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Ground Conditions in Al-Madinah Al-Munawarah, Saudi Arabia

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ABSTRACT. The Saudi Arabian City of Al-Madinah is situated in a depositional basin surrounded by lava plateaus and hills within the western part of the Arabian Shield. Within a maximum depth of 45 m, the sub-soil in Al-Madinah consists of nine soil types (one "fill", six natural cohesive and two cohesionless) and three rock types. The cohesive soils vary from highly compressible organic clay and soft compressible/swelling grey-green clay to hard clay while the cohesionless soils are of medium to very dense relative density. The rocks vary from weak limestone to massive gabbrow. The "fill" and some of the other soils occur at the top while the rocks occur either at depth or as isolated hilly outcrops.

Poor or problematic ground conditions are encountered down to a maximum depth of 15 m in some areas to the south, east and north-east of the Prophet's Mosque due to the presence of weak soils with high compressibility and/or swell potential.

Protective measures for foundation concrete and reinforcement are necessary due to aggressive ground conditions. Ground water control measures are generally not required for usual constructions.

1. Introduction

The holy city of Al-Madinah Al-Munawarah is located in Western Saudi Arabia. The recent oil-boom initiated a large volume of development work in it. The site investigation reports of some of the recent major projects of Al-Madinah like the large-scale expansion of the Prophet's Holy Mosque and The Ring Roads contain a large volume of geotechnical data about the Al-Madinah sub-soil which has little been studied except for Erol *et al.* (1981), Dhowian *et al.* (1990) (on the swelling potential of two Al-Madinah clays), Sabbagh and Abuzaid (1991) (on reduction of swelling pressure of a remolded Al-Madinah clay), Fatani and Al-Zahrani (1991) (on stabilization of a Al-Madinah clay by scoria plus cement), the two latter works being based on two M.Sc. theses by Al-Zahrani (1989) and Abuzaid (1990) respectively. In particular, 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, and in this process, it shows that the number of Al-Madinah clays with swelling potential is more than two recognized by earlier researchers and that they occur at different depths in different areas, and it also shows that there are some areas in Al-Madinah which are free of swelling clays.

2. Location, Climate, Physiography, Landuse, Geology and Hydrological Setting

Al-Madinah Al-Munawarah is located within the western part of the Arabian Shield with the Prophet's Holy Mosque at the city centre at a latitude of about 24° 28′N and a longitude of 39° 26′E (Fig. 1).

Al-Madinah area is characterized by an arid climate with the maximum summer temperature, sometimes, reaching 48°C and minimum winter temperature going down to 2°C. The maximum average monthly rainfall (in winter) reaches upto 17 mm (M.A.W. 1984a, 1984b).

Figure 2 shows that the city of Al-Madinah is built on a nearly flat basin area about 6 km × 10 km surrounded by hills (e.g. Jabal Uhud on the north, Jabal Ayre on the south-west, the Arabic word "Jabal" meaning a hill) and lava plateaus. The ground surface elevation in the city area is around 600-610 m above mean sea level (m.s.l.) except for some isolated small hills like Jabal Sela, and there is a gentle downward slope towards the north-west. The elevations of the lava plateaus and the hills are in the ranges of 620 to 750 m and of 900 to 1100 m respectively above the m.s.l.

The Prophet's Holy Mosque at the city centre appears to have influenced the growth of the urban area outwards with two sets of roads: one set of radial roads and the other set of ring roads, leaving the areas with date palm gardens on the north, north-east, south and south-east.

Figure 3 shows the geological map of Al-Madinah area based on Brosset (1976) and Pellaton (1977 and 1981). The oldest rocks in Al-Madinah are two main groups of Upper Proterozoic rocks namely, Al Ays Group, represented by the Urayfi formation and the overlying Furayh Group represented by the Qidirah and Dawnak formations. The Urayfi formation consists of epiclastic and interbedded silicic volcanic rocks occurring in the north (e.g. Jabal Uhud) and in the north-east and it is intruded by gabbro stocks at some places (e.g. Jabal Sela in the city area). The Qidirah formation is composed of volcanic rocks like andesite and basalt outcropping as small hills south-west of the city while the Dawnak formation is composed of various detrital rocks such as sandstone, conglomerate, siltstone, tuff and marble outcropping south of Al-Madinah (e.g. at Jabal Ayre). The Furyah Group is intruded by a granitic stock

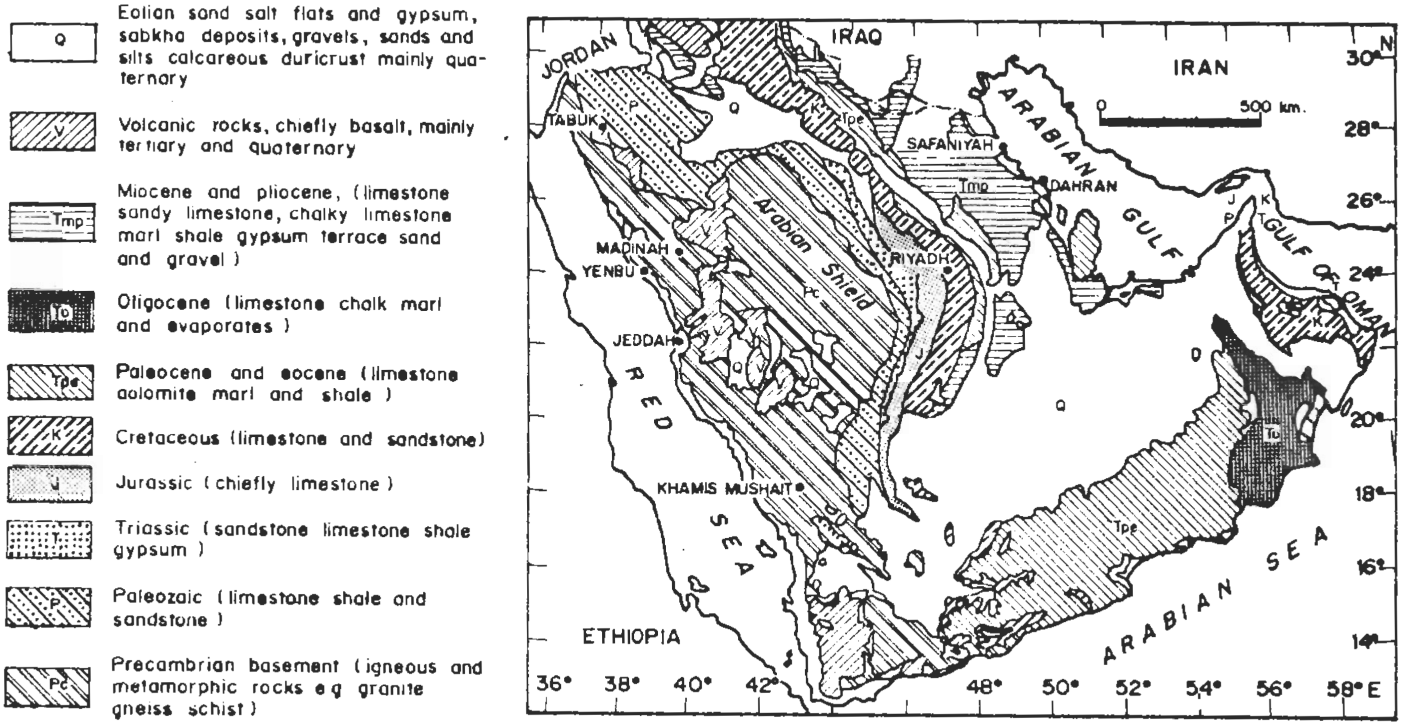

FIG. 1. Location of Madinah within the Arabian Shield (After, Oweiss and Bowman 1981).

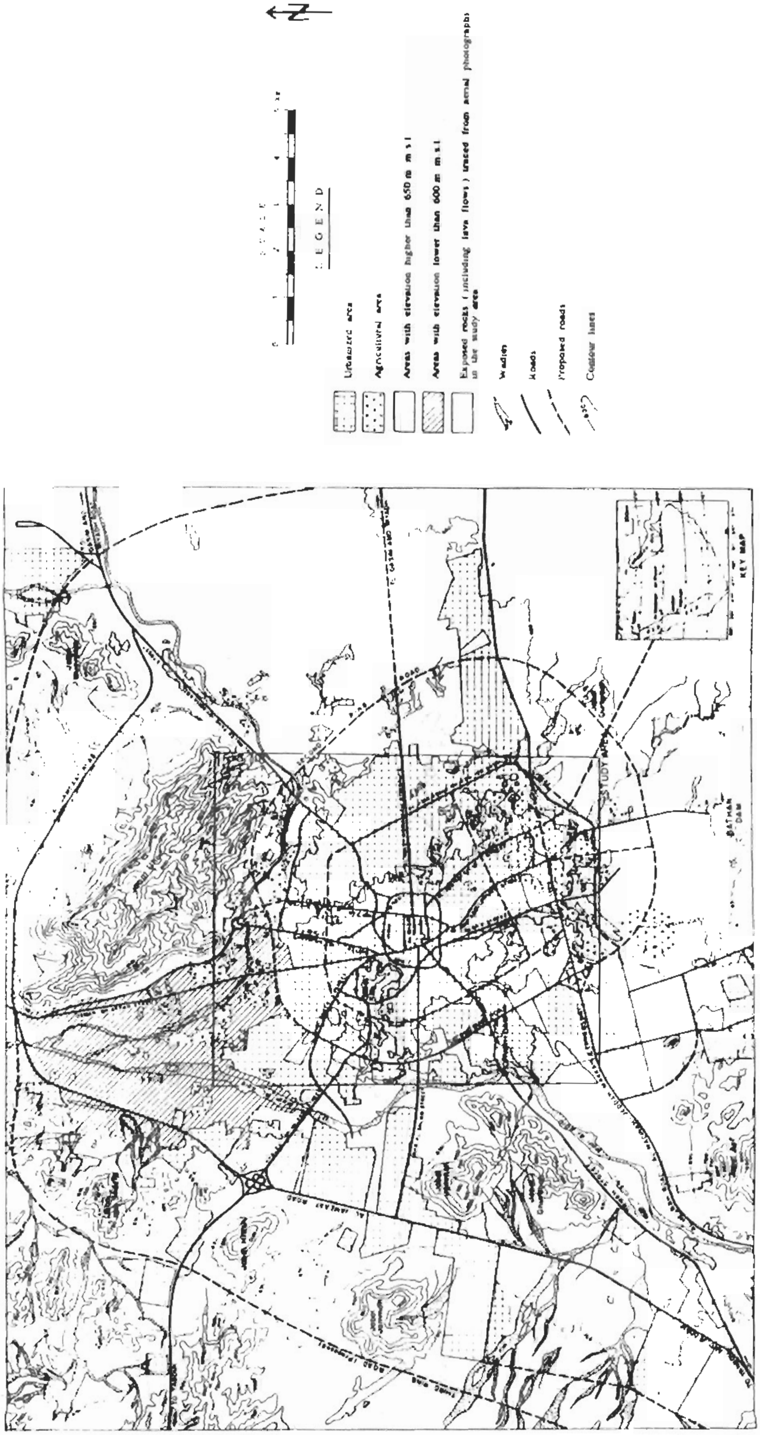

FIG. 2. Physiography, Elevation and Landuse Map of Madinah Area (After Farsi 1986).

found to the west and north-west. In many places, these rocks are covered by basaltic lava flows.

The lava plateaus of Harrat Rahat surrounding the city from east, south and west (Fig. 3) are of Tertiary and Quaternary age. According to Abed (1977), the latest lava flow occurred in 630 A.H. (i.e. after Hijrah) at a location north-east of Al-Madinah.

Two major wadis border Al-Madinah. They are the Wadi Al-Aqiq and Wadi Qana. Wadi Al-Aqiq flows northward along the west and after it is joined by Wadi Qana from the east, if flows further north with the name Wadi Al-Himd. These wadis form the main drainage outlet for the Al-Madinah basin which stands on the up-stream side of their confluence and hence was the site of relatively still water in the geological past. On the surrounding basalt plateaus, the drainage pattern is less developed, as erosion has not yet affected the basalt very deeply, and only a few small shallow intermittent wadis stand out. They generally end up in small closed depressions or sabkhas (i.e. land area with salt-rich sub soil) but some of them are directed towards the city (e.g. Wadi Bathan south of the city).

