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Application Of Engineering Geophysics Techniques In Subsurface Investigation Of Building Collapse Sites In Parts Of Anambra State

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ABSTRACT
Geophysical and geotechnical surveys were employed in post-failure investigations on four building collapse sites from the north senatorial zone in Anambra State, Nigeria. The study is aimed at uncovering the probable causes of the collapses and ascertaining the suitability of vertical electrical sounding (VES) for site investigations. Visual inspections helped to gather useful information about the rubbles and the collapse environs; boreholes were drilled to retrieve soil samples; cone penetration test (CPT) determined the cone resistance of soils and delineated the soil stratigraphy; foundations were probed for their suitability with respect to the imposed load; index properties (moisture content, Atterberg limits and sieve analysis) of retrieved soil samples were evaluated in the laboratory and VES (geophysical survey) was done to delineate the lithology and determine the apparent resistivities of identified strata. A positive relationship was established between cone resistance (CR) from geotechnical data and apparent resistivity (AR) values from geophysical survey and the following predictive quantitative relationships were obtained between the two variables: CR = 26.664 + 0.025AR. Hence VES can be employed in the absence of and/or in combination of the geotechnical for site investigation. The main causes of the four collapse incidents with their percentage contributions as revealed from the research are materials' inadequacy (36%); subsoil inadequacy (27%); foundation inadequacy (18%) and unprofessionalism (18%). The study establishes that use of substandard building materials and subsoil incompatibility are key causes of building failure in the zone.
Keywords: Building collapse, geotechnical, geophysical, subsoil, apparent resistivity.

1. INTRODUCTION

Building collapse remains an unconquered opponent in the contest for sustainable development. This is because the built industry is the most complex of all the industries in the economy and the basis of its complexity is founded on the simple fact that, all other industries and sectors of the socio-economy depend on it for the environment in which they operate. The industry is to all practical purpose an all-comers affair (Akindoyeni, 2002). The industry plays an important and dynamic role in the process of sustainable economic growth and development because provision of safe, secured and affordable homes are major contributors to sustainable development of any nation. Therefore, achieving a sustainable built industry contributes in no small measure to achieving major Sustainable Development Goals (SDGs).

A great number of definitions has been given to building collapse by professionals in construction fields. It is the failure of load-bearing structural elements, causing a building to fall or fail catastrophically

(catastrophic failure). An act of omission, occurrence, or performance. Progressive structural collapse is defined by the National Institute of Standards and Technology (NIST) as 'the spread of an initial local failure in a manner analogous to a chain reaction that leads to partial or total collapse of a building' (Ellingwood et al., 2007; Olagunju et al., 2013; Fakere et al., 2012)

In summary, building collapse can be defined as a sudden or progressive, total or partial failure of building component(s), leading to its inability to perform the primary functions of comfort, satisfaction, safety, and stability. Olusola et al., (2011) further explained that in a partial collapse only a portion of the building falls down; in a progressive failure there will be signs of weakness noticeable either by presence of cracks which widen with time or unusual sound in the building due to structural members gradually giving way from each other. In sudden collapse the building falls down suddenly as the name denotes, it may not even give any sign prior to falling down.

Many factors have been highlighted as causes of this global menace. Adebayo, (2000), stated that efficiency in skill and experience is important in creating valuable workmanship in building construction. He affirmed that unwillingness of the clients to pay for high quality materials and for expert professional services was as the main cause of building collapse incidences. In their own view, Ayinuola et al, (2004), pointed accusing fingers to all parties in the building industry, clients, architects, engineers, town planners in the local authorities and contractors stating that they have contributed to building failures in various ways. According to Madu, (2005), causes of building failure include factors such as omission, carelessness, use of deficient structural drawings, absence of proper supervision of projects, alteration of approved drawings, use of substandard materials, corruption in the Nigerian system, building without approved drawings and translocation of building plans to different sites. He equally identified natural occurrences such as earthquakes, tornadoes, flood as other causes of this menace.

The opinion of Hollis (2006) was that buildings fail not only because of how they are designed, but also because of how they were built and the management of a building during its life will also affect its life expectancy. He added that the greatest risk to a building may come when it is being upgraded to meet a new standard. Unless the quality of the building has been identified prior to that work, the risk of a major failure during that work cannot be avoided. Ukpata (2006) traced the causes of building failures to defects or deficiencies at design and construction stages, and unsafe actions of parties involved in building process starting from clients to building consultants, contractors and users.

Windapo and Rotimi (2012) listed structural failure, poor workmanship, carelessness, excessive loading, illegal conversion, hasty construction and obstruction of water course as some causes of building collapse. Aremu et al (2019) included absence of proper site and soil investigation among the causes they enumerated. They cautioned that the failure to determine suitability of the terrain and soil's bearing capacity, which influences foundation type spells danger.

Effects of Building Collapse range from loss of human lives through injury and disability, financial losses, damage of components and materials to loss of professional integrity [Ayedun et al. (2012), Boye (1995), Arayela and Adam (2001)].

