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Need for Prior Geotechnical Engineering Studies for Foundation Design: Cases of Collapsed Buildings in Port Harcourt and Environs, Nigeria

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NEED FOR PRIOR GEOTECHNICAL ENGINEERING STUDIES FOR FOUNDATION DESIGN: CASES OF COLLAPSED BUILDINGS IN PORT HARCOURT AND ENVIRONS, NIGERIA

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ABSTRACT

Cases of collapsed buildings have been on the increase in the city of Port Harcourt and environs in Rivers State, in particular and other major cities in Nigeria in recent times. A critical evaluation of the modes of failures indicates that absence of and / or inadequate subsurface geotechnical investigations have been responsible for these building foundation failures. Case histories of four major building foundation failures within the municipality of Port Harcourt and environs in the southern Niger Delta sub-region of Nigeria in recent times are presented and discussed in this paper. The first case history involves a five-storey building that collapsed because it was constructed across a river channel that had sand and gravels as major subsurface materials beneath the building site. As a result of excessive increase in groundwater table during the rainy season and the attendant excessive pore water pressures build-up that led to a rapid loss of the bearing strength of the subsurface materials, it collapsed in the form of a "punching failure". The second case was a bearing capacity failure due to rapid construction that did not leave enough time for the dissipation of pore water pressures to allow the foundation soils gain shear strength. It collapsed soon after construction was completed. The third case failed as a result of lack of sufficient time to allow for curing of the block materials used for the building. This was a case of structural failure. The fourth case failed as a result of a complete lack of soil investigations that prevented a detailed foundation design for the residential buildings near the banks of a creek at Opobo town, a suburban settlement along a tidal creek. The paper presents and discusses in details the geology, hydrogeology and modes of failures of these four structures and draws attention to the need to carry out detailed subsurface investigations and abide within the building codes (if any).

INTRODUCTION

When the foundation materials upon which buildings are to be constructed are not put into consideration or thought not to be important, then one prepares to suffer the effect of eventual collapse of structures if the "conditions become right for the collapse" to occur. Port Harcourt and Opobo are situated within the Tropical Zone and in the southern-most section of the Nigerian Niger Delta sub-region (Figure 1). The Niger Delta is zoned into three, namely: Coastal, "Transition" or Mangrove and Freshwater zones (Teme, 1988).

The 'Transition' or Mangrove (Middle Delta) Zone coincides with the Mangrove brackish water zone with its numerous inter-tidal flats and mangrove vegetation interspersed with a preponderance of nippa palms (a recent development in this zone). Sub-soils here are characterized by a typical *fibrous, pervious clayey mud (that exhibits large values of compressibility and consolidation),* underlain by *silty sands which most often grade into poorly-graded sands and further downwards into well-graded sands and gravels.* The geotechnical engineer should determine the engineering properties of the sub-soils, their load bearing capacities, settlement potentials under imposed loads and the soil/water interfaces present at the proposed building site in order to provide adequately designed foundations to withstand anticipated differential settlements that may arise from the fluctuations of groundwater table and the attendant variations in the shear strength characteristics of the sub-soils.

Building foundations.

A successful sub-soil investigation provides the basis upon which decisions for foundation options are made because the building structures have direct contact with the soil and transmit the load of the structures to the ground. Depending on the soil properties encountered, any of the various foundation options could be chosen. Since any good geotechnical engineering design is to guide against failure, such should make use of the allowable bearing capacity *(q_a)* values by dividing the ultimate bearing capacity by a suitable factor of safety of the soil instead of using the soil's limiting shear resistance (ultimate bearing capacity), q_u. Such safe foundation designs provide for a suitable factor against shear failure of the soil and excessive settlement.

Types of foundation.

Foundation types are broadly divided into two - deep and shallow foundations based on soil properties and envisaged weight of the superstructure.

