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Seismic wave attenuation characteristics of tertiary sediments in niger delta field

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ABSTRACT

Seismic attenuation analysis is important for several reasons, including aiding seismic risk evaluation. Quality factors and attenuation coefficients have been estimated for an X-field in the Niger Delta, whose near surface sediments has remained largely uncharacterized. Using surface waves extracted from seismic data acquired by conventional reflection methodology and employing the quality factor versus offset (QVO) technique of attenuation analysis, reliable attenuation coefficient and quality factor distributions for the field covering about 25 km^2 has been generated. The value of quality factors obtained indicate that the near surface sediments are low in attenuation to surface waves, being largely unconsolidated. The value of quality factors ranges from 20 to 80, corresponding to attenuation coefficients of between 0.0006 to 0.002 m^{-1}. The estimated attenuation factors in this study tend to have some form of dependence on the thickness of unconsolidated sediments. In most parts of the field, especially in the northern parts it is observed that areas with thin unconsolidated sediments thickness have higher attenuation factors than areas with thick unconsolidated sediments. These results correlates well with those of previous studies in similar geologic settings. Generally, the field is low in attenuation with high quality factors and therefore, susceptible to seismic hazards due to surface wave amplifications. This however, will enhance stress levels and distribution in the near surface sediments which will affect the stability of civil structures. Therefore, appropriate engineering standards must be adopted to ensure stability of engineering structures in the field.

Keywords: Seismic attenuation, Quality factor, Attenuation coefficients, Seismic risk, Stress level.

INTRODUCTION

The energy losses that occur as seismic pulses propagate through the earth's subsurface in the process known as seismic attenuation, depends on several factors including but not limited to transmission losses, spherical divergence, and multiple reflections [1]. Seismic attenuation studies find relevance in two major forms in earth studies. Firstly, anelastic attenuation processes resulting in the loss of high frequency seismic signals; a situation that affects the resolution of seismic images produced by conventional seismic surveys and thus requiring compensation using an inverse Q filter [2,3]. Secondly, the attenuation characteristics of rocks are diagnostic of rock lithology, structure and saturation [4,5,6].

The attenuation characteristics of seismic waves are described by the attenuation parameters. These are the attenuation coefficient (α) and the quality factor (Q). Seismic attenuation coefficient (α) is an exponential index describing the rate of seismic energy decay, while the quality factor (Q) is a measure of the magnitude of damping seismic energy suffers within a medium. These parameters are key to unravelling the nature and constitution of component rock units and their interaction with seismic elastic waves.

Studies to estimate seismic attenuation parameters are necessary considering how vital they can be in providing engineering, environmental, geological and geotechnical insight into the nature and integrity of the near subsurface of the earth. However, the derivation of optimum benefits from seismic attenuation, whether in terms of compensating for its effects on seismic data or for rock characterization, requires an accurate estimation of these attenuation parameters.

The present study was carried out in an "X" field located in the Niger Delta, about 44 km north-east of Port Harcourt, Nigeria (Figure 1). The Niger delta is a Cenozoic sedimentary basin situated on the continental margin of the Gulf of Guinea, in equatorial West Africa, bordering the Atlantic Ocean between latitudes 3^o and 6^o N and longitudes 5^o and 8^o E.

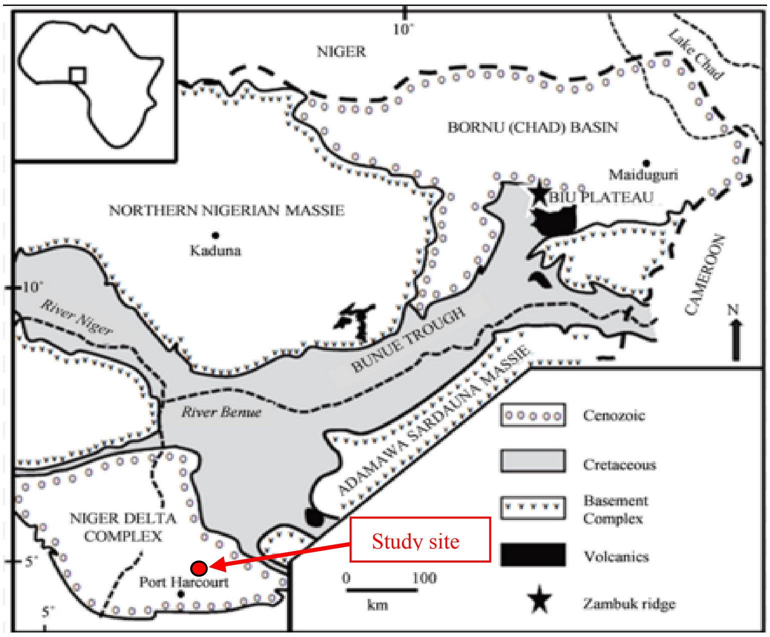

Figure 1: Location and Geologic map of the study area.