Measures to mitigate building collapse menace have been in the research of many experts in construction profession such as Adebayo (2000), Oyebode et al. (2014), Akpokodje (2017), Akosile (2010), Olasunkanmi (2022), National Economy (2022) and Nwoyiri et al (2023). Some of their submissions are testing the integrity of all high-rise buildings, reliability checks on structural designs, identifying and prosecuting offenders, overhauling and restructuring relevant agencies and ministries, government's collaboration, enforcing laws and policies, site investigation or subsoil compatibility tests among others. This last remedy is very relevant to this research as less attention is often paid to the condition of the subsurface that bears the foundation. The need to understand and determine the load carrying capacity of these soils in order to recommend the appropriate foundation type for the structures as the basic geotechnical and civil engineering requirement before construction is grossly overlooked by many stakeholders in construction industry. The result of this error is persistent episodes of building failures with all its attendant grave consequences.

In recent times, the incessant incidents of building collapse in the country and particularly in Anambra State have generated numerous questions whose answers are yet to be completely filled. Notable among these collapse incidents are the practical sinking into the subsoil of multi-floor buildings in some parts of Anambra states. On the eleventh of September, 2019, an inhabited three-storey building at 22 Nkisi Aroli Street, Onitsha, was captured caving into the ground before the catastrophic shattering of the upper part of the superstructure.

Similarly on a visit to a site of collapse incident which took place on the 16th of September, 2019, only roofing sheets and rafters were observed on the surface while most parts of the superstructure were buried into the subsurface. The facility was a three-storey building at plastering stage located after the back gate of Nnamdi Azikiwe University, Ifite-Awka in Anambra State.

Furthermore, eye-witness accounts on the building collapse incident at Eke Oyibo market Amawbia which took place on 4th of July, 2024 testified that the building was seen sinking before the upper parts shattered.

This sinking style of building collapse in the state is worrisome and a pointer to subsurface incompatibility. Hence this work seeks to ascertain why collapse incidents are increasing in the State and why the buildings cascade vertically into the subsurface with focus on the north senatorial zone of the state.

Fig 1: Total Collapse of a 4-floor Building at Ezenwa Street Onitsha on 24/07/2018.

Fig. 2: Total Collapse of a 6-floor Building at Basdan Street, Fegge Onitsha on 10/03/2024.

2.0 STUDY AREA

The study areas include four (4) multi-floor building collapse sites that cut across three geologic formations in the north senatorial zone of Anambra state (see table 1).

Table 1: Study Areas in Parts of Anambra State

Site	Date of collapse	Location	Latitude	Longitude	Elevation	LGA	Geology	Geologic Formation
A	08/01/18	Opposite Otuocha local stadium Aguleri	N06° 20 19.5	E006° 50 25.2	36 m	Anambra East	Nanka sand	Ameki Formation
B	22/05/19	Ezenwa street by new mkt Rd Onitsha	N06° 09 06.4	E006° 46 51.3	47 m	Onitsha North	Coastal Plain Sand	Ogwashi-Asaba Formation
C	11/09/19	22 Nkisi Aroli Street, Onitsha	N06° 08 58.5	E006° 48 49.2	108 m	Onitsha North	Coastal Plain Sand	Ogwashi-Asaba Formation
D	June 2023	Plot No. 803A Amenyi Family Land, Nkwelle Ezunaka,	N06° 11 53.4	E006° 49 26.0	120 m	Oyi	Friable Sand	Nsugbe Formation

3.0 MATERIALS AND METHODS

The materials and tools employed in this research included handheld GPS device, standard shell and auger percussion rig, open tube and split spoon samplers, airtight bags, Dutch Cone Penetrometer, Earth Resistivity equipment, electrodes, cables and laboratory tools.

The methods employed are visual Inspection, boring, cone penetration test, foundation probe, laboratory testing and vertical electrical sounding (VES) and the progress of the investigations is summarized in the flow diagram in Fig 3.

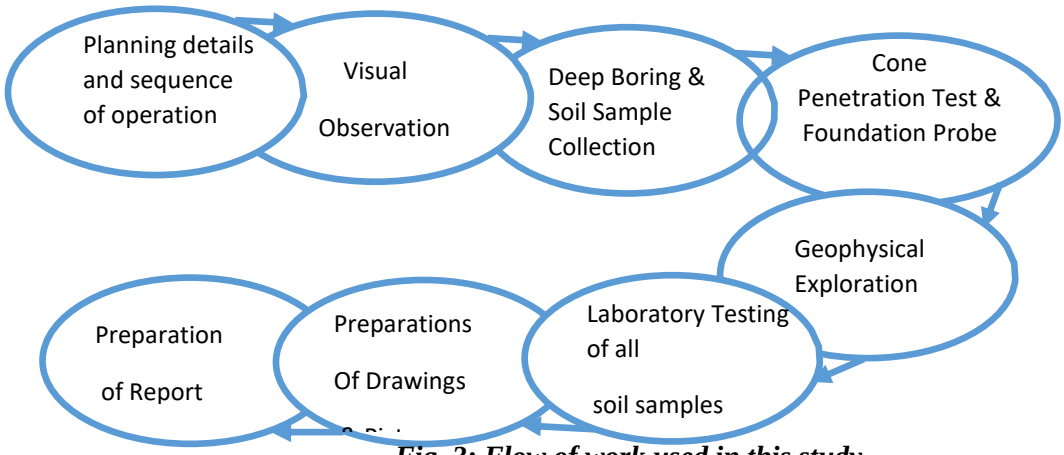

Fig. 3: Flow of work used in this study.