Shallow foundations. In cases where the foundation loads could be transmitted directed to a rock formation or other competent soil stratum few meters below surface, shallow foundations could be either spread footings, wall footings rafts etc. are used at depth ranges of between 1.0 meter to 2.5 meters (the 2.5 m involves cases where excavations are required to some depth). Residential, commercial, and even industrial structures of light to moderate loads have been constructed on shallow foundations.

Deep foundations, In cases where the strata within the upper layers of the soil have low bearing strength or are highly compressible, the foundation loads may have to be transferred to a competent layer at a greater depth by means of either piles or drilled piers, as the case may be.

Bearing Capacity of a foundation

The bearing capacity q_f of a foundation is the mean total stress on the surface of the underlying soil when the latter is on the point of collapse. It is a function of the foundation geometry, the soil weight, and the soil strength which will be assumed to be defined by the Mohr-Coulomb failure condition

$$\tau_f = c + \sigma \tan\varphi \qquad (1)$$

where τ_f is the shear strength, c is the cohesion, σ is the total normal stress, and φ is the angle of internal friction.

If the soil strength is defined in terms of effective stress, in the form $\tau_f = c'' + (\sigma_n\text{-}u) \tan \varphi'$, the same analytical methods may be used to compare the effective bearing capacity q_f which is the mean effective contact stress when the underlying soil is on the point of collapse.

Collapsed Buildings .

When the foundation materials upon which the buildings are to be constructed are not put into consideration or thought not to be important, then we prepare to eventually suffer the effect of eventual collapse if the "conditions become right for the collapse" to occur.

1.2 Architectural Practice

The initial concepts of any building project are usually carried out by the architect either as directed by the client or as conceived originally by the architect. Thus it is the architect that "dreams" about the original shape, size, configuration or esoteric esthetics of the proposed buildings before it is built. Soon after the architectural drawings are completed, the expected loads at the various points of the structure should be estimated and the document handed over to the geotechnical engineer who commences the soil investigations to determine the engineering properties of the sub-soils, their load bearing capacities, settlement potentials under loads and the soil/water interfaces present at the proposed project site.

Collapsed Buildings

From the fore-going initial discussion in the introductory section of this paper, one can easily see why buildings should collapse. When the foundation materials upon which the buildings are to be constructed are not put into consideration or thought not to be important, then we prepare to eventually suffer the effect of eventual collapse if the "conditions become right for the collapse" to occur.

Causes of Building Collapses

Some vital causative factors are attributable to the collapse of buildings. These include but not limited only to the following:

(i) Soil conditions,

(ii) Imposed load of the structure more than the bearing (load carrying) capacity of the soils upon which the buildings are erected.

(iii) environmental factors

Soil Conditions. There are two broad groups of soils namely (i) Cohesive soils and (ii) Non-Cohesive (or Cohesion-less) soils. The cohesion-less soils form better foundation materials and are less prone to building foundation failures except in the presence of highly saturated conditions in "quick" conditions. On the other hand, the cohesive soils when completely made up of clays with little or no friction (ie when $\phi \sim 0.00^o$) can easily not be supportive of building loads. Also, when either types of soils are completely flooded for a period of time, the shear strengths of the soils rapidly deteriorate and lose their capacity to support loads.

Imposed Load of the structure more than the bearing capacity of the soils upon which the buildings are erected. When the loads imposed on the foundation soils are much more than the bearing capability of the soils, there will be sinking of the building into the ground. This can be referred to as ***"punching"*** failures of buildings. Often times the buildings are initially bungalows or simple one-storey buildings put up when their owners were not very financially comfortable. With an increase in the financial fortunes of the owners, most times without proper advise or refusal to take appropriate advice, more floors are added to these bungalows and one-storey buildings thus significantly increasing the building loads. At a point when the imposed loads become excessive over the soil bearing capacities, building collapse occurs through any of the collapse mechanisms that will be discussed soon in this paper.

