Ground conditions of Sana'a City, Yemen Republic

KHALID AHMED AL-SUBA'I[1] AND KHALID ABDULLAH BARAT[1]

[1]*Earth & Environmental Sciences Department, Faculty of Science, Sana'a University, P.O. Box: 13226, Sana'a, Yemen (E-mail: ksubai@yahoo.com)*

ABSTRACT: Sana'a city, the capital of Yemen Republic, situated in a depositional basin surrounded by mountains and hills within the Yemen Highlands. In the surface and within a maximum depth of 25 m, a geotechnical assessment of subsoil and rock outcrops of the city is made.

The identified ground units consist of nine soil types (one fill, six natural cohesionless and two cohesive) and five rock types. The fill is of variable composition and consistency. The cohesionless soils are of medium to very dense relative density while the cohesive soils are varies from medium stiff to hard, low to high plasticity silt and medium stiff to hard, low to high plasticity clay. The rocks vary from moderately weathered, closely fractured medium strong basalts to fresh, widely fractured strong basalts and sandstone.

The results are presented as a computer output contour maps and plain surface map utilizing the Kriging technique and SURFER computer program for interpolation and combination.

The possibility of encountering the fill and the cohesive soils within the top 25 m of depth deserves particular attention in a Sana'a project. In the city margin areas where at least medium dense gravelly and sandy soils of appreciable thickness are found at the top, footings can be used for low to medium - rise buildings. In places where rocks are encountered, their strength, compressibility and thickness as well as those of the underlying layers, should be adequately evaluated before assigning a high bearing pressure on foundations placed on them. Care will be necessary to avoid sliding and collapse when a structure is founded on highly fractured stratoid or cavernous volcanic rocks.

Groundwater control measures are generally not required for usual construction. The sulphate and chloride contents in soil and groundwater are generally not call for protective measures for foundation concrete and reinforcement.

Résumé:

Les conditions du sol de la ville de Sana'a, République du Yémen

La ville de Sana'a, capitale de la république du Yémen, est située dans un bassin sédimentaire entouré par des montagnes et des collines sur les hauts plateaux du Yémen.

A la surface et jusqu' à une profondeur maximale de 25m, une expertise géotechnique concernant le sous - sol et les affleurements de roche de la ville a été réalisée.

Neufs types de sol ont été identifiés (un rempli, six naturellement non cohésif et deux cohésif), ainsi que 5 types de roche. Le remplissage est de composition et de consistance variables.

Les sols non cohésif ont une densité moyenne à élevée, tandis que les sols cohésifs varient de modérément dur à dur, avec des silts de plasticité faible à élevée, à modérément dur à dur avec des argiles de plasticité faible à élevée.

Les roches sont tantôt des basalts altérés et très fracturés, tantôt des basaltes et des grés moins altérés et fracturés .

Les résultats sont présentés sous forme de cartes utilisant la technique de krigeage_et le logiciel SURFER à été utilisé pour l'interprétation.

La possibilité de rencontrer de sol rempli dans les 25 premiers mètres nécessite une attention particulière dans le projet de Sana'a. Aux alentours de la ville ou une épaisseur appréciable de sols constitués de graviers et de sable modérément dense se trouve au sommet, des fondations peuvent être utilisés pour construire des immeubles de faible hauteur ou de hauteur moyenne.

Aux endroits où les roches sont présentes, leur résistance, leur compressibilité et leur épaisseur (comme celles des niveaux sous-jacents) devraient être évaluées avec justesse avant d'imposer une pression importante aux fondations édifiées dessus. Une attention particulière sera nécessaire afin d'éviter des glissements et des effondrements lors de l'édification d'une structure sur des strates intensément_fractureés ou sur des roches volcaniques cavrerneuses.

Des mesures de contrôle des eaux souterraines ne sont généralement pas demandées pour les constructions usuelles. Les contenus en sulfates en chlore des eaux souterraines ne sont généralement demandées en tant que mesures de protection pour le béton des fondations et leurs renforcements.

Keywords: geotechnical assessment, ground conditions, Sana'a city, geology of cities, Yemen.

1. INTRODUCTION

Sana'a, the biggest city of Yemen, is stand on northwest of Yemen highlands between latitudes 15° 16' N and 15° 30' N and longitudes 44° 09' and 44° 16' E. During the last few years, the city has been growing fast both vertically and horizontally to provide housing, business and other facilities to the ever increasing population which reach 1.75 million in the year 2004.(Central Statistical Organization,2005). For the period between 1988 – 2004, the city expanded by more than 3 times its area in 1988. Being restricted on the east and west by the mountains and hills, the city has been extending along the north-south axis and has already reach Al-Rahabah and Heziaz, about 20 km on both sides of the city center.

Al-Gassous**,**(1988) studied the deformation and shear strength characteristic of a part of the Sana’a soil and the site investigation reports (GDRL, 2002 and CEC, 2002) of some of the recent projects and buildings contain some geotechnical data about the Sana'a sub-soil. In particular, there is no investigations have so far been made to evaluate the basic geotechnical conditions of the rocks and there is also no systematic study has so far been made to combine the data available in the reports or to supplement them and to draw a general picture of the sub-soil pattern for use as a general guide in planning site investigations or in making preliminary assessment of foundation requirements of new projects. The present work is an attempt in this direction

