DEALING WITH SENSITIVE AND VARIABLE SOILS IN NAIROBI CITY

Caroline K. Onyancha[1*], Eliud M. Mathu[2], Sixtus K. Mwea[3] & Wilson M. Ngecu[4]

[1]Civil and Structural Engineering Department, Masinde Muliro University of Science and Technology, Kakamega, Kenya
[2]Department of Geological Sciences South Eastern University College, Kitui, Kenya
[3]Department of Civil and Construction Engineering, University of Nairobi, Nairobi, Kenya
[4]Department of Geology, University of Nairobi, Nairobi, Kenya
E-Mail: conyanja@yahoo.com

ABSTRACT

Nairobi City is mainly underlain by pyroclastic volcanic rocks that were deposited during the formation of the East African Rift Valley. Some of the volcanic rocks were deposited in aqueous conditions over a long period of time and are intercalated with lacustrine sediments. River valleys and other depressions that existed during the periods of intermittent inactivity were filled with alluvium and clays. At building sites, the alluvium, clays as well as decomposed volcanic tuffs are found to have variable thicknesses and sensitive to moisture. The objectives of this research were: to identify localities covered by the sensitive and variable soils; to determine the geotechnical properties of the soils and to examine the methods and processes that make for a successful construction program. Geotechnical test results and reports from fifty seven sites underlain by these soils were analysed. The results show that structures with defects exist side by side with those in sound condition. It is concluded that some methods of construction work well in these soils. These successful construction methods that are applied to avoid/ remedy total and differential settlement in buildings are discussed here. Since the methods are quite successful, the authors suggest use of the same approach for addressing similar subsoil problems.

Keywords: *Nairobi subsoil, Sensitive and variable, Geotechnical properties, Construction methods.*

1. INTRODUCTION

Nairobi City is mainly underlain by pyroclastic volcanic rocks that were deposited during the formation of the East African Rift Valley. Some of the volcanic rocks were deposited in aqueous conditions over a long period of time and are therefore intercalated with lacustrine sediments. River valleys and other depressions that existed during the periods of intermittent inactivity were filled with alluvium and clays. At building sites, the alluvium, clays as well as decomposed volcanic tuffs are found to have variable thicknesses and sensitive to moisture. The main formations underlying Nairobi City are shown in Figure 1. The topography and surface geology of the city are largely the result of the Cenozoic volcanic processes (Saggerson, 1964).

For the last one hundred years, the population of Nairobi has been steadily increasing; human activities have caused large-scale landscape modifications. Formerly sloping grounds have been levelled with fill from construction sites and sold to unsuspecting developers. The increase in population has also caused developers to move to sites with poorer subsoil characteristics such as river valleys, swamps, former springs and dump sites. Due to inadequate knowledge of the geotechnical conditions, constructors are faced with a challenge of change in assumed subsurface conditions revealed during excavation**.** In some cases, project construction increases underground erosion, disturbs moisture-sensitive soils, and produces construction-related vibration causing distress in some structures.

To avert these problems, the City Council of Nairobi has set guidelines for the design of structures within the city. However, geotechnical site investigations before construction of new buildings are not part of these guidelines. When requests for increasing the height of old buildings are made, the City Council requests that the engineers confirm the state of the existing foundations and determine whether they are capable of supporting additional load. They also request for a specification on how the adjacent structures are going to be supported during demolition, excavation and construction operations. Some structures within the city have suffered distress due to inadequate information obtained during the investigation, variation in subsurface conditions, lack of knowledge on the state of the existing structures in the vicinity, or disregard of professional advice during construction. Records indicate that old low-rise structures within the city centre were designed to carry at least two additional floors so any increase beyond this height will overstress the subsoil. The objectives of this research were: to identify areas covered by sensitive and variable soils; to determine the geotechnical properties of the soils and to examine the methods and processes that make for a successful construction program.