3.1 Planning Details and Sequence of Operations

Reconnaissance field visitations were made to each of the twelve building collapse sites in Anambra State with a view of getting preliminary knowledge of the sites mainly through visual inspection. It also provided insights into the financial demands of the tasks and adequate plans were made. Afterwards, machines and tools for the main investigations were mobilized to the sites. Geotechnical investigations preceded geophysical surveys.

3.2 Visual Observation

This was the first step taken in this study on all the investigated collapse sites and it allowed for the collection of valuable evidence and data. The conditions of the building were carefully observed to ascertain any visible damage to the foundation, walls, roof, and other structural elements. Cracks, bulges and other signs of distress were noted.

3.3 Borehole Drilling/Deep Boring and Soil Sample Collection

In this study, boreholes were made in the ground and varying soil samples collected. Boring helped in obtaining the extent of each stratum of soil, nature of stratum, engineering properties of soil and location of groundwater table. A total of eight (8) boreholes (BH) were drilled, two on each of the four (4) investigated sites.

These geotechnical boreholes were drilled using a standard shell and auger percussion rig. It was used to cut drill holes through the sandy and clayey strata. The borehole was lined with either 150 mm or 250 mm diameter steel drilling casings, utilizing the 250 mm diameter casings to a depth of 6 m before changing to the 150 mm diameter until the termination of the hole. The drilling tools consisted of an open-tube with a non-return flap valve at one end called a shell, for non-cohesive (sandy) strata, and mixed soils. A clay cutter is normally employed to drill through stiff cohesive soils. This is attached to the drilling weight called sinker-bar and subsequently attached to the drilling string. The borehole casings were turned down using chain grips, but in occasional cases, may be driven down using a special hammer.

During drilling operations, disturbed samples were regularly taken at depth interval of 0.75 m and whenever changes of soil type were observed. In cohesive soil strata, apart from the usual disturbed samples, relatively undisturbed soil samples were taken using the conventional open tube sampler by driving a 100 mm diameter sampler through a total of 450 mm length. All samples comprised those from

the split spoon sampler of the standard penetration test, and those from the cutting shoe of 100 mm diameter sampler. These samples were packed in airtight bags in order to retain their natural moisture content, and taken to laboratory for the needed tests.

3.4 Cone Penetration Test (CPT) and Foundation Probe

The Cone Penetration test (CPT) as one of the most effective means for investigation of soils in their natural state provided information on the type of soils and their stratification for load bearing purposes. CPT was carried out using 2.5 tonnes capacity Dutch Cone Penetrometer equipment which measured the resistance to penetration into soil layers. The sequence of layers was then interpreted from the variations of the cone end resistance with depth. The cone was pushed into the ground for 20 cm or 25 cm by means of attached winch system at a uniform rate of about 20 mm per second. The resistance to penetration of the cone registered on the pressure gauge connected to the pressure capsule was recorded on each borehole. The tube was then pushed down to the cone and the process described above was repeated. From the series of recorded pressure gauge readings, a plot of the cone resistance against depth was made for each borehole. This forms a resistance profile which indicated the strata sequences penetrated (see Fig.4).

Fig.4: Cone Penetration Test machine in operation at site B

Foundation probe was conducted by excavating the soil below the foundation depth on some of the sites to determine the adequacy and sizes of the building foundations with respect to possible foundation soil defects and to perform an analysis of the foundation system for its suitability for load bearing. Presence of rubbles and inaccessibility made it impossible to run probe on foundations of some investigated sites.

3.5 Schlumberger Electrode Array

The geophysical investigation was made with Earth Resistivity equipment, Geoprobe model 500 which is highly sensitive with a digital readout. The investigations were carried out at the untarred roads/spaces in front of or within sites of the collapsed buildings. The instrument has the ability of giving out direct resistances of the earth layers which when multiplied with their individual geometric factor gives apparent resistivity of different layers. The Vertical Electrical Sounding (VES) method was used to acquire the data using Schlumberger configuration. A field outlay of the operation is shown in Fig.5.

Fig. 5: Operational demonstration of equipment and field outlay for Schlumberger

3.6 Laboratory Testing

Laboratory investigations were carried out on the soil samples collected during deep boring at the collapsed building sites to ascertain the characteristics of the subsurface materials upon which the failed structures laid. The tests carried out on the borehole samples include particle size distribution, the Atterberg limit, natural moisture contents and triaxial compression tests with Bs 1377: Part 2: 1990 Soil Classification Test reference standard. An operational demonstration of some laboratory tests is shown in Fig.6.

Fig.6: Photo showing laboratory analysis of some soil samples.

3.7 Preparations of Drawings, Graphs and Photos

This involved collection and organization of data and presenting them in a readable form that would aid data analysis and interpretation. Most of the data collected in this research are presented in graphs, charts, photos and tables such as geoelectric sections, cone resistance and resistivity profiles.

3.8 Preparation of Report

The final stage involved interpretation and discussion of the findings of the research with necessary recommendations. Major findings were pointed out, adequately discussed and relevant recommendations made. To avoid ambiguity and falsehood relevant calculations in this research were carefully made and dully reported.

4.0 RESULTS

4.1 Visual Inspection Results

Summaries of the surfaces and rubbles of the investigated sites gotten from visual inspections are presented in table 2.