2. LOCATION AND PHYSICAL CODITIONS

Sana'a city (Figure 1) is located in NW Yemen mainly in the southern part of Sana'a basin. The basin has an area of 3200 km2 and a mean altitude of about 2300m a.m.s.l. and it thought to be of Jurassic age with Jurassic sediments outcropping around much of its presumed northern portion while thick Tertiary flood basalts and eruptives (Yemen Volcanic Group) hide its possible southern extension (Beydoun, As-Satori, and Baraba, 1996). According to Al-Ubaidi and Al-Kotbah (2003), three main fracture trends was recorded in the basin. The first one is NE-SW which represent the old trend and probably rejuvenated from Hajaz Orogeny, the second trend is NW-SE which represent the most dominant fractures and major faults results in the formation of Jurassic basins and were accompanied with compressional strike slip and thrust faults which rejuvenated from Najid fault system, and the third and youngest trend is E-W which coincides with the trend of the Gulf of Aden. However, the old fractures of Jurassic and Cretaceous are obscured by the youngest trends of the Red Sea and the Gulf of Aden where all localities are highly dissected by these two trends. Figure 2 shows the surface lithology of Sana'a area. It includes a series of Mesozoic sedimentary rocks, Tertiary and Quaternary volcanic rocks and Quaternary alluvium sediments (Italconsult, 1973; Al-Subbary, 1990; Robertson Group plc,1990 and Al-Kadasi, 1994),

Morphologically, the area fashioned by the flat alluvium sediments Sana'a plain in the middle with an area of about 500 km^2 and rocky outcrops of irregular topography surround it. Flat tabular forms with deeply entrenched valleys characterize the area. Sana’a city is located on Sana'a plain and along a series of wadis which intersect the surrounding mountains and hills. The average temperature of the area is generally moderate (18 C^o). This average often increases in summer (23C^o) while it goes down in winter (13 C^o). The rainfall is bi-seasonal; the first one is the spring season (March - May) while the second season is the summer season (July- September). The average annual rainfall is 220 mm. The physical restrictions has limited the development of the city to the plain and main wadis which provide natural drainage course of the surface flow. Flooding by wadi waters was one of the problems of Sana'a in the past (Al-Moniafi, 1994;**,** Al-Shalaby, 2000; and SAWAS,1997**)**. However, a stormwater drainage system is now under construction in the city. This project well changed the hydro-geological situation in Sana'a area and is also having its Water table increasingly lowered by pumping from wells for urban use. This new setting is expected to improve the geotechnical behavior of the Sana'a soils described later in this paper

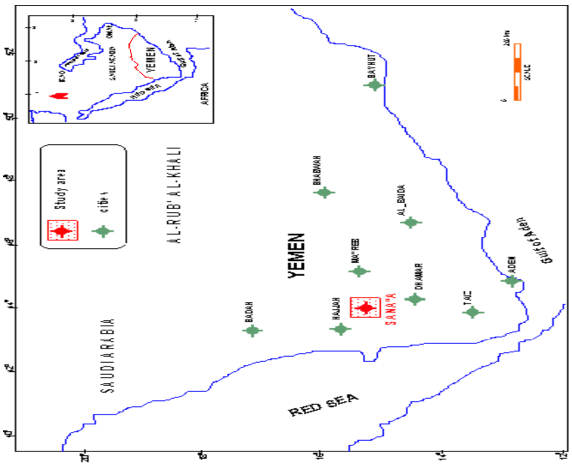

Figure 1: Location map of study area**.**

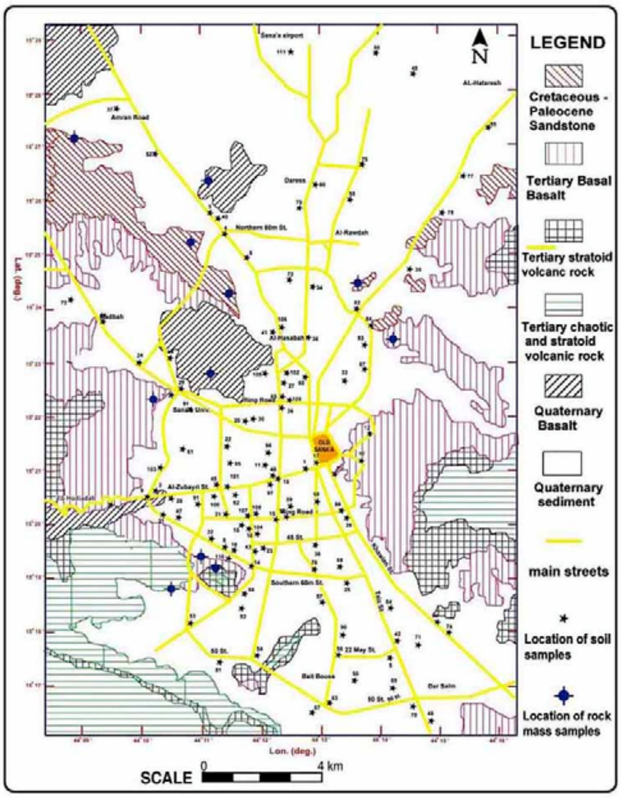

Figure 2: Generalized geological map of study area showing the main streets in Sana'a city and the locations of soil and rock samples**.**

3. MATERIALS AND METHODOLOGY

From the geotechnical point of view, the rock masses in the Sana'a area has not been subjected to any geotechnical studies in the past. In the present study, the Basic Geotechnical Description of rock mass (BGD) technique introduced by the International Society of Rock Mechanics, ISRM, (1981) was used to describe the geotechnical condition of surface rocks in the area.

The geotechnical data on soils were collected from site investigation reports of 69 projects completed or ongoing up to 2002 provide by the General Directorate for Researches and Laboratories (GDRL) in the Ministry of Public Works and Highways and by Consulting Engineering Center (CEC) (Sajdi and Partners, Yemen Branch) and from authors' own work at 42 stations. The reports most commonly include a borehole logs with soil descriptions and N-values from Standard Penetration Test (SPT) designated as N(SPT) . The authors' field work included (i) soil and water sampling from pit of buildings foundations and more frequently from trenches and pits of sewage sewerage; (ii) standard penetration test (SPT); and (iii) undisturbed soil sampling from the bottom of open excavations, while the laboratory work included (i) determination of Physical properties;(ii) classification; and (iii) direct shear test which are reported in detail by Barat (2003). Figure 2 shows the spot locations of sampling sites.

