Engineering geological mapping of the holy city of Makkah Al Mukarramah, Saudi Arabia

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Abstract: The growth of the holy city of Makkah demonstrates a unique example among the birth of cities in the world. It flourished in a desert area, having no reliable source of water, food, or any other human culture. With the continuous growth of the city, the area around the Holy Mosque becomes heavily populated and the density of buildings increases. Naturally the city expands along the surrounding open land. However, some natural constrains are imported upon its development by the physical geography of the city. These obstacles are aligned along a series of narrow wadis flanked by bare steep-sided mountains. Because of these problems and the strategic importance of the holy city, Makkah was selected by the Saudi Geological Survey to undertake an engineering geological mapping program. The mapping of the engineering geology of Makkah followed the program suggested by the Association of Engineering Geology to map the geology of the major cities of the world.

Geologically, Makkah is covered by different types of igneous, metamorphic and sedimentary rocks of Precambrian and lower Palaeozoic era. In addition, there are subordinate sedimentary rocks and basaltic lava flow of Tertiary and Quaternary age. A geological map at a scale of 1:50,000 was prepared as a base map for the engineering geological map. The geotechnical properties of the different geological units were tested, a database was prepared, the sources for water and construction materials around the city were examined and evaluated, and the constrains that affect the city were also considered and evaluated. A comprehensive surface engineering geological map was accordingly prepared. The map shows 11 engineering geological rock and soil units having different geotechnical properties.

Site investigation reports were also collected from the different contracting companies and different subsurface analytical engineering geological maps were also prepared. With the information given in the database a large number of the analytical maps can also be prepared upon the request of the investigating engineer or planner.

Résumé: La croissance de la ville sainte de La Mecque – Al Mukarramah est un exemple mondial et unique de la naissance d'une ville. Elle s'est initialement implantée dans une zone désertique où n'existait aucune ressource durable en eau ou en nourriture ni aucune culture développée par l'homme. Avec la croissance continue de la ville, la zone avoisinant de la Mosquée Sainte devient fortement peuplée et la densité des immeubles augmente. La ville s'accroît naturellement dans les zones libres qui l'entourent. Toutefois, certaines contraintes naturelles liées à la géographie physique du site limitent ce développement ; des obstacles sont alignés sur une série de vallées étroites bordées par des montagnes et collines dénudées et fortement pentues. Du fait de ces freins au développement et de l'importance stratégique de la ville sainte, La Mecque a été choisie comme objet/cible pour la cartographie géologique et géotechnique par le Service Géologique Saoudien (SGS). Cette cartographie de la ville de La Mecque a été réalisée selon le programme proposé par l'Association de la Géologie de l'Ingénieur visant à cartographier la géologie des principales villes du monde.

Le site de la ville de La Mecque est caractérisé par différentes formations de roches volcaniques, métamorphiques et sédimentaires d'âge compris entre le Précambrien et le Paléozoïque inférieur. Celles-ci sont par ailleurs recouvertes par des formations sédimentaires et des coulées basaltiques d'âges tertiaire et quaternaire. Une carte géologique élaborée à l'échelle 1 / 50 000 a servi de support à une carte géologique et géotechnique. Les caractéristiques géotechniques des différentes unités géologiques ont fait l'objet d'études et de tests dont les résultats sont regroupés dans une base de données ; les ressources en eau et en matériaux de construction ont par ailleurs été étudiées et évaluées de même que les contraintes susceptibles d'affecter le développement de la ville. Une carte géologique et géotechnique de surface détaillée, élaborée à la suite de ces différentes études, permet de classer sols et roches en 11 unités présentant des caractéristiques géotechniques spécifiques.

Les rapports d'études de sites ont été collectés auprès de différentes sociétés d'ingénierie et différentes cartes d'analyse des propriétés géotechniques du sous-sol ont également été établies. La base de données qui regroupe l'ensemble de ces données permet par ailleurs d'établir un grand nombre de cartes analytiques répondant aux besoins spécifiques d'ingénieurs ou de planificateurs.

Keywords: compressive strength, engineering geological maps, igneous rocks, landslides, metamorphic rocks, slope stability.

INTRODUCTION

Makkah Al-Mukarramah is the holiest city of the Islamic world. Its holiness is due to the Holy Mosque also known as Al-Haram that contains the First house of God Kábah built by prophet Ibrahim and his son Ismail. It is located in the western region of Saudi Arabia, 80 km inland from the Red Sea (Figure 1) at the foothills of the Hijaz mountain range. Makkah has grown from a small settlement around the Kábah into a big city spread over an area of approximately 1000 km^2 with population of 1.5 million. Additionally, millions of Muslims visit the city for the annual pilgrimage, the *Hajj*, and throughout the year for the lesser pilgrimage the *Umrah*. The number of the visitors is growing by the year and so is the city. Makkah, in addition to being a religious centre, is also the administrative centre of a vast region of western Saudi Arabia.