At the moment, there is no available geo-hazard data for the Niger delta to allow for a comprehensive evaluation of environmental and infrastructural development activities. This situation calls for concern considering the profuse nature of fracture zones extensions (most especially, the Chain and Charcot fracture systems) of the South Atlantic ridge system towards the Niger delta [7,8,9]. Also, the Niger delta being a relatively young delta has been reported to be composed of a sequence of largely unconsolidated and saturated sediments [10]. These conditions affects seismic wave propagation and consequently, make the delta sediments susceptible to environmental, geotechnical and seismic hazards.

In an earlier study, multichannel analysis of surface waves method was employed to generate shear wave velocity profiles for the study area, from which depths to consolidated sediments were inferred [11]. In a bid to provide more detailed description of the near surface soil properties in the area, seismic attenuation analysis has been carried out using the same data set.

The aim of this study is to characterize the near surface sediments in an X-field, a part of the Niger delta in terms of the attenuation parameters; attenuation coefficient (α) and quality factor (Q) by adopting the quality factor versus offset (QVO) technique to analyse seismic surface wave data. This is intended to serve as a reference material for environmental, civil and geotechnical activities in the area.

GEOLOGY OF THE STUDY AREA

The delta is a Cenozoic sedimentary basin underlain by three stratigraphic units, the topmost Benin Formation, the middle Agbada Formation and the deepest Akata Formation (Figure 2). The Benin Formation is mainly made up of unconsolidated continental sand deposits with thin lenses of clays/shales at intervals. The approximately 2 km thick formation is characterized by shallow low velocity layers and is the main water bearing formation [12]. The Niger Delta region enjoys a substantial amount of rainfall all year round which largely ensures that the Benin Formation remains water saturated with shallow lying water table.

Below the Benin Formation is the reservoir sands column of the Agbada Formation, which is a sequence of alternating sands and shales with thickness of about 3.7 km [12]. This is unconsolidated and known to house the oil and gas resources of the Niger Delta. The Akata Formation which is about 7 km thick is the oldest stratigraphic unit and consists predominantly of marine shales [12], is considered primarily as the source rock, although it also occurs as a reservoir rock units deep offshore and over pressured.

THEORETICAL BACKGROUND

Considering the relationship governing the dissipation of seismic energy during wave propagation based on the constant-Q model [13]