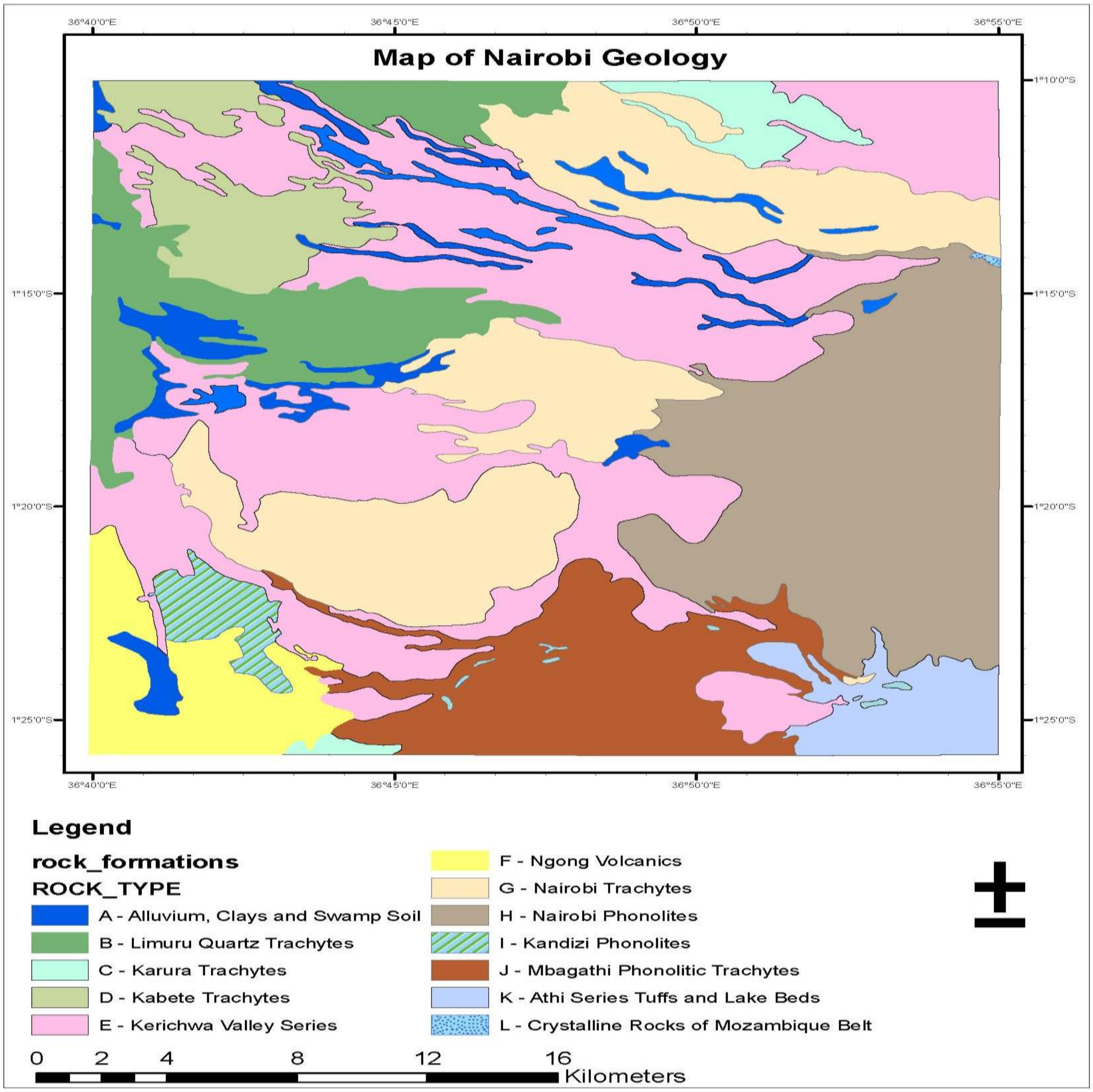

Figure 1: Geological map of Nairobi City (digitized from Saggerson, 1964)

2. LITERATURE REVIEW

Nairobi City comprises several spots of sensitive soils and variable/inclined ground profiles. The surface is covered by any of the following soils: black cotton clays, red or brown clays, red silty soils, laterites, decomposed tuffs, alluvium or swamp soils. Sikes (1934) indicates that existence of swamps made some parts of the city unsuitable for structural development. Many borings as well as trial pits beneath and around building sites show that the thickness of the soft and sensitive deposits varies from 0.8 to 21 m below the ground surface. Groundwater level varies considerably with surface topography and season and lies between 0.5 m to 18 m below the ground surface. The shallow groundwater is found to flow towards nearby rivers creating underground rivers that flood foundation excavations and in a few cases it is found to recharge from the nearby rivers. Most of the rivers draining the city join River Athi that discharges water to the Indian Ocean.

Constructors routinely use a variety of methods to minimize adverse effects on structures supported on sensitive and variable soils. The approach used is to minimize total settlement under footings to a range of 4 to 8 cm or by use of foundation types that are able to bridge over the soft spots such as strip footings or rafts. Floating rafts have rarely been utilized because of factors such as: the depth that the foundation should be placed to get full flotation, need for shoring to prevent heaving and cave-ins, the groundwater that might need lowering, and, the effect of deep excavation on adjacent foundations that cannot be adequately determined.

Taking foundations to rest on rock below the sensitive and soft soils is a common practice in Nairobi City. However, challenges arise when the rock surfaces are sloping with the depth of encounter ranging between 1.5 m and 6 m within a site and the rock is too hard to be excavated. The presence water flowing at high velocity at the interface between the rock and overburden makes the construction work more tedious. The water causes softening of foundation soils and can lead to differential settlement because of the variation in the depth of wetting. Fenton *et. al.* (2003) carried out studies on the effects of variability in soil properties on total and differential settlement of structural foundations. From the study, they concluded that unless the total settlements themselves are particularly large, it is actually differential settlements which lead to unsightly cracks in façades and structural elements, possibly even structural failure. A study by Richardson (1991) has shown that settlement cracks are nearly always vertical while soil bearing failure cracks occur at each side of a portion of the foundation wall that is undergoing downward movement.

For a long time it was thought that settlement due to construction on soft soils such as clays stops 3-5 years after completion (Coduto, 2001). But Richardson (2005) noted that constructional settlement does not always stop; old overloaded buildings set on deep clays will not achieve equilibrium but will show slight settlement. Settlement in old buildings supported on soft soils also occurs as a result of open construction cuts (Ciancia et al, 2006). Judgement is required to assess the consequences of estimated settlement and inward yielding, which must take into account the time the excavation will remain open. Gevaerts (1964) recorded encounter of channels containing water during building operations and sealing of underground basements to large buildings. He noted that this resulted in the diversion of water producing an additional hazard to the foundations of older buildings supported on Kerichwa Valley Series of limited loading capacity. Studies of ground and moisture movement have shown that the problem of finding a suitable type of foundation has two main approaches: to place the foundation in a zone where the soil and moisture conditions are stable or to reduce the variation of the moisture to an acceptable minimum and thus reduce ground movement to an acceptable value.