Geostatistical Kriging technique introduced by Matheron (1963) and extended by a number of authors (e.g. Krige, 1976; David, 1977; Journel & Huijbregts,1978; and Myers, 1984) was used for interpolation and combination the data for construction of spatial and vertical distribution maps of different soil types in Sana'a city and the SURFER computer program (Golden Software Company, 2002) ,ver.8, was utilized to produce these maps.

4. GEOTECHNICAL GROUND CONDITIONS

4.1. Geotechnical Characteristics of Soil Types

Within a maximum depth of 25 m and based on all the data on the composition, plasticity, classification and consistency/relative density of soils from the reports and from authors' tests, the soils of Sana'a city could be categorized into 9 groups one "fill" and 8 natural varieties of soils, of which six are cohesionless and two are cohesive. Table 1 show the ranges of the geotechnical characteristics of these soil types and some general comments are made in the following paragraphs.

4.1.1 Fill (non-engineering)

This layer is a mixture of disassembled natural soil, building remains and rubbish. It may contains some materials such as wooden piece, paper, tins, bricks and stone. The thickness of this layer is ranged between 0.4 and 3 meters and it mainly occurred in the surface.

Table 1. The ranges of the geotechnical characteristics of naturally soil types in the Sana'a city

Soil type	W_c (%)	G_s	$_b$ gm/cm^3	$_d$ gm/cm^3	LL (%)	PL (%)	PI (%)	C (Kg/cm^2)	ϕ degree	N
Well to poorly graded gravel	4-14	2.6-2.9	1.6-2.2	1.4-2	-	-	-	-	-	40-R*
Well to poorly graded gravel with silt	4-20	2.6-2.8	1.7-2.2	1.5-1.8	27-52	14-35	2.6-17	-	-	31-R
Well to poorly graded silty gravel	2-17	2.6-2.8	1.9-2.2	1.7-1.9	24-56	22-32	2.5-24	-	-	24-R
Well to poorly graded sand	6-18	2.6-2.7	1.7-2.1	1.7-2	-	-	-	-	-	26-R
Well to poorly graded silty sand	5-29	2.5-2.8	1.5-2.2	1.4-1.9	24-54	17-41	0.6-14	0.02-0.21	12-40	14-R
Well to poorly graded clayey sand	5-22	2.6-2.8	1.6-2.3	1.4-2	19-42	10-24	8-21	0.0-0.26	24-38	19-R
Low to high plasticity silt	6-44	2.5-2.8	1.5-2.3	1.3-1.9	25-64	22-43	0.3-29	0.0-0.26	18-42	6-51
Low to high plasticity clay	8-39	2.5-2.8	1.4-2.1	1.1-1.9	24-62	13-29	8-32	0.0-0.1	15-38	8-38

* W_c: water content * G_s: specific gravity * $_b$: Bulk density * $_d$: dry density * LL: liquid limit * PL: plastic limit
* PI: plasticity index * C: cohesion * ϕ : internal friction angle *N value from SPT * R : refusal to penetration

4.1.2. Gravel, gravel with silt and silty gravel

Figure 3 shows the gradation limits curves for these soil types in study area which are largely overlapping. The moisture content (W_c) ranges from 2.4 to 20 % while specific gravity (G_s), bulk density (γ_b) and dry density (γ_d) are in the ranges of 2.6 - 2.9, 1.6 - 2.2 gm/cm^3 and 1.4 - 2.0 gm/cm^3 respectively. All these soil types are dense to very dense soil, with N-value ranged between 31 and Refusal to penetration (R). The PH values are generally ranged between 7.5 and 8, which indicating slightly alkaline. The average of sulphate, chloride and organic matter content are 0.05 %, 0.05 % and 0.02% respectively.

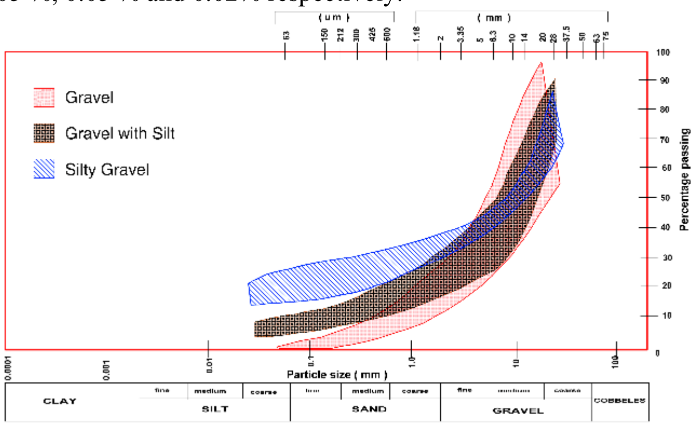

Figure 3: Gradation limits of gravel, gravel with silt, and silty gravel soils

4.1.3. Sand, silty sand and clayey sand

These soil types have a wide extent in the study area with gray to brown color. The limits of gradation curves for them are given in Figure 4 which are partially overlapping. The ranges for moisture content, specific gravity, bulk density and dry density are 6 - 28%, 2.6-2.7, 1.7-2.1 gm/cm^3 and 1.7-2 gm/cm^3 respectively. All these soils have relative density of medium to very dense. The averages of PH value, sulphate content, chloride and organic matter content are 8, 0.021%, 0.02%, 0.03% respectively. The P^H indicate slightly alkaline and sulphate contents indicate negligible to low aggressive soil. The range of cohesion is from 0.02 to 0.21 kg/cm^2 and the internal friction angle from 12^0 to 40^o . These values and the predominance of these soil types indicate the validity of the commonly used method of strength estimation based on $N_{(SPT)}$ for general geotechnical activities in Sana'a city.