Table 2: Visual Inspection Results of Investigated Sites

Locations		Surface observations	Observations on Rubbles/Debris
Anambra North Senatorial Zone	Site A @ Aguleri	Relatively flat terrain with grasses	Local stones used. Inappropriately-sized columns and steel bars. 3floors built in less than 2 months.
	Site B @ Onitsha	Plain terrain. Busy area.	Local stones used.
	Site C @ Onitsha	Flat terrain	Predominant use of 12mm reinforcement bars and wrongly-spaced stirrup on reinforcement bars. Local stones used.
	Site D @ Nkwelle Ezunaka	Hilly & undulating terrain. Partially collapse building	Inappropriately -sized column. Poor connectivity of elements. Good type and quality of exposed rods. Concrete quality appears very weak, probably due to uncontrolled mix, using local stones. Generally, workmanship was poor.

4.2 Deep Boring Results

The subsoil strata encountered in the four (4) collapse sites are presented in Table 3 which originated from information recorded during drilling operations in the borehole (BH) logs.

Table 3: Subsoil Description of Investigated Sites

Site Designation	BH No	Top Stratum (m)	Base Stratum (m)	Description of Stratum	Thickness of Stratum (m)	Total Depth of BH(m)
Site A (Aguleri)	BH 1	0.0	0.4	Light brown topsoil	0.4	15
		0.4	15.0	Reddish brown lateritic clayey sand	14.6	
	BH 2	0.0	7.0	Reddish brown sand	7.0	15
		7.0	15.0	Reddish brown sand with gravel	8.0	
Site B (Onitsha)	BH 1	0.0	0.2	Top soil	0.2	
		0.2	3.5	Reddish Brown Lateritic Clayey sand with gravel	3.3	
		3.5	10.0	Reddish brown lateritic clayey sand	6.5	
	BH 2	0.0	6.5	Reddish Brown Lateritic Clayey sand	6.5	20.0
		6.5	20.0	Purple sand with traces of gravel	13.5	
Site C (Onitsha)	BH 1	0.0	5.0	Reddish brown sand	5.0	15.0
		5.0	6.5	Reddish brown lateritic clayey sand	1.5	
		6.5	15.0	Reddish brown sand with gravel	8.5	
	BH 2	0.0	4.0	Reddish brown sand	4.0	13.5
		4.0	8.0	Dark grey organic matter mixed with clayey silts	4.0	
		8.0	13.5	Brown sand with gravel	5.5	
Site D (Nkwelle Ezunaka)	BH 1	0.0	4.0	Reddish brown lateritic soil with lots of gravel	4.0	10
		4.0	10.0	Reddish brown lateritic sand	6.0	
	BH 2	0.0	4.0	Reddish brown lateritic sand with lots of gravel	4.0	10
		4.0	10.0	Reddish brown lateritic sand	6.0	

4.3 CONE PENETRATION TEST (CPT) RESULTS

The results of the CPT on the investigated building collapse sites are shown in Table 4.

Table 4: Results of Cone Penetration Test

Average Cone resistance (kg/cm^2)	Depth (m)																			
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00
Site A	20	20	20	25	25	30	30	30	30	30	30	30	35	35	35	35	40	40	45	45
Site B	20	20	20	25	30	35	40	45	45	45	50	50	50	50	50	55	55	55	60	60
Skte C	20	20	20	25	25	25	30	30	30	30	30	30	35	35	35	20	10	10	10	10
Site D	10	15	15	15	20	20	25	25	25	30	30	30	30	30	35	35	35	40	40	45

4.4 Allowable Bearing Pressure of Investigated Sites

Based on Cone Penetration Test (CPT) readings and the bearing capacity formula [Meyerhof: qa = 5 x Cu / 2.5 Where qa = allowable bearing pressure; Cu = undrained cohesion], the allowable bearing pressures by layers or respective depths for shallow foundations are calculated. These data are useful in recommending appropriate foundation designs (See Table 5).

Table 5: Allowable bearing pressure of investigated sites

Sites	Average Allowable Bearing Pressure (KN/m^2)							
	@0.5m	@1.0m	@1.5m	@2.0m	@2.5m	@3.0m	@3.5m	@4.0m
Site A	140	170	170	170	170	200	200	200
Site B	100	120	120	140	140	140	140	140
Site C	80	80	100	110	120	120	118	115
Site D	300	300	300	300	365	365	400	400

4.5 Foundation probe findings

Table 6 shows results of foundation probe carried out in some of the investigated building collapse sites.

Table 6: Foundation probe findings on the building collapse sites

S/N	Site	Foundation Probe Findings
1.	A @ Aguleri	Isolated column pad footings about 1.6m x 1.6m x 0.3m (Depth) each located at about 1.7m from the ground floor slab to foundation depth. The height of the substructure from natural ground level (NGL) to foundation depth is 1.3m. Isolated pad footings with strip foundation for the walls were adopted for the shallow foundation. Vertical wall heights are about 3.4m and 3.2m respectively for ground and first floor.
2.	B @ Onitsha	Inaccessible foundation
3.	C @ Onitsha	No wall footings were noticed supporting the wall section probed. Isolated pad footings with base 1.2m X 1.2m X 0.5m and depth of 1.5m. Foundation tie beams were not evident viewing from the upper layers.
4.	D @ Nkwelle Ezunaka	Probe of column foundation towards rear showed foundation to have been located almost at natural ground level. It measured about 1.2m x 1.2m x 0.4m, with column eccentricity of about 400mm. No settlement or soil movement. The height of the substructure measured 1.9m from ground floor slab level to the foundation depth. Upper Layer tie-beams seen at the foundation

4.6 Laboratory Test Results of Investigated Sites

The different types of laboratory tests done on soil samples collected from investigated sites and the results are presented in Tables 7.