3. MATERIALS AND METHODS

The study utilized subsoil data available from geotechnical investigations carried out at building sites and failure investigations performed at different locations and depths over a long period of time. The study determined the geotechnical characteristics of each of the sensitive deposits based on results of particle size analysis, swelling pressure, Atterberg limits, bulk density, one-dimensional consolidation and double oedometer for collapse. The liquid limit and plasticity index values of the samples were plotted on the Casagrande plasticity charts to determine the overall homogeneity and compressibility of the soils. Results of grading of soils from each site were plotted on the same page on GGU software to compare the soils and classify them according to British Soils Classification System (BSCS). GGU is written by CivilServe Software of Germany and comprises 43 programs covering a wide range of applications in geotechnical design, site investigation and laboratory analysis. By inputting the raw data to any of the GGU programs using the online manual provided, one can be able to analyse simple and complex data useful for design and construction of structures.

In the cases where distress in structures was reported, trial pits were dug to expose the foundations at the corners and at midway along the walls. The soil profile and the level of the foundations at the site were studied. Undisturbed samples were taken from underneath the foundation and flooded and non-flooded double oedometer tests were carried out at different loading conditions. Settlement curves of the results were plotted using GGU software to obtain settlement expected at different pressures. From the curves, constrained modulus could also be obtained. Results of settlement at bearing pressures of 100 kN/m², 200 kN/m² and 500 kN/m² were summarised in a table.

Swelling pressure was determined in consolidation cells of fixed-ring type by subjecting three soil samples to different magnitudes of pressures and then allowing them to saturate. Under the different load intensities, some of the soil specimens would compress after saturation while some other would swell. After volume change (compression or swelling), a load intensity versus volume change plot was obtained from the results. From this plot, the pressure corresponding to zero volume change was read and denoted as the swelling pressure for the soil.

Subsurface profiles were plotted on Strater software to express variation in succession beneath Nairobi. Strater Software is developed by Golden Software of Golden Colorado, USA for plotting log information and creating cross sections of the subsurface. For a profile to be plotted the following information must be provided for each drill hole log: borehole identity (BHID); thickness of the stratum (from-to); the name of the geologic unit (formation) or hydrogeologic unit identity (HGUID) as well as description of the formation and code (HGUcode). Using simple procedures provided in the tutorials, one can draw various profiles and sections. It is possible to plot several profiles on one page and compare the succession if the difference in borehole depths is small.

4. RESULTS

Figure 2 presents subsurface profiles encountered at three different sites within Nairobi City centre. As it can be observed, different successions were encountered at the three sites. Actually, the profiles represent a compromise between the successions at the sites because there were variations from hole to hole within the sites. At Continental House, three geotechnical investigation boreholes were sunk up to maximum depth of 13.25 m. Water was struck in all boreholes at depths between of 2.0 and 2.7 m. Crushing tests on selected samples of the core show that the rock varies considerably both in material quality and in the state of the rock mass as a whole. Continental House is supported on 8 m by 6 m grid of pad foundations with a suspended ground floor slab. The founding level is 4 m deep, on yellowish-grey tuff with a design bearing pressure of 400 kN/m².

At Sixeighty Hotel, six boreholes were sunk to a maximum depth of 15.4 m. Water was struck in all boreholes at depths varying from 0.9 to 1.1 m. Observations of the water level over a two week period resulted in fluctuations between 0.8 and 1.3 m depth. The agglomeratic tuff is mainly made of large angular phonolite boulders in a matrix of yellow tuff. The boulders are very hard but the matrix is so weak that the core samples are often very broken. On testing, most samples exhibit brittle failure with considerable variation in the elasticity modulus. The Sixeighty Hotel is built as ten storeys above street level with one basement and is supported on pad foundations taken to rest on black tuff at 4.5 m with design bearing pressure of 800 kN/m².

The surface beneath Lutheran church was found to comprise of soft overburden up to 22 m. At 6 m to 8 m depth, the clay content range is 62-79% and soil tests yielded liquid limit results ranging from 91-105% and plasticity indices of 61-71. All these plotted as extremely high plasticity soils on the plasticity chart (Figure 3). According to the Casagrande classification of fine-grained soils, these soils can be termed as very unusual soils. Oedometer tests indicate that the soils settle when loaded under natural moisture content and when flooded under load. The "old" St Andrews Church within the vicinity built in 1910 is founded on this deep alluvium. An underground river within this site flows into Nairobi River. By 1930, there was concern as to whether the St Andrews Church building was in a state of collapse, but it is still standing thanks to buttressing and repair work. In 1964, the church was found to have settled by approximately 0.2-0.5 m (Ministry of Works, 1969).

