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Research Article

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Ground Variation, Geotechnical Uncertainties and Reliability of Foundation Design for Sustainable Building Infrastructures with Case Histories

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ABSTRACT
The foundation of any civil engineering structure serves to transfer the superstructure load to the ground without causing any uneven response, excessive settlement and movement. The choice and design of any foundation requires consideration for the load, subsoil type, mineralogy and variation; suitable bearing capacity, groundwater conditions, geological and stress history, tolerable settlement and understanding of the genesis and stratigraphy of the site. Uncertainties are signature characteristic of geotechnical paramterization and design. Application of reliability analysis is recommended for choosing the optimal design and construction materials and method.. Therefore a Geotechnical Consultant designate is required throughout the project life cycle to forestall collapse.

Keywords: Geotechnical and Geological Factors, Uncertainties, Reliability of Foundations

Introduction
Building projects are synonymous with urban planning, development of cities, construction of industrial facilities and associated infrastructure entailing opening of new grounds. Buildings and indeed all infrastructures are very important in any human society underscoring their designation as sustainable development goals 9 and 11 by the United Nations Agenda 2030 [1]. Implicit in the concept of sustainability of buildings and other infrastructures is resilience and enduring performance meeting the objectives of future generations. All buildings and other infrastructures are founded on or in the ground and the sub-structural elementsbears and transmits all the loads to the ground. The ground having been formed by endogenic (internal) geological processes such as plate tectonic movement which still persist, volcanism, magmatic crystallization and rock formation, metamorphism, seismicity, ground subsidence; and shaped by exogenic (external) processes within the framework of the geomorphic and hydrological cycles over the geologic time scale, leaves an inherent stress history on the geomaterials constituting the foundation of all infrastructures. The tectonic setting of any place also influences the stress and faulting regime, seismicity, surface geomorphology, tectonic ground subsidence, geohydrology; weathering processes, erosion, transportation and deposition which play a pivotal role in soil formation, chemical composition, strength, deformation, hydraulic and rheological behaviour of foundation subgrades. Thus, heterogeneity and anisotropy is inherent in the material composition of soils leading to vertical and lateral variation in the soil profile within the ground. These variations can range from less than a metre to kilometers, introducing a scaling factor in ground modeling and engineering design. Buildings are often always founded in soil which is a weathering product of the different types of rocks. These soils reflect the mineralogy and chemical composition of the parent rock from which the soil is derived and the stress history over the time past. Clay constitute the most abundant soil encountered in engineering construction and or excavation of the ground. However, clays are of different classes with their distinctive engineering behaviours. Gillot described the persistence of minerals on weathering, order of stability and the average chemical composition of clay [2]. Post depositional diagenetic reactions also introduce alterations in the clays. A typical weathering product of the sodic plagioclase, Albite and the Feldspathoid Nepheline results in the formation of Na-montmorillonite clay, the most problematic clay soil in the foundation of civil engineering structures. Na-montmorillonite is a 2:1 clay with a very weak (vander waal) interlayer hydrogen bond that bequeath to it very high geotechnical properties range such as liquid limit (100-900%), plastic limit (50-100%), shrinkage (8.5-15%) and activity (1-7) reported by Mitchell [3]. The bond's interlayer spacing is highly amenable to water absorption, expansion and swelling upon wetting; and shrinkage when dry. The need for evaluation of the behavior of ideal minerals and the aggregate behavior of clay materials in soils for civil engineering projects has been recognized by Reddi and Inyang, Reeves et al. and Murthy [4-6]. Soft, organic and weak