Table 7: Laboratory Test Results of Investigated Sites

Properties/ Parameters	Site A	Site B		Site C	Site D
Natural Moisture Content (%)	11-19	17-29		14-20	18-24
Liquid Limit (%)	32-38	N0n-plastic	27-54	27-42	44-65
Plastic Limit (%)	19-21		12-29	15-18	21-28
Plasticity Index (%)	13-17		15-25	12-24	23-37
Silt Content (%)	38	-	34-84	25-43	29-62
Sand Content (%)	62	66-79	16-19	57-72	38-71
Gravel Content (%)	-	11-31	-	-	2
Particle Density (Mg/m^3)	2.63	2.60		2.6	2.63
Cohesion, C(KPa)	80.23	-	27	37.62	43.48
Angel of Internal Friction, θ (◦)	3.67	-	7	16.82	6.02
Coefficient of Consolidation, Cv (m^2/sec)	2.49×10^{-6}	1.66×10^{-6}		1.53×10^{-6}	1.41×10^{-6}
Coefficient of Volume Compressibility, Mv (m^2/MN)	0.215	0.07		0.13	0.19
Permeability Coefficient, K (m/sec)	2.75×10^{-10}	6.59×10^{-10}		2.94×10^{-10}	3.23×10^{-10}

4.7 Geophysical Data of the Sites

At site A (Aguleri), a total of 20 points were picked and the geoelectric section shows that the surveyed area has five (5) layers and is made up of dry sand at the surface, followed by clayey sand, dry sand, shale and water-saturated shaly sand (Fig. 7).

At site B (New market Road, Onitsha), a total of 15 spreads were picked and the geoelectric section shows that the surveyed area has four (4) layers and is made up of red earth at the surface, followed by dry sand, water-saturated sands and dry sand (Fig. 7).

At site C (Nkisi Aroli Street, Onitsha), a total of 16 spreads were picked and the geoelectric section shows that the surveyed area has five (5) layers and is made up of red earth at the surface, followed by lignite seam, dry sand, water-saturated sands and clay (Fig. 7).

At site D (Nkwelle Ezunaka), a total of 20 spreads were picked and the geo-electric section shows that the surveyed area has four (4) layers and is made up of lateritic ironstone at the surface, followed by dry sand, shale and water-saturated sand (Fig. 7).