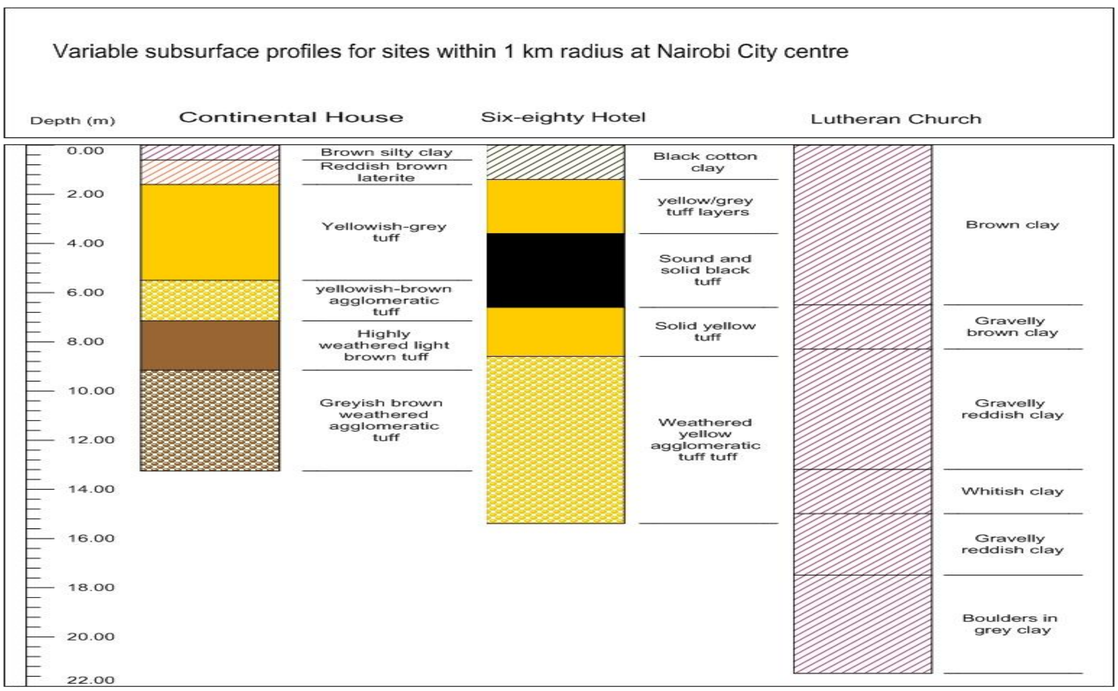

Figure 2: Subsurface profiles at Continental House, Six-eighty Hotel and Lutheran Church

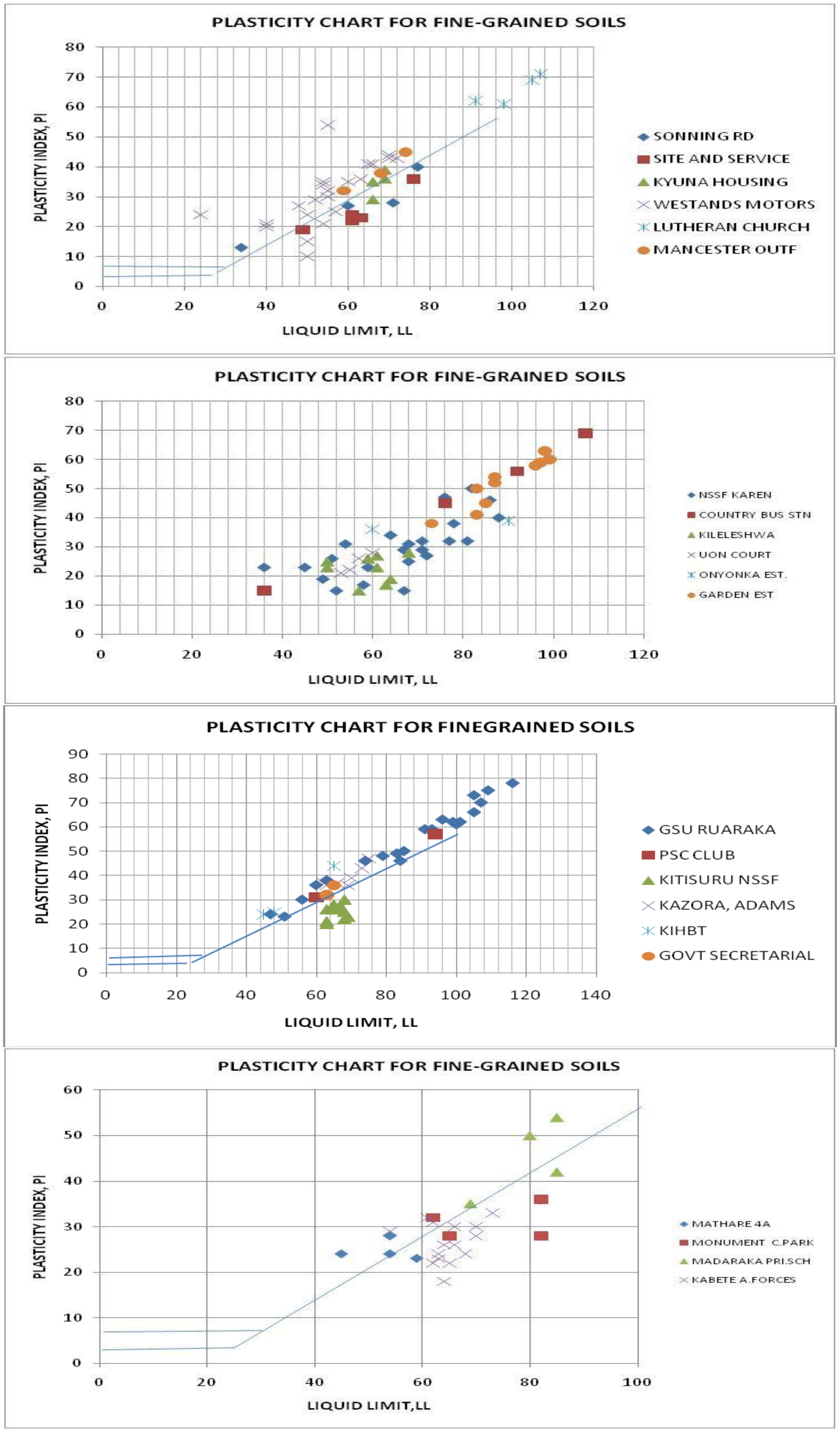

Figure 3: Plasticity charts for some sites in Nairobi City

Grading curves were plotted for various sites and an example of the Lutheran Church site is presented in Figure 4. From the grading curves, the soils were classified and compared with the BS 5930:1981 based on the plasticity terms as shown in Table 1. This enabled the identification of the various soil types in the study area namely: clays of intermediate to high plasticity, silts of intermediate to high plasticity and clays of very high to extremely high plasticity.