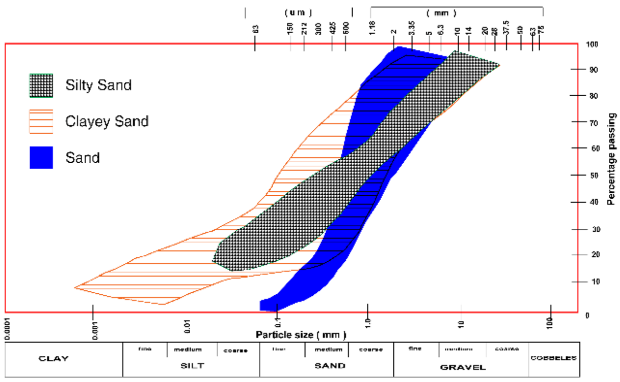

Figure 4: Gradation limits of sand, cayey sand, and silty sand soils

4.1.4. Low to high plasticity silt (ML, MH).

It is of light to dark brown color. The grading limits and the plasticity characteristics for this soil type are given in Figure 5 and Figure 6 respectively. The range of plasticity index indicated low to high plasticity soil. The moisture content varies with depth from 6 to 44%. These natural water contents which are closer to the plastic limits than to the liquid limits suggesting this soil to be over-consolidated to various degrees. The ranges of specific gravity, bulk density and the dry density are 2.5 - 2.8, 1.5 - 2.3 gm/cm^3 and 1.3 - 1.9 gm/cm^3. The P^H value, sulphate content, chloride content and organic matter averages are 7.7, 0.03%, 0.03% and 0.029% respectively. The P^H indicate slightly alkaline and sulphate and chloride contents indicate negligible to low aggressive soil. The ranges of cohesion and internal friction angle which obtained from direct shear test for undisturbed samples are 0.0 - 0.26 kg/cm^3 and 18 - 42^o respectively. This indicated medium strength. The N-values are in the range of 6 – 51 which indicate medium stiff to hared soil.

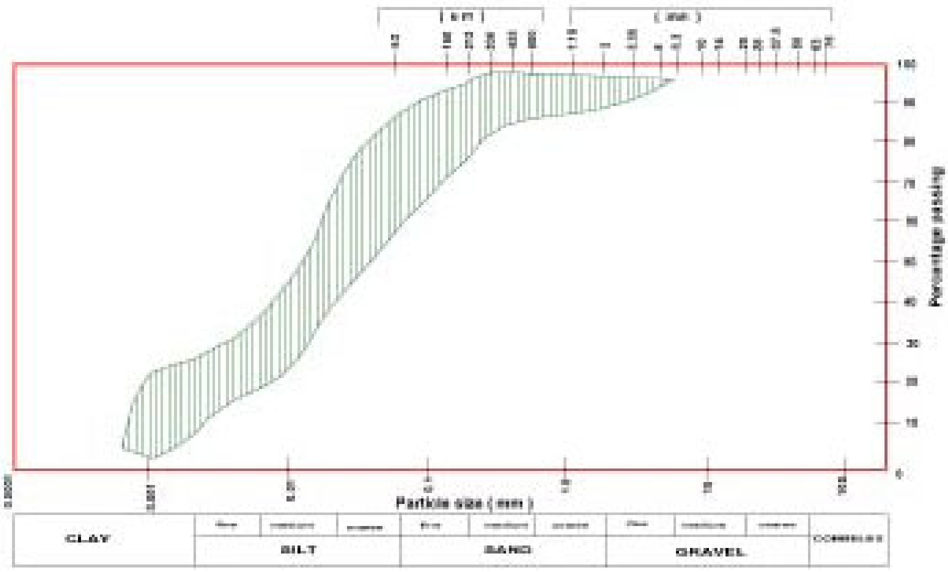

Figure 5: Limits of Grading curves for silt soil

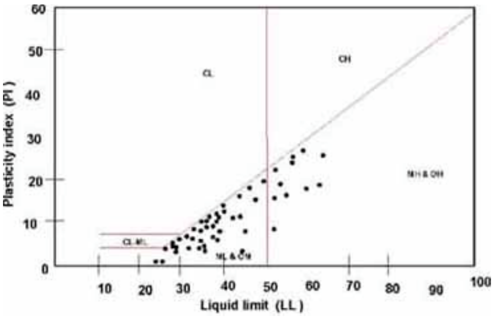

Figure 6: Plasticity chart for silt soil

4.1.5. Low to high plasticity clay (CL, CH).

Figure 7 shows the position of this soil type on the plasticity chart. The soil is very similar to the silt soil in respect of the color, grading ranges, physical and chemical properties and the value of liquid limits. The soil is the weakest soil in Sana'a city with $N_{(SPT)}$ value in the range of 8 to 38 and cohesion and internal friction angle in the ranges of 0.0-0.1 kg/cm^3 and 15-38^o respectively.

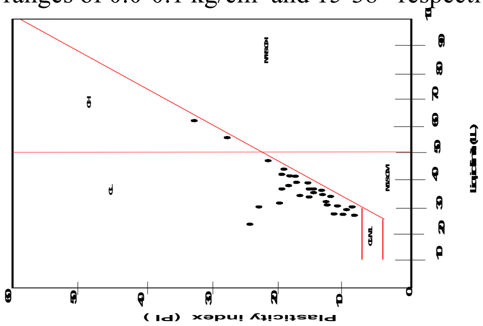

Figure 7: Plasticity chart for clay soil

4.2. Main Rock Types and its Geotechnical Characteristics

According to previous geological studies (e.g. Italconsult,1973; Al-Subbary, 1990; Robertson Group plc,1990 and Al-Kadasi, 1994) five rock types are outcropped in the surface of Sana'a city. No geotechnical data on these rocks are available in previous studies and there is no boreholes extended to rock-head at depth in the available site investigation reports. The authors' own inspection include a preliminary geotechnical investigations on the outcrops and along sides of open excavation of these rock types using the basic geotechnical description technique(BGD) of ISRM (1981). Table 2) summarized the ranges of the geotechnical characteristic of these rock types at the surface whereas some general comments are given in the following paragraphs. The uniaxial compressive strength were generally estimated from Schmidt hammer hardness readings through the approximate correlations of Dear and Miller (1966). The friction angle values were approximated based on Hoek and Bray (1981).