The above hydro-geological setting led to the desposition of large thickness of Tertiary and Quaternary deposits in Al-Madinah in the geological past (Parsons Brown International 1977). Flooding by wadi waters was one of the problems of Al-Madinah in the past. However, three dams (two of them namely, the Bathan Dam and the Orwah Dam shown in Fig. 2) were constructed within the last fifty years to reduce flood and to recharge the basaltic aquifer south of the city (Group of Arab Consultants for Development and Reconstruction 1980). These dams have changed the hydro-geological situation in Al-Madinah area (Makki 1979) which is now free of floods and is also having its water table increasingly lowered by pumping from wells for urban use. This new setting is expected to influence the geotechnical behaviour of the Al-Madinah soils described later in this paper.

3. Geotechnical Data

Geotechnical data for the present study were collected from site investigation reports of 84 projects, completed or ongoing in 1987 and listed in Table A-1 in Appendix, and from authors' own work at 17 stations. The reports most commonly include borehole logs with soil descriptions and N-values from Standard Penetration Test (SPT) designated as $N_{(SPT)}$. Some of the important projects whose site investigation reports were studied are:

i) the Prophet's Holy Mosque Expansion Project (Bin Ladin Organization 1983).

ii) Extension of Quba Mosque, Al-Madinah (Jazzar Trow Middle East 1984).

iii) Al-Madinah Ring Road and Multi-storey Car Parks Phase-4 (Parsons Brown International 1977) and

iv) Manakha Street Tunnel, Al-Madinah (Cansult Ltd. 1981).

Figure 4 shows the locations of the studied projects and the authors' stations. The authors' field work included (i) auger boring with soil and water sampling; (ii) static

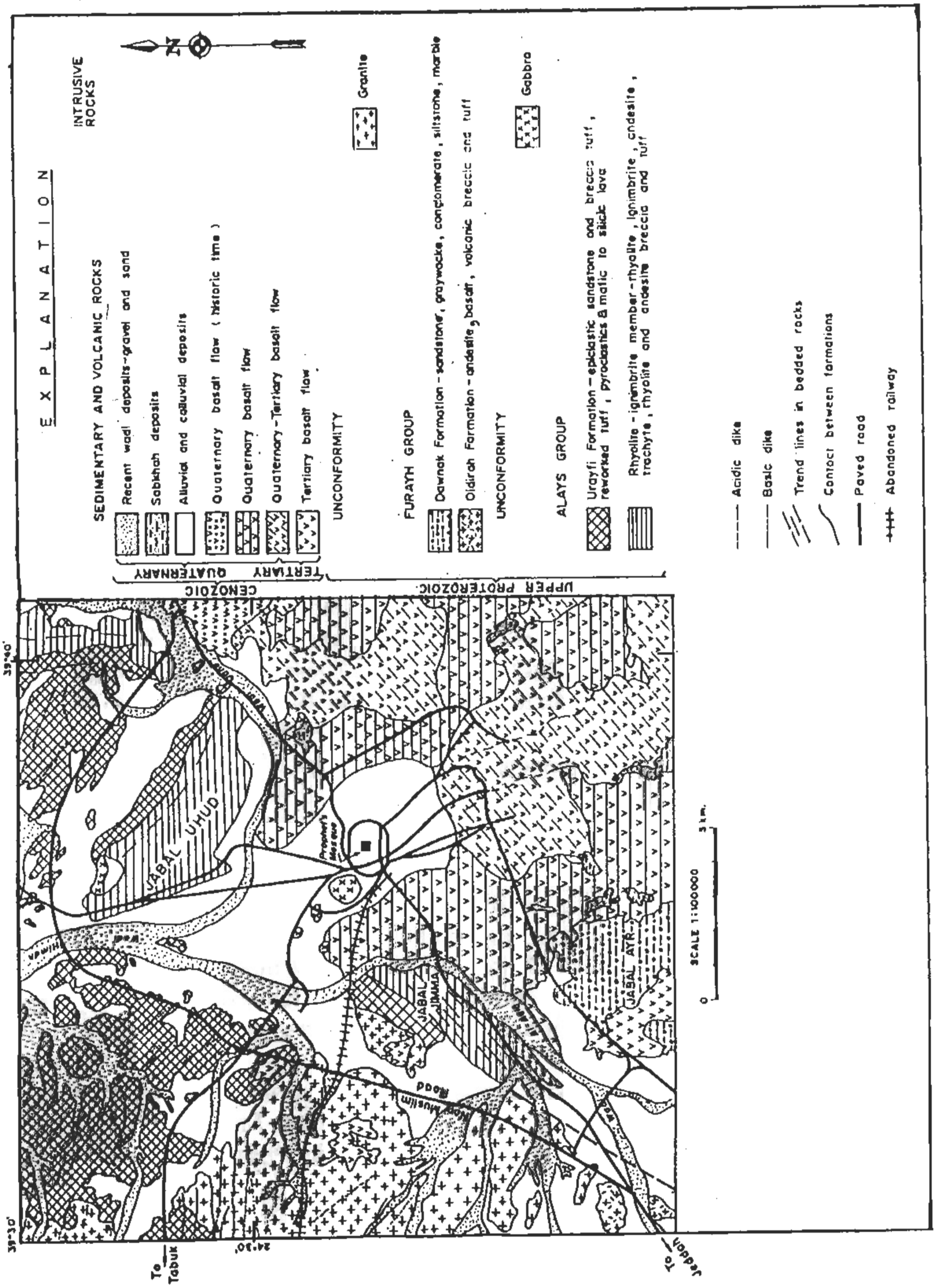

FIG. 3. Geological Map of Al-Madinah area (After Brosset 1976; Pellaton 1977 and 1981).

cone penetration test (CPT); (iii) Mackintosh probing (Chan and Chin 1972); and (iv) undisturbed soil sampling from the bottom of open excavations, while the laboratory work included (i) consolidation tests; (ii) swelling tests; and (iii) X-Ray Diffraction (XRD) studies which arc reported in detail by Matsah (1989) and Matsah and Hossain (1993a).

4. Ground Conditions

4.1 Main Soil and Rock Types

Based on all the data on composition, plasticity, color and consistency/relative density of soils from the reports and from authors' tests and using the classification system of ASTM (1975), all the soils of Al-Madinah could be categorized into 9 groups. The consistency of cohesive layers and relative density of cohesionless layers were generally estimated from the $N_{(SPT)}$ through the approximate correlations of Terzaghi and Peck (1967). In some cases the undrained shear strength, s_u from pocket penetrometer test or from CPT were used for this purpose. The calcareous nature of some soil layers were indicated by reaction with hydrochloric acid. Three rock types were identified by petrographic examination of hand specimens with a geologist's hand lense. Thus:

A) *the soil types consist of:*

1) very soft to stiff "FILL" material,

2) soft to very stiff white to light grey calcareous CLAYEY SILT (ML to MH),

3) medium to very stiff brown to greyish brown calcareous CLAYEY SILT with some sand (CL to ML to MH),

4) soft to very stiff grey-green highly plastic CLAY (CH to MH),

5) stiff to hard yellowish to greyish brown calcareous CLAYEY SILT to SILTY CLAY (CL to ML to CH to MH),

6) medium to very dense brown to greyish brown SILTY GRAVELLY SAND (SM),

7) very stiff to hard brown to dark reddish brown SILTY CLAY to CLAYEY SILT with some sand (CL to CH to ML to MH),

8) medium to very dense brown SILTY SAND with some gravel (SM),

9) stiff black to dark grey ORGANIC CLAY (OH), and

B) *the rock types include:*

1) weakly cemented white to light grey LIMESTONE,

2) dark grey to black vesicular olivine BASALT and

3) dark grey massive GABBRO.

4.2 Geotechnical Characteristics of the Soil and Rock Types

***A)* Soil Types**

The above listing shows one "fill" and 8 natural varieties of soils, of which six are cohesive and two are cohesionless. Table 1 shows the ranges of their geotechnical characteristics while some general comments are made in the following paragraphs.

i) The Fill (soil type 1)

The "fill" is variable in composition and consistency but is mostly composed of

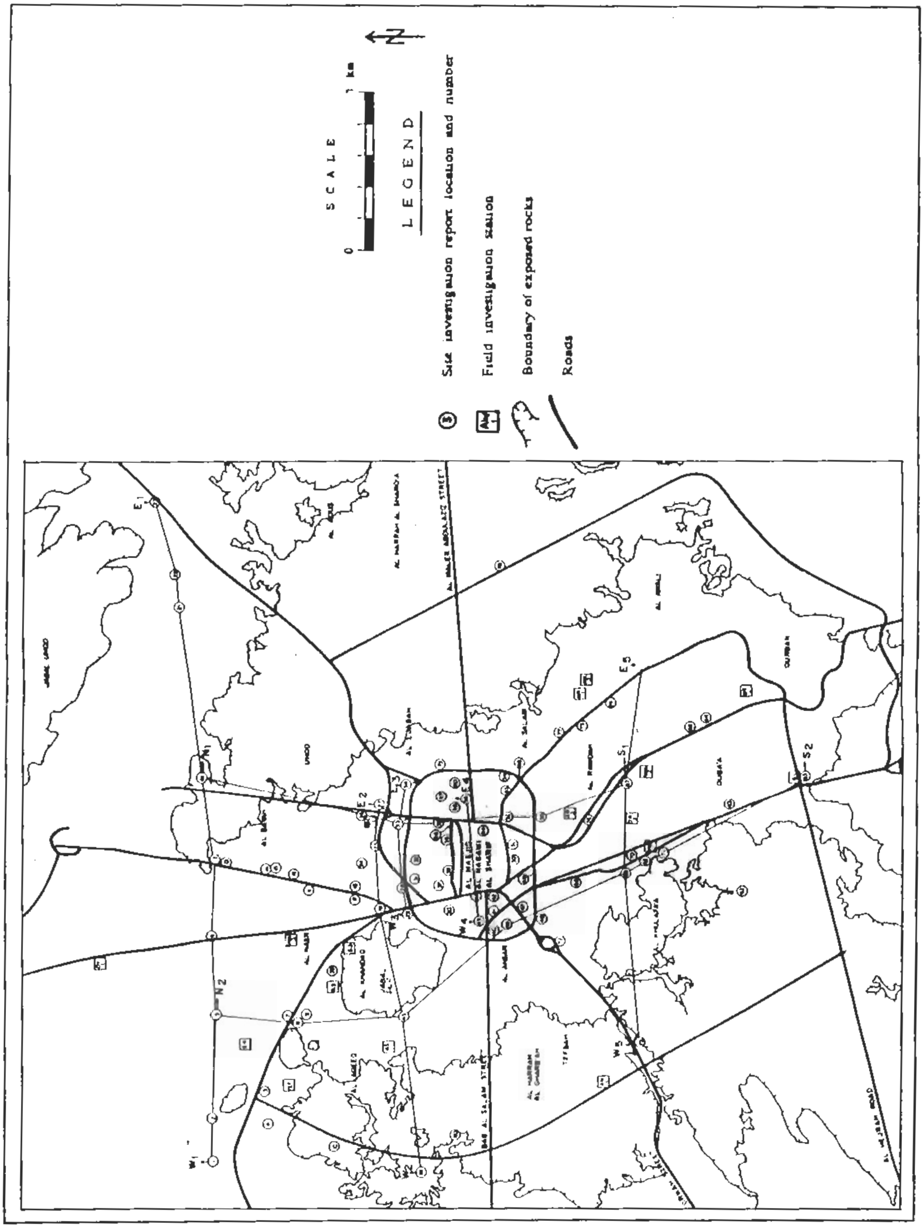

FIG. 4. Locations of the studied projects, authors' stations and cross sections.

TABLE 1. Ranges of geotechnical characteristics of soil types.

