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Engineering Geological Assessment of Sandstone Rock from Jebel Aulia New Hydroelectric Power Plant Site, Jebel Aulia Dam, Sudan

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Abstract: This study presents the engineering geological assessment of sandstones from Jebel Aulia New Hydroelectric Power Plant (NHPP) site, situated at Jebel Aulia Dam, 50 km south of Khartoum; the capital of Sudan. This is the first time is thought over to make use of the dam in generating hydroelectric power. The study has been conducted by geological fieldwork and geophysical investigations (Vertical Electrical Sounding and Seismic Refraction), drilling, petrographic studies and laboratory testing of sandstone rock samples. The fine, medium and coarse-grained sandstones are cemented mainly by silica, kaolin, iron oxides, manganese oxides and calcium carbonate. The petrographic studies indicated that the sandstones are mainly composed of quartz, rock fragments, little feldspar (less than 5%) and micas. Accordingly, these sandstones can be classified as greywacke or quartz wacke based on Pettijohn's definition. The fractures analyses of Jebel Aulia indicated that, they are probably tectonic in origin and were formed due to the effect of Jebel Aulia fault. The average hydraulic conductivity of the sandstones is interpreted as high with no significant vertical variation in the water level and seepage occurrence on the foundation. Generally, the degree of weathering and porosity decreases with increasing of depth and the values of the RQD, TCR, specific gravity, bulk density, UCS and point load strength test results increase with increasing of depth unless other conditions may disturb this sequence. The depth to the fine to medium-grained sandstone varies from about 2.5-10 m.

Key words: Jebel Aulia dam, sandstones, New Hydroelectric Power Plant (NHPP) site

INTRODUCTION

Jebel Aulia Dam is a masonry dam, constructed in 1937. It sits across the White Nile with total length of 4.3 km and 22 m in height. The capacity of the reservoir is about 3.5×10^8 m^3 and the area of the reservoir is about 12.2×10^4 m^2. The lake resulted from the dam is about 629 km in length with average dimension ranges between 6.0-2.3 km. The dam is situated in Khartoum State, about 50 km south of Khartoum; the capital of Sudan (Fig. 1). It bounded between latitude 15° 36' N and longitude 32° 32'E. It has been constructed as a storage reservoir for irrigation in Egypt, to hold back part of the White Nile while the Blue Nile is in flood and to control the White Nile floods but, it has become redundant due to the construction of Aswan High Dam in 1964, it handed over to Sudan government in 1977. The valley above Jebel Aulia Dam is very flat and open, at maximum capacity the reservoir extends some 480 Km up stream therefore, a great deal of water is lost by evaporation and seepage.

The height of Jebel Aulia area according to the bench marks is 372 m above Mean Sea Level (MSL). The general