Table 2: The ranges of geotechnical characteristics of the rock unites in the Sana'a city.

Rock name	Weathering	L cm	F cm	S MP	A angle	Density KN/m^3
Cretaceous-Paleocene Sandstone L_1, F_1, S_2, A_2	W_1	>200	165 - >200	65 – 100	35 – 45^o	23-27
Tertiary Basal Basalt L_1, F_4, S_3, A_2	W_2 to W_3	>200	12 – 18	40 – 52	35 – 45^o	26-30
Tertiary Stratoid Volcanic Rock (Ignimbrite) L_2, F_2, S_3, A_2	W_1	110 - <200	48 – 120	24 – 46	35 – 45^o	24-27
Tertiary Chaotic and stratoid volcanic rock L_1, F_2, S_3, A_2	W_2	>200	50-<200	24-46	35 – 45^o	23-27
Quaternary Basalt L_0, F_2, S_2, A_2	W_1	massive	84 - 184	140 - 152	35 – 45^o	27.6-28.4

L= Layer thickness, **F**= Fracture intercept, **S**= Uniaxial compressive strength, **A**= Friction angle

4.2.1. Cretaceous - Paleocene Sandstone (L_1, F_1, S_2, A_2)

This rock type is light brown in color and has a wide spatial extent in study area. It is exposed along Amran road and Wadi Dhahr road, Northwest of study area, as well as along Mareb road, northeast of study area (Figure 2). The outcrops are generally fresh (W_1) with slight discoloration to black on surface. The layer thickness is of more than 200 cm, which indicate very large thickness (L_1). The fracture intercept is of 165 cm to more than 200 cm. This indicate wide fracture intercept(F_1). The density is between 23 and 27 KN/m^3 and the uniaxial compressive strength is between 65 and 100 MP. This range indicate high compressive strength rock (S_2). The friction angle value is between 35 and 45^o which indicate high friction angle (A_2). According to ISRM (1981), this rock mass can be classified as : Cretaceous-Paleocene Sandstone L_1, F_1, S_2, A_2 .

4.2.2. Tertiary Basal Basalt (L_1, F_4, S_3, A_2)

Tertiary basal basalt have a widely spread in east and west of study area (Figure 2). It dark green to dark gray color and fine grains. The thickness varies from more than 10 m to less than 30 m. The range of weathering is from slightly to moderately weathered (W_2 to W_3). limited areas may has highly weathered and in some locations shows small caves with diameters between 20 to 30 cm. The layer thickness (L_1) is more than 200 cm with close fracture intercept (F_4). In some locations it shows columnar Features. The averages of Schmidt hammer hardness and the density of this rock type are 26 and 30.1KN/m^3 respectively which indicate moderate compressive strength (S_3). The approximate friction angle value is between 35 and 45^o which indicate high friction angle (A_2). The geotechnical description of this rock unit in study area can be assigned as: Tertiary Basal Basalt L_1, F_4, S_3, A_2.

4.2.3. Tertiary Stratoid Volcanic Rock (L_2, F_2, S_3, A_2)

This rock type is outcrop in east and west of study area (Figure2). It is fine grained tufts with some coarse grained pyroclastic fragments. It have green, red and pink color with different thickness which is generally less than 10 m. Mostly, it unweathered (W_1) and has slight discoloration on the surface. The range of the layer thickness is between 120 and 160 cm which indicate large layer thickness (L_2). The fracture intercept is wide (F_2). It is of low density and low to moderate strength(S_3). The friction angle is between 35 and 45^o which indicated high friction angle (A_2). The general geotechnical description of this rock unit in study area is Tertiary Stratoid Volcanic Rock (Ignimbrite) L_2, F_2, S_3, A_2.

4.2.4. Tertiary Chaotic and Stratoid Volcanic Rock (L_1, F_2, S_3, A_2)

This rock unit outcrops in the east, west and southwest of the study area (Figure 2). It is dark gray in color with thickness of more than 100 m specially in the southwest part of the study area. The rock unit is slightly weathered (W_2), very large layer thickness (L_1) and wide fracture intercept (F_2). It has moderately compressive strength (S_2) and high friction angle (A_2). The general geotechnical description of this rock unit in study area is: Tertiary Chaotic and Stratoid Volcanic Rock L_1, F_2, S_3, A_2

4.2.5. Quaternary Basalt (L_0, F_2, S_2, A_2)

The outcrop of this rock unit lies in the center and northwest of study area in Madbah, Dahban and Wadi Dhahr road (Figure 2). It is fine grained massive and sheet rock with dark gray color. The thickness of the bed is less than 10 m. This rock type is generally unweathered (W_1), and massive (L_0). The range of fracture intercept is between 84 and 164 cm, which indicate wide fracture intercept (F_2). The averages of density and Schmidt hammer hardness of this rock type are 28 KN/m^3 and 51 respectively. This indicate high compressive strength (S_2). The approximate range of friction angle is between 35 and 45^o which indicate high friction angle. The general geotechnical description for this rock unit in study area is Quaternary Basalt L_0, F_2, S_2, A_2 .

5. WATER TABLE

During the 1995, the ground water table in Sana'a city was at a depth range of 47 to 270 m (below the ground surface) except for perched water at smaller depths in some locations possibly related to local sanitary facilities in absence of modern sewerage lines. Very little groundwater problem is encountered now-a-days during ordinary construction work in Sana'a city due to the lowering of the water table to depths exceeding 47 m.