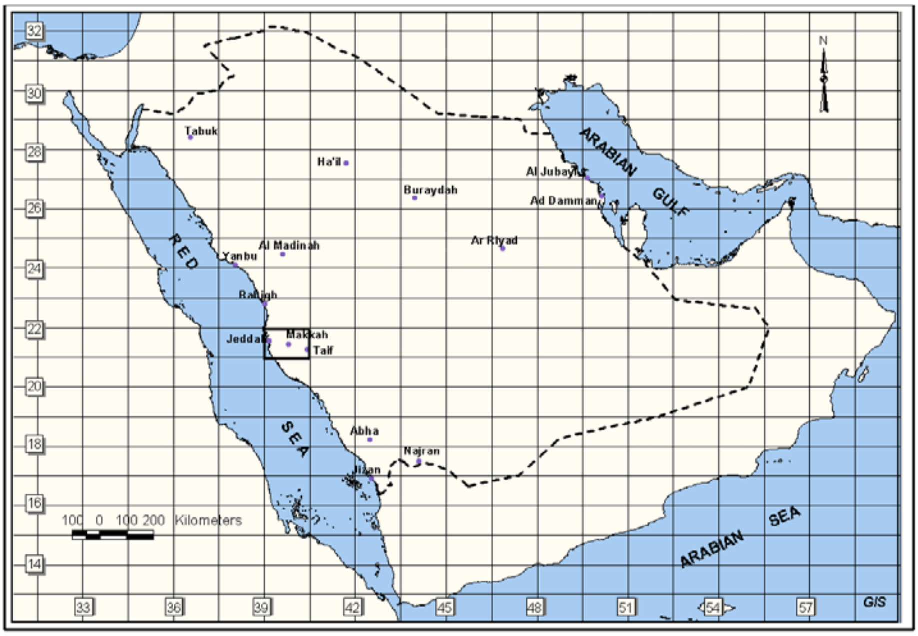

Figure 1. Location of Makkah city

To cope with the increasing number of visitors, major vertical growth is continuing around the Holy Mosque. The new trend is to demolish the old multi-storeyed buildings and replace with high-rise housing and commercial complexes with more than ten basements for parking and other utilities. In parallel to vertical growth around Holy Mosque there is a considerable lateral growth as well. However, natural geological constrains restricted the urban development along a series of narrow wadis flanked by bare steep-sided mountains and hills. With the availability of modern engineering equipment and know-how some of the hills are being removed by blasting and excavations to make plots for high-rise complexes. The municipal authorities have very ambitious plans for developing additional residential areas in the city, particularly in the neighbourhood of the Holy Mosque.

For design of any civil engineering project it is essential to determine engineering properties of the site of intended structure, which are locally obtained by geotechnical investigations. While these investigations are the site-specific giving detailed profile of engineering properties, the town planers require more general information of engineering properties of the area intended for urban development. The starting point can be a geological map. However, geological maps often have shortcomings in engineering projects since they group rocks of different engineering properties as single units based on age or lithology. They also lack quantitative information on the physical properties of rock types such as the nature of the discontinuities and the extent of weathering, the ground water conditions, and the potential geological hazards for engineering structures. For this, it is essential to produce engineering geological maps. Engineering geological map provides more information that is relevant to the needs of engineers than is available on conventional geological maps. Therefore an engineering geological bias to the basic mapping is invaluable for development in respect of terrain evaluation and to delineate areas of various degrees of suitability for construction

Recognising the importance of engineering geological map for a growing city the Saudi Geological Survey (SGS) initiated a project for mapping engineering properties of the area covering Makkah and surroundings. The studied area bounded between lat 21º 20' 6.62" N and 21º 35' 47.16" N, and long 39º 40' 00" E and 40º 00' 0.6" E.

The scope of the project was as follows:

- Geological mapping of the area at a scale of 1:50,000 using aerial photographs and satellite images.
- Identification of rock and soil types and classification and description of rocks and soils for engineering geological mapping.
- Assessment of geohazards conditions to identify flood-prone areas and areas of rock slope stability problems.
- Locating sites for supply of construction materials.

- Producing a comprehensive engineering geological map.

This paper is based on some of the results of the project.