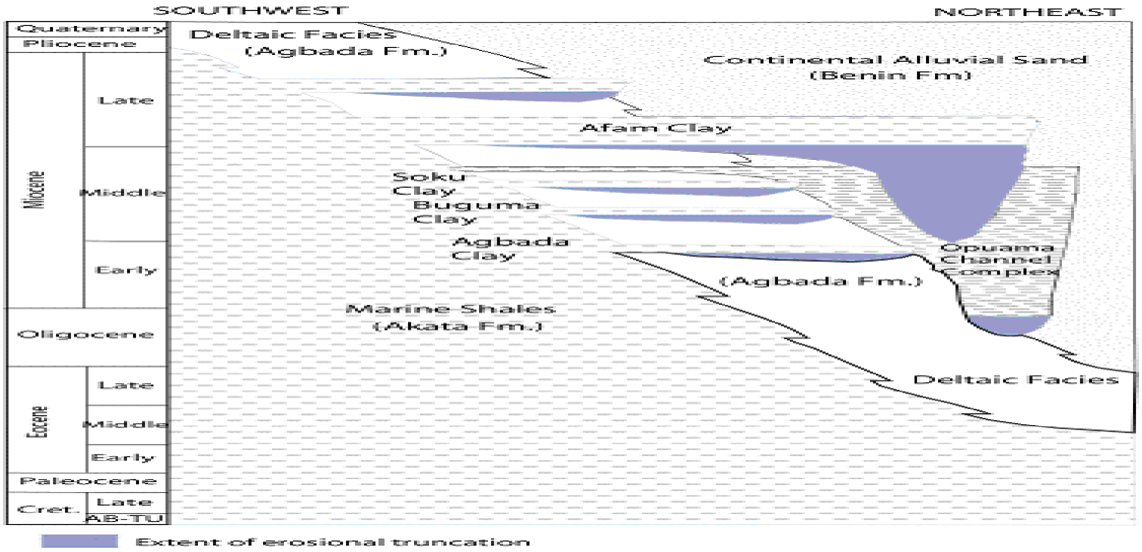

Figure 2: Geologic map of the study area.

$$A(f,x) \propto exp^{-(\acute{a}(f)x)}$$

$$A(f,x) = A_0(f,x)exp^{-(\acute{a}(f)x)} \quad (1)$$

where α is the attenuation factor, x is the offset and A_o and A are the amplitudes at the source or the first receiver and at any other offset x, respectively

Equation 1 represents an exponential curve fitted through the points of a plot of amplitudes against offsets. Performing a simple logarithmic transformation as outlined below, the attenuation factor can be obtained as the gradient of a straight line fitted to a plot of the logarithm of amplitudes against offsets.

Given from equation 1 that:

$$A = A_o e^{-\acute{a}x}$$

we can write that

$$e^{-\acute{a}x} = \frac{A}{A_o} \quad (2)$$

The geometric spreading factor has been conveniently set to unity in this formulation, considering the distances applicable in this study [14].

taking the logarithm of both sides of the equation we have:

$$-\acute{a}x = \ln\frac{A}{A_o} = \ln A - \ln A_o$$

$$\therefore \ln A = -\alpha x + \ln A_o \quad (3)$$

Equation 3 represents a straight line plot whose gradient gives the attenuation factor for any linear geophone spread.

The attenuation factor ∝ may be written in a general form as;

$$\propto = \frac{\eth f}{Qv} \quad (4)$$

where f is the frequency, Q is the quality factor and v is the phase velocity.

From equation 4, the quality factor may be estimated as;

$$Q = \frac{\eth f}{\acute{a}v} \quad (5)$$

where f is here taken to be the peak frequency present on dispersion images and v is the phase velocity at that frequency. The peak frequency corresponds to the shortest wavelength which characterizes the shallowest portion of the subsurface where our interest lies. We also note that since shear waves are known to have dominant influence on Rayleigh wave characteristics, the estimated quality factors may approximate the shear wave quality factors (Q_s) in the area.

METHODOLOGY

The data for the present study was acquired by the conventional CMP technique for seismic reflection work. Seven seismic lines with different numbers of shots, covering an area approximately 25 km^2, were analysed (Figure 3). The QVO technique developed by Dasgupta and Clark [15], was employed in the Q estimation from conventional CMP gathers

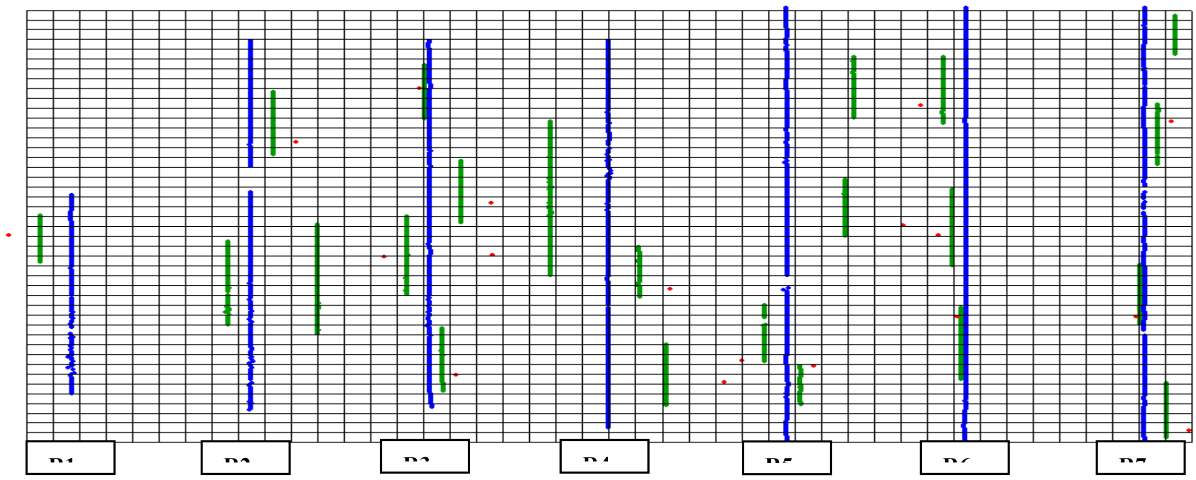

Figure 3: Seismic geometry map showing receiver lines covering 25 km^2.