6. SURFACE SOIL AND ROCKS MAP

Figure 8 shows the surface distribution of the different soil and rock types in the Sana'a city. It is observed that the central part of study area show eight different soil types in surface (Fill, Sand, clayey sand, clay, silt, silty sand, silty gravel and gravel) while the northern and southern parts of study area show four soil types (silt, silty sand, clay and silty gravel) in the surface. The silt and silty sand soil are the dominant surface soil types in study area. Fill forms a surface layer in very small scattered areas.

Tertiary Volcanic rocks form a surface layer mostly in the southern, eastern and western parts of study area and the Quaternary Volcanic rocks appear on the surface in the northwest while the Cretaceous-Paleocene Sandstone occurred in the northwest and northeast parts of study area.

7. SPATIAL AND VERTICAL DISTRIBUTION OF MAIN SOIL TYPES

The horizontal and vertical extent of the various soil types can be assessed from Figure 9 through Figure11. Because the boundaries between strata are more or less irregular, all of these figures are of erratic type. Although these figures are self explanatory, a few general comments are made herein.

The fill layer appears to be of local occurrence found as a thin layer with maximum thickness of 1.5 m in the central part of study area.

Figure 9 shows the horizontal and vertical extent of gravel soils (gravel, gravel with silt and silty gravel). It is generally a subsurface layer and has a maximum horizontal extent in the central part of study area along Al-Zubayri street. The maximum thickness of this soil is 15 m in the northwest of study area. The gravel with silt had narrow horizontal

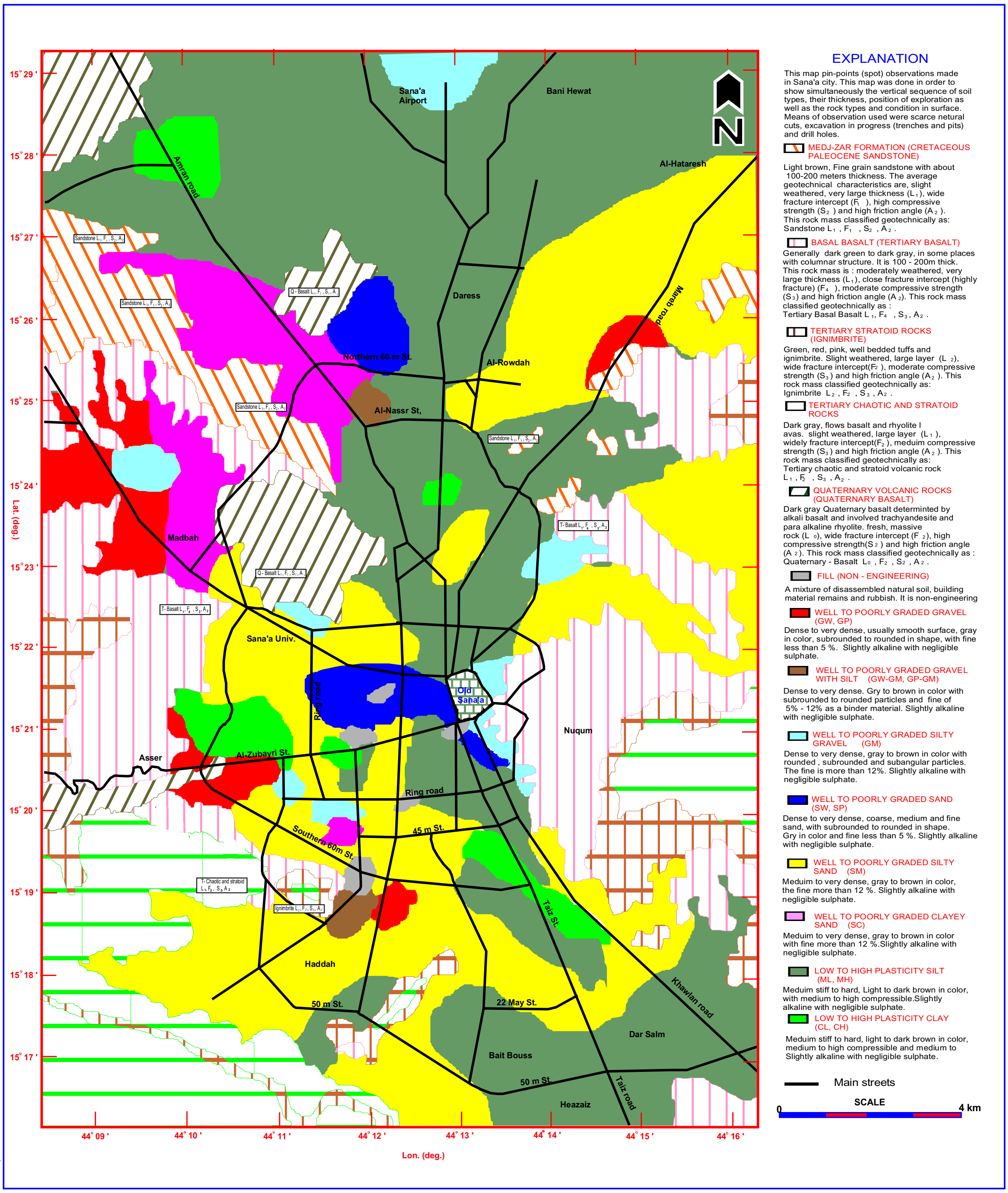

Figure 8 : Distribution of the different surfacial soil and rock types in Sana'a city