Environmental Factors. Flood plains and old river courses, for instance, are not ideal for placement of buildings. However, owing to the non-availability of suitable lands for building erection due to phenomenal increase in population in most parts of the urban centers, including Port Harcourt and environs, lots of people have resorted illegally to erecting unauthorized buildings on these flood plains and old (ancient) river courses. The results are severe and constant flooding which lead to a major reduction of the soil strengths beneath these buildings. These reduced soil strengths often become lower than the loads of the superstructures of the buildings and eventually lead to collapsed buildings. Also important factors that need to be considered when designing buildings are the environmental factors such as the location, size, slope and shape of the land upon which buildings are to be erected. All these contribute significantly towards the need for a properly engineered structure such as residential, commercial or even industrial building. All the above variables may lead to the phenomenon of *"collapsed buildings"* if proper subsurface site investigations are not carried out prior to the erection of the buildings.

Geotechnical characteristics of the sub-soils / foundations.

For a fairly detailed study of the subsurface of a proposed project site, *Tomlinson (1980)* has suggested the following characteristics required of a geotechnical study.
(i) General topography of the site as it affects foundations design and construction such as: surface configuration, adjacent property, presence of water courses, ponds, hedges, trees, rock outcrops etc.

(ii) Location of buried services such as electric power and telephone cables, water mains and sewers.

(iii) General geology of the project area with particular reference to the main geological formations / units.

(iv) Previous history and use of the site including information on any defects or failures of existing or former buildings attributable to foundation conditions,

(v) Any special features such as the possibility of earthquakes or climatic factors such as flooding, seasonal swelling and shrinkage or erosion,

(vi) The availability and quality of local constructional materials such as aggregates, building stones/sand and water for constructional purposes,

(vii) A detailed record of the soil and rock strata and ground water conditions within the zones affected by the foundation bearing pressures and construction operations, or any deeper strata affecting the site conditions in any way.

(viii) Results of laboratory tests on soils and rock samples appropriate to the particular foundation design or construction problems,

(ix) Results of chemical analyses on soil or ground water to determine possible deleterious effects on foundation structures

Foundation systems for designed architectural structures

Depending on the soil type(s) and strata and / or the imposed loads of the buildings (number of floors of building etc), the foundation may be either a shallow or a deep one.

Shallow vs Deep foundations. Shallow foundations are usually applicable to bungalows and other smaller structures such as single storey buildings that do not impose heavy loads on the foundation soils.

Shallow foundations. According to Terzaghi and Peck (1967), a shallow foundation is one which has a width equal to or greater than its depth; that is:

$$\boldsymbol{B \geq D_f} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (1)$$

Examples of shallow footing foundations are Strip footings and Rafts.

Deep foundations. According to Tomlinson (1980), deep foundations are those whose ratios of Depth – to Width are equal to or greater than 5; that is:

$$\boldsymbol{D/B > 5} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (2)$$

Deep foundations are usually needed where the soils at the normal foundation levels are not capable of supporting the structures
Examples of Deep foundations are Piled foundations; Caisson foundations etc.

CASES OF COLLAPSED BUILDINGS IN PORT HARCOURT AND ENVIRONS.

Causes of Collapsed Buildings

The causes of collapsed buildings are mainly due to: (i) Soil conditions, (ii) Imposed load of the structure more than the bearing (load carrying) capacity of the soils upon which the buildings are erected and (iii) environmental factors

These broad areas of the causes of building collapses can be conveniently put under two (2) sub-groups namely:
(a) Foundation failures and
(b) Structural failures

Foundation Failures. Foundation failures may take several forms such as: (i) Punch Failure, (ii) Bearing Capacity Failures and / or (iii) Overturning failures.

Punch Failures. Punch Failures occur when the subsurface soils (usually cohesion-less and granular materials) are so much saturated that the intact building structure "sinks" as it were nearly vertically into the ground without much heave around the structures. During the movement that follows such failures, sections of the superstructure of the building also collapses due to uneven distributions of loads as the building collapses. A case of this is the *Tombia Street Extension, GRA III Port Harcourt* which is discussed in this paper.

Bearing Capacity (heave) Failures. Bearing capacity failures occur usually when the bearing capacity of the soils at the foundation level is less than the imposed load on the soil. Such failures are usually followed by "heave" outside the buildings signifying the extrusion of soils from under the foundation levels.