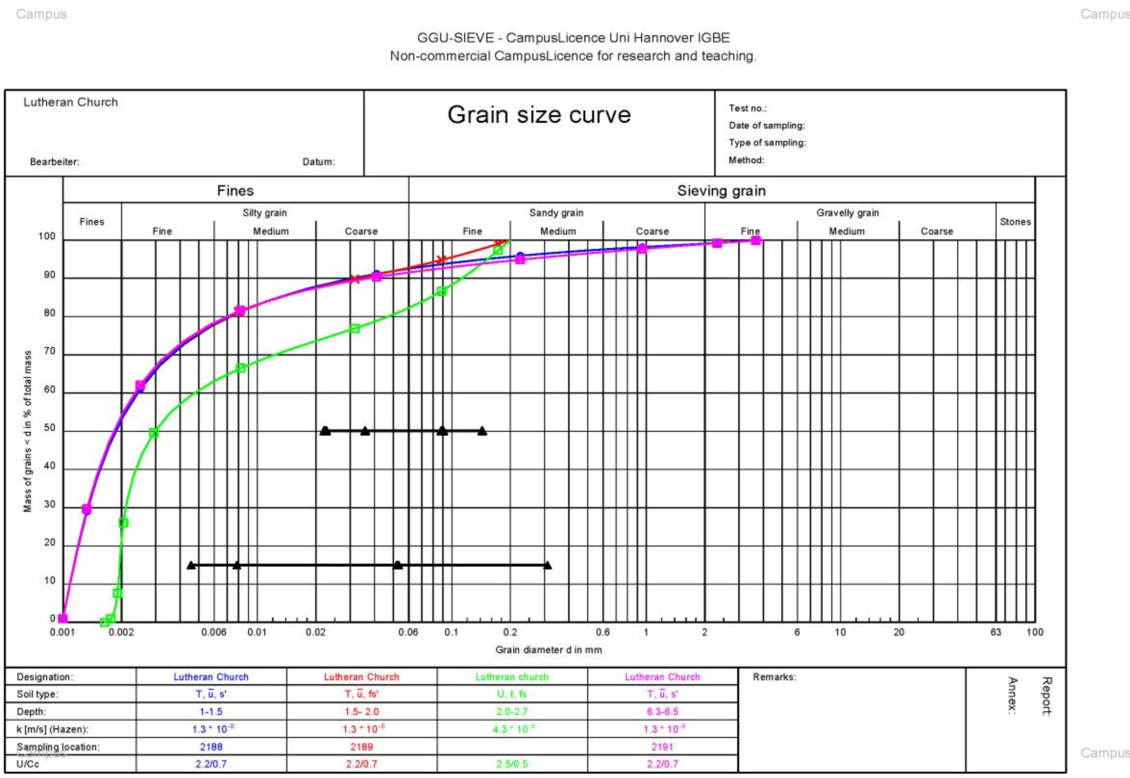

Figure 4: Grading curves for soils samples recovered at Lutheran Church site

Table 1: Classification of soils from the grading curves and plasticity charts

Site	**Soil class**	**Plasticity term**	**Group symbol (BS 5930:1981)**
Manchester outfitters	Clayey sandy silt	High	CH
KIHBT	Silty clay	Intermediate to high	CI to CH
NSSF Karen	Clayey silty sand	Intermediate to high	CI to CH MI to MH
Country Bus station	Silty clay	Intermediate to extremely high	MI to MV
Kileleshwa	Silty clay	Intermediate to high	CI to CH
Univ. of Nairobi Sports Field	Clayey sandy silt	High	CH
Onyonka Estate	Silty clay	High to very high	CH to CV
Garden Estate	Silty clay	Very high to extremely high	CV to CE
Sonning Road Kibera	Clayey SILT	Intermediate to high	MI to MH
Site and Service Scheme	Clayey sandy silt	Intermediate to high	MI to MH
Kyuna	Sandy silt	High	MI to MH
Westlands Motors	Sandy clayey silt	Intermediate to high	MI to MH
Lutheran Church	Silty clay	Extremely high	CE
GSU Ruaraka	Silty clay	intermediate to extremely high	CI to CE
PSC Club	Sandy clayey silt	High to very high	CI to CV
Kitisuru NSSF Estate	Clayey SILT	High	MH
Kazora Flats	Silty clay	High	CH
Mathare 4A	sandy clayey Silt	Intermediate to high	CI to CH
Madaraka Pri. Sch.	Silty clay	Very high	CV
Kabete Armed Forces	Silty clay	High	MH

The variability of the engineering characteristics of the soils based on the core recovered, Atterberg limits and grading was found to be highest as GSU Ruaraka and Country Bus Station sites. The most uniform conditions are at Kabete Armed Forces, Kyuna and Kitisuru areas that are mainly covered by silts or silty clays of high plasticity underlain by Kabete or Limuru Trachytes. Garden Estate is covered by clays of very high to extremely high plasticity while Madaraka Estate is covered with clays of very high plasticity and both localities have many distressed structures. The swell pressures of the clay at Garden Estate were found to be in the range of 151-206 kN/m² and thus slightly higher than the foundation pressures from lightly loaded structures that are in the range of 120-160 kN/m². The soils at Madaraka, Kongoni and Kabete were also found to be collapsible as shown in Table 2 and capable of causing trouble on structures.

