3a: Shear Wave Velocity Model Along Traverse One

From the surface to the depth of about 20 m throughout the traverse line, the P-wave velocity (Figure 3b), bulk modulus (Figure 3c), Poisson's ratio (Figure 3d), shear modulus (Figure 3e), and the young's modulus (Figure 3f) are ranging from 1440 m/s to 1680 m/s, 3.7 GPa to 4.9 GPa, 0.468 to 0.496, 40 kPa to 280 kPa, and 100 kPa to 700 kPa respectively depicting very soft clays sediment having pockets of relatively soft clay having 1720 m/s to 1840 m/s of P-wave velocity, 4.9 GPa to 5.9 GPa of Bulk modulus, 0.46 to 0.448 of Poisson's ratio, 340 kPa to 440 kPa of shear modulus, and 900 kPa to 1300 kPa of elastic modulus while below to the depth of 27 m lies the soft clay with the p-wave velocity, bulk modulus

Poisson's ratio, shear modulus, and young's modulus with values of 380 m/s to 500 m/s, 4.9 GPa to 5.9 GPa, 0.46 to 0.448, 340 kPa to 440 kPa, and 900 kPa to 1300 kPa respectively.

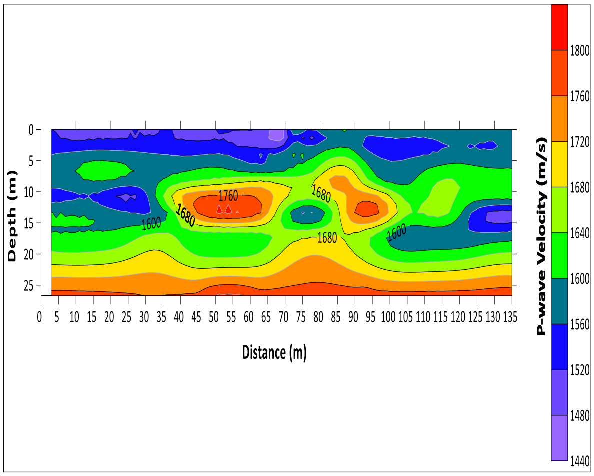

Fig 3b: P-wave Velocity Along Traverse One

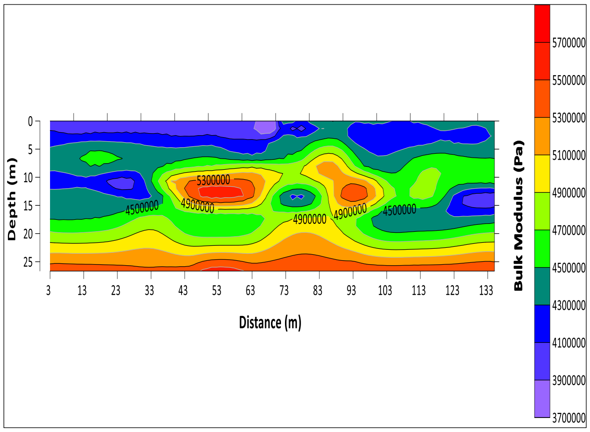

Fig 3c: Bulk Modulus Along Traverse One

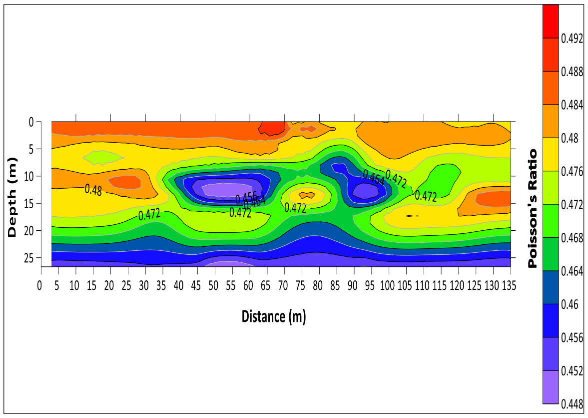

Fig 3d: Poisson's Ratio Along Traverse One

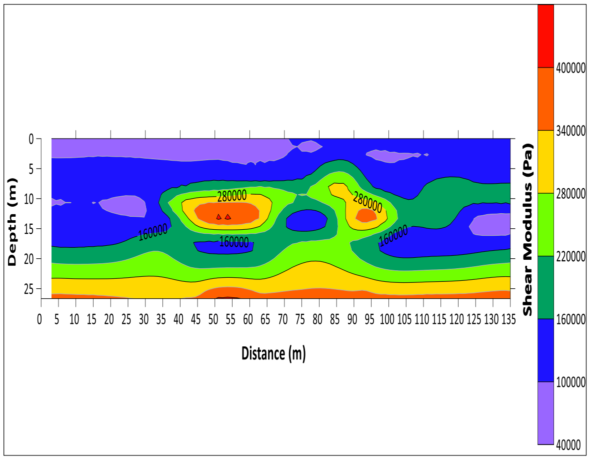

Fig 3e: Shear Modulus Along Traverse One

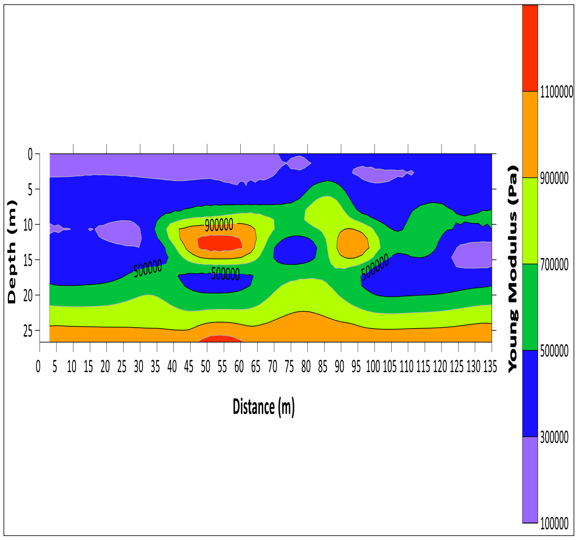