Layer type	Range of			Soil class.*	Fine fraction %	Clay fraciton < 5μ %	Clay fraction < 2μ %	Max. thickness m	Range of		Relative Position vertically
	w_l %	w_n %	I_p %						S_u kN/m2	N-values from SPT	
1) Fill material (brown clayey sandy silt with gravel)								7		2-10	top
2) Soft to very stiff white to light grey calcareous clayey silt	40-140	22-70	12-53	ML to MH	50-93	17-70	11-60	5	40-200	2-29	to or below Fill Material
3) Medium to very stiff brown to greyish brown calcareous clayey silt with some sand.	34-85	15-62	4-35	CL to ML to MH	39-88	19-50	11-38	5.5	60-250	6-30	top or below fill material and white clayey silt
4) Soft to very stiff grey-green highly plastic clay	47-280	34-136	14-99	CH to MH	65-100	22-78	13-69	10.5	30-180	2-25	below the brown calcareous clayey silt and the limestone
5) Stiff to hard yellowish to greyish brown calcareous clayey silt to silty clay	25-79	17-52	5-43	CL to ML to CH to MH	78-98	29-65	16-41	7	75-250	14 to over 50	below the grey-green clay layer
6) Medium to very dense brown to greyish brown silty gravelly sand				SM				7		20-62	below the yellowish brown clayey silty layer (5) and below the green clay
7) Very stiff to hard brown to dark reddish brown silty clay to clayey silt with some sand	30-73	20-61	9-35	ML to MH	36-100	10-78	5-52	15	175-300	21 to over 50	below the brown sandy layer to the bottom of the sections
8) Medium to very dense brown silty sand with some gravel				SM	5-41			13		10 to over 50	top or surfacial
9) Stiff black to dark grey organic clay	78-102	44-64	37	OH	86-93	42-52	27-45	1.5		8-12	below the fill

w_l = Liquid limit, W_n = Natural Water Content, I_p – Plasticity Index
* As per ASTM (1975), S_u = undrained shear strength.

brown clayey to sandy silt with gravel and it sometimes includes pieces of brick and wood. A few available $N_{(SPT)}$-values in the range of 2 to 10 suggest it to vary from very soft to stiff.

ii) Natural Cohesive Soils (soil types 2 to 5, 7 and 9)

Three of the cohesive soil types (i.e. 2, 3 and 5) are calcareous. Figs. 5, 6 and 7 show the grading limits and Figs. 8 and 9 show the plasticity characteristics of these soils. In the discussion that follows, the soil units 2, 3, 4, 5, 7 and 9 are designated as "white clayey silt", "upper brown clay", "grey-green clay", "lower brown clay", 'very stiff brown clay" and "organic clay" respectively for the sake of brevity.

The white clayey silt is very similar to the upper brown clay in respect of the grading ranges (ref. Figs. 5 and 6) and the upper limit of $N_{(SPT)}$-value. But it is relatively more plastic with its highest value of liquid limit, w_l (i.e. 140%) nearly double that of the latter or that of the other two brown clays (i.e. types 5 and 7). The highest w_l of the grey-green clay (i.e. 280%) is double that of the white clay. According to ASTM (1975) classification, the cohesive soil layers vary from ML to MH (i.e. silts of low to high compressibility) and from CL to CH (i.e. clays of low to high plasticity). However, as per BSI (1981), some of the clays with w_l-values exceeding 70% would be classed as MV to ME (i.e. silts of very high to extremely high compressibility) or CV to CE (i.e. clays of very high to extremely high plasticity).

The weakest soil in Al-Madinah is the grey-green clay with s_u in the range of 30 to 180 kN/m^2 and $N_{(SPT)}$-value in the range of 2 to 25, followed by the white clayey silt with s_u in the range of 40 to 200 kN/m^2 and $N_{(SPT)}$-value in the range of 2 to 29. The upper brown clay with s_u in the range of 60 to 250 kN/m^2 and $N_{(SPT)}$-value of 6 to 30 is stronger than these two soil types but is itself weaker than the lower brown clay having an S_u of 75 kN/m^2 or more.

The swell characteristics of the Al-Madinah clays described elsewhere (Matsah and Hossain 1993a) indicate that the swell potentials of the three calcareous soils (i.e. types 2, 3 and 5) are in the range of low to high and that of the grey-green clay (i.e. type 4) is in the range medium to very high according to the classification of Williams (1958). Thus there are 4 swelling clays in Al-Madinah instead of 2 reported by Erol *et al.* (1981) and Dhowian *et al.* (1990) from downtown Al-Madinah and 1 used by Sabbagh and Abuzaid (1991) or Fatani and Al-Zahrani (1991). However, it appears that the samples of these researchers were from the white clayey silt and the green clay layers of the present study. XRD analyses by Matsah and Hossain (1993a) show that the soil types 3 and 4 contain an abundant proportion of expansive clay mineral smectite. The basaltic lava around Al-Madinah is considered to be the source of this smectite.

The natural water contents of the cohesive layers are closer to their respective plastic limits than to their liquid limits suggesting them to be over-consolidated to various degrees. This is conformed by the results of consolidation tests on undisturbed samples of the soil types 2, 3, 4, 5 and 9 made by the authors and presented in Table 2 and those from the studied reports summarized in Table 3. Fig. 10 shows the e-log p curves from one of authors' test on a sample of green clay and from another on white calcareous silt.

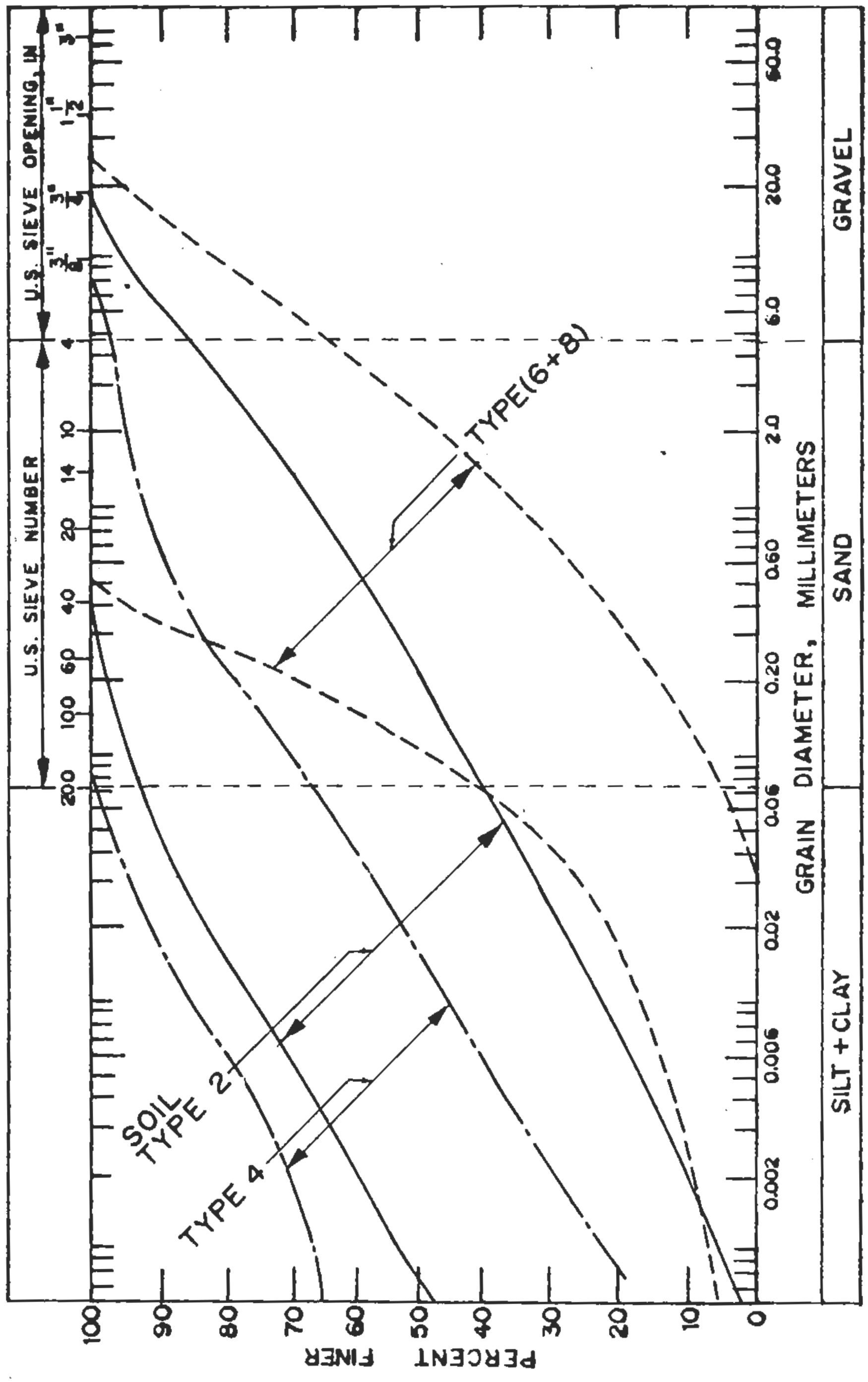

FIG. 5. Limits of grading curves for the white calcareous clayey silt (soil type 2), the grey-green clay (soil type 4) and the cohesionless soils (soil types 6 and 8).

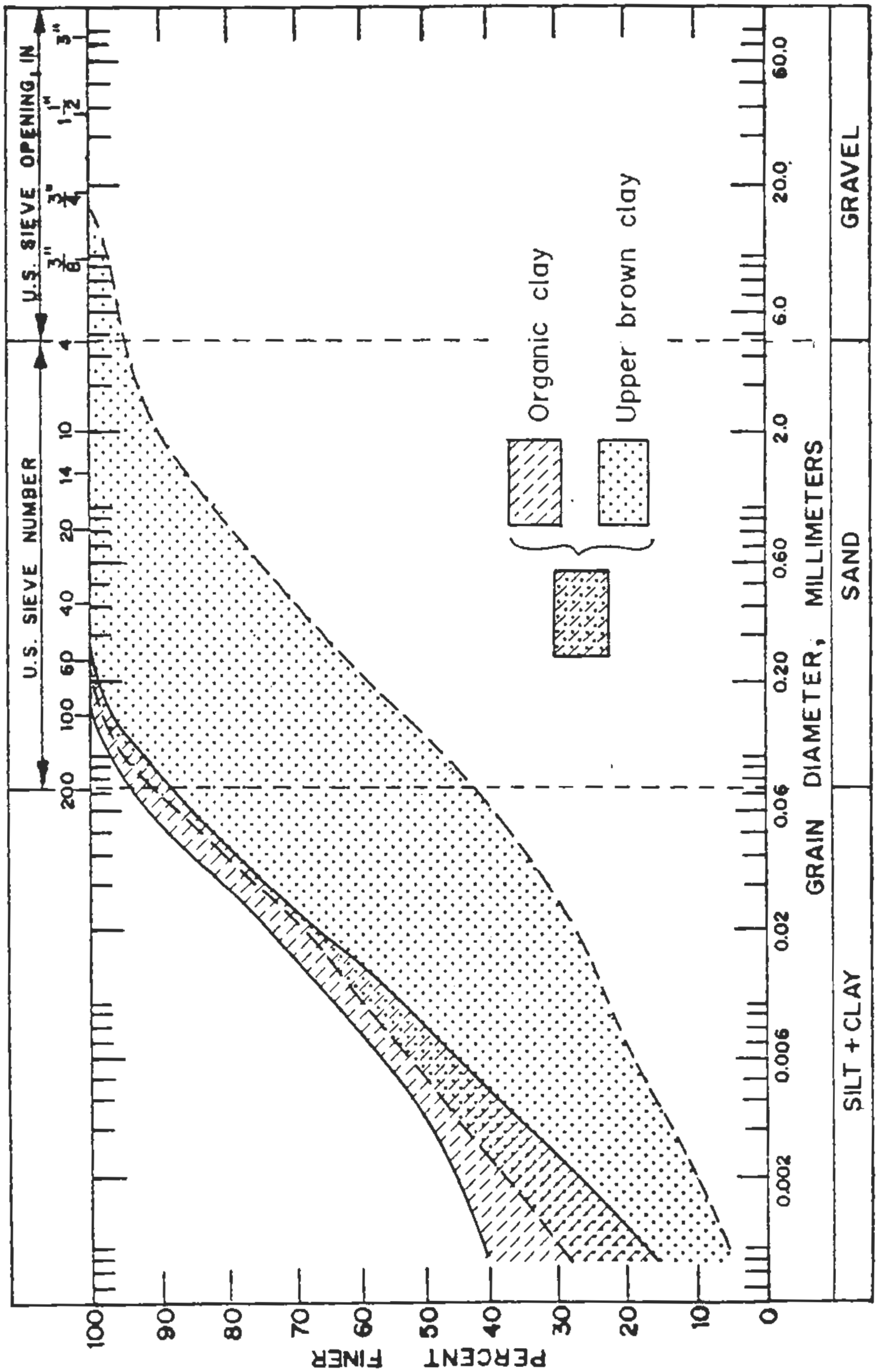

FIG. 6. Limits of grading curves for the upper brown calcareous clay (soil type 3) and the organic clay (soil type 9).