Previous work

Saudi Arabian Mining Syndicate did the earliest geological work in the area in the 1930s (Larken 1936). Delineation of Precambrian and Cenozoic lithostratigraphic units was done in 1950s (Karpoff 1955; 1957a, b; 1958; 1960). Later geological maps were prepared at different times, which include Southern Hijaz Geological map at 1:500,000 scale (Brown *et al.* 1963), followed by more detailed study of smaller parts by the students of King Abdulaziz University, Jeddah (Al Shanti 1966; Hashem 1971; Nebert *et al.* 1974). Regional mapping at 1:100,000 scale was done by Saudi Arabia's Deputy Ministry of Mineral Resources (DMMR) formerly Directorate General of Mineral Resources (Skiba *et al.* 1977; Tayeb 1983). Moore and Al-Rehaili (1989) compiled geologic map of the Makkah quadrangle at 1:250,000 scale.

In 1986 Ministry of Petroleum of Saudi Arabia prepared the first engineering geological map at 1:10,000 scale for the central part of the city (Ministry of Petroleum and Mineral Resources 1986). This map shows local relief and water table contours. Sonbul (1995) mapped engineering geology of north–western area of Makkah at 1:10,000 scale. Al-Harthi & Amin (1997) studied sources of natural aggregates in six wadis—Wadi Na'man, Wadi Al-Yamanyah, Wadi Al-Shamyah, Wadi Hwarah, Wadi Alaf and Wadi Faydah — in the vicinity of Makkah. Their qualitative and quantitative assessment of coarse and fine aggregates indicated that their properties satisfied the ASTM, BS and Saudi standards.

GEOLOGY AND GEOMORPHOLOGY

Geology

The studied area is located within the southern part of Hijaz region on the west-central part of the Arabian Shield, which is dominated by different types of igneous, metamorphic and sedimentary rocks of Precambrian and lower Palaeozoic era (Greenwood *et al*. 1976). In addition, there are subordinate sedimentary rocks and basaltic lava flow of Tertiary and Quaternary age (Sonbbl 1995).

Mainly Precambrian intrusive rocks cover the area. Intermediate rocks, ranging in composition from diorite to Tonalite, predominate in the Makkah batholiths and are assigned to the Kamil suite. The dominant structural trend is northeast to north-northeast and reflects three major phases of Precambrian deformation and Tertiary faulting.

Geomorphology

The region has high topographic features resulted from the uplifting associated with Red Sea rifting. The elevations vary mainly between 300 and 980 meters above sea level (masl). In the middle of the mapped area elevation increases and the topography tends to be rugged and high massive mountains of weakly deformed and slightly weathered rocks dominate.

From west to east the area shows a very steep slope with elevation of 340 to 560 masl at Jabal Abu Ghurrah. This mountain is folded and drains into Wadi Fatimah graben in the extreme northwestern part with NE – SW trending.

To the southeast of Wadi Fatimah, moderately high mountains with elongated shapes and some hills are separated by Wadi Sarf and other small wadis. Moderately high mountains represent central part to the southwestern part the area and some hills surrounded by these mountains.

In the middle part, the relief becomes more rugged as the elevations increase at Jabal At-Tarfi, Jabal Al-Ahdab and Jabal Mina with elevations varying between 610 and 980 masl. Some isolated hills exist as small isles in the northeastern part of the area at Shib Burud that are separated by erosional flats and wadi channels. In addition, Wadi Uranah lies in the southeastern part at Arafat area. It extends in NE– SW direction.

SOIL AND ROCK PROPERTIES

Soil properties

Geotechnical investigations carried out by various construction companies at 67 different locations were used to identify soil types and their properties. SGS excavated 38 shallow test pits to supplement this information. Samples from the pits were analysed for engineering properties in the SGS laboratories. These properties included grain size distribution, liquid limit (LL) and plastic limit (PL), moisture content, specific gravity and hydrometer test. Field density measurements were performed at sites. All the tests were performed according to relevant ASTM method. Information on Soil Penetration Test (SPT) was obtained from the reports of the construction companies.

From the grain size analyses the uniformity coefficient (UC) and curvature coefficient (CC) were determined which help classify the soils as well graded (WS) and poorly graded (SP). WS soil is classified as having $UC>6$ and $3<CC>1$, and SP soil is classified as having $UC<6$ and $CC<1$. Tables 1 and 2 summarise the distribution of UC and CC respectively. The two tables show that about 50 percent of the samples fall under WS category and the rest under SP category.