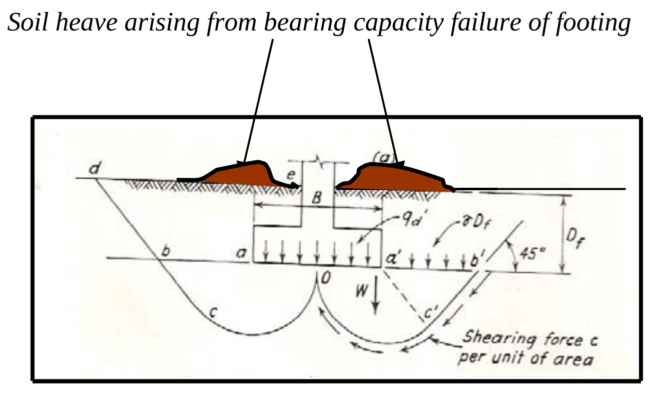

Figure 1: **Bearing Capacity failure arising from "heave"** *(adapted and modified from Peck, Hanson and Thornburn, 1974)*

The *Gross Ultimate Bearing Capacity* $q^{d'}$ of the soil beneath the foundation is given as:

$$q^{d'} = c\, N_c + \gamma\, D_f \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (3)$$

.where,

c = cohesion,
N_c = *Terzaghi Bearing Capacity factor for cohesion*
γ = *Unit weight of the soil*
D_f = *depth of foundation*

On the other hand, the *Net Ultimate Bearing Capacity* (q_d) which governs the failure of the foundation is given as:

$$q_d = q^{d'} - \gamma\, D_f = c\, N_c \quad \ldots \quad \ldots \quad \ldots \qquad (4)$$

Overturning Failures. Overturning failures are similar to the bearing capacity failures except that in Overturning failures, there is an un-even distribution of stresses which lead to one section of the foundation structure elevated above the other section.

Most cases of collapsed buildings tend to follow this trend due to the unequal distribution of stresses in any given building, especially in multi-storey buildings when the separate members of the buildings act independently as during building collapses.

Structural Failures. These failures have to do with the collapse of the super-structural members of the building and are mainly due to failures due to inadequacy of building material strength properties. The use of inferior or sub-standard materials for building constructions are mainly responsible for these categories of building collapses even when the foundations upon which these building are erected are certified to be very good. In recent times this type of failure has been found to become quite common owing to the use of sub-standard materials in buildings owing to the scarcity of funds due to the depressed economy.

CASES OF COLLAPSED BUILDINGS

Few select cases are hereunder presented to show the modes of foundation failures

Description Of The Failed Project Areas

The failed projects are located within the Tropical Zone and in the southern-most section of the Niger Delta sub-region of Nigeria, specifically at Port Harcourt and Opobo Town of Rivers State. Geographically, the project areas are situated approximately between Latitudes 04° 45' and 04° 20' North of the Equator and Longitudes 07° 15' and 07° 40' East of the Greenwich Meridian *(Fig.2)*.

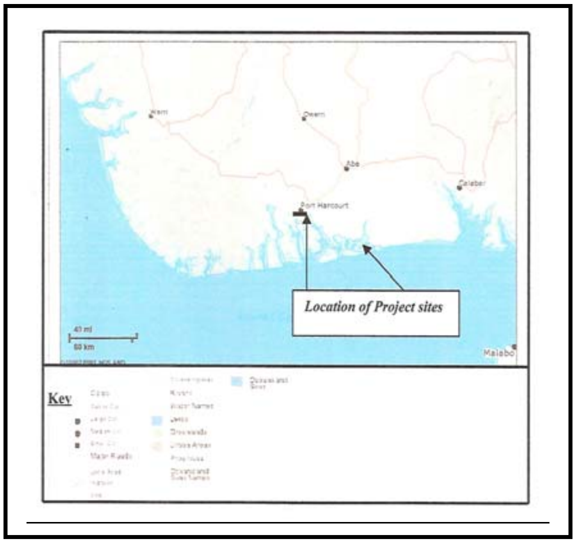

Fig. 2. Locations of the Project sites.