Surface wave amplitudes were extracted as functions of offset at every 50 m offset increments from offset for each of the seven receiver lines. This was done by summing absolute amplitude values within a variable sliding time window with maximum length 2000 ms, which was moved systematically within the surface wave cone. A total of thirty five (35) amplitudes values were extracted for each receiver line in the field. Subsequently, the natural log of the extracted amplitudes were plotted against offset for each of the receiver lines from which the attenuation factor (α) was estimated.

RESULTS PRESENTATION

The results obtained from the surface wave attenuation analysis are presented below. Typical values of amplitudes per trace and their logarithms as functions of offset for receiver line six (RL 6) in the field (Table 1), show large variations in the observed values of amplitudes extracted from the traces for different shots on the receiver lines, and for different receiver lines. These variations may be attributed to several factors including source coupling and strength and receiver conditions during acquisition.

Table 1: Amplitudes versus offset data for RL 6

Receiver line 6 (RL 6)								
Offset (m)	Shot 300		Shot 700		Shot 800		Shot 2500	
	Amp	Ln Amp	Amp	Ln Amp	Amp	Ln Amp	Amp	Ln Amp
0	1078.23	6.983076	194.13	5.268528	502.07	6.21874	8138.35	9.004343
50	936.43	6.842075	129.5	4.863681	267.78	5.590166	7237.52	8.887034
100	519.87	6.253579	83.92	4.429864	117.29	4.76465	3777.79	8.236894
150	341.67	5.833845	79.48	4.375505	126.99	4.844108	2419.3	7.791234
200	393.79	5.975818	54.13	3.991389	86.05	4.454929	1574.26	7.361541
250	291.34	5.674491	54.67	4.001315	96.51	4.569647	1257.9	7.137199
300	217.8	5.383577	51.9	3.949319	112.04	4.718856	2430.34	7.795786
350	187.42	5.233352	48.28	3.877017	108.66	4.688224	1290.98	7.163157
400	894.34	6.796086	56.51	4.034418	96.1	4.565389	1081.35	6.985966

450	714.75	6.571933	218	5.384495	113.07	4.728007	712.8	6.569201
500	694.26	6.542847	64.95	4.173618	118	4.770685	844.94	6.739266
550	118.28	4.773055	63.26	4.147253	134.23	4.899555	922.91	6.827532
600	132.65	4.887714	59.5	4.085976	143.4	4.965638	840.17	6.733604
650	146.23	4.985181	52.7	3.964615	127.47	4.847881	1075.08	6.98015
700	104.98	4.65377	56.2	4.028917	93.33	4.536142	823.19	6.713187
750	155.59	5.047224	58.15	4.063026	75.81	4.32823	885.32	6.785949
800	53.72	3.983785	50.27	3.917408	68.85	4.23193	715.32	6.57273
850	65.76	4.186012	158.75	5.067331	50.74	3.926715	771.81	6.648738
900	73.94	4.303254	46.89	3.847804	47.48	3.860309	850.6	6.745942
950	63.7	4.154185	46.5	3.839452	42.75	3.755369	557.25	6.323014
1000	58.41	4.067487	39.83	3.68462	40.98	3.713084	739.43	6.60588
1050	76.1	4.332048	33.79	3.520165	36.29	3.591542	695.87	6.545163
1100	48.19	3.875152	36.99	3.610648	36.71	3.603049	506.4	6.227327
1150	44.99	3.80644	35.08	3.557631	37.28	3.618457	627.19	6.44125
1200	34.63	3.54472	38.41	3.648318	33.59	3.514228	628.22	6.44289
1250	29.04	3.368674	37.25	3.617652	29.35	3.379293	491.96	6.198397
1300	41.72	3.730981	38.84	3.659451	28.29	3.342508	589.04	6.378494
1350	45.21	3.811318	27.42	3.311273	23.25	3.146305	500.03	6.214668
1400	37.44	3.62274	34.51	3.541249	28.56	3.352007	596.53	6.39113
1450	53.53	3.980242	31.42	3.447445	69.6	4.242765	559.75	6.32749
1500	65.43	4.180981	45.43	3.816173	24.93	3.216072	495.16	6.204881
1550	44.61	3.797958	42.34	3.745732	26.37	3.272227	442.62	6.092712
1600	36.41	3.594843	22.45	3.111291	22.33	3.105931	582.49	6.367312
1650	32.03	3.466673	26.53	3.278276	23.1	3.139833	732.88	6.596982
1700	26.97	3.294725	21.01	3.044999	-	-	420.2	6.040731