LL and PL tests were performed on 38 samples. The plasticity Index (PI) was then calculated from PI=LL-PL %. These tests are used to estimate the shrinkage limit, which indicates volume change that may occur when soils undergo different cycles of dryness and wetness. PI ranged between 0.11 to 5.66 %. According to PI range only three samples were classified as fine grained soils as inorganic clays of low plasticity (CL) and rest came under the class of inorganic silts of low plasticity (ML)

Moisture content ranged between 0.4 to 7.74 %. Only 4 samples had relatively higher moisture content than that of the rest of the samples.

Table 1. Distribution of UC of 38 soil samples

UC	Frequency	Percentage	Cumulative Percentage
2	2	5.13	5.13
4	10	25.64	30.77
6	9	23.07	53.85
8	6	15.38	69.23
10	1	2.56	71.79
>10	11	28.20	100.00

Table 2. Distribution of CC of 38 soil samples

CC	Frequency	Percentage	Cumulative Percentage
0.5	6	15.38	15.38
1.0	13	33.33	48.72
1.5	19	48.72	97.44
2.0	0	0.00	97.44
>2	1	2.56	71.05

Specific gravity test are used to calculate the unit weight of the solid particles, which is an important variable in calculating and estimating the soil suitability for engineering purposes. 23 samples taken close to the ground surface were tested and the specific gravity ranged between 2.55 and 2.90.

Hydrometer test determines fraction of fines that pass through the sieve size 200 (0.075 mm). In other words it determines the silt and clay content. Hydrometer tests were performed on 23 samples. The results showed that clay percentage ranged from 0.6 to 1.93. Silt percentage range was up to 78.6% and about 86 % samples had silt content less than 30 %. Table 3 summarises silt percentage.

Table 3. Distribution of silt percentage in 23 soil samples

Silt %	Frequency	Percentage	Cumulative Percentage
10	6	26.08	26.09
15	5	21.74	47.83
20	1	4.34	52.17
30	8	34.78	86.90
40	1	4.34	91.30
50	1	4.34	95.65
>50	1	4.34	100.00

The soils were also classified according to Unified Classification System (USCS). Table 4 summarises various soil classes.

Table 4. Soil classes according to USCS

Number of Samples	Soil Class	
	Description	Symbol
1	Sandy silt	MS
10	Poorly graded sand	SP
9	Silty Sand	SM
7	Poorly graded sand with silt	SP-SM
4	Well graded sand with silt	SW-SM
4	Silty sand with gravel	SM
1	Poorly graded gravel with sand	GP
1	Poorly graded sand with gravel	SP
1	Well graded sand	SW

Using sand cone, 28 *in situ* tests were performed to determine soil density. Bulk density ranged between 1.32 and 1.93 kN/m^3

Rock mass properties

There are many classifications that assign numerical values to properties of rocks and soils. The Rock Mass Rating (RMR) system proposed by Bieniawski (1973; 1974; 1976; 1989) and the Q-system proposed by Barton, Lien & Lunde (1974) are extensively applied to evaluating the rock mass quality for different engineering purposes. Al-Harthi (1993) found that amongst all the rock mass classification systems for engineering purposes, the RMR system was the most suitable for arid environments of Saudi Arabia. Therefore it was adopted for this study.

RMR is a composite property of rock taking into account several other properties. The properties included in the system are (a) strength of intact rock mineral represented by Uniaxial Compressive Strength (UCS) and Point Load strength index, (b) Rock Quality Designation (RQD), (c) Spacing of discontinuities, (d) condition of discontinuities or degree of weathering and (e) Groundwater (Bieniawaki 1989). Each of these properties is given a rating according to its magnitude and the sum of these ratings is the RMR of the rock. All the rocks are dry therefore groundwater is has a zero rating. The rock is then defined as very good rock, good rock, fair rock, poor rock and very poor rock according to RMR ranges of 100-81, 80-61, 60-41, 40-21 and <20 respectively.

Strength

Schmidt hammer readings of intact rock were taken at the 116 investigated stations and with the knowledge of unit weight of rock UCS was calculated by a chart given by Deere & Miller (1966). Accordingly, rock strength is classified into seven categories —extremely strong (S_1, σ_c>200 MPa), very strong (S_2, σ_c=100-200 MPa), strong (S_3, σ_c=50-100 MPa), moderately strong (S_4, σ_c=12.5-50 MPa), moderately weak (S_5, σ_c= 5-12.5 MPa), weak (S_6, σ_c=1.25-5MPa), and very weak (S_7, σ_c<1.25 MPa.). Summary of strength grades of nine rock types found in the study area is presented in Table 5.