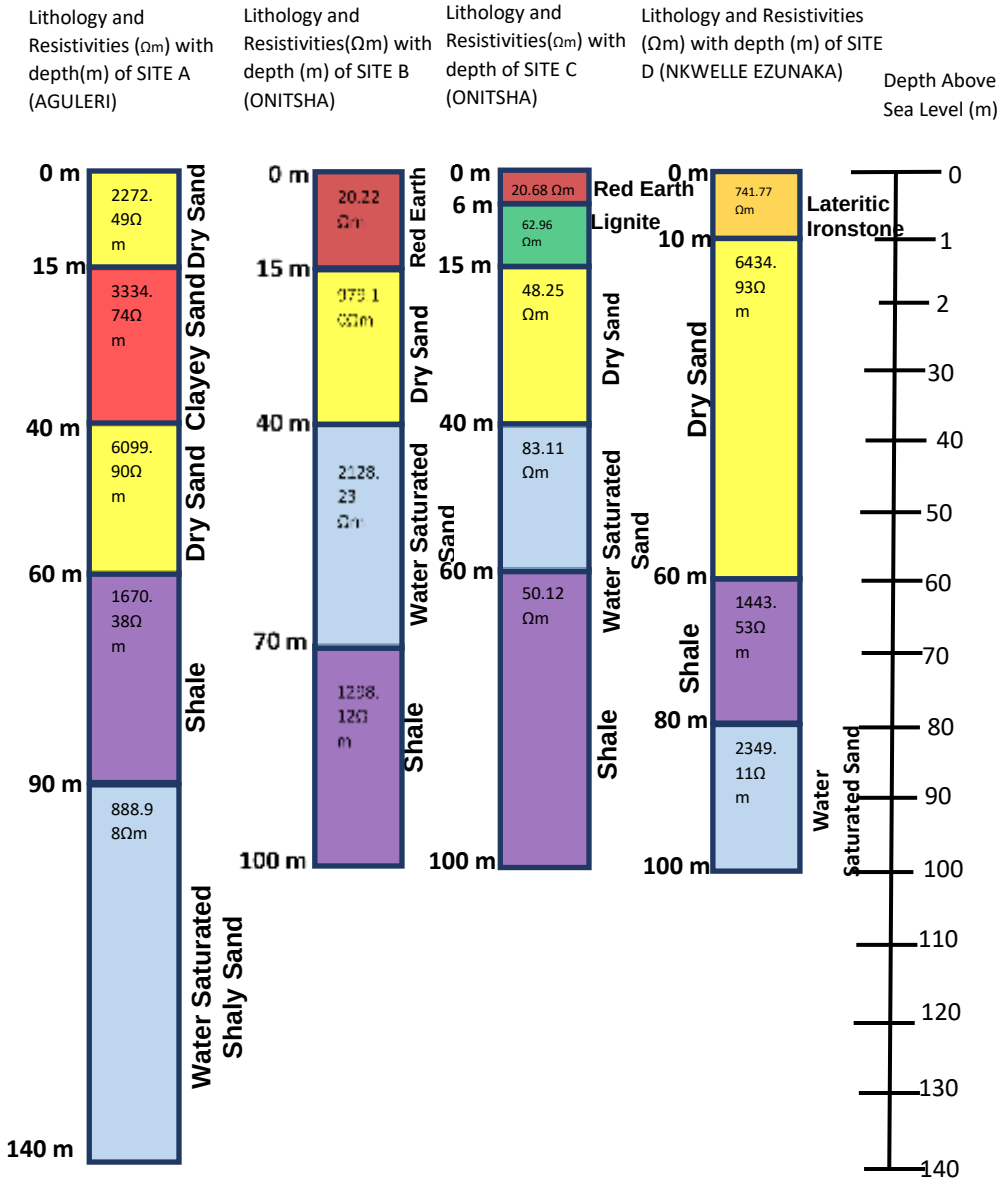

Fig 7: Geolectric sections of the surveyed sites

4.8 CORRELATION OF CONE RESISTANCE AND APPARENT RESISTIVITY

The mean values of cone resistance and apparent resistivity obtained from the four (4) surveyed sites are compared in Table 8.

Table 8: Data used in Correlation of Cone Resistance and Apparent Resistivity

Site	Average Cone resistance (kg/cm^2) @ various depths		Apparent Resistivity (Ωm) @ various depths	
	@2.0m	@4.0m	@2.0m	@4.0m
Site A	30	35	531.68	1326.91
Site B	45	55	20.54	24.3
Site C	30	20	32.26	14.12
Site D	25	35	129.41	397.57

In this study, the correlation analysis estimates the degree of the linear association between the cone resistance and apparent resistivity in all the investigated areas. The correlation in Anambra north senatorial zone is presented in Table 9.

Table 9: Correlation matrix showing relationship between cone resistance and apparent resistivity

	Cone Resistance (Kg/cm^2)	Apparent Resistivity (Ωm)
Cone Resistance (Kg/cm^2)	1	
Apparent Resistivity (Ωm)	0.981	
[p-value]	[0.019]	1
95% Confidence Interval (95%C.I.) = .356 to 1.000		

Result of the correlation estimate in Table 9 above indicates that there is a strong positive association between cone resistance and apparent resistivity ($r = 0.981$, $p=0.019<0.05$). That is to say, as the apparent resistivity of the soil increases, the cone resistance value also increases, and vice versa (Fig. 8).

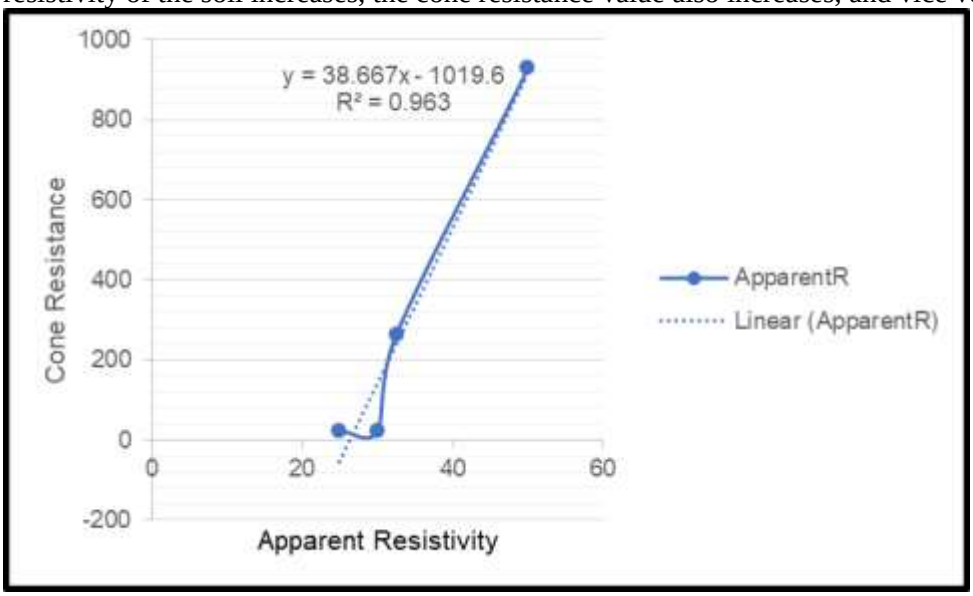

Fig. 8: Correlational graph of cone resistance and apparent resistivity

Generating the equation relating the cone resistance and apparent resistivity values in Anambra north senatorial zone, ordinary least squares regression analysis observing the curve estimation graphs was performed. The regression result is presented in Table 10.

Table 10: Regression result {Dependent variable cone resistance (Kg/cm^2)}

					95% C.I.	
Parameters estimated	*Coefficients*	*Std. Error*	*t-Stat*	*P-value*	*Lower*	*Upper*
Intercept (β_0)	26.66412	1.667406	15.99138	0.003888	19.48985	33.83838
Apparent Resistivity (Ωm)	0.024906	0.003451	7.218056	0.018658	0.01006	0.039752
R-Sq. = 0.963; Adj. R-Sq. = 0.945						

From the regression result it is established that

Cone resistance value (CR) = 26.664 + 0.025 Apparent Resistivity (AR)

The regression coefficient result shows that apparent resistivity work in direct proportionality with the cone resistance. In other words, increase in apparent resistivity will lead to increase in cone resistance. Particularly, a percentage appreciation in apparent resistivity will cause about 0.3% increase in cone resistance. The p-value statistics (p-value<0.05) confirmed that the increase or decrease from either cone resistance or apparent resistivity drives the other.