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ground conditions also dominate most grounds especially in coastal areas due to incomplete, anaerobic microbial degradation of plant and animal remains in waterlogged areas under shallow water, alluvial, estuarine and deltaic environments [7,8]. Geotechnically, problematic foundation ground conditions include metastable soils (collapsible and expansive soils), liquefiable ground, landfill sites, reclaimed ground, slopes and their inherent instability and sliding potential; seismically prone zones, dilatant soils and kinematically unstable rock masses underlying a structure. Foundations add load to the ground which can settle; excavations remove load and the ground heaves. Man-made slopes should remain stable but may need support from retaining walls. Dam slopes must remain stable and the dam must retain water. Road pavements are made from soil and rock underlining the need for application of sustainable geotechnical practices for construction on and in the ground using natural soils and rocks [9]. In geotechnics, sustainability translate into robust design and construction, involving minimal financial burden and inconveniences, minimal use of resources and energy in planning, design, construction and maintenance of geotechnical facilities and the use materials and methods. The foundation of any civil engineering structure serves to transfer the superstructure load to the ground without causing uneven response and excessive movements[10]. Its design requires knowledge of the geological conditions under the structure and characterization of stress related behaviour of the soil/rock. The choice of any type of foundation must consider the superstructure load, subsoil conditions, tolerable settlement, thorough understanding of the geological factors including soil type and origin, stratification and groundwater conditions [11]. The ability of any foundation to support the superstructure load and resist failure depends on the (1) material composition of the ground (soil and or rock), (2) ground water table and (3) depth of suitable materials to support the proposed design load and resist the stresses. The design of building foundations is concerned with both the ability of the soil to support the load and the structural design of the sub-structural element which transmits the load onto the ground. Design must ensure that the probability of failure is kept at the barest minimum or an acceptably low value under ultimate limit state condition (bearing capacity) and satisfactory serviceability (settlement) behaviour guaranteed. Research has shown that buildings with heights of 828m (the Burj Khalifa in Dubai) and 1000m (the Kingdom Tower, Jeddah, Saudi Arabia have been constructed and evidently performing and standing the test of time [12]. In spite of these, building collapse has assumed phenomenally unprecedented dimension in Nigeria especially in the coastal commercial nerve centre, Lagos where it occurs at a rate of 2-3 in a month during the wet season in recent times. Studies by Ebehikalu and Dawam revealed that one hundred and forty (140) collapse of buildings were recorded between 1974 and 2012 [13]. Over seven hundred and ninety-eight (798) lives were lost during the period with 54.17% of the reported cases of collapsed buildings being residential buildings. The locational distribution of the collapsed building shows a high prevalence in Lagos, Port Harcourt and Abuja. Olagunji et al. noted that Nigeria like many other countries is witnessing building collapse at alarming rate. Aghamelu et al. investigated thegeotechnical properties of structural failures of building projects in parts of Awka, Southeastern Nigeria [14,15]. Most buildings in Nigeria and less developed nations are designed and supported by shallow foundation due to economic reasons. In the design of shallow foundations, the allowable soil pressures for the foundation soil types is determined at the footing level for the proposed foundation. The design method ignores many important factors affecting the behavior of a foundation hence excessive settlements and failures frequently occurred. Lutenegger and DeGroot observed that shallow footings provide a much more economical system, and can result in substantial cost savings for a project [16]. Unfortunately, the uncertainty involved in the estimation of settlement of shallow footings on granular soil deposits, e.g., silt, sand and gravel, etc. and the deformation and rheological characteristics of clays and organic soils presents a monumental problem to the geotechnical engineer and engineering geologist. The deformation behavior of shallow foundations deriving their support from primarily granular particulate soil deposits such as sands and gravels controls the final design of structures resting on these materials. This is due largely to the fact that the ultimate limit equilibrium behavior, i.e., the bearing capacity of shallow foundations resting on granular deposits is typically of such a large magnitude, that the allowable settlement criteria will control the overall design. Provided that settlements can be accurately estimated against tolerable limits, a shallow foundation would provide a more economical foundation than either driven or drilled deep foundations. Inadequate foundations have been observed to constitute the major cause of structural failure of buildings [17]. Identification of problem soils such as metastable soils amenable to large volume change and settlement upon saturation, liquefiable slopes, seismically prone areas, reinforced soils and foundation under water is of prima facie consideration to prevent foundation failures and building collapse. Moreso, since the behavior of the substructure depends on the characteristics of the supporting soil as well as the possible structural influence of the superstructure, the engineer should consider the structure, the foundation and the supporting soil as a whole rather than as independent elements [17]. On the role of geology, Terzaghi observed that many problems of structural engineering can be solved solely on the basis of information contained in textbooks, and the designer can start using this information as soon as he has formulated his problem [18]. By contrast, in applied soil mechanics a large amount of original brain work has to be performed before the procedures described in the textbooks can safely be used. If the engineer in charge of earthwork design does not have the required geological training, imagination, and common sense, his knowledge of soil mechanics may do more harm than good. Instead of using soil mechanics he will abuse it. Ter-Stepanian also adducedthat considerable schematization of geological structure was needed for applying soil mechanics solutions, limited by a number of simplifying assumptions and using mathematical methods; therefore, the obtained results, in case of complicated geological and hydrogeological conditions, were far from reality [19]. Engineering geological factorsconstituting limit state design considerations include dipping beds, underground rock structure such as faults, fractures and fissures, interbedded soft and hard soil and rock strata, solution cavities, presence of shrinkage and swelling clays, organic soils, loess materials, adequate bearing strata, weight of the soil and water, earth pressure, fresh water pressure, kinematic feasibility of rock blocks; environmental factors such earthquakes, subsidence and climate. Others are interference with construction loads and actions, load removal, ground excavation and traffic loads [21]. The limit state condition for foundation footings include loss of overall stability, bearing resistance failure, failure by sliding, combined failure in ground and in the structure, structural failure due to foundation movement, excessive settlement, excessive heave due to swelling and unacceptable vibrations all of which must be considered in selecting the foundation of a structure. Geotechnical engineers involved in the design of foundations for buildings and other infrastructure in very soft and unstable ground conditions, where complex foundation solutions may be needed are leaving behind empirical methods and are employing state-of-the art methods increasingly [12]. Uncertainties in the gotechnical design parameters which may be epistemic due to lack of knowledge of subsurface ground conditions and or aleatoric due to randomness in testing locations within a site, equipment and methods of investigations must be accounted for if the reliability of the substructure design must be guaranteed. This paper is aimed underlining the importance of incorporating the multiciplicity of different ground conditions in the choice of the foundation type, design and construction of sustainable building infrastructure in Nigeria.

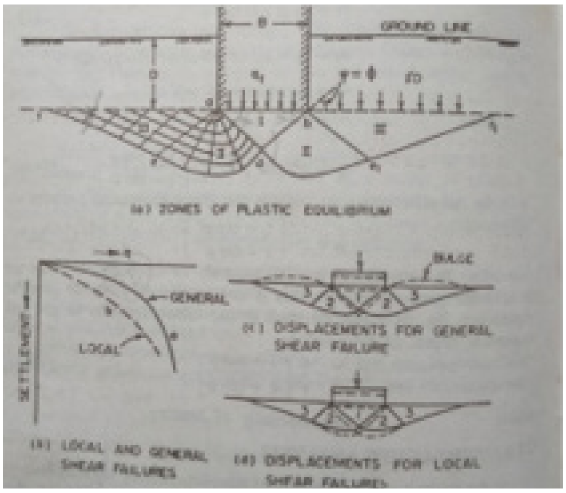


Figure 1: Terzaghi's analysis of foundation failure

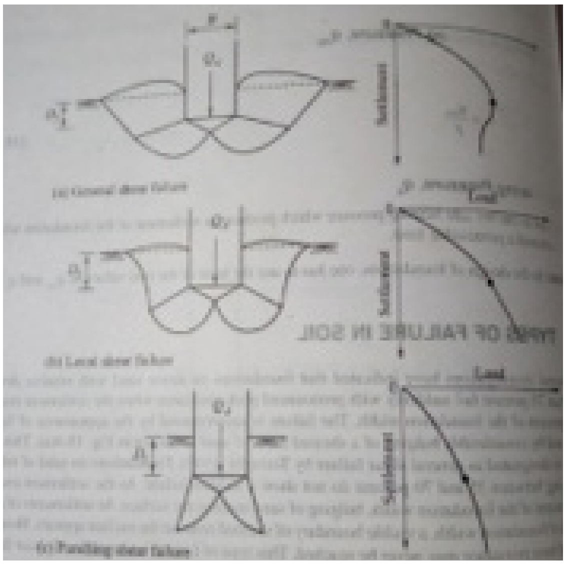


Figure 2: Modes of bearing capacity failure

Figure 3: The Leaning Tower of Pisa, Italy [21]

Ground Conditions and Mechanisms of Foundation Failure

Generally, foundation failure occurs in two modes: bearing capacity and Settlement failures. The intensity of ground loading which can cause shear failure of the soil is directly linked to material composition, groundwater condition, strength and deformation of the foundation subgrade. Terzaghi, proclaimed that most of the foundation failures that occurred were no longer "acts of God [22]. Bearing capacity failure has been reported in the Transcona elevator failure in which a homogeneous soil profile was assumed in spite of the site specific disparity underscoring the assertion by Fellenius that before a foundation design can be undertaken, the associated soil profile must be established [23,24]. Soils and rocks behave differently from synthetic matrials. Their strength is a measure of their ability to withstand external load which can cause internal stresses to develop within the soil and or rock mass. These external loads can cause them to fail under different conditions of stresses such as shear, compression, tension, bending or torsion. Figure 1 presentsTerzaghi's analysis of foundation failure depicting two soil elements: I immediately beneath the footing and II just beyond the edge of the footing and adjacent to element (I). Increasing the load on the footing to a value q, results in a state of plastic equilibrium and shear failure of the soil element under the footing and resulting in failure of element II by lateral thrust from element I.