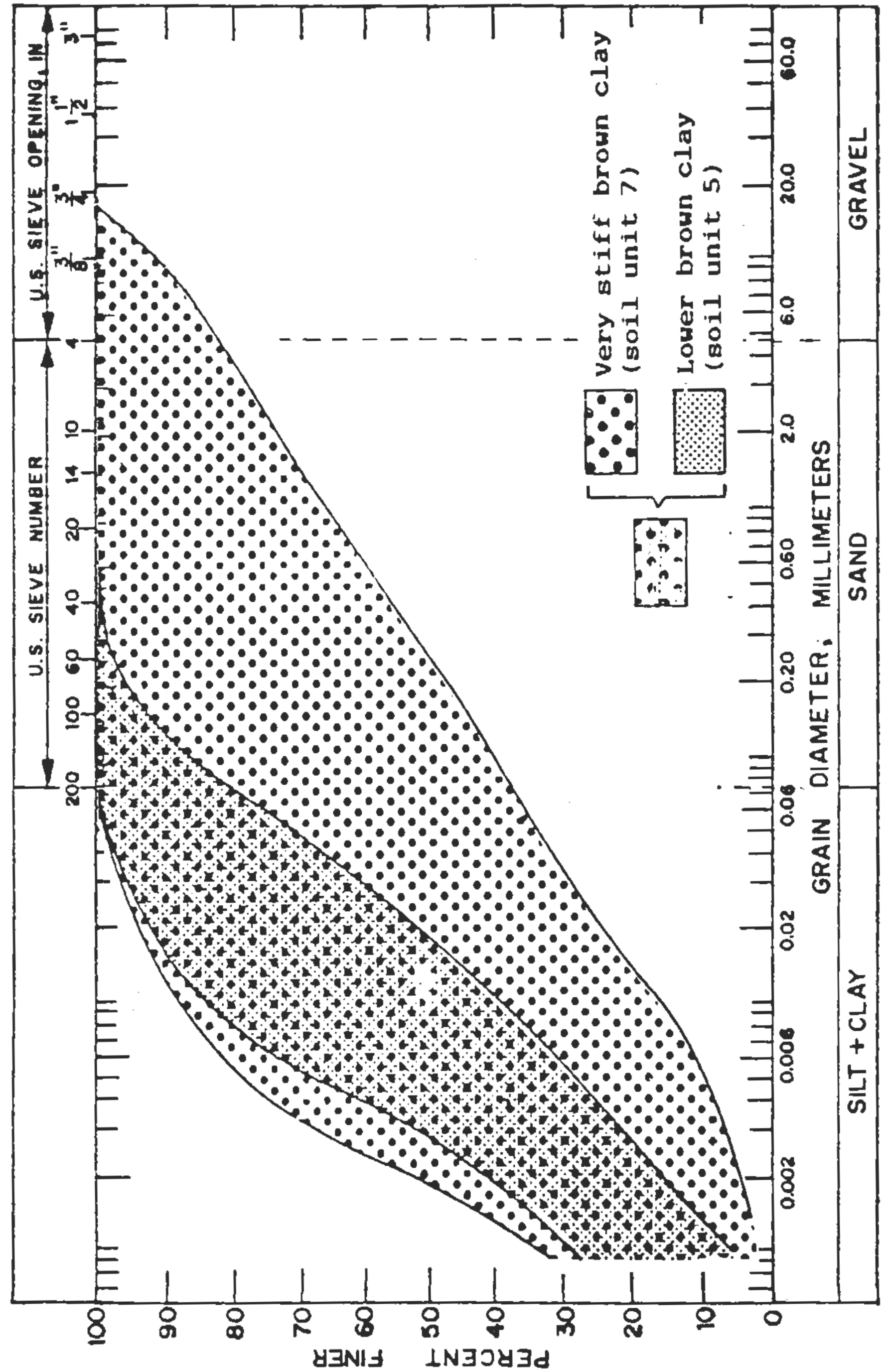

FIG. 7. Limits of grading curves for the lower brown calcareous clay (soil type 5) and the very stiff brown clay (soil type 7).

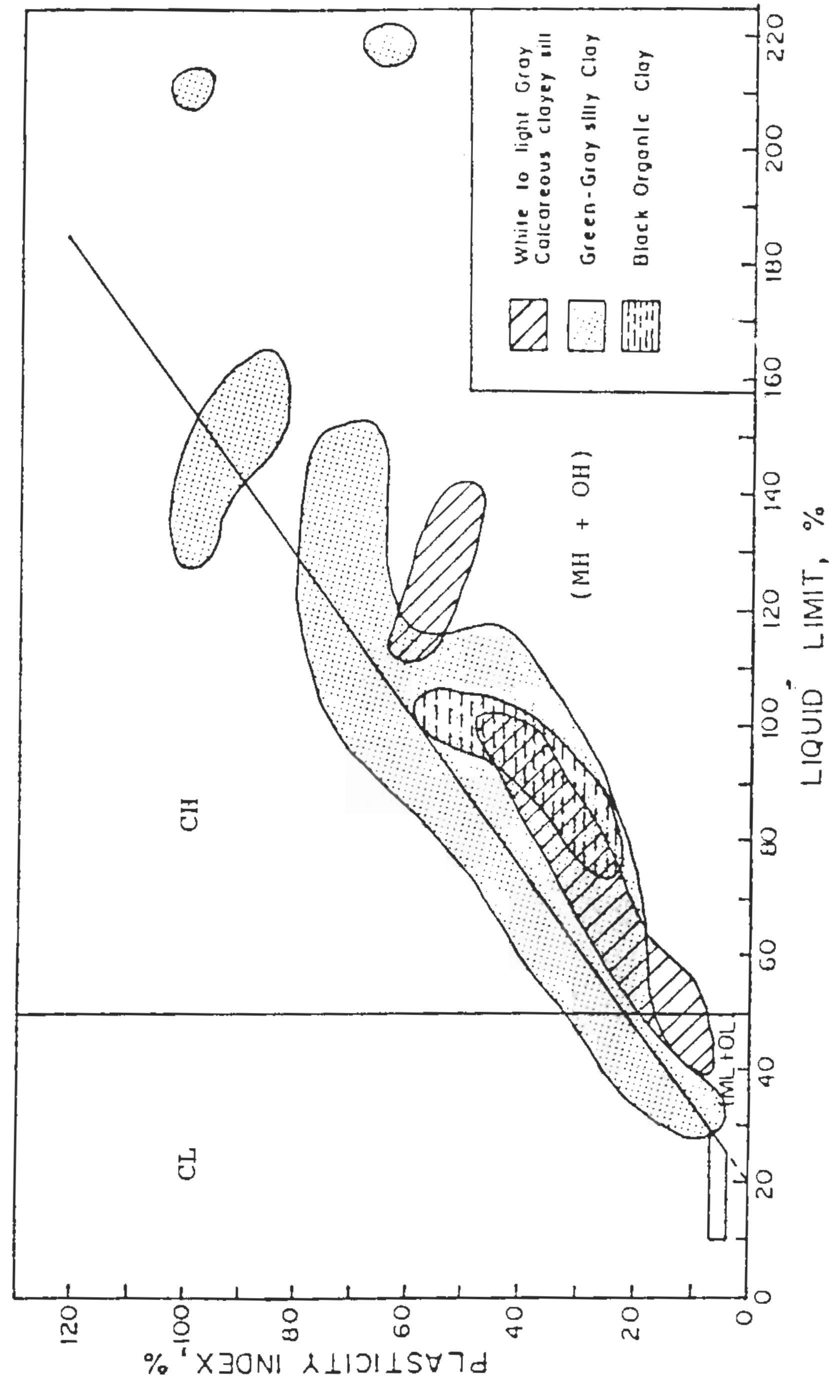

FIG. 8. Plasticity chart showing the positions of the soil types 2 (white calcareous clayey silt), 4 (grey-green clay) and 9 (organic clay).

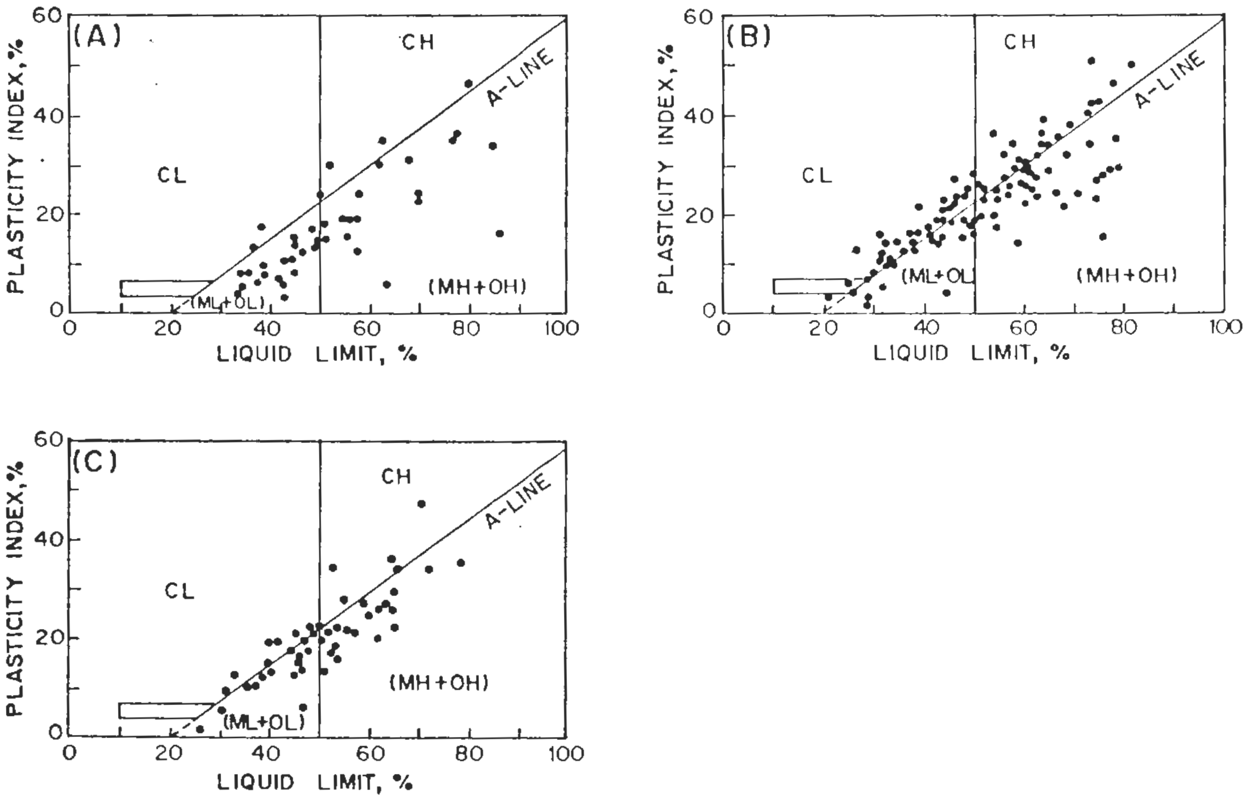

FIG. 9. Plasticity chart showing the positions of the soil types (A)3 (upper brown clay), (B)5 (lower brown clay) and (C)7 (very stiff brown clay).

TABLE 2. Summary of authors' consolidation test results.

Sample No.	Location Area	Soil Unit	Soil Class. as per ASTM	Depth m	ρ_n Mg/m³	w_l %	w_p %	w_n %	P'_c kPa	O.C.R.	C_c	C_s	e_o	m_v
PMS.1	Prophet's Mosq.	Green Clay	CH-MH	5.25-5.75	1.56	103	49	67	410	4.78	0.990	0.154	1.94	0.218
PMS.2	Prophet's Mosq.	Green Clay	CH-MH	4.9-5.3	1.55	91	40	63	450	5.68	1.018	0.15	1.88	0.167
PMS.3	Prophet's Mosq.	Green Clay	CH-MH	7-7.5	1.55	117	52	70	290	2.6	0.804	0.148	2.10	0.217
PMS.4	Prophet's Mosq.	Organic Clay	OH	4.5-5	1.40	102	78	73	410	6.17	0.770	0.037	1.93	0.171
QRU.2.2	Qurban	Green Clay	MH	4-4.5	1.22	259	163	180	250	4.82	2.74	0.30	4.61	0.428
QUR.2.3	Qurban	Green Clay	MH	4.5-5	1.21	281	186	157	320	5.59	2.89	0.42	5.14	0.350
AWU.1.1	Al-Awali	Green Clay	CH-MH	2.1-2.6	1.66	91	44	55	320	7.6	0.438	0.103	1.68	0.190
AWU.1.2	Al-Awali	Green Clay	CH	2.6-2.9	1.78	83	36.4	41	270	5.5	0.285	0.075	1.29	0.14
QU.1.1	Quba	White calc. Silt	MH	2.6-2.8	1.62	60	34	42	150	3.36	0.264	0.035	1.32	0.233
QU.1.2	Quba	White calc. Silt	CL	4.3-4.5	1.82	49	26	38	380	4.69	0.303	0.02	1.05	0.146
ABU.1.5	Abu-Thar St.	Green Clay	CH	8.5-9	1.81	82	34	42	200	1.27	0.397	0.122	0.934	0.336
ABU.1.6	Abu-Thar St.	Green Clay	CH	9-9.5	1.70	78	28	42	460	2.62	0.507	0.082	1.04	0.324

C_c Compression index. C_s Swelling index. O.C.R. Overconsolidation ratio = P'_c / P'_o.
P'_c Preconsolidation pressure. P'_o, e_o In-situ effective overburden pressure and void ratio respectively.
ρ_n, w_n Natural density and water content respectively. w_l Liquid limit. w_p Plastic limit.