The R-Squared estimate (R^2 = 0.963%) provided that about 96.3% of the changes in cone resistance can be explained by apparent resistivity. This explanatory power of the model is very high, indicating that the model is a good one.

5.0 DISCUSSION OF RESULTS

From the research, some probable causes of building collapse of the four sites investigated within the zone are identified and pointed out in the following subsections. Attention is paid especially on subsoil compatibility with the imposed load.

5.1 Discussion of Findings from Site A at Aguleri, Anambra East LGA

The subsoil strata encountered at site A are reddish brown lateritic clayey sand, which indicates very stable bearing for the soil foundation. The top soil is light brown in colour and about 0.4 m thick. The site area is not prone to flooding which could weaken the foundation soil and cause differential settlement leading to building collapse. The cone resistance values are high and consistently increased with depth indicating an equivalent 170 KN/m^2 allowable soil bearing capacity at about 1.0 m depth from the ground level. Laboratory results reveal low to moderate moisture content and medium plasticity. The apparent resistivities of the subsurface strata were high confirming the stability of the soil foundation. Thus, it can be inferred that the soil investigated has a good bearing capacity and may not have been a probable cause of the collapse.

However, the building team confirmed that the 2-nos suspended concrete slabs were constructed in less than 2 months thereby subjecting the concrete slabs to less than the stipulated 28 day curing period for concrete. It was also observed from visual inspection that poor building materials (local stones as the coarse aggregate) and inappropriate steel bars were used. In addition, the foundation probe revealed inadequate foundation consideration in view of the potential for differential settlement due to seasonal variations in the water table. These could have affected the integrity of the 3-floor structure.

5.2 Discussion of Findings from Site B at Ezenwa Street, Onitsha, Onitsha North LGA

For site B, the subsoil strata encountered are primarily lateritic clayey sand interspersed with gravels. From the soil profile analysis, CPT and from the high apparent resistivity values, it could be inferred that the bearing capacity of the soil was adequate for the imposed 4-floor load. By implication, the subsoil upon which the superstructure was erected has a high bearing capacity but the substructure was not accessible in order to confirm its suitability with respect to the imposed 4-floor load.

Laboratory tests reveal that soil samples have low to medium moisture content with plasticity range from non-plastic to low plasticity. Non-plastic soils are more prone to settlement and instability and require deeper foundations to resist settlement and bearing capacity failure which can lead to structural damage and foundation failure

Therefore, use of poor construction materials as observed from visual inspection and poor foundation considerations could have contributed to the building collapse.

5.3 Discussion of Findings from Site C at Nkisi Aroli Street, Onitsha, Onitsha North LGA

The subsoil conditions encountered during drilling at site C were relatively good with high CPT readings which increased with the depth. The encountered subsoil comprises of lateritic clayey sand and gravel and this indicates a stable bearing capacity of about 100 KN/m2 at the foundation soil depth. It was however noted that the cone resistance values from this site started dropping from 4.0 m which corresponds to the presence the layer of organic matters mixed with clayey silty (from drilling), and a lignite seam (from geophysical survey). It is therefore inferred that the lignite layer over time got wetted, expanded and contracted and initiated an uneven settlement that ultimately led to the building collapse. The long-time effect of the activities within this layer could have resulted to the sinking and cascading vertical collapse of the building.

Laboratory tests reveal that moisture content of the soil samples ranged from 14 % to 20 % with low to medium plasticity range and plasticity index of 12 % to 24 %.

In addition, some construction errors such as predominant use of 12 mm reinforcement bars, local stone and wrongly-spaced stirrup on reinforcement bars were observed from the rubbles. The inadequately reinforced structural members could have failed to safely accommodate the transmittable loads of the

structure and this probably led to the loss of vertical load carrying capacity in critical building components leading to the collapse.

5.4 Discussion of Findings from Site D at Nkwelle Ezunaka, Oyi LGA

For site D, no groundwater was encountered at the foundation of the building, while the reddish-brown lateritic sand with lots of gravel as observed at the foundation depth during probe/drilling is adjudged to have good bearing capacity from the high CPT values. The test result for cone resistance indicates soil with allowable bearing capacity of about 300KN/m2 at the foundation depth which is considered adequate for a 3-floor building.

The lateritic ironstone recorded from geophysical survey also proves a stable foundation soil. The existing building foundations/column pad footings of 1.2 m x 1.2 m x 0.4 m as stated in the foundation probe findings is considered adequate for a 3-floor imposed load relative to the soil bearing resistance at the foundation depth.

Laboratory results reveal moderate moisture content and medium plasticity. Visual inspection indicates that the partially collapsed sections/floors of the building has been inadequately framed as evident in the lack of structural connectivity, non-existence/inadequacy of beam elements on some upper floors' interior structural grids and non-alignment of some columns on the ground floor with those on the upper floors of the building. The sectional collapse therefore is mainly as a result of failure of some columns on the first floor that were not properly aligned from the ground floor or properly provided for, in addition to lack of structural rigidity for the entire upper floors on that section of the building.