Table 5. Strength grades of various rock types

Rock Type	Strength Grade Range
Diorite	S_1-S_4
Quartz-Diorite	S_1-S_5
Tonalite	S_3
Granodiorite	S_2
Amphibolite	S_2-S_4
Gabbro	S_2
Meta Basalt	S_3-S_4
Chlorite	S_1-S_3
Phyllite	S_7

Rock Quality Designation (RQD)

RQD is defined empirically on the basis of number of joints per m_3 (J_v) and is given by RQD=115-3.3J_v (Palmstrom 1982). Rocks are divided into five classes according to RQD percentage. They are very good (R_1, RQD=90-100%), good (R_2, RQD=75-90%), Fair (R_3, RQD=50-75%), poor (R_4, RQD=25-50%) and very poor (R_5, RQD=<25%). RQD was determined at the 116 investigated stations and the results are summarised in Table 6.

Table 6. Range of RQD classes of various rock types

Rock Type	Strength Grade Range
Diorite	R_1-R_5
Quartz-Diorite	R_2-R_5
Tonalite	R_4
Granodiorite	R_2
Amphibolite	R_2-R_5
Gabbro	R_3-R_4
Meta Basalt	R_5
Chlorite	R_3-R_4
Phyllite	R_5

Discontinuity spacing

Average distance between adjacent pair of joints controls the size of individual blocks of rock masses, which govern the stability of rocks structures. It is measured by counting the number of discontinuities, which intersect a line of known length, and is expressed as a mean joint spacing. Geological Society of London (1977) has divided discontinuity spacing into six classes— extremely wide spaced (F_1, >200mm), widely spaced (F_2, 60-200mm), moderately wide spaced (F_3, 20-60mm), closely spaced (F_4, 6-20mm), very closely spaced (F_5, 2-6mm), and extremely closely spaced (F_6, 2mm). The summary of results of joint spacing at different stations is given in Table 7.

Degree of weathering

Weathering is identified by signs of discoloration or decomposition, or changes in the texture and fabric of the rock. Geological Society Engineering Group Working Party (1977) describes weathering in five grades—fresh or unweathered (W_1), slightly weathered (W_2), moderately weathered (W_3), highly weathered (W_4), and completely weathered (W_5). Summary of weathering grades of various rock types is presented in Table 8.

Table7. Range of discontinuity spacing of various rock types

Rock Type	Strength Grade Range
Diorite	F_3-F_4
Quartz-Diorite	F_2-F_4
Tonalite	F_4
Granodiorite	F_3
Amphibolite	F_3-F_5
Gabbro	F_3-F_4
Meta Basalt	F_4
Chlorite	F_3-F_4
Phyllite	F_4

Table 8. Weathering grades of various rock types

Rock Type	Weathering Grade Range
Diorite	W_1-W_5
Quartz-Diorite	W_1-W_5
Tonalite	W_3-W_4
Granodiorite	W_1-W_2
Amphibolite	W_1-W_4
Gabbro	W_1-W_4
Meta Basalt	W_3-W_4
Chlorite	W_3-W_4
Phyllite	W_3-W_4

Rock Mass Rating (RMR)

Using the above parameters RMR of all rock types was calculated at the 116 investigated stations. The results are summarised in Table 9. The predominant rock type is Quartz Diorite followed by Diorite and Amphibolite. Other rocks occurring in the area include Gabbro, Tonalite, Meta Basalt, Chlorite Schist and Phyllite. All the rocks are Good and Fair and some Very Good. Poor rock, Quartz Diorite, was found at one location only.

Table 9. Rock types and RMR classification

Rock Type	Number of Stations				
	RMR				
	Very Good	**Good**	**Fair**	**Poor**	**Very poor**
Diorite	**1**	**13**	**4**		
Quartz-Diorite	**5**	**47**	**15**	**1**	
Tonalite			**1**		
Granodiorite	**1**				
Amphibolite	**1**	**11**	**4**		
Gabbro		**4**			
Meta Basalt		**1**	**2**		
Chlorite		**2**	**1**		
Phyllite			**1**		

Rock excavability

Excavability of rock is a function of RQD, UCS and discontinuity spacing. Figure 2 combines these three parameters and divides rock types into five classes I, II, III, IV and V, and four excavation methods (i) Blast to fracture (ii) Blast to loosen (iii) Rip and (iv) Dig. Table 10 summarises classes of excavability of various rock types.