TABLE 3. Summary of consolidation test results from site investigation reports.

Project Name and Number	Layer type	Soil Class. as per ASTM (1975)	Depth m	ρ_n Mg/m³	w_n %	w_l %	w_p %	e_o	C_c	C_s	P'_c kN/m2	O.C.R.
Prophet's Holy Mosque (82)	Green Clay	ML	9.2	1.89	35	47	33	1.04	0.5	0.06	680	4.25
	Green Clay	MH	6.2	1.27	159	220	156	4.52	2.73	0.14	360	3.13
	Green Clay	MH	6.7	1.52	146	155	62	3.97	2.50	0.24	330	2.75
	Green Clay	MH	8.2	1.5[illegible]	64	83	53	1.87	1.00	0.60	370	2.64
	Green Clay	CH-MH	8.4	1.63	45	84	38	1.33	0.79	0.50	340	2.61
	Green Clay	MH	12.8	1.78	45	68	40	1.44	0.71	0.50	490	2.33
	Green Clay	MH	9.2	1.73	44	77	41	1.30	0.52	0.50	410	2.73
	Green Clay	CH	10.7	1.74	42	111	37	1.24	0.62	0.063	350	2.50
Over bridge and underpass (34)	Green Clay	MH	14.2	1.46	93	97	54	2.33	1.85	0.10	520	2.00
	Green Clay	CH	13.7	1.65	49	90	30	1.57	0.94	0.055	390	1.77
	Green Clay	MH	12.2	1.73	38	77	36	1.14	0.43	0.30	560	2.54
	Green Clay	CH	7.7	1.48	74	131	33	2.13	1.43	0.078	210	1.75
Prophet's Holy Mosque (82)	Upper brown calcareous Clay	CH-MH	7.7	1.81	57	50	28	1.75	1.1	0.60	430	3.07
Prophet's Holy Mosque (82)	lower brown calcareous Clay	CL	24.2	1.85	26	34	20	0.71	0.41	0.02	860	1.83
		CH	12.2	1.36	38	65	26	1.16	0.62	0.03	440	2.09
Prophet's Holy Mosque (82)	Organic Clay	OH	6.2	1.61	76	100	43	2.34	1.57	0.09	290	2.9

Notations are same as in Table 2.

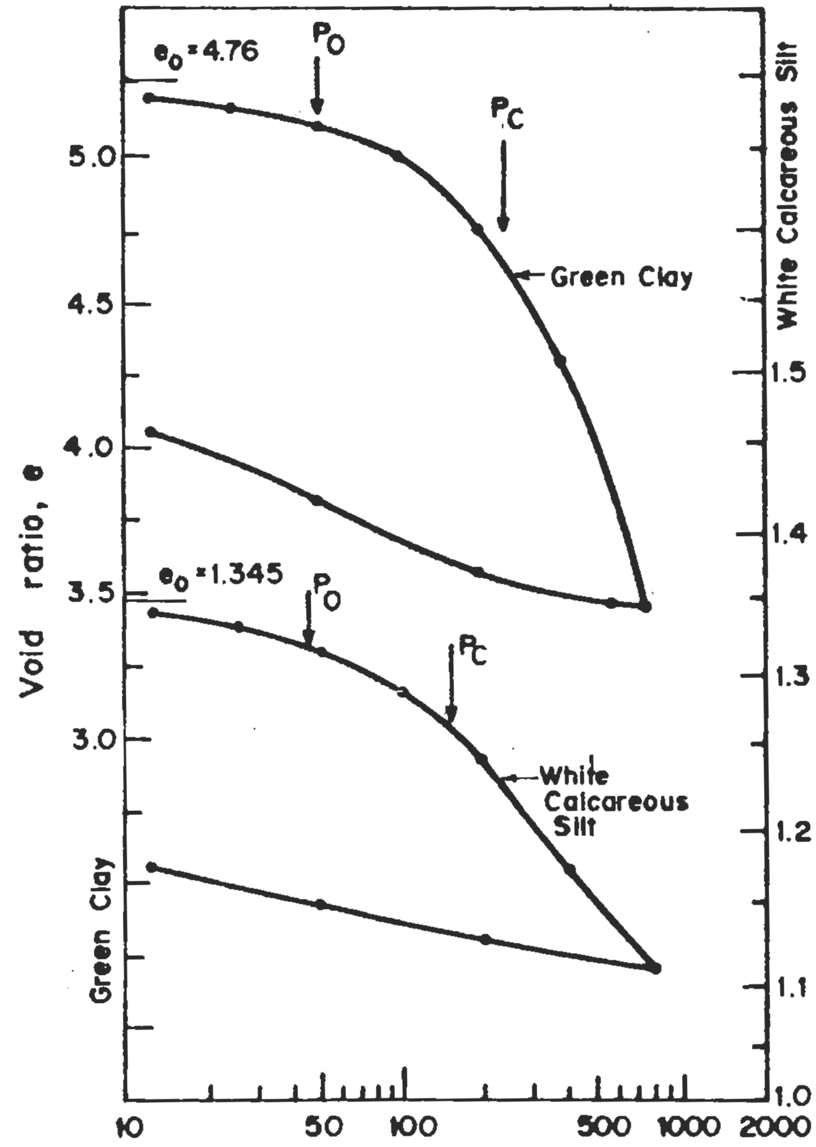

FIG. 10. Typical e-log p curves for green clay and white clayey silt.

The values of the coefficient of volume compressibility, m_v calculated by the BSI (1975) method for soil types 2 and 4 from authors' tests are in the ranges 0.15-0.23 and 0.14-0.43 m^2/MN respectively while the values of compression index, C_c for the soil types 2, 4, 5 and 9 from both the sources are in the ranges 0.26-0.30, 0.29-2.9, 0.41-0.62 and 0.77-1.57 respectively. The m_v-values suggest the units 2 and 4 to be clays of medium and high compressibility respectively according to Tomlinson's (1980) grouping.

The low strength, the high natural water content and voids ratio and low density, high compressibility and very high swell potential of the grey-green clay give it the distinction of being the most problematic one among the Al-Madinah clays.

iii) Natural Cohesionless Soils

The grading ranges of the two cohessionless soils observed in Al-Madinah (soil types 6 and 8) are largely overlapping and hence are shown together in Fig. 5, although the soil type 6 shows slightly higher gravel contents. Both these soil types are of medium to very dense relative density.

B. The Rock Units

Available geotechnical data on the rocks are rather limited due to the limited number of projects located on rock outcrops or those having boreholes extended to rock-head at depth. The authors' own inspection of the sides of open excavation showed that the weakly cemented white to light grey limestone is characteristized by small cavities and concentric zone forms while the reports noted its $N_{(SPT)}$-values generally above 50.

4.3 Representative Cross Sections

The pattern of sub-soil in Al-Madinah are shown by 2 north-south and 3 west-east cross-sections in Figs. 11 to 15. Their locations are shown in Fig. 4. These cross sections are:

1) North-south cross-section N1-S1 (along borehole numbers 61.6, 26.2, 27.8, 33.6, 35.2, 52.1, 55.5 and 67.1), with its central part along the Abu Thur Al-Gafary Street east of Prophet's Mosque, and crossing successively southward from north 1.1 km of lava flow in Uhod area, one wide valley in central city areas and two narrow valleys in the south.

2) North-south cross-section N2-S2 (along borehole numbers 5.3, 8.2, 45.2, 46.1, 68.1, 69.1, 71.2, 63.14 and 83.7) west of Prophet's Mosque, and starting from Al-Naser area in the north-west, crossing Al-Khandak area and then extending southward sub-parallel to the Al-Seeh and Al-Quba Streets to Quba area.

3) West-east cross-section W1-E1 (along borehole numbers 1.1, 2.2, 5.3, 6.4, 12.5, 61.6, 21.7, 22.8 and 23.9) across the northern areas, and starting near the Wadi Al-Aqiq in the west and crossing the Wadi Qana obliquely in the eastern part.

4) West-east cross-section W4-E4 (along borehole numbers 43.1, 44.5, 84.23 and 59.1) across Prophet's Mosque in downtown area.

5) West-east cross-section W5-E5 (along borehole numbers 79.2, 69.1, 67.1 and 56.11) across the southern areas of Al-Khulafa (west end), Quba and Al-Awali (east end).

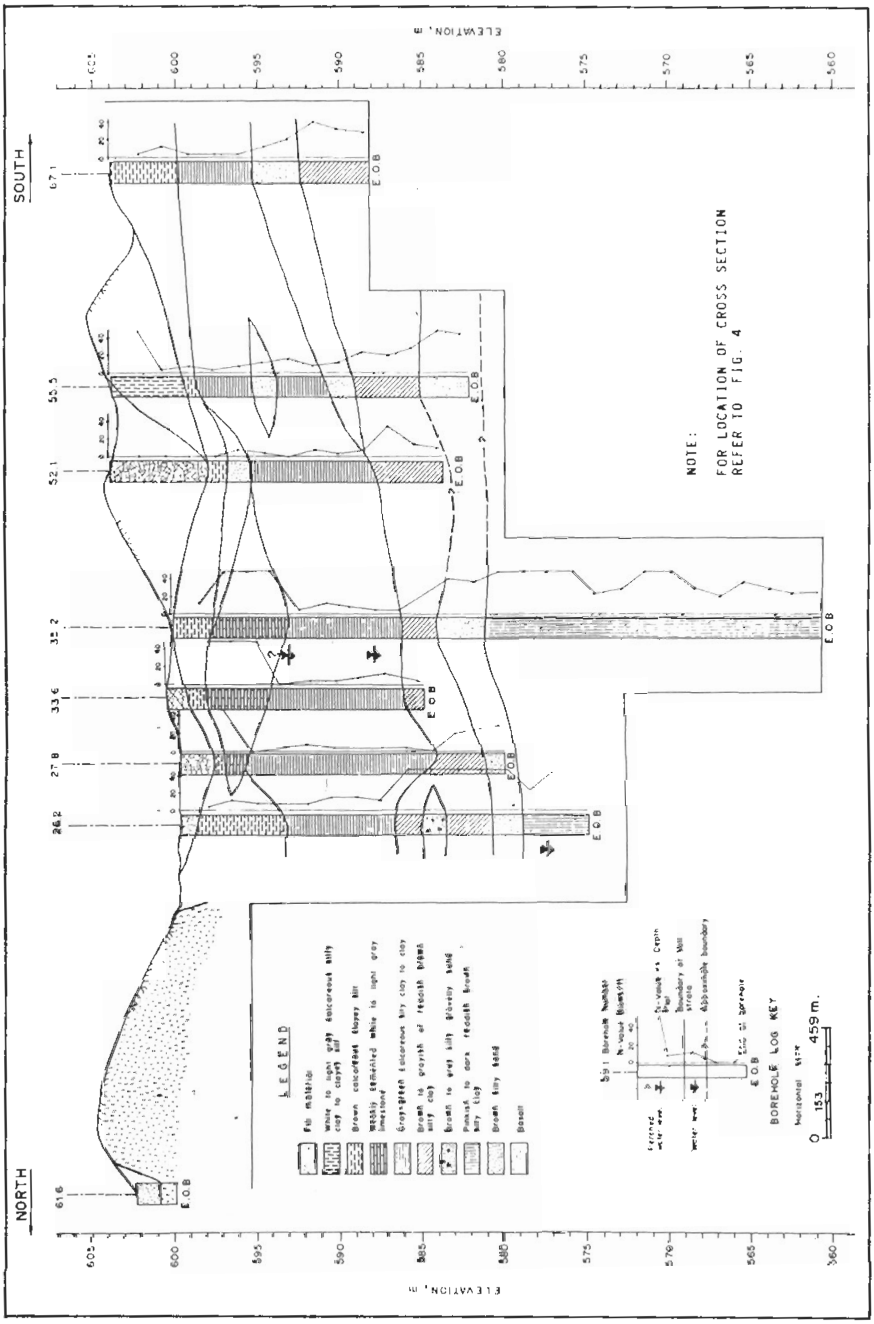

FIG. 11. North-south cross section N1-S1 east of the Prophet's Holy Mosque.