Plots of the logarithms of amplitudes against offsets for RL 6 are shown in (Figure 4). From these plots, effective attenuation factors were obtained as the gradients of the fitted straight lines. The plots show a general decay of amplitudes with offset as expected, although outlier points occur; especially for the first three receiver lines, where data quality is noted to be relatively poor. The occurrence of non-conforming points, having anomalously higher amplitudes is considered the result of the inclusion of several noise wave forms such as noise trains and burst energies, while the anomalously low amplitudes may be acquisition related. These anomalous amplitudes however, are considered to have only little influence on the results as the general decay trend is still well preserved.

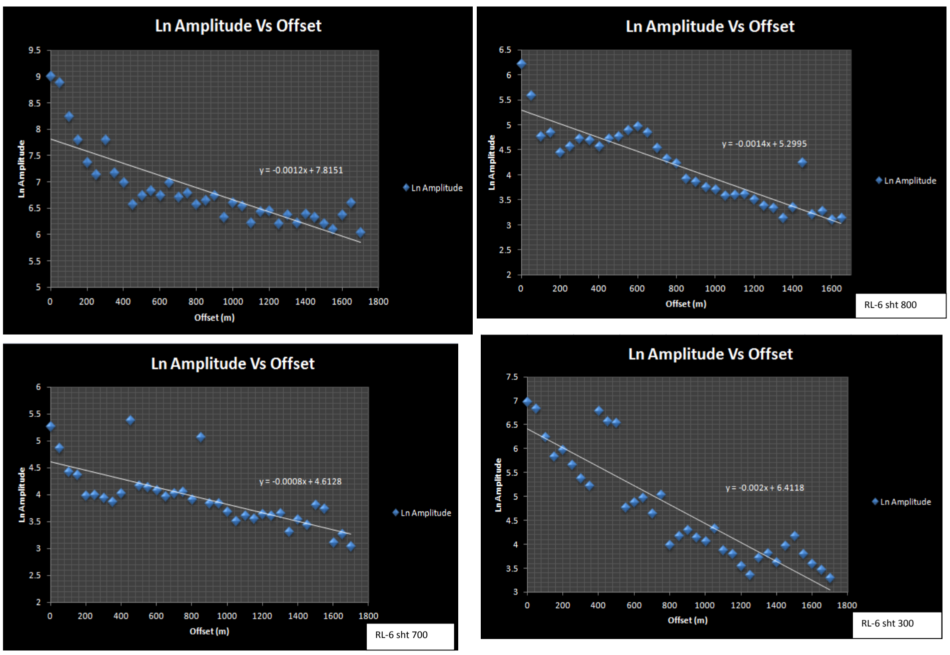

Figure. 4: Log amplitude against offset for RL-6 (a) shot 2500 (b) shot 800 (c) shot 700 (d) shot 300.

The estimated sediment thickness, shear wave velocity, attenuation factors and quality factors for the field are shown in Table 2. The result show that these parameters vary for each of the receiver lines in the field. The least sediment thickness, Vs, α and Q of 4.4 m, 294.0 m/s, 0.0006 m^{-1} and 24.5 respectively, were estimated in lines RL5, RL2, RL4 and RL6. While largest sediment thickness, Vs, α and Q of 30.2m, 413.2m/s, 0.002 m^{-1} and 81.8 respectively, were estimated in lines RL2, RL4, RL3,6,and 7 and RL4. The results of the analyses show that α decreases with sediment thickness while Q increases non-linearly with sediment thickness in the field.