Table 2: Potential hydrocollapse strain ranges for some sites

Site	Soil type	Potential hydrocollapse strain range	Classification (Coduto, 2001)
Central Park	Brown clay	0.01-0.035	Moderate trouble
Madaraka Pri	Black silty clay	0.142- 0.198	Severe trouble
Kongoni Pri	Silty clay	0.19-0.210	Severe to very severe trouble
Kabete Armed Forces	Red clay	0.08- 0.815	No problem to very severe trouble

Figure 5 presents settlement curves for one sample taken at Onyonka Estate. Under non-flooded condition, the soil would settle by 26 mm, 37 mm and 50 mm when loaded with 100 kN/m², 200 kN/m² and 500 kN/m² respectively. When flooded, the same soil would settle by 36 mm, 60 mm and 84 mm when loaded with 100 kN/m², 200 kN/m², and 500 kN/m² respectively. Site investigation at in Onyonka Estate was carried out in recognition of distress reported in structures in the nearby estates such as at Ngei Estate. Construction of the structures at Onyonka Estate employed precautionary measures that included setting of foundations below the sensitive soils and provision of proper surface drainage around the buildings.

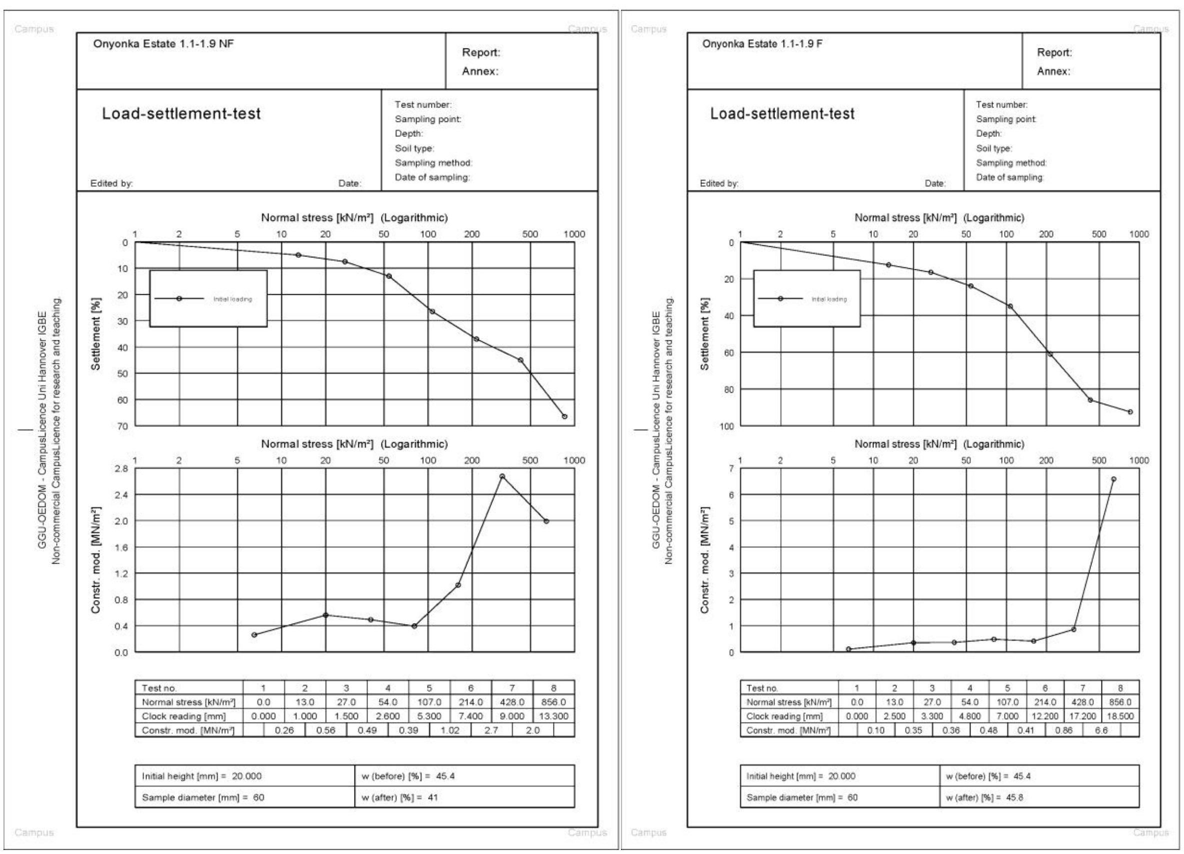

Figure 5: Non-flooded and Flooded condition settlement curves for Onyonka Estate

Table 3 is a summary of magnitudes of settlement obtained from settlement curves for samples tested under flooded and non-flooded conditions. From the table, it can be observed that most settlement values are within tolerable limits of 4 to 8 cm (Fenton et. al., 2003) when flooded at 200 kN/m² except for Kenya Soil Survey and one site at Kileleshwa Estate. However several lightly-loaded structures in these localities have suffered distress of different scales.