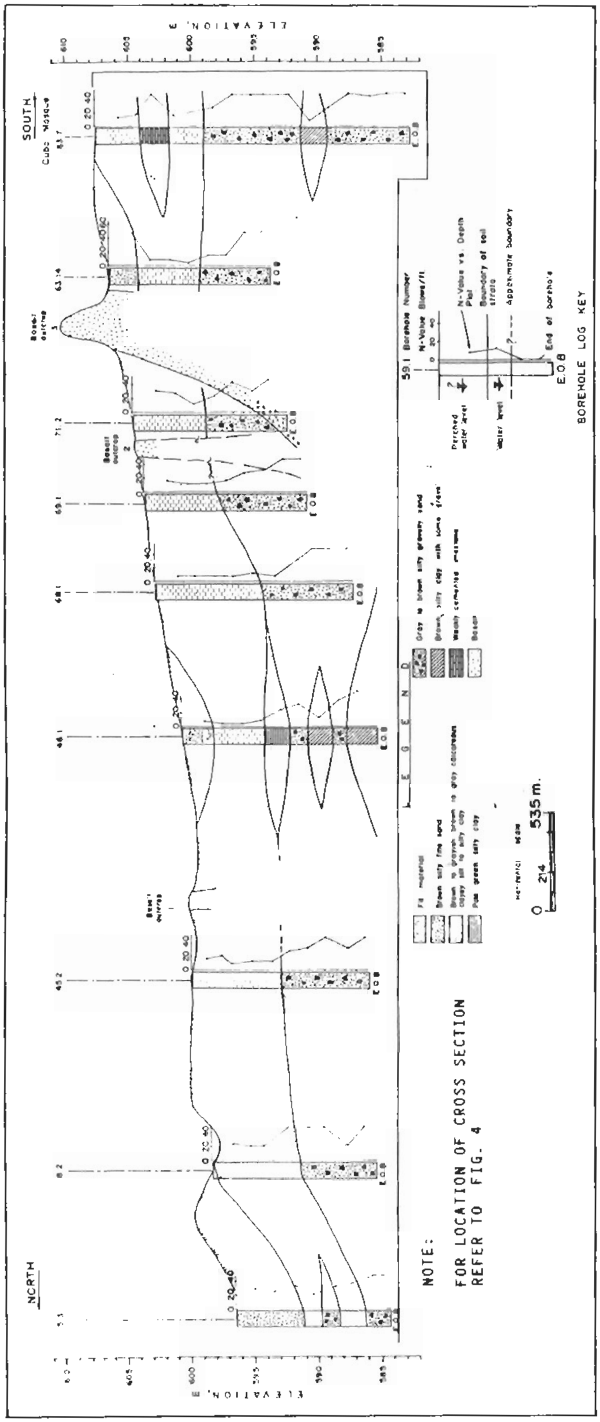

FIG. 12. North-south cross section N2-S2 west of the Prophet's Holy Mosque.

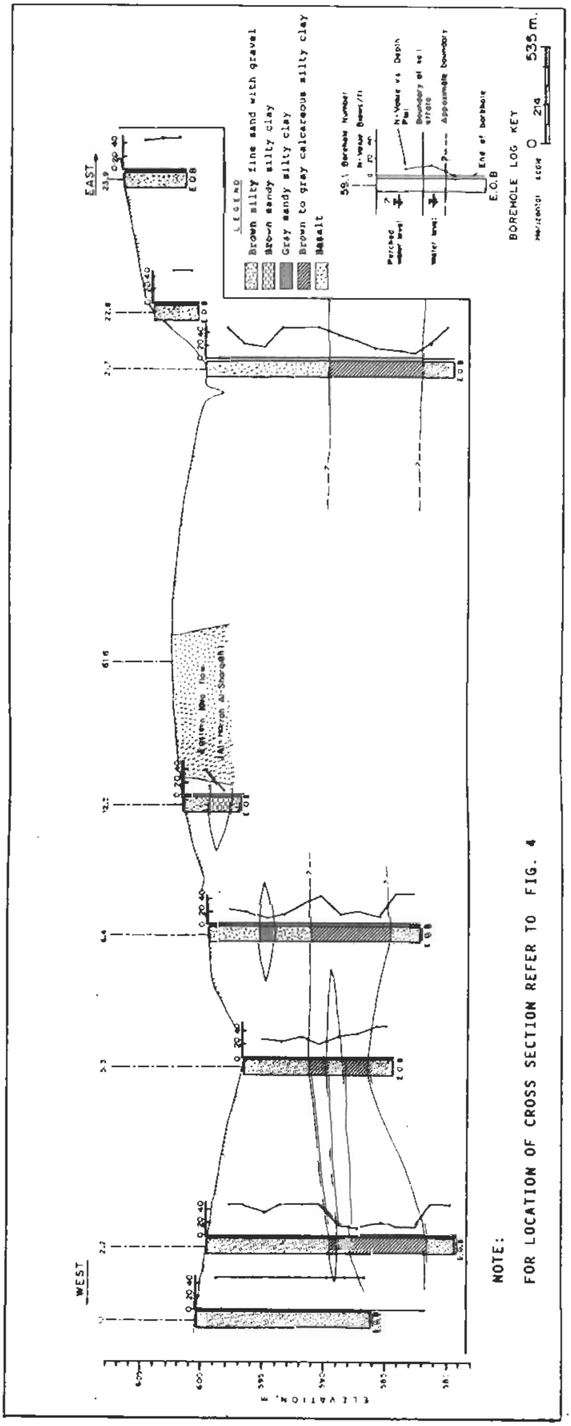

FIG. 13. West-east cross section W1-E1 across north Madinah.

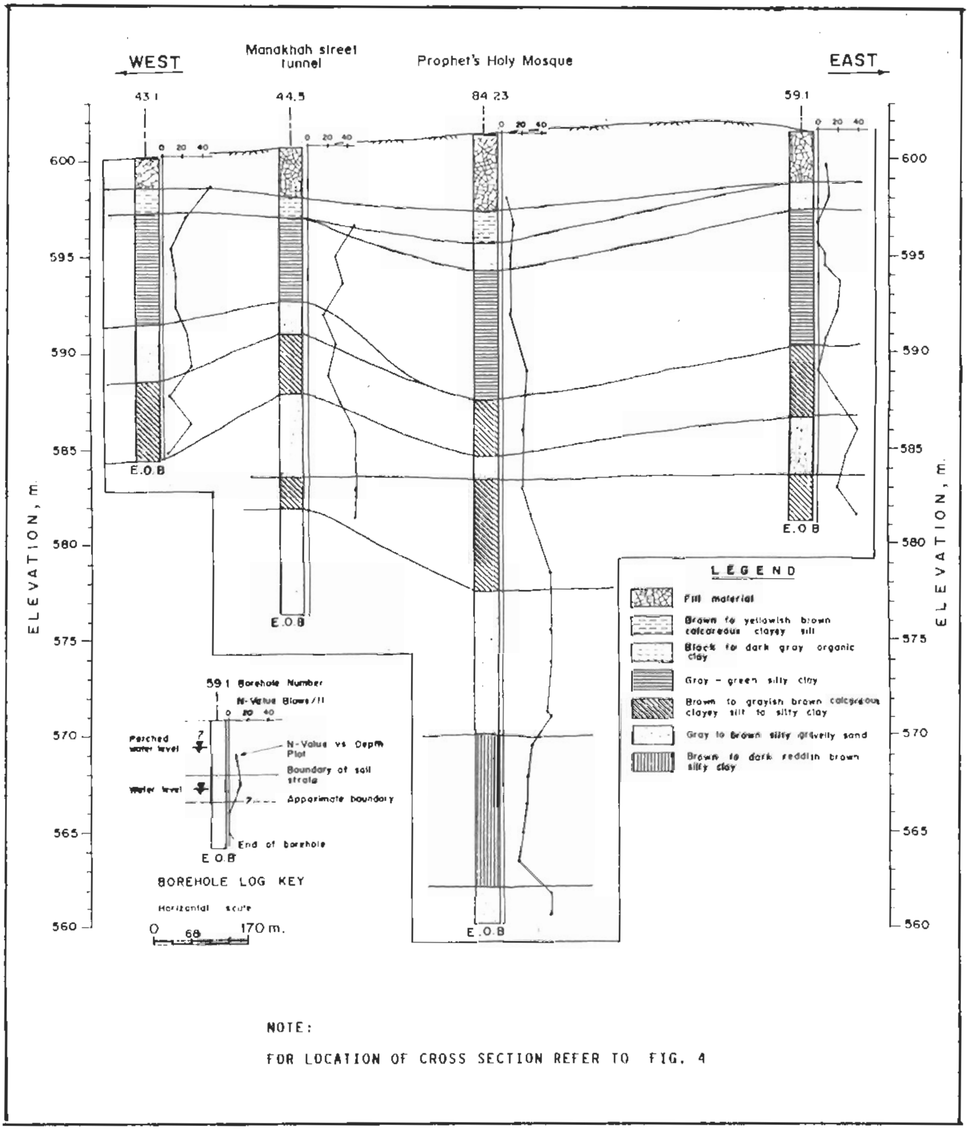

FIG. 14. West-east cross section W4-E4 across central Madinah.

The deepest borehole of a project was used in drawing these cross-sections in which, the part of a borehole number before the decimal point denotes the project number (Ref. Table A-1) and the part after it the serial number within the particular project. The ground surface elevations were determined from the contours of a topographic map of Al-Madinah prepared by M.M.R.A. (1977). The $N_{(SPT)}$-values have been plotted against depth beside the respective borehole.

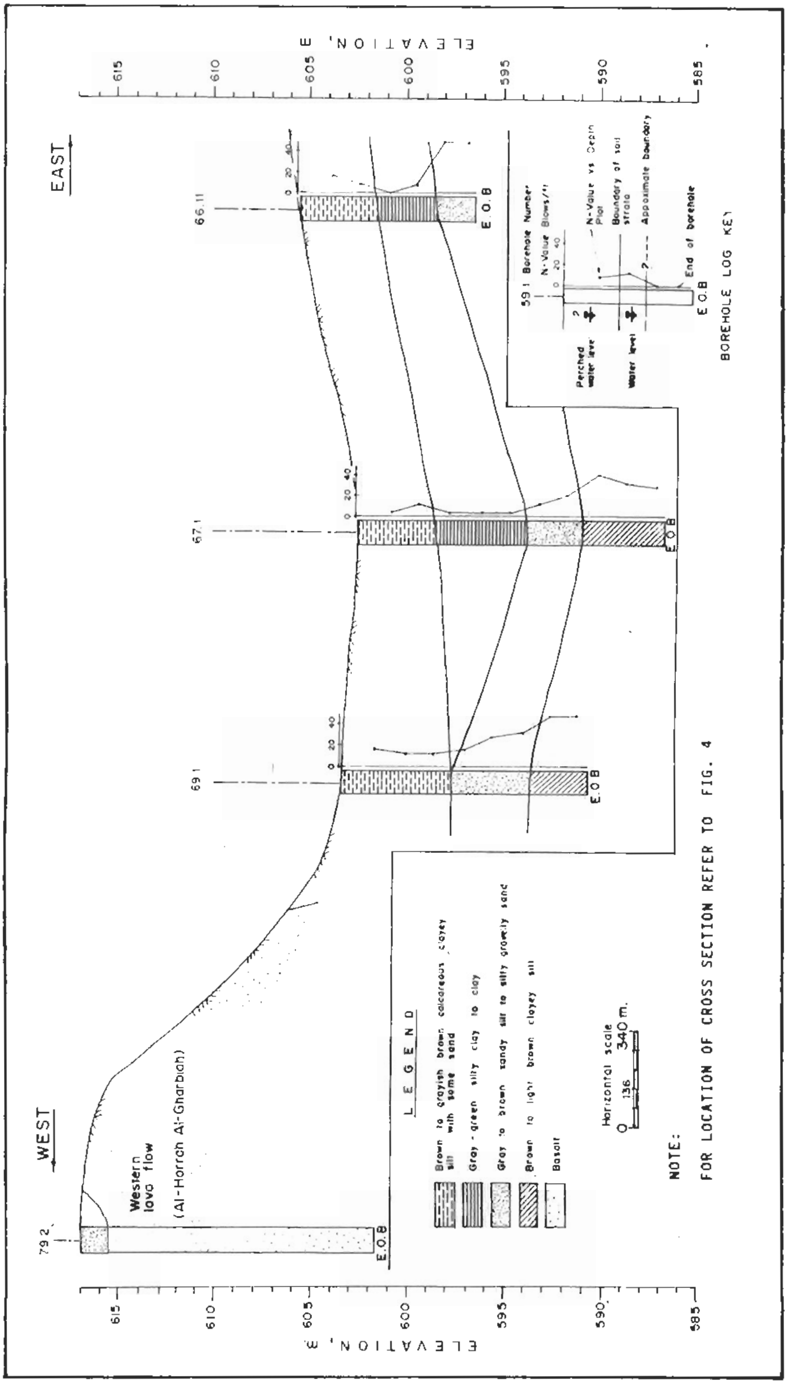

FIG. 15. West-east cross section W5-E5 across south Madinah.