General Shear Failure

Terzaghi recognized general shear failure in dense sands with relative density > 70% with pronounced peak resistance when the settlement reaches 7% times the width of the foundation [18]. General shear failure is accompanied by appearance of failure surfaces and by considerable bulging of a sheared mass of sand (Figure 2). Assumption is that soil behaves as an ideal plastic material. Rankine and Terzaghi (shallow foundation) show that failure of the soil under a footing causes radial failure of adjacent soil by lateral thrusting. Terzaghi analysis of foundation failure recognized a zone of elastic equilibrium under the footing adjoined by zones of radial and linear shear. Failure under the footing extends beyond these zones through lateral thrust which was also observed by Rankine. Meyerhof, extended the theory to deep foundations where plastic equilibrium or shear failure in the shear zones can be established from boundary conditions starting from the shaft of the deep foundation [25].

Local Shear Failure

Foundations in sand with relative density 35% < Dr <70% do not show sudden failure. Failure starts when settlement exceeds 8% times the foundation width causing bulging of sand that starts at the surface. Full failure indicated by visible boundaries of sheared zones occurs when settlement is at about 15% of the foundation width and the peak base resistance may never be reached in a local shear failure.

Punching Shear Failure

Punching shear failure occurs in foundations on relatively loose sand with relative density <35% when the rate of settlement increases and reaches a maximum value at about 15% - 20% of the foundation width and footing sink into the sand without bulging of the sand surface. It also occurs on sils of high compressibility and in such a failure, there is vertical shear around the foundation footing, perimeter and coptression of the soil immediately under the footing while soils on the sides of the footing remain practically uninvolved. During settlement, sudden jerks or shears can be observed as soon as settlement reaches 6-8% of the foundation with. Punching shear (Figuer 3) also occurs in soft compressible clays and organic soils [18,22].

Variable Ground Condition and Eccentric Loading of Building Foundations

Tijani and Abija noted that variable grounds under a building, can cause some foundation footings to rest on firm soil while some others can be founded on weak and highly compressible ground [8]. This is exemplified by the leaning tower of Pisa (Figure 3) in Italy which has tilted due to shear failure of the foundation soil under some footings as a result variable ground condition under the substructure. Variable soil stratigraphy causes settlement of some footings while some other remain at the initial foundation depth. This results in change in the load transfer mechanism from the designed axial to eccentric loading condition due to change in the centroid of the building forcing the load to act outside the centre of gravity of the foundation footing. When the load is is eccentrically placed on the foundation base, the pressure is not uniformly spread but varies from maxiimum at the end nearer the centre of gravity of the load to minimum at the opposite end and some parts of the foundation may experience zero bearing capacityfor large eccentricity causing bearing capacity failure [26]. This change in the loading mehanism of a building causes the foundation of a structure to experience moments in addition to the vertical compressive load, tensile stresses, bending action and lateral loads making members to behave as both column and beam. In addition, soils cannot take tensile stresses; therefore, the substructure becomes separated from the underlying bearing ground. The maximum eccentricity allowed for a structure is one-sixth (1/6) of the foundation width, therefore for any building's eccentricity greater than B/6, the minimum pressure distribution will be negative generating tension in the foundation soil. This foundation failure phenomenon is also accompanied by diferential settlement of the superstructure and collapse of the building.

Mechanisms of Foundation Failure in Rocks

Foundation instability and failure is cause by direct application of load and creation of new slip surfaces along the rock structure or from movement of the pre-existing discontinuities [27-29]. The rock structure interaction at the foundation bearing the load, discrete rock blocks, associated forces and stress distributions, kinematic instability mechanisms whether planar, wedge, and different toppling, moveable blocks beneath the foundation loading region and groundwater flow through the rock structure are pre-requisite geotechnical design considerations for design of sustainable building infrastructures. The prognosis for foundation failure involve investigation of modes of failure and kinematic admissibility test using field structural and engineering geologic attitude and geometrical attributes field data. Post field data analysis is carried employing lower hemisphere stereographic projection and rock mechanics analysis.

Prognosis for Foundation Failure in Soil

Though it is difficult, Punmia et al. a geotechnical investigation should identify the limiting conditions for which shear failure of the bearing capacity (general and local or punching shear) at a site can occur, the following points can be used as a guide [30].

(a). Stress-Strain Test (C- φ)
General shear - < 5% strain
Local shear - Stress-strain curve continues

(b). Angle of shear resistance
General shear - $\varphi > 360$
Local shear - $\varphi < 280$

(c). SPT
General shear failure - $N \geq 30$
Local hear failure - $N \leq 5$

(d). Density Index
General shear failure - ID > 70
Local hear failure - ID < 20

(e). Plate Load Test

The shape of the load settlement curve determines whether general or local shear failure.

- For Purely cohesive soil, local shear failure criteria are as follows: UCS ≤ 100kN/m^2 or Cu ≤ 50kN/ m^{2-}soft-medium.