Table 2: Summary of estimated sediment properties and attenuation parameters in the field

SHOT	Thickness (m)	Vs (m/s)	∝(m^{-1})	Q
		RL1		
1800	11.9	313.8	0.0017	28.9
1600	11.9	312.4	0.0018	27.3
		RL 2		
2400	4.7	294	0.0011	44.6
1800	12.4	302	0.0017	28.9
2100	30.2	323.9	0.0011	44.6
		RL 3		
900	12.1	332.3	0.0017	28.9
1200	12.1	303.8	0.0018	27.3
1400	20.5	339.4	0.002	24.5
2400	4.6	311.8	0.0018	27.3
		RL 4		
500	12.3	314.2	0.0011	44.6
1100	30	413.2	0.0013	37.7
1200	4.6	307.2	0.0013	37.7
1400	20.7	313.5	0.0006	81.8
		RL 5		
200	19.4	324.1	0.0015	32.7
1700	28.4	402	0.0012	40.9
1000	4.4	297.4	0.0014	35
2500	4.4	322.8	0.0014	35
		RL 6		
300	20	302	0.002	24.5
700	20	324	0.0008	61.3
800	11.8	314.9	0.0014	35
2500	29.1	387.4	0.0012	40.9
		RL 7		
100	20.6	331.1	0.0015	32.7
400	12.2	351.5	0.002	24.5
1900	12.2	324.4	0.0012	40.9
2300	4.6	297.8	0.0014	35

The attenuation and quality factor distributions in the field are shown in Figures. 5 and 6, respectively. The seismic attenuation factor (Figure 5), is highest in the north, partly intermediate in the north central and low towards the north, -north east and south of the field. The quality factor (Figure 6), is highest towards the north, partly intermediate in the south and low in the north central of the field. Result show that areas of high α values are associated with low Q distribution and vice versa. This suggests that seismic surface wave energies will generally decay faster over areas with decreasing Q factor and sediment thickness and slow over areas with increasing Q factor and sediment thickness. However, the rate of these energy decay varies over the field as a function of the specific values of quality factor, which varies non-linearly with sediment thickness.

DISCUSSION OF RESULTS

This study investigated the attenuation characteristics of sediment units to the propagation of seismic wave energies in an X-field. The result of study show that attenuation by sediments in the field is mild (small). The attenuation factors (α) ranges from about 0.0006 m^{-1} to 0.002 m^{-1}, corresponding to estimated quality factors (Q) in the range of 20 to about 81 for near surface sediment in the field.

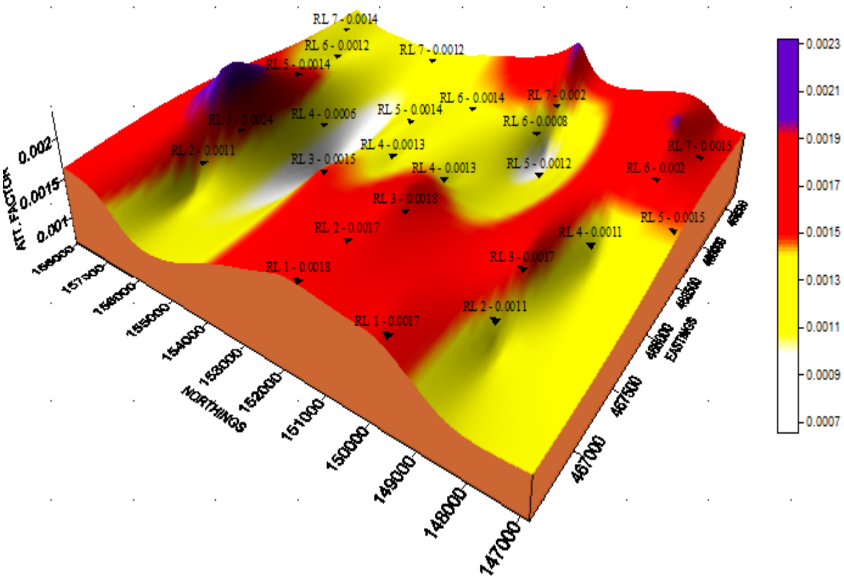

Figure 5: Variation of Attenuation coefficients (α) in the field.