4.4 Vertical and Horizontal Distribution

The thickness and horizontal extent of the various soil and rock types can be assessed from the cross sections of Figs. 11 through 15 which clearly indicate the predominance of cohesive soils in Al-Madinah, specially in downtown areas. The first five of the soil types generally appear in succession downwards in the central areas and their maximum thicknesses vary from about 5 m (soil type 2) to about 10.5 m (soil type 4). The very stiff brown clay occurs below the lower brown calcareous clay and its thickness upto a maximum of 15 m was recorded (ref. Fig. 11). The organic clay appears to be of local occurence found as a thin layer (maximum thickness 1.5 m) between the upper brown clay and the grey-green clay in the new northern and eastern extensions of the Prophet's Holy Mosque (ref. Fig. 14) and at some locations at the northern boundary of Al-Baqee cemetery (east of Prophet's Mosque). The silty gravelly sand (soil type 6) occurs below the lower brown clay and its thickness appears to increase westward reaching a maximum of about 7 m. The silty sand (soil type 8) forms the top layer several meters thick over wide areas in the north and along the foothills on other margins of the city (ref. Figs. 13 and 16, discussed later). The maximum observed thickness of the fill layer is about 7 m occurring in some parts of the Prophet's Holy Mosque Expansion Project.

The limestone layer with a maximum thickness of about 4.5 m was encountered below the upper brown calcareous clay at a few locations north-east of the Prophet's Mosque (ref. Fig. 11) and as a lense within the grey-green clay in the southern part – e.g. at Quba Mosque (ref. Fig. 12). The basalt was found at the eastern, southern and western boundaries of the study area (ref. Fig. 16). The gabbro occurs as isolated hills within the city area (e.g. Jabal Sela shown in Fig. 16).

4.5 Surface Soil Map

Figure 16 shows the distribution of different soil types at the ground surface within Al-Madinah. It is observed that the "fill" forms a surfacial layer mostly in the central and north-eastern parts and the white clayey silt appears on the surface in the east and south-east while the upper brown clay in the south-west and along a narrow strip in the north-west. The silty sand appears along the city margins beside the surrounding hills, specially in the northern areas along Wadi Qana.

5. Water Table

During the period 1980-85, the ground water table in Al-Madinah was at a depth range of 22 to 24 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.

6. Chemical Nature of Soil and Groundwater

Table 4 shows the chemical characteristics of soil within the top 20 m based on the studied reports while Table 5 presents authors' own test data. The pH values are generally greater than 7 indicating an alkaline environment. The sulphate, chloride and

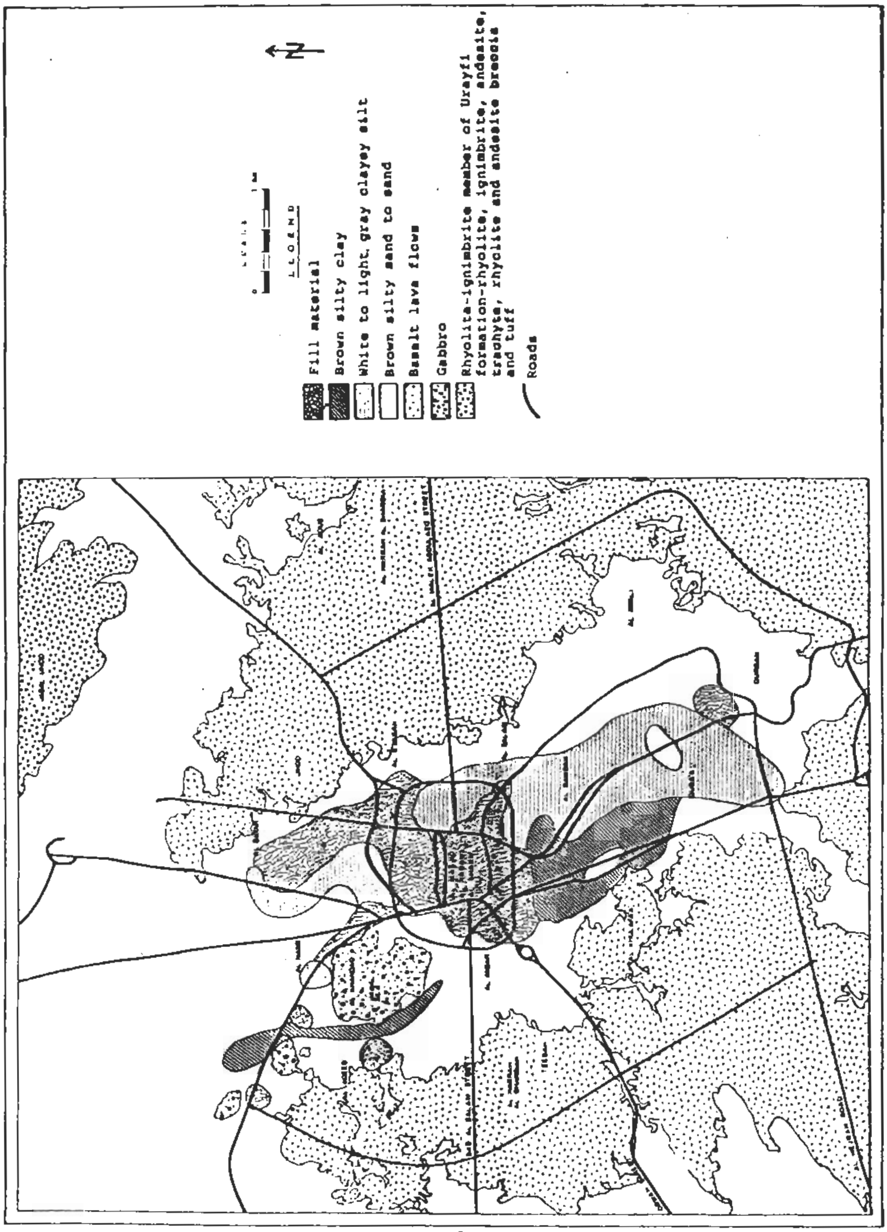

FIG. 16. Distribution of the different surfacial soil types in Al-Madinah.

total soluble salt (TSS) contents are in the ranges of 0.0013-8.59%, 0.0012-2.24% and 0.42-4.14% respectively.

TABLE 4. Summary of soil chemical analysis results from site investigation reports.

Range of Depth in meters	Ranges of		
	pH	SO_4 %	Cl %
0-2	8.0-8.2	0.01-0.3	0.0068-0.4
2-5	7.1-9.0	0.0013-0.257	0.0012-0.6
5-10	7.75-8.3	0.003-0.1875	0.002-0.318
10-20	7.2-8.3	0.004-0.07	0.004-0.05

TABLE 5. Summary of authors' soil chemical analysis results.

Sample No.	Sample Depth m	Soil Type	pH	Cl %	SO_4 %	T.S.S. %
QU.1.1	2.6-2.8	Light gray silty clay	7.4	0.330	0.161	1.52
QU.1.2	4.3-4.5	Light gray silty clay	7.7	0.660	0.119	1.78
SH.1.D.1	0.6-0.8	Brown sandy clayey silt	7.75	1.060	1.38	4.08
SH.1.D.2	1.7-1.9	Brown clayey silt	8.05	0.594	1.08	2.16
SH.1.D.3	3.8-4.0	Brownish gray silty clay	7.7	0.725	0.390	2.16
SH.1.D.5	5.1-5.3	Brownish grey silty clay	7.8	0.594	0.574	1.70
SD.1.1	5.1-5.3	Brown clayey silt	8.05	0.200	0.136	0.80
SD.1.4	1.9-2.1	Brown clayey silt	7.85	1.85	6.49	13.0
SD.1.5	0.7-0.9	Brown clayey silt	8	1.48	8.59	13.0
QD.1.3	0.5-0.8	Brown clayey silt	8.95	0.200	0.251	1.96
QD.1.4	1.0-1.3	Brown sandy silty clay	8.6	0.264	0.111	1.44
Sample.7	2.7-2.9	Greenish gray silty clay	7.4	0.660	0.199	1.78
Sample.9	0.9-1.1	Brown sandy clayey silt	7.9	2.24	0.264	4.14
Sample.12	1.8-2	Light gray clayey silt	7.7	0.660	0.330	2.32
QRU.2.2	4 -4.5	Greenish gray silty clay	6.7	0.791	0.311	2.84
QRD.1.1	1.5-1.7	Brown silty gravelly sand	7.8	0.420	0.066	0.42
QRD.2.1	2.6-2.8	Brown sandy clayey silt	7.9	0.400	0.369	1.40

The sulphate and chloride contents are higher in soils near the surface specially within the top 5 m of the sub-soil. These sulphate contents indicate aggressiveness of class 1 to 4 to concrete as per BSI (1972). Such aggressive ground conditions occur in many places with hot and arid climate (e.g. in United Arab Emirate as reported by Epps 1980, in Obhor and Jeddah in western Saudi Arabia reported by Hossain and Ali 1988 and Abu-Hajar and Hossain 1991 respectively... etc.).

7. Geotechnical Implications

The predominance of cohesive soils of varied strength and other characteristics influences all aspects of geotechnical activity in Al-Madinah as discussed in more detail by Matsah and Hossain (1993b). It is suggested that the commonly used method of estimating s_u of cohesive soils from $N_{(SPT)}$ should be checked by laboratory strength tests on undisturbed samples. Further, field vane shear tests in the soft to medium strong cohesive layers and CPT in all types of Al-Madinah soils supplemented by undisturbed sampling in selected cohesive layers for consolidation and/or swell tests appear more appropriate.

The possibility of encountering the "fill" and of the very soft and/expansive clays within the top 15 m of depth deserves particular attention in a Al-Madinah project. Using $N_{(SPT)}$ as an indicator of strength (although rather crude for cohesive soils), Matsah and Hossain (1993b) shows that although a large area to the south of the Prophet's Mosque has the weakest soil at shallow depth, some areas to its east and north-east have weak soil down to a depth of 15 m. These later areas also have the greatest thickness of the grey-green clay and hence are considered to be geotechnically the most problematic. Thus in these areas, rafts, piles or diaphragm walls and barrets may be required except for 1-2 storied residential/Office buildings or similar light structures which may be founded on footings with low bearing pressures.

In the city margin areas, specially those in the north, where at least medium dense sandy soils of appreciable thickness are found at the top, footings can be used for low to medium-rise buildings (say upto 6 stories) and for over-bridges of moderate spans. 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.

Very little gound water problem is encountered now-a-days during ordinary construction work in Al-Madinah due to the lowering of the water table to depths exceeding 22 m. However, care will be necessary to avoid heave from post-constructional wetting when a structure is founded on dry or partially dry expansive clay layers.

8. Conclusion

The city of Al-Madinah is situated in a depositional basin surrounded by lava plateaus and hills within the western part of the Arabian Shield. Its ground surface elevations are around 600-610 m above mean sea level with a gentle downward slope towards the north-west. Within a maximum depth of 45 m, the sub-soil in Al-Madinah consists of nine soil types and three rock types. The soil types are: 1) the "FILL" of variable composition and consistency, 2) the soft to very stiff white to light grey calcareous CLAYEY SILT, 3) the medium to very stiff brown to greyish brown clacareous CLAYEY SILT with some sand, 4) the soft to very stiff grey-green highly plastic CLAY, 5) the stiff to hard yellowish to greyish brown calcareous CLAYEY SILT to SILTY CLAY, 6) the medium to very dense brown to greyish brown SILTY GRAVELLY SAND, 7) the very stiff to hard brown to dark reddish brown SILTY CLAY to CLAYEY SILT with some sand, 8) the medium to very dense brown SILTY SAND with some gravel and 9) the stiff black to dark grey ORGANIC CLAY, while the rock types are: 1) the weakly cemented white to light grey LIMESTONE, 2) the dark grey to black vesicular olivine BASALT and 3) the dark grey massive GABBRO.

The cohesive soils and the "fill" form the top layer over most of the city areas while cohessionless soils occur at surface along the city margins, specially in the north, and at depths more than about 15 m in other areas.