Table 3: Summary of settlement values obtained from settlement curves for some sites

Site	**Depth (m)**	**Settlement (mm)**					
		100 kN/m²		**200 kN/m²**		**500 kN/m²**	
		NF	F	NF	F	NF	F
Lillian Towers	2.9 13.3	14 9	16 16	17 18	18 21	26 39	36 44
Lutheran church	5.6	27	32	33	42	42	47
KIRDI	1.5	24	26	28	38	40	52
Onyonka	1.2	25 20	36 25	36 26	61 42	50 45	84 72
Ngei	1.8	17		22		25	
Adams Arcade	3.0	28		39		49	
Sonning Road	1.3	8	28	10	29	12	40
Kileleshwa		18 16 40 21	22 21 78 24	23 21 62 31	42 42 92 42	30 45 105 42	70 61 150 70
Kenya Soil Survey	1.2	25	62	56	88	120	128
Kangemi United Club	1.5	40		56		108	
Langata Barracks	1.5		42		58		84
Government Sec Col.	1.3	10	18 48	25	36 80	40	64 116
Dandora Water Supply	1.0	10	17	15	22	24	27
Athi River	1.2		58		74		79

(F- Flooded, NF- non-flooded)

5. DISCUSSION OF RESULTS

The silty clays of intermediate to high plasticity at several sites in the Westlands area of the city lead to extensive cracks on the exterior walls and uneven sidewalks. To prevent distress, some sites are inundated for several days to attain the maximum moisture content. The pad foundations for supporting columns are taken below the sensitive soil to rest on weathered rock. The sides of excavation are protected with timber shoring to avoid failure during construction. After inundation, a four inch layer of red soil is placed on the soaked soil to provide a working platform on the softened clays. The red soil is then covered with polythene to maintain the moisture in the underlying soil. Spacer blocks are placed on the polythene and the ground floor slab is cast. Ground beams are provided to support the loads. Most structures constructed using this method are in good condition while the nearby structures are distressed. The problem of inundating of soil is that as the soil would have softened, a large superimposed loading may cause settlements as serious as the heave movement. For this reason, pre-heaving by flooding only appears to be a feasible technique for lightly loaded structures.

At Westlands Motors, the investigation encountered variable subsoil unlike nearby sites that are covered by open-textured silty clays with thixotropic characteristics. A subsurface gully, possibly an old river course runs through the site discharging its water to Nairobi River. Dark grey to brown silty clays of high plasticity were recovered from some test holes and groundwater table was encountered at the lower elevation. In some holes, the soil was found to include appreciable amounts of organic matter. To avoid distress in the structure, French drains were constructed along the perimeter of the site to a depth of 2.5 m to keep down the groundwater table, all the organic silt was removed from the site and joints were provided in the pavement slab to prevent damage caused by uneven heave.

Many shallow foundation structures supported on strip and pad foundations combined with the floor slab in Madaraka Estate are not in use because of distress. The other rather different method of construction adopted on this soil type was in the construction of Akila Phase II Estate. The project involved construction of maisonettes in an area with 2 m deep plastic soil whose effect on shallow foundation structures had caused damage on the Phase I causing the developer to take the contractor to court. The Phase I structures were founded on 50 cm layer of this plastic soil and suffered distress before they could be sold out. To build the Phase II maisonettes, all the sensitive soil was excavated and wasted and polythene was laid on the underlying laterites because of the flowing water that could seep through the slab. Mass concrete was placed at 45º to increase bearing area to support pad foundations. Polythene was provided on the sides of the foundations to prevent moisture migration and proper surface drainage was established to lead storm water towards a nearby river. This method of construction led to a successful project in an area well known for distress in structures.

During the period of this research, four building projects were going on concurrently at Strathmore University within Madaraka Estate. Various subsoil problems were encountered at the construction sites. The most prominent one is sloping of underground strata causing variation in the depth of encounter of suitable foundation soil to be in the range of 2-6 m. Water from a nearby river was found to flow along the bedding plane causing softening of the subsoil and flooding construction excavations. French drains were constructed all round the excavations to control groundwater flow and sump pumping was continuously done towards the river. Foundations and slabs at three sites were constructed utilizing U-Boot Technology of Italy that makes slabs that are lighter than the conventional slabs thus reducing the prospect of excessive settlement. The fourth structure that is located at a site with 6 m deep soft clay was supported on a raft foundation with steel columns to mitigate total and differential settlement.

Red clay soils cover many areas underlain by Kabete, Karura, Limuru and Nairobi Trachytes. Laboratory tests on some samples of red clay indicate that the soil has very low unit weight (12-14 kN/m^3) and that it is very sensitive to settlements. It particularly has high additional settlement when soaked with water while subjected to load. Lightly-loaded structures supported on strip footing have undergone severe distress. One distressed structure at Red Hill Road had severe cracks at one corner of the building. Geotechnical and structural investigations were undertaken at the site. The evaluation indicated that the structure had undergone edge curl at that corner, and the foundation base was 100 mm lower than the expected grade. A trial pit excavated beyond the foundation base indicated the presence of termite sinkholes at the corner. No termite sinkholes were observed in trial pits along the wall. It was concluded that footing foundation at that corner was settling resulting in higher levels of foundation distortion along the area of influence. The sinkhole was probably present for a long time prior to the damage, but the growth of the sinkhole was accelerated by rainwater percolating into the subgrade beneath the structure. The rainwater flowed beneath the building because of improper grading of a parking lot next to the building. The downward migration of the deposits into underlying openings in subsoil and the formation and collapse of the cavities were accelerated by increase in the velocity of movement of water and induced recharge.

In the vicinity is one successful project whose site was found to have a problem of flow of surface water from the neighbourhood and shallow groundwater level apart from the problem of sensitive soils. Pad foundation system supporting columns was found to be the most cost effective alternative for the single storey structure. The column bases were set at 5 m depth where murram was encountered; they were tied at intermediate sections to avoid buckling. A ground beam was provided to support the loads from the structure and was suspended completely off the ground. Surface drainage was developed all round the compound to lead away the water. Hardcore was placed to form underground passage to allow the water to drain away. To avoid distress in houses at Kyuna and Kitisuru Estates, Kangemi United Club and Kenya Soil Survey, inverted T-beam foundations were used on the silty clay (commonly known as Kabete Red Clay) with allowable bearing pressures of 150 kN/m^2 as well as provision of good surface drainage. In addition, settlement monitoring after construction was recommended for the Kangemi United Club and Kenya Soil Survey sites.