Therefore, the partial collapse is due to a combination of poor concrete strength of some structural members, inadequacy of building frame/connections and poor construction methods.

In summary, the investigations on all the four (4) sites of the collapsed structures through visual observations, in-situ tests, foundation probe, laboratory tests, geophysical surveys and relevant discussions, the following points are adjudged:

- All the investigated sites omitted preconstruction site investigation.
- All sites within the zone had relatively stable sandy layers (clayey sand, lateritic sand) with high cone resistance values which increased consistently with depth except at site C where the CPT values began to decrease from 4.0m which corresponded with the identified lignite seam.
- Cone resistance and allowable bearing capacity of the investigated sites within the senatorial zone are relatively high. This information could be used as a control for building sites around the investigated areas.
- Assessments from foundation probe indicate that foundation types and dimensions adopted for construction of some of the collapsed buildings were considered inadequate.
- Laboratory evaluations on soil samples pointed out the contribution of soil's characteristics to building failure. Non plastic and highly plastic soils are more prone to settlement and instability which can lead to structural damage and foundation failure. Similarly, soil samples with very low and very high moisture content would increase risk of instability. Medium or moderate plasticity and moisture content enhance stability, safety and durability.
- It was also noted that fine-grained, cohesive or plastic soils are prone to structural failures and collapse especially after saturation with water.

These points are collectively captured in Table 8.

Table 8: Summary of the probable causes of investigated collapse incidents

S/N	Identified Causes		Sites Affected	No. of sites	% Cumulative
1.	Related to Materials	Aggregates	A, B, C, D,		
2.		Steel bars	A, C		
3.					
4.		Concrete	A, D	4	36.4 (approx.:36)
5	Related to Nature of soil				
6		Low Resistivity	C		
7					
8		Lignite	C		
9.		Soil saturation by rain/Volume changes	B, C, D		
10.					
11		Non-plastic	B	3	27.3 (approx.:27)
12.	Foundation-related		A, B	2	18.2 (approx.:18)
13	Unprofessionalism		A, D	2	18.2 (approx.:18)
Total / Cumulative				11	100

- More importantly, geologically-conditioned predictive model for preconstruction and post-failure site investigation was developed in this study as follows: CR (Cone Resistance) = 26.664 + 0.025 AR (Apparent Resistivity). This relationship will be a guiding tool for builders within the zone in the state as regards preconstruction site investigations.

6.0 CONCLUSION

The research has achieved its objective of applying engineering geophysics techniques to investigate subsoils of some building collapse sites in Anambra State. With regards to lithology, a predictive model has been developed for the zone in the state.

There was no record of sinking-style type of building collapse in this zone of the state apparently because of the high cone resistance, resistivity and allowable bearing pressure of the subsoil as shown in the research results.

The main conclusion from the research is that preconstruction site investigation is vital to the success of any construction project and omitting it can lead to very large construction cost overruns. Hence subsoil compatibility checks must be mandated as a prerequisite before approval of any structure in the state. If site investigation is to be effective then it must be carried out in a systematic way, using techniques that are relevant, reliable and cost-effective. Therefore, geophysical and geotechnical explorations should both be employed for site investigations, while VES survey detects vertical variations in lithology and also give an idea of their bearing capacities, boreholes provide detailed information about the strata where they are sunk (which enhances better interpretation and correlation of the geophysical measurements) though they provide no information about the ground in between. However, it is pertinent to mention that in the absence of the cost-intensive geotechnical techniques, geophysical surveys are readily available and affordable for quick subsoil compatibility checks. Hence evasion of preconstruction site investigation on the basis of financial implications will be eliminated or greatly minimized.

Thus, the study has established a basic level of awareness and understanding that an appropriate combination of in-situ geotechnical and geophysical methods will yield a high standard of results especially in complex terrains and where detailed interpretation is required.

7.0 RECOMMENDATION

For sustainable structural development in Anambra State in focus and Nigeria as a whole, the following recommendations are deemed fit:

1. The government at all levels should also enforce subsoil investigation on all construction sites. This will ensure that the right foundation design is put on the right substructure.

2. For multi-floor buildings in the places underlain by construction-unfriendly soils such as silty clay or clayey silts, shale, lignite, and mudstones, foundation at shallow depth may be unsuitable. Special foundation design and engineering should be employed to ensure adequate support and stability.
3. The natural variability of the ground and groundwater conditions must be properly addressed for most construction projects. This will enhance both financial viability, and physical stability during construction and during the use of the building.
4. Facility managers and other building service consultants should create the awareness by informing top management of the importance of proper subsurface investigation before construction.
5. The government at all levels should also enforce subsurface investigation on all construction sites. This will ensure that the right foundation design is put on the right substructure.
6. The Nigerian Government should create the enabling environment by providing adequate funding for procurement of geotechnical and geophysical survey tools in relevant departments in tertiary institutions and incorporate the training as part of undergraduate and postgraduate learning experience
7. Professionals in the built industry globally should ensure that better building codes and standards that can be implemented in different countries are developed.
8. Organising of building collapse-related training programs, workshops and seminars for engineers, architects, builders and others in the built industry to improve their knowledge and skills.
9. Partnerships and cooperation among different organizations and countries to share information and best practices on building collapse prevention must be encouraged.

COMPETING INTERESTS

Authors herein declare that no competing interests exist.

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