The presence of the "fill" or weak natural soils (types 1, 2 and 4) and the swell potential of the cohesive soils, specially that of grey-green clay often govern the geotechnical practice in Al-Madinah. Thus a large area to the south of the Prophet's Mosque has the weakest soil at a shallow depth, while some other areas to its east and north-east have weak soil down to a depth of 15 m and are geotechnically the most problematic.

The high sulphate and chloride contents in soil and ground water calls for protective measures for foundation concrete and reinforcement. Ground water control measures are generally not required for usual construction except for localized perched water but care is necessary to avoid heave.

Acknowledgement

This paper is based on the M.Sc. thesis of the first author under the supervision of the second author at the Faculty of Earth Sciences, King Abdulaziz University. The authors acknowledge with thanks the cooperation of the various site investigation companies and building owners who allowed access to their site investigation reports during this study and whose names could not be included in the reference list for the sake of saving space.

References

Abed, A.M. (1977) Al-Madinah harra (basalts) petrology and geochemistry. *Bulletin, Faculty of Science, King Abdulaziz University,* **1:** pp. 119-128.

Abu-Hajar, I. and **Hossain, D.** (1991) Ground condition in Jeddah and its influence on selection and design of foundation, *J. KAU, Earth Sciences,* **4:** pp. 45-66.

Abuzaid, A. (1990) *Sand replacement methods for Al-Madinah expansive clays,* M.Sc. thesis, Faculty of Engineering, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia, (unpublished).

Al-Zahrani, A. (1989) *Scoria-Portland cement soil stabilization,* M.Sc. thesis, Faculty of Engineering, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia, (unbublished).

ASTM, (1975) *Annual Book of ASTM Standards, Part 19,* Natural building stones, Soil and rocks, peats, mosses and humus. American Society for Testing and Materials, 464p.

Bin Ladin Organization (1983) Geotechnical investigation of the proposed extension of the Prophet's Holy Mosque in Madinah, Kingdom of Saudi Arabia, *Project M*-**83028.**

Brosset, R. (1976) Geology and mineral exploration of the Al-Madinah Quadrangle, 24/39D, *B.R.G.M. Technical Record* **77,** *JED4.*

BSI (1972) CP 2004: 1972, *Code of Practice for Foundation,* British Standards Institution, London, 158p.

BSI (1975) BS 1377: 1975, *Methods of test for soils for civil engineering purposes,* British Standards Institution, London, 143p.

BSI (1981) BS 5930: 1981, *Site investigations,* British Standards Institution, London, 147p.

Cansult Ltd. (1981) Geotechnical investigation for the proposed Manakha Street Tunnel, Madinah, Saudi Arabia, *Project No. M*-**81005,** 79p.

Chan, S.F. and **Chin, F.K.** (1972) Engineering characteristics of the soils along the Federal Highway in Kuala Lumpur, *Proceedings of the third South-east Asian conference on Soil Engineering,* pp. 41-5.

Dhowian, A., Erol, O. and **Yousef, A.** (1990) *Evaluation of expansive soils and foundation methodology in the Kingdom of Saudi Arabia,* General Directorate of Research Grants Programs, King Abdulaziz City for Science & Technology, Riyadh, 123p.

Epps, R.J. (1980) Geotechnical practice and ground condition in coastal regions of the United Arab Emirates, *Ground Engineering,* **13:**(3) pp. 19-25.

Erol, O., Yousef, A. and **Dhowian, A.** (1981) Swelling potential of Madinah clays, *Proc. Symposium on Geotechnical Problems in Saudi Arabia, King Saud University Libraries, Riyadh,* **1:** pp. 83-106.

Farsi, Z.M.A. (1986) *Map and Guide of Al-Madinah Al-Munawara,* Publ. Engr. Zaki, A. Farsi, Saudi Arabia.

Fatani, M.N. and **Al-Zahrani, A.** (1991) Scoria stabilized soils, *Proc. 1st Geotch. Engg. Conference, Cairo University, Cairo, Egypt, Sept. 30-Oct. 3 (1991)* pp. 44-52.

Group of Arab Consultants for Development and Reconstruciton (1980) Madinah Action Master Plan, existing conditions and physical survey, *Technical Report No.. 5,* **Vol. III.**

Hossain, D. and **Ali, K.M.** (1988) Shear strength and consolidation characteristics of Obhor Sabkha, Saudi Arabia, *Quarterly Journal of Engineering Geology, London,* **21:** pp. 347-359.

Jazzar Trow Middle East (1984) Geotechnical investigation of the proposed extension of the Quba Mosque, Madinah, Saudi Arabia, *Project No. M-***83067,** 56p.

Makki, M.S. (1979) Dams around the holy city of Madinah and the pressure on its water supply, *Journal of Arid Environments,* **2:** pp. 363-367.

Matsah, M.I. (1989) *Preliminary assessment of ground conditions in Al-Madinah Al-Munawarah,* M.Sc. thesis, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia, (unpublished).

Matsah, M.I. and **Hossain, D.** (1993a) *Consolidation and swelling characteristics of Madinah clays,* (in preparation).

———— (1993b) *Foundation Practice and Problems in Madinah, Saudi Arabia,* (in preparation).

M.A.W. (1984a) *Water Atlas of Saudi Arabia,* Water Resources Development Department, Ministry of Agriculture and Water, Govt. of the Kingdom of Saudi Arabia, 112p.

———— (1984b) *Daily and monthly rainfall data for the year 1984,* Water Resources Development Department, Ministry of Agriculture and Water, Govt. of the Kingdom of Saudi Arabia, Hydrological publicaiton No. 111, 385p.

M.M.R.A. (1977) *Topographic and Town Plan Map of Al-Madinah, Project 101,* Ministry of Municipal and Rural Affairs, Govt. of the Kingdom of Saudi Arabia, scale 1:10,000.

Oweiss, I. and **Bowman, J.** (1981) Geotechnical considerations for construction in Saudi Arabia, *J. Geotech. Engg. Div., Proc. Am. Soc. Civ. Engrs.* **107** GT(3): 319-338.

Parsons Brown International (1977) Madinah ring road and multistorey car parks phase 4 soil investigation report for Ministry of Municipal and Rural Affairs, Saudi Arabia, *Project No. S* **1065,** 99p.

Pellaton, C. (1977) Geology and mineral exploration of the Wadi An-Nuqumi Quadrangle 24/339D, *B.R.G.M. Technical Record* **79** *JED4,* p. 27.

———— (1981) Geologic map of the Al-Madinah Quadrangle, Sheet 24D, Kingdom of Saudi Arabia, *Geologic Map GM-52C, DGMR, Govt. of the Kingdom of Saudi Arabia.*

Sabbagh, A.W. and **Abuzaid, A.A.** (1991) Minimizing swell pressure by sand cone replacement, *Proc. 9th Asian Regional Conf. Soil Mech. & Foundn. Engg., Bankok, Thailand December 9-13 (1991)* pp. 159-162.

Terzaghi, K. and **Peck, R.B.** (1967) *Soil Mechanics in Engineering Practice,* Second Edition, John Wiley and Sons, New York, 729p.

Tomlinson, M.J. (1980) *Foundation Design and Construction,* 4th Edn. Pitman, London, 793p.

Williams, A.A.B. (1958) Discussion on Jennings, J.E. and Knight, K., The prediction of total heave from the double oedometer test, *Trans. S. A. Inst. Civ. Engrs.,* **Vol 8,** No. 6.

TABLE A-1. List of studied projects.

Project No.	Project Type	Location	No. of Stories	Project No.	Project Type	Location	No. of Stories
1	Bridge	Al-Nasr area		43	Building	Al-Haram area	7
2	Bridge	Al-Nasr area		44	Tunnel	Al-Haram area	
3	Bridge	Al-Nasr area		45	Building	Al-Khandag area	6
4	Bridge	Al-Nasr area		46	Building	Al-Haram area	8+1
5	Bridge	Al-Nasr area		47	Building	Al-Anbariah	9+1
6	Bridge	Al-Nasr area		48	Building	Al-Haram area	10+1
7	Building	Al-Nasr area	7	49	Bridge	Al-Haram area	
8	Building	Al-Khandag area	6+2*	50	Building	Al-Haram area	8+1
9	Building	Al-Khandag area	6	51	Car Parks	Al-Haram area	
10	Bridge	Al-Aqiq area		52	Building	Al-Haram area	6+1
11	Building	Al-Bayah area	5	53	Building	Al-Haram area	10+1
12	Bridge	Al-Bayah area		54	Building	Al-Haram area	7+1
13	Building	Al-Bayah area	5+1	55	Building	Al-Rawdah sec.	8
14	School	Al-Bayah area	2	56	Underpass	Al-Haram area	
15	Building	Al-Bayah area	5	57	Building	Al-Haram area	7+1
16	Building	Al-Bayah area	5	58	Building	Al-Haram area	10+1
17	Building	Al-Bayah area	6+1	59	Building	Al-Haram area	12
18	Building	Al-Bayah area	5	60	Building	Al-Haram area	8+1
19	Building	Oyoon road	5+1	61	Bridge	Uhod area	
20	Building	Sultana road	6+1	62	Bridge	Al-Khulafa sec.	
21	Bridge	Uhod area		63	Bridge	Quba sec.	
22	Bridge	Uhod area		64	Building	Qurban sec.	6+1
23	Bridge	Uhod area		65	Bridge	Qurban sec.	
24	Building	Al-Bayah area	5+1	66	Bridge	1st Ring road	
25	Building	Al-Bayah area	7+1	67	Building	Al-Rawdah sec.	8+1
26	Building	Al-Bayah area	5+1	68	Building	Al-Khulafa sec.	7+1
27	Underpass	Abu-Thar street		69	Building	Al-Khulafa sec.	4
28	Building	1st Ring road	6+1	70	Building	Al-Khulafa sec.	6+1
29	Building	1st Ring road	7+1	71	Building	Al-Khulafa sec.	6+1
30	Building	Al-Haram area	10+1	72	Building	Al-Anbariah	7
31	Building	Al-Haram area		73	Building	Al-Rawdah sec.	12+1
32	Building	Al-Haram area	8	74	Building	Al-Rawdah sec.	7
33	Underpass	Al-Haram area		75	Building	Al-Ejabah sec.	7+1
34	Bridge	Al-Haram area		76	School	Al-Rawdah sec.	
35	Building	Al-Haram area	12+3	77	School	Al-Salam sec.	3
36	Building	Al-Haram area	10+2	78	Bridge	Al-Harrah Alsharqiah	
37	Car parks	Al-Haram area		79	Building	Al-Khulafa sec.	7+1
38	Building	Al-Haram area	15+2	80	Bridge	Al-Aqiq sec.	
39	Car parks	Al-Haram area		81	Market	Al-Aqiq sec.	1
40	Building	Al-Haram area	6+1	82	Building	Al-Khulafa sec.	7
41	Building	Al-Haram area	8+1	83	Mosque	Quba Mosque	1
42	Building	Al-Haram area	7+1	84	Mosque	Al-Haram	2+1

* It means 6 floors above ground + 3 underground floors.

طبيعـــة التربـــة في المـــدينـة المنـــورة بالمملكة العربية السعودية

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المستخلص . تقع مدينة المدينة المنورة بالسعودية في حوض رسوبي محاط بهضاب وتلال من صخور اللافا في نطاق الجزء الغربي من الدرع العربي . تتكون الطبقات تحت السطحية في المدينة وعلى عمق أقصاه **٤٥** متر من تسعة أنواع من التربة : واحدة ردميات وستة تربة متـماسكة واثنين من التربة مفككة بالإضافة إلى ثلاثة أنواع من الصخور . تتباين التربة المتماسكة من طين عضوي عالي التضاغط إلى طين رمادي وأخضر لين ومتضاغط ومنتفش إلى طين صلد . أما التربة المفككة فهي ذات كثافة نسبية متوسطة إلى عالية الكثافة جدًا . تختلف الصخور من حجر جيري ضعيف إلى صخور الجابرو الكتلي . تتواجد الردميات وبعض أنواع التربة الأخرى إلى أعلى ، أما الصخور فتتواجد إما على عمق أو على هيئة مكاشف تلالية متفرقة .

تتواجد أنواع التربة الضعيفة أو ذات المشاكل حتى عمق أقصاه **١٥** متر في بعض المناطق جنوب وشرق وشمال شرق الحرم الشريف وذلك لوجود تربة ضعيفة ذات تضاغط عالي أو محتملة الانتفـاش و/أو كلاهمـا . ولذلك يجب ضرورة اتخاذ الاحتياطات الوقائية لحماية وتقوية الاساسات الخرسانية وحديد التسليح وذلك من جور طبيعة التربة الصعبة . أما احتياطات التحكم في المياه الجوفية فهي غير لازمة للمنشأت العادية .