Foundation Subsoil Exploration and Site Characterization

Geotechnical characterization derives the information for geotechnical models based on prima facie consideration of all geological factors. Day noted that without adequate and meaningful data from a site investigation, the engineering analysis is doubtful and leding to error [31]. The risks associated with minimizing investment in ground investigation and site characterization such as (1) certainty or uncertainty of ground subsurface conditions, (2) design risks due to inadequate subsurface information compromising the design decision, (3) potential for changed ground conditions during construction, (4) performance risks were recognized by McNeilan and Smith [32]. Methods involves preliminary desk review, field reconnaissance andfield geophysical techniques helps in identifying the stratigraphic succession of the soil profile at the site prior to geotechnical boring which must be appropriately spaced and depth of investigation chosen based on load or total height of the building.Localized anomalies in the ground profile such as cavities, sinkholes or pockets of softer or harder material, consolidation state of the clays, state of densification of the sand layers, bedrock levels and bedrock structure must be identified and their shear strength, consolidataion and other engineering properties predicted; ground slope and susceptibility to instability and sliding potential, presence of of metastable and liquefiable soils, etc. and provision of quantitative measurements for the shear wave and compression wave velocities Hoek submitted that the scope of a site investigations should be based on the engineering objective which is applicable to design in soil or rock [33]. Due to vertical straitification and lateral compositional changes which can occur at metre intervals bequeathing to the geomaterials inherent characteristic heterogeneity, anisotropy, elasticity and deformation behaviour, Das and Subhan observed that engineering geological and or geotechnical investigation is carried out to establish such changes within a site and characterize the engineering properties of each material layer taking into consideration the project scope and objective [34]. This information can be used to estimate the in situ values of soil stiffness at small strains and hence to provide a basis for quantifying the deformation properties of the soil.

Poulosobserved that contemporary foundation engineering systems incorporate both piles and a raft, it is therefore required to assess the ultimate skin friction for piles in the various strata along the pile, ultimate end bearing resistance for the founding stratum, ultimate lateral pile-soil pressure for the various strata along the piles, the ultimate and allowable bearing capacity of the raft, the stiffness of the soil strata supporting the piles, in the vertical direction, the stiffness of the soil strata supporting the piles, in the horizontal direction and the stiffness of the soil strata supporting the raft upon which foundation design is based [12].

Use of Geophysical Methods

Geophysical techniques offer a useful tool in probing into the subsurface and for engineering applications, its required to probe to depths that will exposed the geologic units, active fault, presence of dilatant and liquefiable soil and groundwater conditions that could affect stability, liquefaction and sliding of the soil and or rock mass beneath a site. After site reconnaissance, resistivity, ground penetrating radar and seismic refraction surveys should be first carried and results interpreted to delineate the vertical successtion of the soil layers at the site. In this regard, combining electrical tomography and vertical electrical sounding and ground penetrating radar has proven to be very advantageous in understanding of the subsurface lithologic profile and the approximate layer thicknesses underlying a site. The interpretation will also guide in choosing the boring and test points since the entire foundation area cannot be investigaed. Seismic refraction survey can also complement the interpretation while borehole seismics and vane shear test have also proven usefule in determination of elastic behaviour especially for predicting dynamic properties of the subsurface layers. Results of the geophysical investigations are presented as geological ground models and cross section and for design applications, model validation with static test results of samples taken from the exact depths must be carried out.

Geotechnical Boring

Since engineering design is based on statically determined strength, deformation and rheological properties of the geomaterials, it is important to derive samples for laboratory analysis. Geotechnical boring with boreholes appropriately spaced and significant depth of investigation probed and representative soil samples collected at the recommended depth. Both disturbed and undisturbed soil samples are taken from the borehole reference depth. Undisturbed soil samples are preferred for determination of strength and deformation behaviour of the subgrades. Disturbed samples are useful for identification and index chracrteristics testing which all must be standardized in accordance with the codes of practice.

In situ Testing

In situ tests have proven higher reliability since the state of densification is not disturbed at the test point. The standard penetration tests (SPT) is conducted in at every required depth usually in sand. Recent applications indicates the test being suitable for clayey soils also. In the field method,

- The borehole is advanced to the required depth and the bottom cleaned.
- The split-spoon sampler, attached to standard drill rods of required length is lowered into the borehole and rested at the bottom.
- The split-spoon sampler is driven into the soil for a distance of 450mm by blows of a drop hammer (monkey) of 65 kg falling vertically and freely from a height of 750 mm. The number of blows required to penetrate every 150 mm is recorded while driving the sampler. The number of blows required for the last 300 mm of penetration is added together and recorded as the N value at that particular depth of the borehole. The number of blows required to effect the first 150mm of penetration, called the seating drive, is disregarded.

The split-spoon sampler is then withdrawn and is detached from the drill rods. The split-barrel is disconnected from the cutting shoe and the coupling. The soil sample collected inside the split barrel is carefully collected so as to preserve the natural moisture content and transported to the laboratory for tests. Sometimes, a thin liner is inserted within the split-barrel so that at the end of the SPT, the liner containing the soil sample is sealed with molten wax at both its ends before it is taken away to the laboratory. The SPT is carried out at every 0.75 m vertical intervals in a borehole. This can be increased to 1.50 m if the depth of borehole is large. Due to the presence of boulders or rocks, it may not be possible to drive the sampler to a distance of 450 mm. In such a case, the N value can be recorded for the first 300 mm penetration. The boring log shows refusal and the test is halted if

- 50 blows are required for any 150mm penetration
- 100 blows are required for 300m penetration
- 10 successive blows produce no advance.

SPT Data Corrections

- **Overburden**

Several investigators have found that the penetration resistance or the N value in a granular soil is influenced by the overburden pressure. Of two granular soils possessing the same relative density but having different confining pressures, the one with a

higher confining pressure gives a higher N value. Since the confining pressure (which is directly proportional to the overburden pressure) increases with depth, the N values at shallow depths are underestimated and the N values at larger depths are overestimated. To allow for this, N values recorded from field tests at different effective overburden pressures are corrected to a standard effective overburden pressure.
The corrected N values given by

$N' = CNN$

in which corrected value of observed N; CN = correction factor for overburden pressure.

If $N' \leq 15$, then $N' = N''$

If $N' > 15$ is an indication of a dense sand. In such a soil, the fast rate of application of shear through the blows of a drop hammer, is likely to induce negative pore water pressure in a saturated fine sand under undrained condition of loading. Consequently, a transient increase in shear resistance will occur, leading to a SPT value higher than the actual one.