ENGINEERING GEOLOGICAL MAPPING

Geotechnical database for Makkah area was designed and constructed to store the field and laboratory data from site investigations and geotechnical information collected from previous reports. This database is divided into two inter-locking tables. The first one stores the surface data for both rock and soil, while the second one is for subsurface data. This information is then retrieved and queried for selected parameters to generate analytical engineering geological maps. The database is linked to ArcView Geographic Information System (GIS) software, which graphically produces such maps.

Engineering properties of surface rocks at 116 rock stations and soil and rock properties at other 67 locations were entered into the database. Using ArcView GIS several maps were constructed. Two of them are presented here.

Engineering geological map

Taking the geological map of Makkah area as a base map and superimposing geotechnical properties of the soil and rocks as determined in this project, a Zonation map was produced. Each rock unit in the study area was categorized into different zones of engineering geological parameters according to the system proposed by the Geological Society Engineering Group Working Party (1977). Figure 3 presents an example of an Engineering Geological Zonation map. Table 11 summarises the various zones of each rock unit with engineering geological parameters. Twenty three zones were identified for Quartz-diorite (Qd), Amphibolite (Xam) was divided into 13 zones, Diorite and Gabbro (Mdg) together were categorised into 14 zones and Gabbro (Gb) into 3 zones. Chlorite Schist (Sb), Phyllite (Zj), Tonalite (xtn) and Meta basalt and volcaniclastic rocks (Zm) were divided into 4, 1, 1 and 2 zones respectively. Three zones were identified for soils.

Table 10. Excavability classes of various rock types

Rock Type	Class
Diorite	**III-II**
Quartz-Diorite	**III-II-I**
Tonalite	**II-I**
Granodiorite	**II-I**
Amphibolite	**IV-III-II**
Gabbro	**III-II**
Meta Basalt	**II-II**
Chlorite	**II-I**
Phyllite	**V**

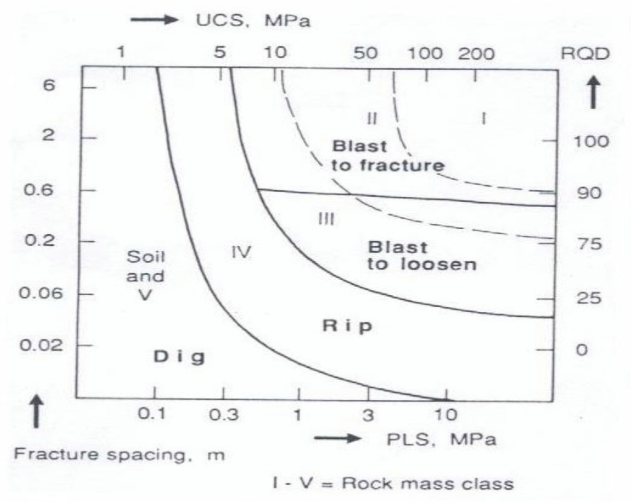

Figure 2. Classes of rock excavability

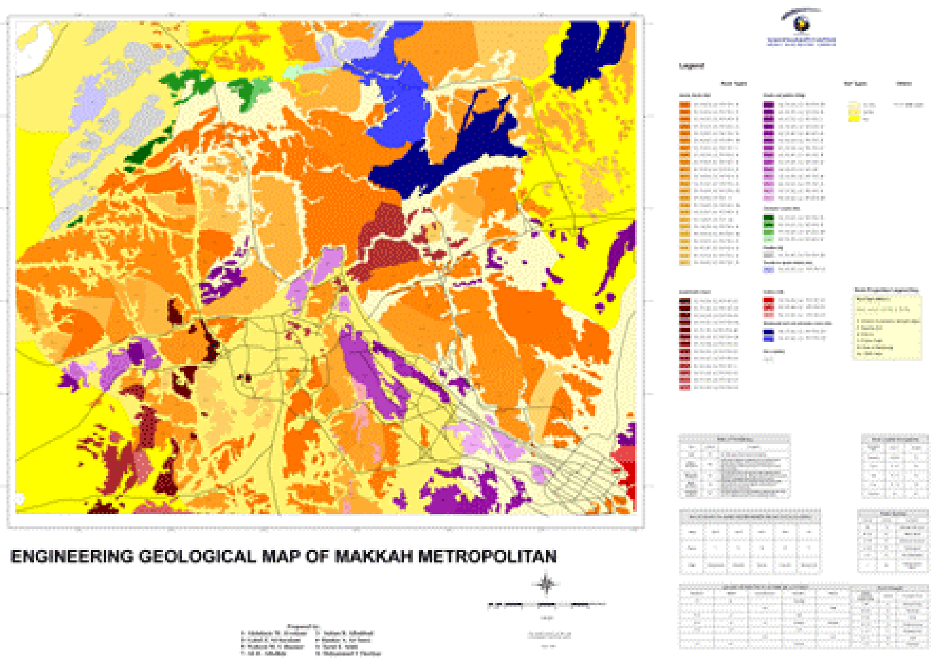

Figure 3. An example of an Engineering Geological Zonation map

Table 11. Engineering geological zones of various rock units and soils in Makkah Area