Fig 3f: Young Modulus Along Traverse One

From Traverse Two, the inverted shear velocity model (Figure 4a) revealing to the distance and depth of about 138 m and 31 m respectively color-coded from about 84 m/s to 434 m/s. From the ground surface to the depth of about 20 m across the section, the shear wave velocities are in the range of about 84 m/s to 317 m/s implying soft to medium-stiff saturated shales and clays/ dry sand/ wet sand while past this zone to the depth of about 31 m lies medium-stiff to stiff saturated shales and clays/ dry sand/ wet sand with shear wave velocity ranging of about 317 m/s to 434 m/s. From the surface to the depth of about 20 m throughout the traverse line, the P-wave velocity (Figure 4b), bulk modulus (Figure 4c), Poisson's ratio (Figure 4d), shear modulus (Figure 4e), and the young's modulus (Figure 4f) are ranging from 1400 m/s to 1520 m/s, 3.4 GPa to 4.8 GPa, 0.478 to 0.498, 20 kPa to 120 kPa, and 50 kPa to 350 kPa respectively depicting possible very soft saturated shales and clays / wet sand sediment while below to the depth of 25 m lies the soft clay with the p-wave velocity, bulk modulus, Poisson's ratio, shear modulus, and young's modulus with values of 1520 m/s to 1780 m/s, 4.2 GPa to 5.6 GPa, 0.478 to 0.454, 80 kPa to 380 kPa, and 450 kPa to 1.05 GPa respectively.