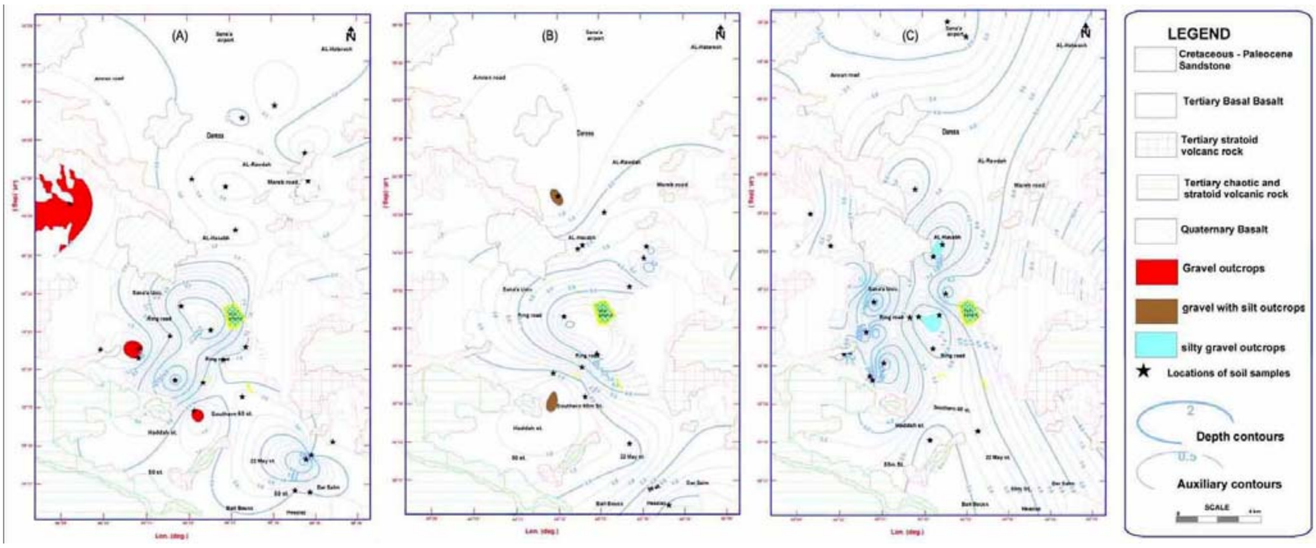

Figure 9: Approximate horizontal and vertical distribution of (A)gravel, (B) gravel with silt and (C) silty gravel soils in Sana'a city (contours in meter)

extent in the Amran road, Southern 60 m street, Al-Safia, Al-Zubayri street. and Airport road with. maximum thickness of 7.1 m in the southern part of the study area. The distribution of silty gravel soil occurred in whole study area with a maximum thickness of 6 m.

The sand soils (sand, silty sand and clayey sand) had wide spread in the study (Figure 10). Sand exposes in limited area in 40 m street and Amran road with maximum thickness of 21 m in the 40 m street. On the other hand, silty sand appear in whole study area either in the surface and subsurface, with maximum thickness of 15.6 m in southern part of study area

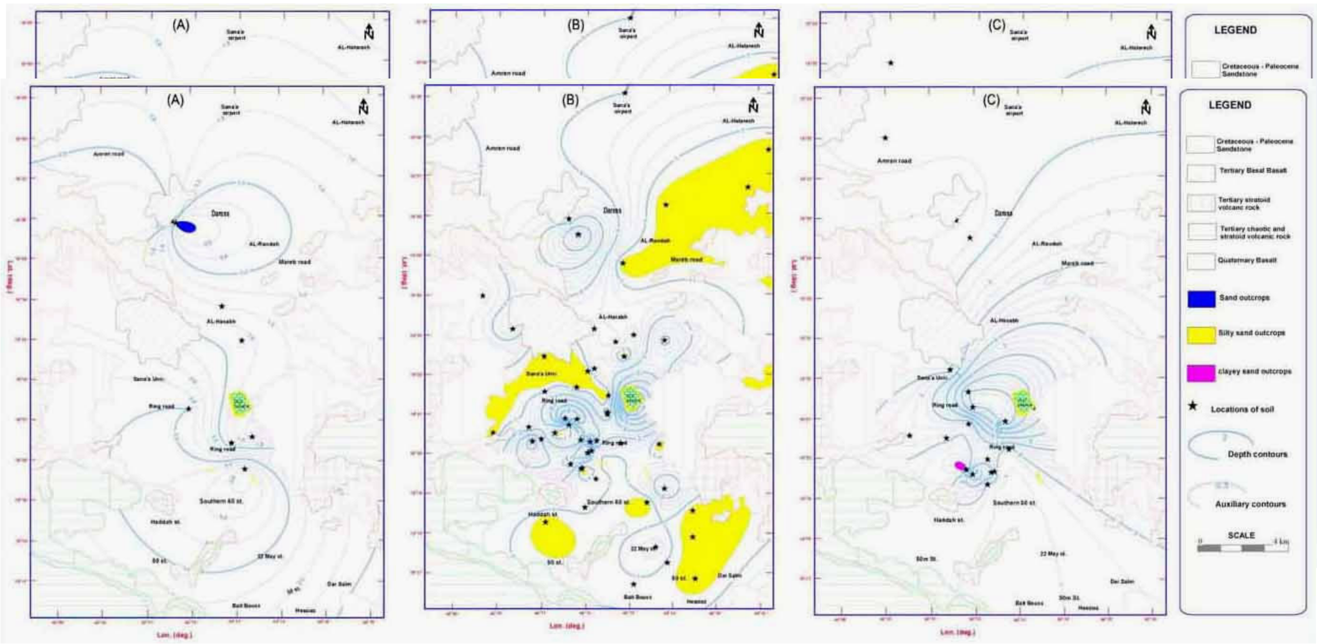

Figure 10: Approximate horizontal and vertical distribution of (A) sand, (B) silty sand and (C) clayey sand soils in Sana'a city (contours in meter)

(Taiz street). The clayey sand layer is found in narrow area in depth of more than 2 m to 23.5 m under the ground surface and with maximum thickness of 11.5 m in the northern part of study area (Amran road).

Figure 11 shows the horizontal and vertical extent of silt and clay soils. The silt soil shows a wide extent in the study area with maximum thickness of 12 m. The clay soil is spread under the ground surface from the crossing between Western 60 m street and Al-Zubayri street in the west to the Khawlan road in the east of study area. The maximum thickness of clay soil is 7.2 m.