Subsurface Conditions. The Subsurface conditions at the project site were studied by sounding in the form of Standard Penetration Testing (SPT), with the aid of Shell-Percussion Rig *(Fig.3)* while retrieving soil samples at specific depth intervals of 1.50 meters for purposes of visual examination of soil samples, laboratory testing and classifications, as the case may be.

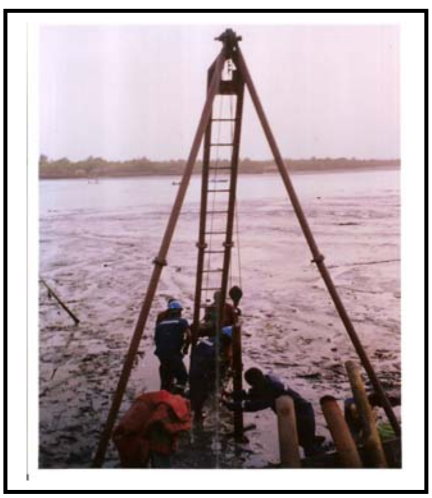

Fig. 3. Percussion Rig used adjacent to the Building Sites.

The bearing capabilities of the various soil horizons at the project site were assessed using the Standard Penetration Test data. This gave valuable information about the sub-surface characteristics at the project area.

Local Geology. The local geology of the project areas is basically that of the Coastal Plains Sands *(Qp)* of the lower Quaternary (Pliocene-Pleistocene) and Alluvium of upper Quaternary (Recent sediments). (Geological Map of Nigeria Series, 1984). The geological configuration of the project sites is given in *Fig.4 below*.

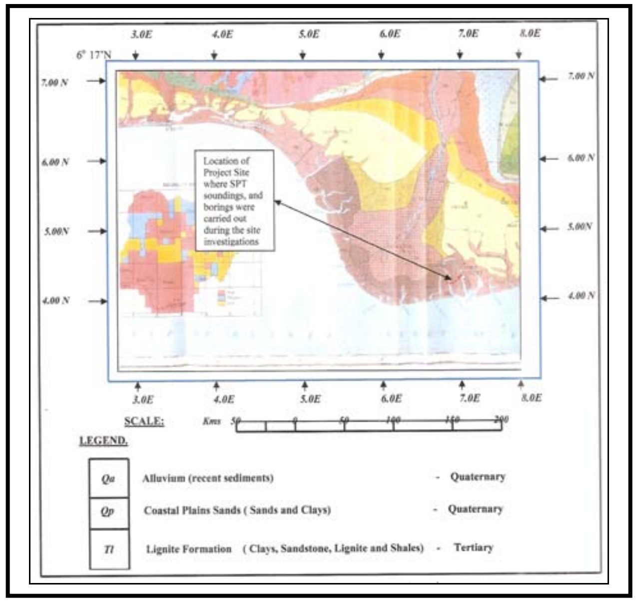

Fig. 4. The geological sequence at the project sites

Water Table. The Water Table at the site was observed to be variable due to the ebb and flow of the tides and found to be between *-0.40meters below ground level during low tide and +0.45 meters* above ground surface during the full tide.

The soil profile near the building is as shown in *Fig. 5*.

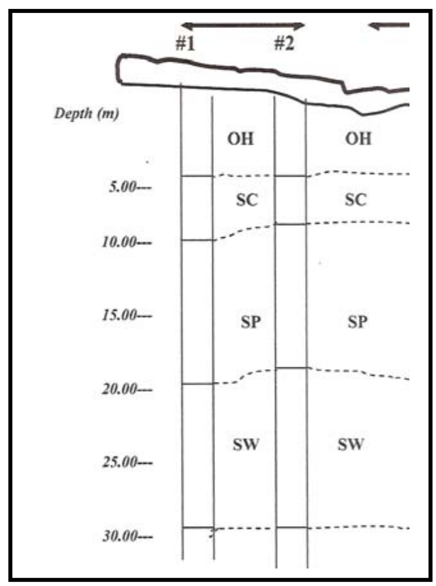

Fig. 5. Soil profile near the building site at Opobo.