ROCK TYPE	ZONE	ENGINEERING PROPERTIES	ROCK TYPE	ZONE	ENGINEERING PROPERTIES
Quartz diorite (Qd)	1	(S2.F4.R4.A2.W3-W4.II)	Diorite and gabbro (Mdg)	1	(S4.F4.R4.A3.W3-W4.III)
	2	(S2.F4.R4.A2.W1-W2.II)		2	(S2.F4.R5.A2.W3-W4.II)
	3	(S2.F4.R5.A2.W3-W4.II)		3	(S2.F3.R1.A2.W1-W2.I)
	4	(S3.F3.R3.A2.W3-W4.II)		4	(S2.F4.R4.A2.W3-W4.II)
	5	(S2.F4.R3.A1.W1-W2.II)		5	(S2.F3.R3.A2.W3-W4.II)
	6	(S4.F4.R5.A2.W3-W4.III)		6	(S2.F4.R4.A2.W1-W2.II)
	7	(S2.F3.R2.A2.W1-W2.I)		7	(S1.F4.R3.A2.W1-W2.II)
	8	(S3.F4.R4.A2.W3-W4.II)		8	(S2.F4.R5.A3.W1-W2.II)
	9	(S2.F3.R3.A2.W1-W2.II)		9	(S1.F3.R3.A2.W1-W2.II)
	10	(S2.F3.R4.A2.W3-W4.II)		10	(S4.F4.R3.A3.W5.III)
	11	(S2.F4.R3.A2.W3-W4.II)		11	(S2.F4.R3.A2.W1-W2.II)
	12	(S2.F3.R3.A2.W3-W4.II)		12	(S2.F3.R3.A2.W1-W2.II)
	13	(S3.F4.R5.A2.W3-W4.III)		13	(S3.F3.R2.A2.W1-W2.II)
	14	(S7.F2.R5.A3.W5.V)		14	(S4.F4.R2.A2.W3-W4.III)
	15	(S5.F4.R5.A3.W3-W4.III)	Chlorite schist (Sb)	1	(S2.F3.R3.A3.W1-W2.II)
	16	(S4.F3.R3.A3.W3-W4.II)		2	(S1.F4.R3.A2.W3-W4.II)
	17	(S3.F4.R3.A2.W5.III)		3	(S3.F4.R5.A3.W3-W4.III)
	18	(S1.F4.R3.A2.W3-W4.II)		4	(S3.F4.R4.A3.W3-W4.II)
	19	(S4.F4.R4.A2.W3-W4.III)	Phyllite (Zj)	1	(S7.F4.R5.A4.W3-W4.III)
	20	(S3.F4.R3.A2.W3-W4.II)	Tonalite to quartz diorite (xtn)	1	(S3.F3.R3.A2.W3-W4.II)
	21	(S4.F3.R3.A2.W3-W4.II)	Gabbro (Gb)	1	(S2.F4.R4.A2.W1-W2.II)
	22	(S3.F3.R2.A2.W3-W4.II)		2	(S2.F4.R4.A2.W3-W4.II)
	23	(S1.F4.R2.A2.W1-W2.II)		3	(S2.F3.R3.A2.W3-W4.II)
Amphibolite (Xam)	1	(S2.F4.R4.A2.W3-W4.II)	Metabasalt and volcaniclastic rocks (Zm)	1	(S4.F4.R5.A2.W3-W4.III)
	2	(S2.F3.R2.A2.W1-W2.II)		2	(S3.F4.R5.A2.W3-W4.III)
	3	(S2.F4.R5.A2.W3-W4.II)	Zonation of Soil	1	(SW-SM)
	4	(S4.F4.R5.A2.W3-W4.III)		2	(SP-SM)
	5	(S3.F5.R5.A2.W3-W4.III)		3	(SM)
	6	(S4.F4.R5.A2.W3-W4.III)			
	7	(S3.F4.R4.A2.W3-W4.II)			
	8	(S4.F4.R3.A2.W3-W4.II)			
	9	(S3.F4.R3.A2.W3-W4.II)			
	10	(S2.F3.R2.A2.W1-W2.I)			
	11	(S4.F3.R2.A2.W3-W4.II)			
	12	(S2.F3.R3.A2.W3-W4.II)			
	13	(S3.F3.R3.A2.W3-W4.II)			

Slope Hazard Map

The prediction of potential landslide areas has been very difficult because of the complexity of the factors involved and their relationship to each other. The integration of the GIS with remote sensing data facilitated the assessment of slope instability hazards.