- **Dilatancy and Strength**

Strength and dilatant behaviour of soils depends on effective stress, strain, density, and confining pressure. A dilatant soil looses strength, therefore consideration should be given to secant rather than tangent angle of internal friction, dilatancy towards critical state which is a function of mineraology, effective stress and soil density which affectsthe rate of a soil’s dilatancy and hence its strength parameters. Bolton noted that soils in the rupture zone will dilate to achieve a critical state at which shear deformation will continue to occur in the absence of volume change [36]. He onservd that failure to bridge the gap between research and practice has many serious consequences and Engineers do not appreciate that ignorantnce of the influence of dilatancy on the strength parameters in terms of the secant angle of internal friction and the conventional tangnt strength parameters can lead to significant errors in the predited ultimate bearing capacity.Di1atancy correction in in situ SPT is to be applied when obtained after overburden correction, exceeds 15 in saturated fine sands and silts. The Terzaghi and Peck recommended dilatancy correction (when N > 15) uses
$N'' = 15 + 0.5(N'^{-15})$

Static Cone Penetration Test (SCPT)

At field SCPT is widely used for recording variation in the in-situ penetration resistance of soil in cases where in-situ density is disturbed by boring method & SPT is unreliable below water table. The test is very useful for soft clays, soft silts, medium sands & fine sands. Design parameters obtained fro the test include soil type, relative density, state parameters, overconsolidated ratio, strength (peak friction angle, and undrained cohesion), stiffness, compressibility, shear, elastic, and constrained moduli, consolidation and permeability.

Figure 4: (a)10 tons cone penetration testing, (b). boring and SPT

Case Histories

1. Niger Delta

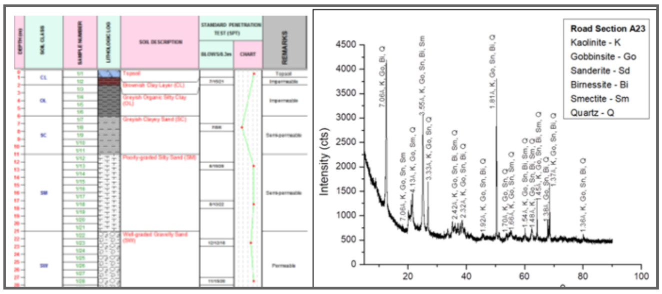


Figure 5: (a)Typical Niger Delta geotechnical model (b). XRD diffractogram for Clay identification

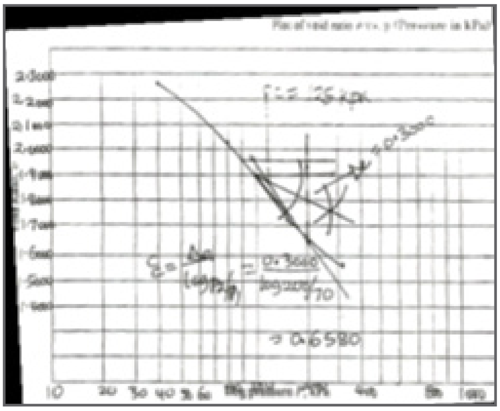
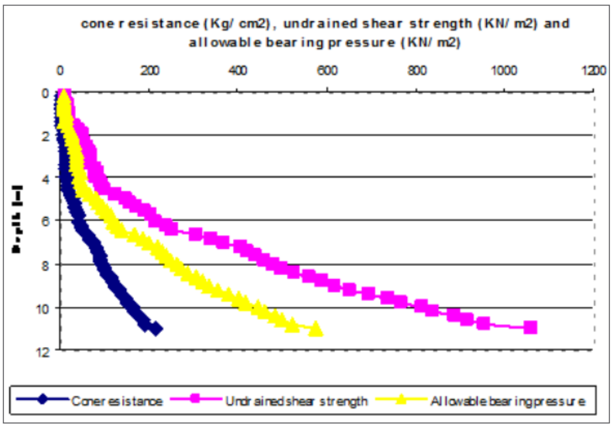


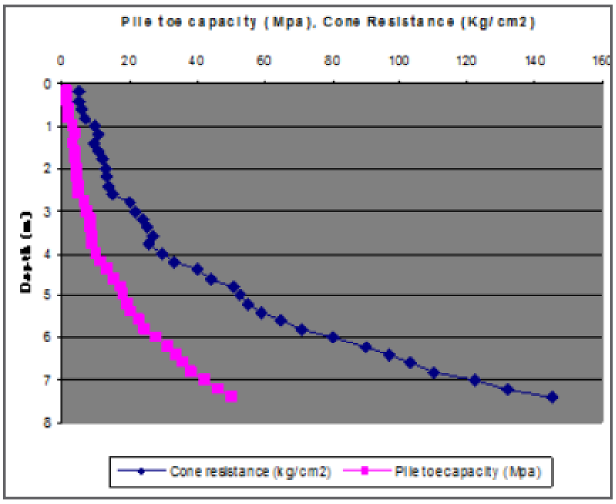
Figure 6: Typical void ratio vs log of pressure curve indication stress history

Table 1: Consolidation Properties of Clays

Consolidation Parameter	Minimum	Maximum	Average
Coefficient of consolidation (Cv) (cm²/min)	4.76×10^{-2}	2.296	1.928
Coefficient of volume compressibility (Mv) kPa-	2.097×10^{-4}	4.965×10^{-4}	3.801×10^{-4}
Pre-consolidation pressure (kPa)	125.0	162.5	160.3
Coefficient of compressibility (av) kPa^{-1}	4.891×10^{-4}	2.406×10^{-3}	1.928×10^{-3}
Overconsolidation ratio	2.75	6.40	4.09



Figuer 7: Typical cone resistance curve showing variation of cone resistance (qc), Undrained shear strength (Cu) and Allowable bearing pressure with depth across the site.



Figuer 8: Typical Variation of cone resistance (qc) and unit pile tip capacity in mPa with depth across the site.