(a) Building situated at New Tombia Street Extension, GRA Phase III, Port Harcourt

From investigations carried out by a team from the writer's consulting firm, it is apparent that this building was constructed across a river channel that had sand and gravels as major subsurface materials beneath the building site. Soon after the failure, a soil investigation carried out by the same team showed that the subsurface profile consisted of an upper layer of silty clays (lateritic layer); this was underlain by silty sands and further underlain by sandy gravels and gravels down to depths of over 20 meters. The construction of this building acted as a Dam across the old river channel and thereby accumulated large volumes of water upstream of the building. Meanwhile the water from the upper reaches of this old river / stream continued to flow and constituted a mini-lake upstream of this building whose foundations had constituted the ***"core"*** of the dam, as it were. The impact of this dammed water was to significantly reduce the shear strength (especially the friction angle (ϕ)) of the cohesion-less soils beneath the building. This scenario can be expressed mathematically as follows:

$$\tau = c + \sigma \tan \phi \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (5)$$

.where:

c = cohesion
τ = *shear strength*
σ = *normal stress (stress from the building on the soil strata)*
ϕ = *friction angle of the soil*

When the water pressure (μ) increases, equation (5) becomes:

$$\tau = c + (\sigma - \mu) \tan(\phi) \quad \ldots \quad \ldots \qquad (5a)$$

and as μ becomes large a time comes when it becomes equal or larger than the normal stress (σ) and the normal stress becomes zero, as shown in the expression below:

$$\tau = c + (\sigma - \sigma) \tan(\phi) = c + (0)\tan(\phi)$$
$$\tau = c \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (5b)$$

This is a clear case of Punching Failure.

Some pictorials of this collapsed building at New Tombia Street Extension are shown below as Figs. *6 a, b, c, and d*, respectively.

Fig. 6a: The collapsed building along the New Tombia Extension Road GRA III, Port Harcourt.

Fig. 6b: Remains of the collapsed building along the New Tombia Extension Road GRA III, Port Harcourt.

Fig. 6c: Remains of the collapsed building along the New Tombia Extension Road GRA III Port Harcourt.

Fig. 6e: Remains of the collapsed building along the New Tombia Extension Road GRA III, Port Harcourt..

Building situated along Abacha Road, GRA Phase II, Port Harcourt

From investigations carried out by us, it was apparent that this building collapsed as a result of bearing capacity failure due to rapid construction leaving not enough time for the dissipation of pore water pressures to allow the foundation soils gain shear strength. It collapsed during or soon after construction was completed. There is the need to allow time for the foundation soils to dissipate pore water pressures during construction by allowing a phased construction to take place, especially in recently reclaimed lands as well as in marginal lands near swamps. Other similar buildings that have been allowed to stand for a longer time during construction stand a better chance of not experiencing collapses. This property has since been fenced round by the owners to avoid photographs being taken.

Building situated opposite the High Court Complex, Old GRA, Port Harcourt

This building collapsed when construction was still on-going when suddenly it collapsed killing a number of workers and food sellers around the complex. The unique thing about this failure was that it occurred at night while the workers were still engaged in construction, contrary to building codes and regulations.
Upon examination of the foundation soon after construction, it was clearly observed that it was not a case of foundation failure but rather a case of structural failure due to the employment of very substandard building materials. For instance, the uniaxial compressive strength of the moulded blocks used for the construction was about 60 – 70% of the normal 28-day strength of moulded blocks. Also, examination of the steel materials used for the construction by a structural engineer showed that they were below the recommended standards.