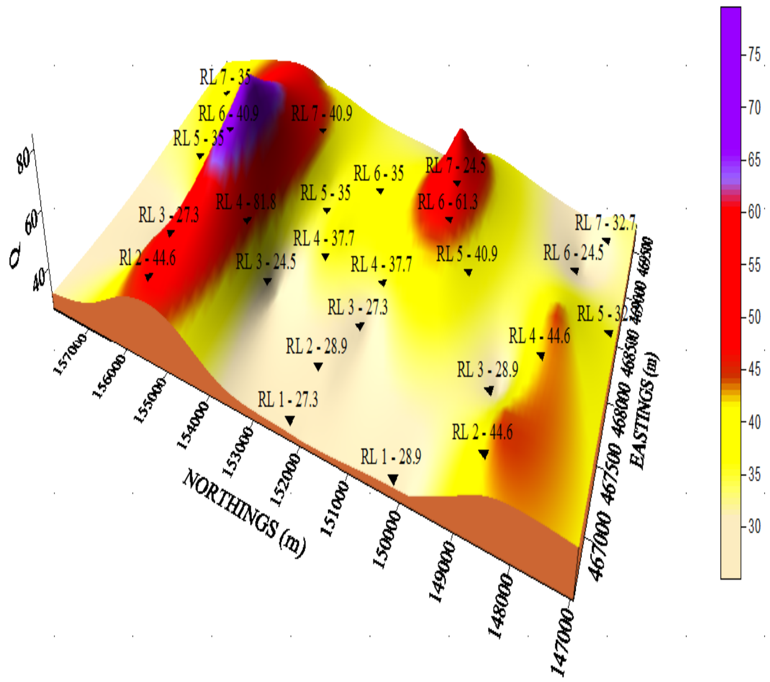

Figure 6: Variation of Quality Factors (Q) in the field.

The low attenuation factor in the field is attributed to the proximity of the water table to the surface and high moisture content or water saturation of the near surface sediments, which may tend to lubricate grains as they deform during wave passage, thus reducing anelastic attenuation, i.e., wave energy conversion to heat.

We note that the results of the quality factors are uncommonly high compared to those reported by other researchers such as Kudo and Shima [16], who estimated Q values in the range of 5 to 20 in Japan, Gibbs and Roth [17], estimated Qs in the range of 4 to 10 in California, Chen et al., [18, estimated Qs in the range of 25 to 30 and Pujol et al., [19], estimated Qs in the range of 34 to 44 for near surface sediments of the Mississippi embayment.

However, Pujol, et al., [19] and Chandler, et al., [20] reported cases of seismic wave amplification by unconsolidated sediment materials leading to high quality factors in their studies. It is envisaged that the high quality factors estimated in this study may likely be due to this wave amplifications by the near surface sediments in the field. Therefore, areas of high quality factors and corresponding low attenuations in the field are prone to seismic surface wave amplifications. These areas are at greater seismic risk than areas with low quality factors and high attenuations of surface waves.

The distribution of attenuation parameters in the field vary from point to point. The seismic attenuation factor is highest in the northern extreme, partly intermediate in the north central and low towards the north, north east and south of the field, while the quality factor is highest towards the north, partly intermediate in the south and low in the north central of the field. Result show that areas with high α values are associated with low Qs and vice versa. This suggests that seismic surface wave energies will generally decay faster over areas with decreasing Q factor and sediment thickness and slow over areas with increasing Q factor and sediment thickness. However, the rate of these energy decay varies over the field as a function of the specific values of quality factor, which varies non-linearly with sediment thickness

The estimated attenuation factors in this study tend to have some form of dependence on the thickness of unconsolidated sediments. In most parts of the survey area, especially in the northern parts it is observed that areas with thin unconsolidated sediments thicknesses appear to have higher attenuation factors than areas with thick unconsolidated sediments. Generally, the X-field is low in attenuation with high quality factors and therefore, susceptible to seismic hazards due to surface wave amplifications. This however, will enhance stress levels and distribution in the near surface which will affect the stability of civil structures in the field. It is recommended therefore, that appropriate engineering practices should be adopted to ensure durability and stability of all civil and engineering structures in the field.

CONCLUSION

Seismic attenuation characteristics have been determined for the field by employing the quality factor versus offset technique and using data acquired by the conventional seismic reflection CMP layout. The estimated attenuation coefficients show that the field is generally low in attenuation of surface seismic waves, indicating that it may be prone to severe seismic hazards and thus appropriate measures should be put in place in course of any civil development in the field.

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