Uncompacted and organic fills support structures in areas such as Lavington, South C, Kibera and some parts of Industrial Area. For instance in Lavington area, a single storey residential house had severe cracks that were opening downwards. Trial pits were dug adjacent to the exterior walls. The investigation determined that the structure was supported on fill that may have been a dumpsite and the fill was settling under the weight of the structure. The vertical cracks indicated that the soil was settling in a sagging mode (Kerisel, 1987). Another single-storey residential house with severe cracks in the interior walls in this vicinity was investigated by use of trial pits. The profile indicated that the overburden is variable with sloping decomposed rock underneath. It was also observed that during construction, 1 m thick mass concrete was placed below the ground floor slab and the non-load bearing walls were set on this slab. Consolidation of the fill below the mass concrete led to settlement and pulled the interior walls with it causing severe cracks. Because the strip foundations supporting the external walls were taken to rest on the decomposed rock, the walls were not affected as much. One method that has been used successfully on these soils is excavation and recompaction of the soils for supporting lightly-loaded structures.

Underground rivers are common in many localities such as Gitanga Road and Cedar Valley in Lavington, Miotoni and Warai Road in Karen and city centre among others. The 10 storey Nginyo Tower along Koinange Street in the city centre sits on an underground river. Geotechnical site investigation established that the subsoil profile across the site is variable and includes a layer of highly fractured pervious rock with a lot of groundwater flow. The bearing capacity tests indicated very low allowable pressures at some spots and it was therefore not possible to adopt the customary pad foundation type without the structure being subject to differential settlement. The foundation concept adopted in view of highly fractured and pervious materials of variable profile was to provide an interconnecting grillage of pad footings with short spans. This particular approach led to a foundation solution that proved simple and repetitive to construct, whilst acknowledging the relatively uncertain conditions and the need for an economical construction. To control the groundwater flow into the excavation, a system of containerising water was developed. This was to enable the heavily waterproofed basement slab to be cast on the pervious rock allowing the water to pass below it as it flowed in its natural course. Since the existing foundations were almost at the same level with new foundation, they were shored by 45º props that were removed as the work progressed.

Soils formed from decomposition of yellow Kerichwa Valley Series tuffs physically look suspicious when excavated. Completely decomposed yellow tuff forms yellowish-brown silty clay with high natural moisture content, high to extremely high plasticity and expansive properties. When dry, the clays are stiff and fissured. On grading, the soils are found to consist of large fractions of either silt or clay and small fractions of sand and gravel. Only one grading curve for this soil has a sigmoid shape. The fine fraction in the decomposed yellow tuff is washed away during rotary drilling and therefore some geotechnical borehole logs indicate no recovery, meaning that it was not recovered as a core. Coarser- grained yellow tuff is weathered to lateritic clay with physical characteristics of laterites but with low bulk densities and sensitivity to moisture changes. Structures supported on the clays or lateritic clays have undergone distress of varying magnitudes depending on the amount of moisture accessed under load. The agglomeratic tuff is also found to weaken when exposed to wet conditions. Because of this sensitivity, contactors use drainage system instead of a watertight basement structure and excavate for pad foundations at alternate positions to avoid disturbing foundations of neighbouring building. When foundation excavations remain open for a long time, the yellow agglomeratic tuffs have been found to be subject to development of slip circles causing distress in nearby buildings. Fast-paced construction projects have performed well in these soils provided that there is no entrapment of groundwater due to construction of deep basement that can have a continuing effect in the stability of the old foundations.

6. CONCLUSIONS AND RECOMMENDATIONS

Geotechnical test results and reports from fifty seven sites were analysed to determine the engineering characteristics of the subsoil underlying distressed structures. Geotechnical and structural failure investigations were also carried out at sites with defects in structures. The subsurface profiles and foundation conditions were critically observed. Undisturbed samples collected from the sites were analysed for bulk density, moisture content, grading, plasticity, swell and collapse. The subsurface profiles were compared with core logs of boreholes drilled within the vicinity. It was observed that distress is common in structures supported on erratic subsoil, expansive clays and collapsible soils that are moisture sensitive. Grading of most of the tested soils shows that they contain a substantial fraction of silt that is extremely moisture sensitive. The moisture sensitivity varies considerably within the layers and the ranges of swell pressures obtained are large. Swell pressure magnitudes of 151-209 kN/m² obtained at Garden Estate indicates that swell pressures from the expansive soils can lift up lightly-loaded structures. Since most of the lightly-loaded structures in Garden Estate exert foundation pressures in the range of 120-160 kN/m², they may have suffered distress because of heave.

Collapse test results for some sites also indicate that they can cause moderate to severe trouble in structures. Because the amount of moisture accessed under load varies at different parts of structures, it can be concluded that the cracking is caused by uneven settlement of different parts of the buildings. Development of pavement around structures will minimize the amount of moisture that accesses the base of the foundations and thus reduce differential settlement.

The results of the study also show that structures with defects exist side by side with those in sound condition. It is concluded that some methods of construction work well in these soils. These successful construction methods that are applied to minimize total and differential settlement in buildings are discussed here. They include use of strapped pad footings and inverted T-beam foundations, support of loads on ground beam in areas with sound layers underlying the soft overburden, laying foundations on mass concrete, removal and replacement or recompaction in layers. Since the methods are quite successful, the authors suggest use of the same approach for addressing similar subsoil problems. The successful methods are slightly more expensive that the conventional methods but cheaper when compared with the cost of underpinning or rebuilding.

7. ACKNOWLEDGEMENTS

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