Bearing Capacity Failure of a Two-Storey Building at Opobo Town

A land developer built for himself a two-storey building in the riverine town of Opobo within the "Transition" zone of the Niger Delta. This was a good example of bearing capacity failure where the building settled differentially similar to that of the legendry "Tower of Pisa" in Italy. Examples of this failure are shown in Figs.*7a,b,c and d* respectively.

Fig. 7a. Frontal view of the two-storey building leaning backwards.

REMEDIATION MEASURES FOR COLLAPSED BUILDINGS

Most of the studies in this area fall within the specialized area of Forensic engineering – a branch of geotechnical engineering that is fast gaining international and national recognition as observed in the proceedings of most modern day Conferences on Case Histories in Geotechnical engineering.

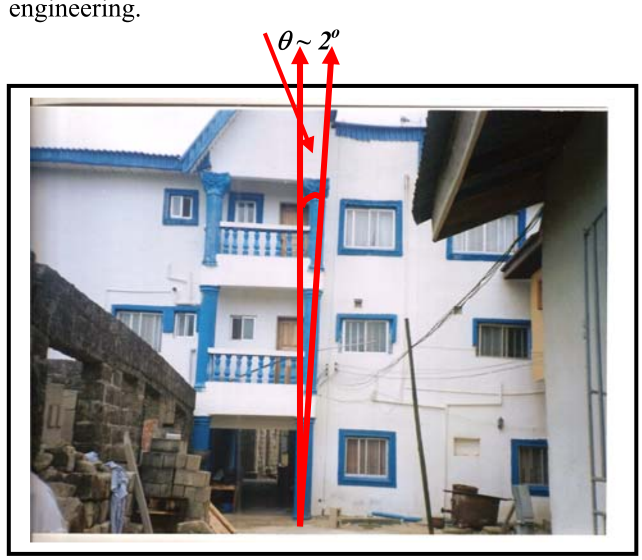

Fig. 7b. Another view of the same building leaning to the right at angle θ

Fig. 7c. A view of the house leaning on an adjacent building

Suggested Options

These options include the copious use of finite element analysis in finding out the causes and thereafter applying remedial measures such as the following:

(i) Appropriate foundations for designed buildings *[AFDB]*
(ii) Breakdown and Re-build with appropriate foundations [BRAF]
(iii) Underpinning

Appropriate foundations for designed buildings *[AFDB].* A sure way of avoiding re-current collapsed building syndrome is the application of Appropriate Foundations for Designed Building ***(AFDB).*** It is very necessary to carry out detailed Soil Investigations, studying the subsurface profiles, carrying out appropriate Laboratory tests on retrieved soil materials and based on the results of the laboratory tests, recommending, designing and constructing appropriate foundations for these buildings.

Breakdown and Re-build with Appropriate Foundations [BRAF]. After an event of Collapsed Building, the entire collapsed structure must be totally evacuated and a new foundation emplaced after another careful soil investigation must have been successfully carried out. In most cases, a new type of foundation is used to replace the one used before the failure occurred.

Underpinning. In cases where only a tilting (that is partial collapse) was observed prior to total collapse, the process of underpinning can be used to remedy the situation. The only draw-back in this application is the very high cost of underpinning. It is estimated to be about 10 times or more the cost of the foundation construction. However, if funds are available, it is an alternate option for the remediation of collapsed buildings.

CONCLUSIONS

It is obvious from the brief discussions above that cases of collapsed buildings occur as a result of lack of appropriate soil investigations to determine the bearing capacities of the foundation materials at site. It is also as a result of lack of any investigations at all. Often times also, the total loads applied to building superstructures are far above what the soils at the project sites can carry.

Lack of Environmental considerations such as flood plains, old river courses, waste dumps and other marginal lands (without appropriate soil investigations and appropriate foundations) are the main reasons for some of the causes of collapsed buildings. There must be a marriage between the designs of the architect and the foundation designs of the geotechnical engineer in order to forestall the rampant and incessant cases of collapsed buildings in our environment where the soils are not very suitable in most cases for the construction of heavy structures such as multi-storey and industrial buildings.

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