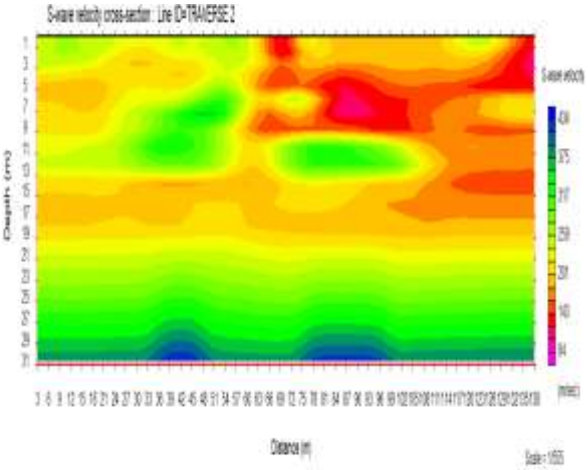

Fig 4a: Shear Wave Velocity Model Along Traverse Two

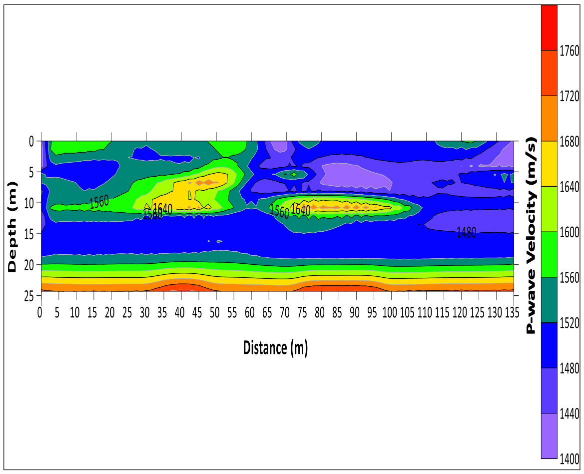

Fig 4b: P-wave Velocity Along Traverse Two

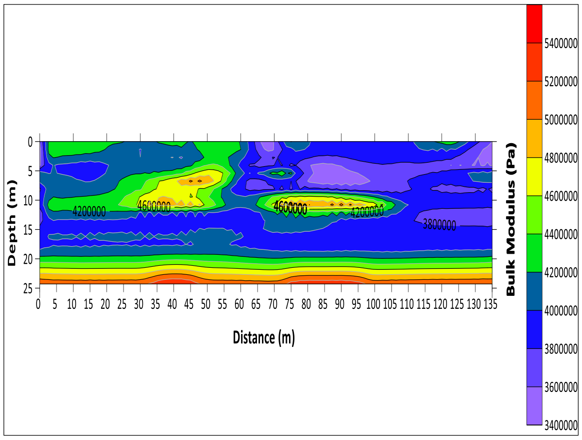

Fig 4c: Bulk Modulus Along Traverse Two

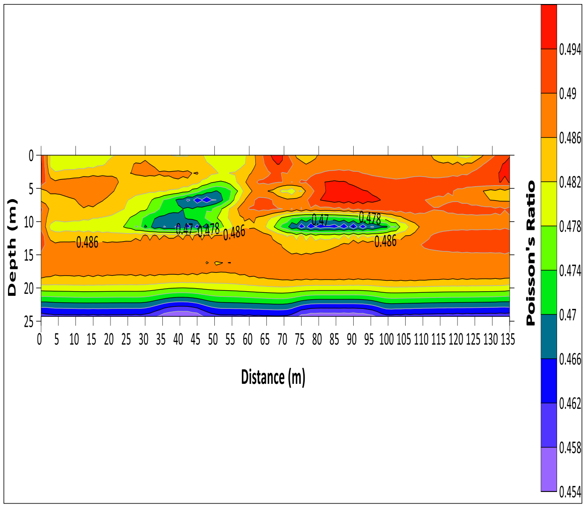

Fig 4d: Poisson's Ratio Along Traverse Two

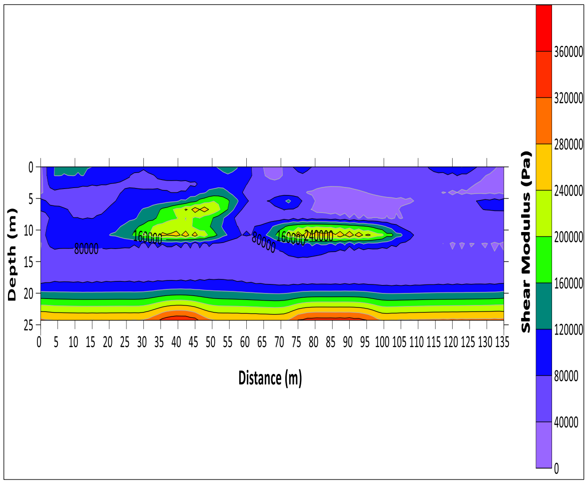

Fig 4e: Shear Modulus Along Traverse Two

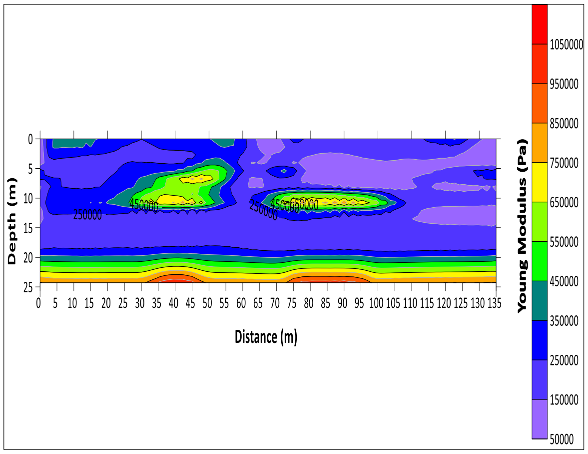

Fig 4f: Young Modulus Along Traverse Two

Conclusion: The elastic properties of soils have been determined around a typical erosion-prone area in Benin City using the Multichannel Analysis of Surface Waves method. The result of the site investigation reveals soft to medium-stiff saturated clays/dry sand/wet sand and medium-stiff to stiff saturated clays/dry sand/wet sand in the study area. The shear wave velocity value ranges from 84 m/s to 504 m/s. The bulk modulus, shear modulus, Poisson's ratio, and Young's modulus range from 3.4 GPa to 5.9 GPa, 20 kPa to 440 kPa, 0.448 to 0.498 and 50 kPa to 1.05 GPa respectively.

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