The horizontal and vertical distribution of different soil types indicate that the study area was under irregular depositional system. These systems consist of two process. The first process is the longitudinal depositional by water channels which extent from south to north such as Al-Saylah channel. The second process is that the study area is affected by the crosscut deposition from the channels of water which came as a result of water bursts in high power from the mountains which are surrounded the study area especially in eastern and western parts. Therefore, it can be mentioned that the recent deposits in Sana'a city is trapped in small basins between the main channels of water due to the effect of the crosscut and longitudinal channels on the depositional process. So it can be consider that the Sana'a city is a large depositional basin containing several minor depositional ones.

(A) **(B)**

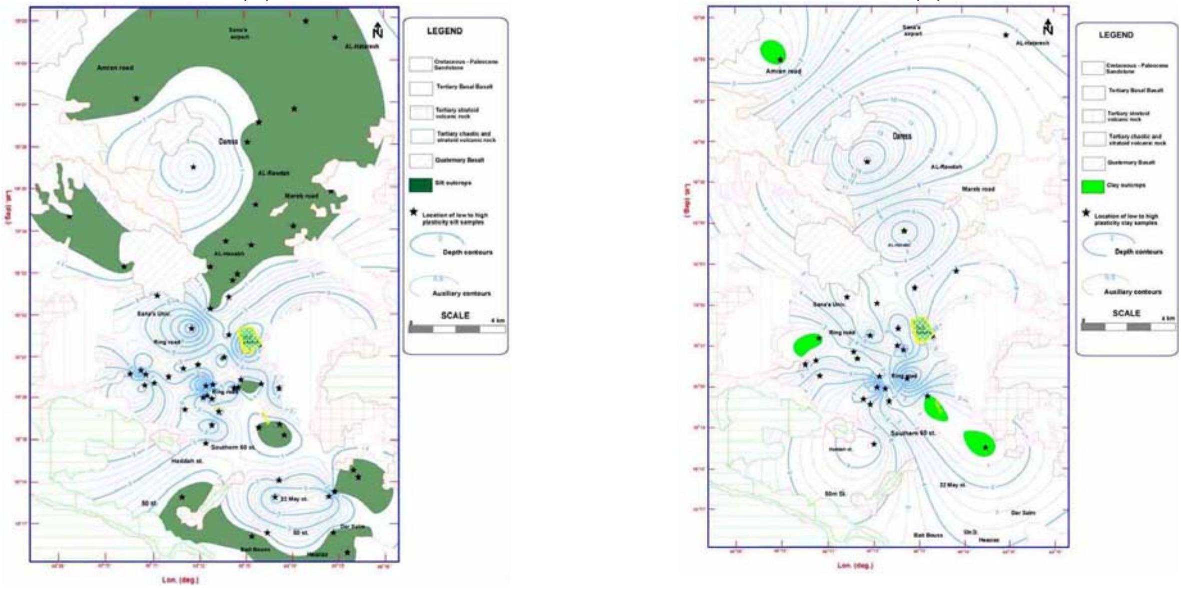

Figure 11: Approximate spatial and vertical distribution of (A)silt and (B) clay soil in Sana'a city (contours in meter).

8. SUMARY AND CONCULOSIONS

The present study reveal the variety of soil and rock types and their preliminary geotechnical characteristics in Sana'a city. The city is situated in a depositional basin of varying thickness increasing northwarded and surrounded by mountains and hills from east, west and partially from the south within the Yemen Highlands. In the surface and within a maximum depth of 25 m, the ground in Sana'a city consists of nine soil types and five rock units.

The soil types are: 1) the fill of variable composition and consistency, 2) the gray dense to very dense well to poorly graded gravel, 3) the gray to brown dense to very dense well to poorly graded gravel with silt, 4) the gray to brown dense to very dense well to poorly graded silty gravel, 5) the gray medium to very dense well to poorly graded sand, 6) the gray to brown medium to very dense well to poorly graded silty sand, 7) the gray to brown medium to very dense well to poorly graded clayey sand, 8) the light to dark brown medium stiff to hard low to high plasticity silt, and 9) the light to dark brown medium stiff to hard low to high plasticity clay.

The rock types are: 1) the light brown, slightly weathered and widely fractured strong cretaceous- Paleocene sandstone, 2) the dark green to dark gray, slightly to moderately weathered and closely fractured medium strong tertiary basal basalt, 3) the green, red or pink, fresh and widely fractured medium strong, tertiaty stratoid volcanic (ignimbrite) rock, 4) the dark gray, slightly weathered and widely fractured, medium strong tertiary chaotic and stratoid volcanic rock, and 5) the dark gray, unweathered, widely fracture and strong quaternary basalt.

The well to poorly graded silty sand and the low to high plasticity silt form the top layer over most of the Sana'a city areas while the gravelly and sandy soils occur at surface in the western part of the city. the Tertiary and Quaternary basaltic rocks occur at surface along the city margins, specially in east and west.

The possibility of encountering the fill and the cohesive soils within the top 25 m of depth deserves particular attention in a Sana'a projects.

In the city margin areas, specially those in the west, where at least medium dense gravelly and sandy soils of appreciable thickness are found at the top, footings can be used for low to medium – rise buildings.

In places where rocks are encountered, their strength, compressibility and thickness as well as those of the underlying layers, should be adequately evaluated before assigning a high bearing, pressure on foundations placed on them. care will be necessary to avoid sliding and collapse when a structure is founded on highly fractured stratoid or cavernous volcanic rock.

Groundwater control measures are generally not required for usual construction in Sana'a city due to the lowering of the water table to depths exceeding 25 m. The sulphate and chloride contents in soil and groundwater are generally not call for protective measures for foundation concrete and reinforcement.

This study is limited by the number of site investigation reports and the accuracy therein, and the number of tests made by the authors and hence the findings should be used as a preliminary guide to plan detailed investigation for any specific project.

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