A slope direction map was generated from the DEM. Field observations indicated that most of the landslides and rock-falls in the area occurred at slope inclination greater than 40^0. Accordingly a slope hazard map was generated, which is presented in Figure 4.

The slope data were developed using ArcView 9.1 and ArcView Spatial Analyst. The grid was generated from satellite imagery to format DEM data. The elevation grid was used to drive the slope grid. The slope grid was re-classed into the four specified Hazard categories and converted to a shape file.

These categories are as follows (Figure 4):

- High danger: Very steep slope (40^0– 90^0) represented by red colour.
- Moderate danger: Steep slope (30^0 – 40^0), represented by orange colour.
- Low danger: Moderate slope (20^0 – 30^0), represented by yellow colour.
- Safe: Gentle slope (0^0 – 20^0), represented by green colour.

According to this classification the very steep area (red colour) are far away from the residential area. However some residential areas are built either within or close to the moderately steep zones (30^0 – 40^0), which may contribute to local rock-fall and pose landslide hazards.

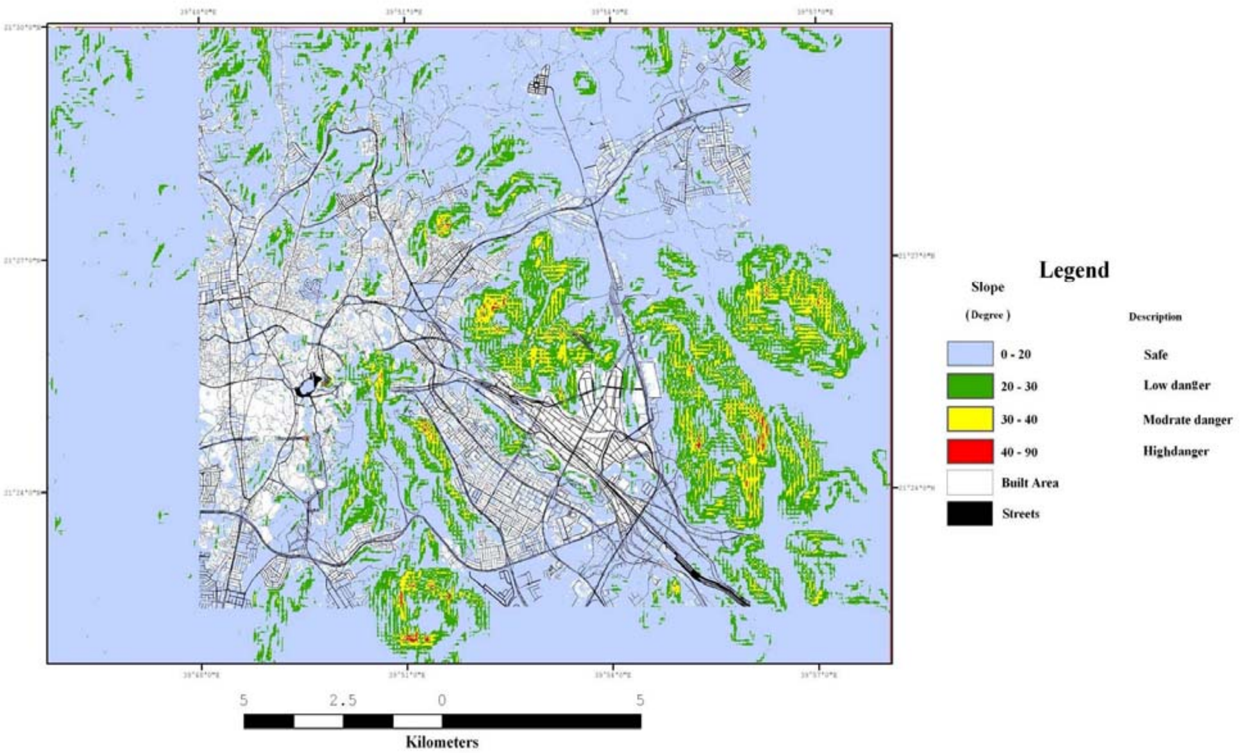

Figure 4. Slope hazard map of Makkah area

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