Investigation of Foundation Failure Potential

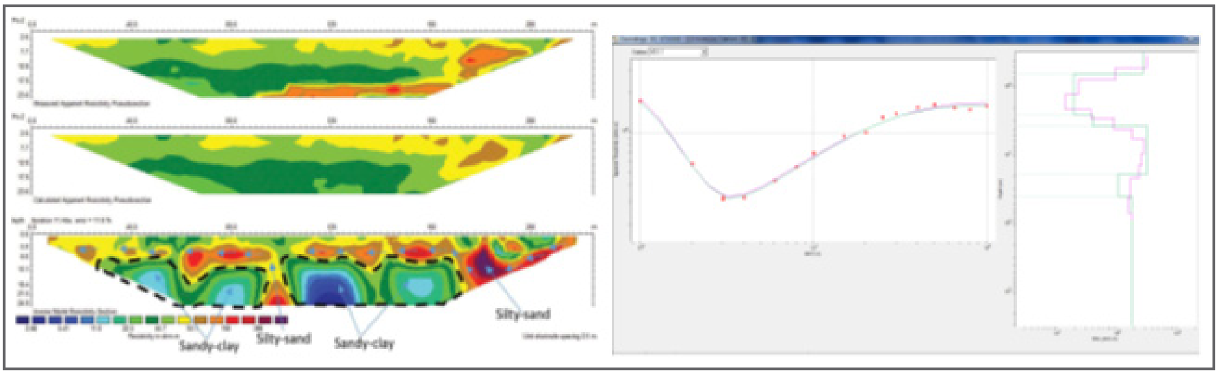
For an angle of internl friction of the clays varying fro 0-80, foundation subgrades depict a potential for local shear failure in the clays.

Foundation Recommendations

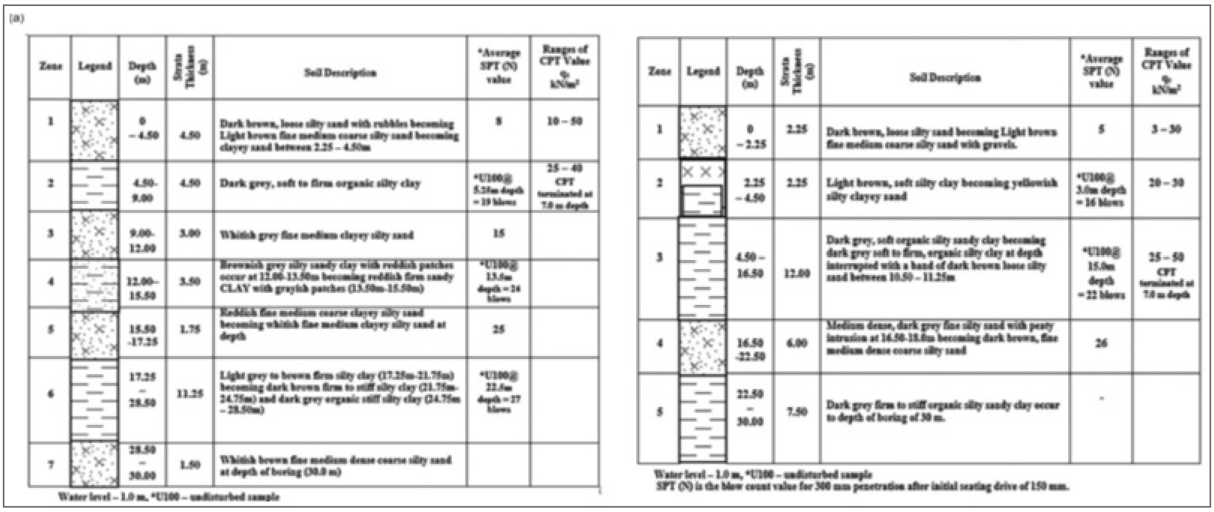
Settlement results for the extra-sensitive to sensitive, high compressibility Kaolinitic, weak bearing mangrove swamp soft clay at th foundation depths amenable to high volume change, swell potential of these clays ranges from 11.45-30.64%, swell index from 0.44-0.57, activity from 7.0-11.0 and swelling pressure 4.776kPa-4.890kPa based the prosed structural loads, stress history and estimated vertical stress at the foundation depth depicts 175.9cm and 146.5cm for a load of 1800 tons, 146.9cm and 101.5cm for 436,7 tons and157.3cm and 124.0cm for the 846.7 tons structures on land and stream channel respectively. These are excessive and beyond tolerable limits of 2.5cm. The immediate settlement varies from 0.861mm-1.74mm. Time rate of settlement due to dissipation of excess pore water pressure as result of applied vertical stress on the clay layers accompanied by an increase in effective vertical stress shows that it will take 6.655 years to achieve 50% settlement and 28.65 years to achieve 90% settlements under the worst case scenario (Abija et al. 2018). Therefore, foundation options considered and choice be made after cots considerations include

1. Raft and depth compensation
2. Excavation, refill with higher bearing granular soil and densify with vibratory roller compactor
3. Use of inverted raft after soil stabilization with lime, cement or bitumen
4. Use of raft on pile
5. Piling to the dense sands with under-reaming bulbs placed in the high density sands.

Osborne Foreshore Estate, Ikoyi, Lagos



Figuer 9: (a)Typical 2D Inverse resistivity model. (b) Typical VES interpretation



(a)

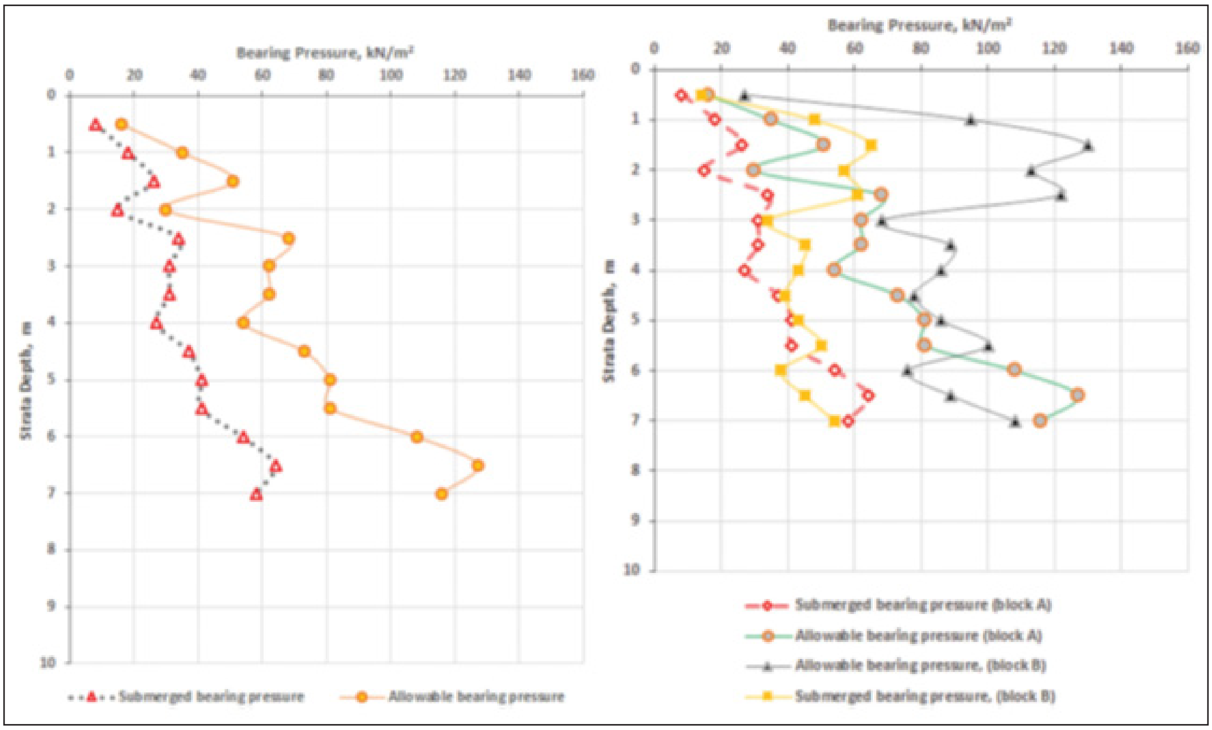
Zone	Legend	Depth (m)	Strata Thickness (m)	Soil Description	*Average SPT (N) value	Ranges of CPT Value qc kN/m²
1		0 – 4.50	4.50	Dark brown, loose silty sand with rubbles becoming Light brown fine medium coarse silty sand becoming clayey sand between 2.25 – 4.50m	8	10 – 50
2		4.50- 9.00	4.50	Dark grey, soft to firm organic silty clay	*U100@ 5.25m depth = 19 blows	25 – 40 CPT terminated at 7.0 m depth
3		9.00- 12.00	3.00	Whitish grey fine medium clayey silty sand	15	
4		12.00- 15.50	3.50	Brownish grey silty sandy clay with reddish patches occur at 12.00-13.50m becoming reddish firm sandy CLAY with grayish patches (13.50m-15.50m)	*U100@ 13.0m depth = 24 blows	
5		15.50 -17.25	1.75	Reddish fine medium coarse clayey silty sand becoming whitish fine medium clayey silty sand at depth	25	
6		17.25 – 28.50	11.25	Light grey to brown firm silty clay (17.25m-21.75m) becoming dark brown firm to stiff silty clay (21.75m-24.75m) and dark grey organic stiff silty clay (24.75m – 28.50m)	*U100@ 22.0m depth = 27 blows	
7		28.50 – 30.00	1.50	Whitish brown fine medium dense coarse silty sand at depth of boring (30.0 m)		

Water level – 1.0 m, *U100 – undisturbed sample

Zone	Legend	Depth (m)	Strata Thickness (m)	Soil Description	*Average SPT (N) value	Ranges of CPT Value qc kN/m²
1		0 – 2.25	2.25	Dark brown, loose silty sand becoming Light brown fine medium coarse silty sand with gravels.	5	3 – 30
2		2.25 – 4.50	2.25	Light brown, soft silty clay becoming yellowish silty clayey sand	*U100@ 3.0m depth = 16 blows	20 – 30
3		4.50 – 16.50	12.00	Dark grey, soft organic silty sandy clay becoming dark grey soft to firm, organic silty clay at depth interrupted with a band of dark brown loose silty sand between 10.50 – 11.25m	*U100@ 15.0m depth = 22 blows	25 – 50 CPT terminated at 7.0 m depth
4		16.50 -22.50	6.00	Medium dense, dark grey fine silty sand with peaty intrusion at 16.50-18.0m becoming dark brown, fine medium dense coarse silty sand	26	
5		22.50 – 30.00	7.50	Dark grey firm to stiff organic silty sandy clay occur to depth of boring of 30 m.	-	

Water level – 1.0 m, *U100 – undisturbed sample
SPT (N) is the blow count value for 300 mm penetration after initial seating drive of 150 mm.

Figuer 10: Typical one dimensional ground model of a site in Osborne Foreshore Estate, Ikoyi, Lagos



Figuer 11: Typical variation of allowable bearing pressure from different test points at a site [36]

Table 2: Basic and strength paraeters at the Ikoyi site

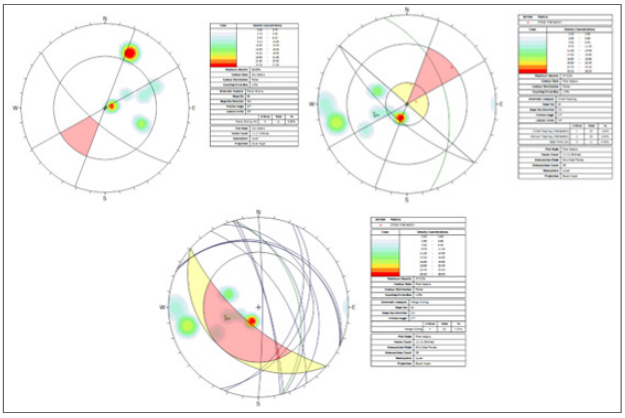
BH Depth	Wn %	Bulk density (Mg/m³)	Undrained cohesion (Cu) KN/m²	Angle of int. resistance (ϕ°)	Lithologic description
BH1, 3.0	18	1.69	26	5	Soft peaty clay
BH1, 15.0	21	1.91	29	6	Soft peaty clay
BH2, 5.5	23	1.81	20	5	Soft peaty clay
BH2, 13.5	25	1.87	35	8	Fir clay
BH 3, 22.5	28	1.89	67	10	Stiff clay

The results from the geotechnical and geophysical investigations confirm the occurrence ofsoft-to-firm clayey soils within the study area have low to moderate shear strength and on basis of the angle of internal friction, all the clays have very high potential for local shear failure.

Foundations on Rocky Grounds Case History

Typical kinematic analysis (Figuer 12) for identification of instability mechanisms and feability for movement of the rock masses at the foundation level. Rock structure data were measured in the field and rock mechanics testing were conducted on the rock samples.

Kinematic analysis was based on the friction angle of the rocks and attitude of the structural discontinuities vis-à-vis the slope direction.



Figuer 12: Typical equal area, lower hemisphere kinematic admissibility stereonets for identification of rock instability mechanisms and failure potential.

Geotechnical or Engineering Geological Maps Case History

Engineering geological or geotechnical maps depict spatial variation in ground engineering, geomorphological and groundwater chacteristics of an area [10]. They are veritable tols for for urban planning and development and desk review tools for planning detailed field geotechnical investigations. Abija et al. applied geotechnical mapping in predicting the landslide susceptibility of parts of Calabar, Nigeria and research provided very usefule maps (figuers 13 a, b, c, d, and e) for urban planning and development [37].

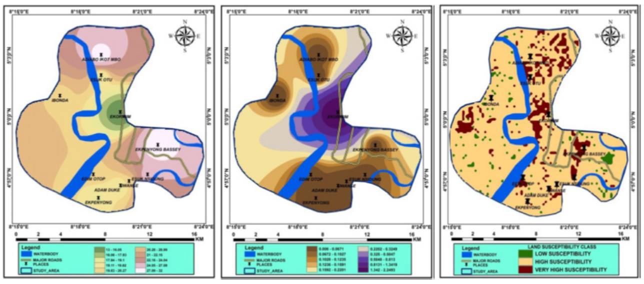


Figure 13: Typical geotechnical maps of Calabar depicting spatial variation of (a) ground slope, (b) slope direction (c) soil cohesive strength (d) hydraulic conductivity (e) landslide susceptibility

These show the importance of geotechnics as a tool for planning and building sustainable cities, communities and infrastructures. Nothwithstanding their importance in planning, site specific geotechnical investigation and subsurface characterization is a requisite for design and construction if the infrastructure must perform optimally and stand the test of time for the future generations.

Reliability Analysis and Foundation Design Considerations

In consideration of foundation design against catastrophic bearing capacity and excessive settlement failures, multiplicity of epistemic and aleotoric uncertainties in geotechnical characterization and quantum of design data arising from adequate and detailed exploratory boring, in situ testing and laboratory analysis, geotechnical and ground modeling as tools for subsurface engineering characterization, reliability analysis offers a veritable design approach for sustainable projects. Reliability is the probability that the foundation will perform without any failure within the project design lifespan. The standard penetration test for example has been applied to determine the probability of exceedance of tolerable settlement of 25mm. The probability of exceedance of the settlement is 30% [38]. In the formulation of the reliability approach, the limit state function equates the capacity or resistance less the the load in this case the ultimate bearing capacity.

Conclusion

Research across Nigeria depicts that most building collapse were caused by failure of the foundation due to the neglect of several geological and geotechnical factors in the design. In this regard, it should be noted that not all the geological factors must be considered for all types of projects but a building development requires broad range of geological factors for sustainability. The list of geological considerations is presented: soil/rock type and mineralogy, bearing capacity for intended load, porosity, void ratios and permeability of subgrades, susceptibility to long term erosion and or weathering; and presence, frequency, spacing, aperture and orientation of discontinuities in the case of rocks. For foundation on slopes, state of stability and sliding potential, presence of liquefiable soils, seimic potential, soil elasticity, swelling, collapsibility, potential for hydrocompaction and subsidence, ground water table, surface runoff and flooding etc. Geotechnical data should not only be an academic exercise but for practical design applications to prevent foundation failures and building collapse.

Recommendations

1. Geotechnical Consultant on all infrastructures
   Independent geotechnical consultant (who must be holders of at least B.Sc. Geology and M.Sc. Engineering Geology and certified by Councilof Nigerian Mining Engineers and Geoscientists (COMEG) and or B. Engr. Civil Engineering and M.Eng. Geotechnical Engineering, certified by Council for the Regulation of Engineering inNigeria (COREN) be retained as Consultanst for all infrastructural projects including buildings. The Project geotechnical life cycle and scope of services for the Geotechnical Consultants on projects (afterLook is presentedbelow [39]:

Project phase	Geotechnical study for types of projects		
	Small	Medium	Large
Feasibility	Desktop study/ Site investigation	Desktop study	Desktop study
Planning			Definition of needs
Preliminary engineering		Site investigation (S.I.)	Preliminary site investigation
Detailed design			Preliminary site investigation
Construction	Inspection	Geotechnical Monitoring/ Inspection	Monitoring/ Inspection
Maintenance		Inspection	

1. The geotechnical consultant must determine potential foundation failure whether in sands or clay.

2. Ground and or Geotechnical Modeling
   Preliminary geotechnical model shouldreveal ground conditions based on in situ investigations. All subsequent work is aimed at refining and adding to the preliminary model. It is most unlikely that any geotechnical model will be exactly correct; the question is the balance between risks from uncertainties and the additional costs of conservative design.
3. Prediction of stress history and estimation of vertical stress
   Overconsolidated soils (cohesive) is sheared, particles are susceptible to expansion due to upward movement, undergo dilation causing shear bands, exhibiting peak shear strength at low confining pressure, any further shearing after peak strength progresses to critical state or ultimate state by strain softening. This implies use of critical state strength envelop for design. The vertical stress due to imposed building load must be determined.
4. Prediction of ground subsidence due hydrocopaction in recent coastal area
   Subsidence can cause eccentricity and cracking of the the structure, therefore it the gotechnical consult must be predicted in coastal terrains where soils are very soft, organic, deposited with much water or land is reclaimed.

Design Recommendations for Grounds with variable soil profile

5. Bearing capacity determination for variable soil profile under a building should be considered for eccentric loading conditions.
6. For Foundations on slopes, stability analysis, sliding susceptibility potential and bearing for slopy ground should be carried. No rule of thumb applications.
7. Foundations on rocks should be based on kinematic feasibility, strength and moduli of the rocks and soils above the rocks
8. Seismic hazards such as liquefaction and earthquake induced slope instabilities should be evaluated.
9. Reliability analysis taking into account all the random variables promises a better design option and is hereby encouraged for practical applications.
10. Effect of ground and surface water and flooding on foundations should be investigated
11. Gonzalez de Vallejo and Ferrer recommended the following methodological procedures for geological engineering and engineering design [40]:
    - Identification of geological materials and geological processes. Analysis of geomorphological, structural, lithological and groundwater conditions.
    - Site and ground investigation.
    - Defining the spatial distribution of materials, structures and discontinuities.
    - Defining the hydrogeological, in situ stress and environmental conditions.
    - Characterization of geomechanical, hydrogeological and chemical properties.
    - Characterization of the geological materials to be used in the construction.

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