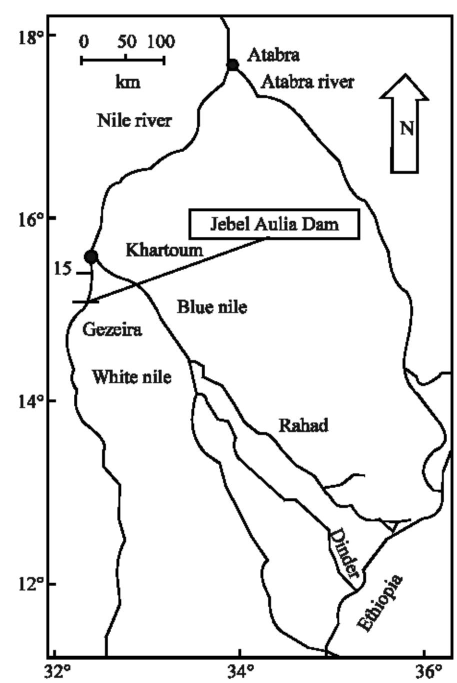

Fig.1: Location map of Jebel Aulia Dam

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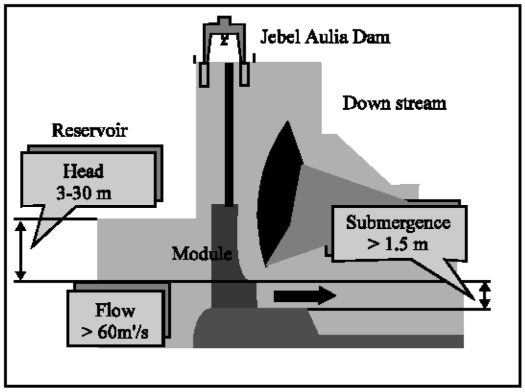

Fig. 2: Application range for the turbine system in Jebel Aulia NHPP

topography of the area is flat to semi flat. Relief sloping from west and east towards the White Nile River, as indicated by the water courses and seasonal streams. The western part of Jebel Aulia is bounded by few scattered iselbergs, qoz sands and gravel accumulations.

The studied site is a part of the semi-arid region, characterized by long dry season, extends from June to September. The rainfall associated with the movement of the intertropical convergent zone and their intensity increases towards the south. It is hot to very hot in summer and it shows a wide range of temperature. The mean monthly temperature shows maximum value in April. The winter season is very short, cool and dry and usually extends from November to February.

The rapid increase of the energy demand, growth of the capital population and the establishment of new development projects has lead to construct Jebel Aulia New Hydroelectric Power Plant (NHPP) at Jebel Aulia Dam. This is the first time is thought over to make use of the Dam in generating hydroelectric power. The project is for design and erection of 80 turbines in 40 modules. Each two turbines are a matrix will be erected at one dam gate (Fig. 2). The turbine out put is 380 KW and the total capacity will be 80×380 kw (30.4 MW).

Mechanical and physical characteristics of rocks are generally fundamental information for engineering purposes, such as assessing foundation support for facilities, instability of artificial and natural slopes and other engineering works. They also may depend on their petrographic characteristics such as composition and textures of rocks as they reflect environments of rocks during sedimentation, diagenesis and weathering in each location. Even in homogeneous sandstones, some characteristics in mechanical and physical properties may be influenced by their characteristics in composition and textures.

This study discusses the engineering geological assessment carried out to evaluate the sandstones rock at Jebel Aulia NHPP site and to know the suitability of the rock as foundation material. The data derived are mainly from geological fieldwork and geophysical investigation (Vertical Electrical Sounding and Seismic Refraction), drilling, petrographic study and laboratory testing of sandstone rock samples.

Geological setting and structure: The region around Jebel Aulia is covered by various types of Basement Complex rocks; it occupies more than 49% of the area of the country (Whiteman, 1971). In the southwest, it occurs as isolated outcrops and consists of felsite, gneisses and schists. Most of the gneisses are covered either with a thin mantle of soil or by a thin cover of dry Nubian Formation.

The Nubian Formation consists of conglomerates, grits, sandstones, sandy mudstones and mudstones. It covers about 28% of the total area of the Sudan (Whiteman, 1971). It overlies unconformably the Basement Complex and it is known to be of Upper Cretaceous age. Berier (1993) adopted the term Omdurman Formation for the sedimentary rocks in the State of Khartoum. He subdivided the Formation into Upper (for its upper part) and Lower for the subsurface strata of the same formation. Awad (1994) mentioned that "Omdurman Formation is extended to include the subsurface and outcropping sediments including Jebel Aulia, which can be classified further into Umm bada and Merkhyiat members". The age is probably of Cretaceous.

The studied outcrops comprised a flat or N/NW gentle dipping sedimentary rocks. The conglomerate is almost grain-supported, sometime cemented by iron oxides. The fine, medium and coarse-grained sandstones are cemented mainly by silica, kaolin, iron oxides, manganese oxides and calcium carbonate. The siltstone and mudstone are also present. The bed thickness varies from thinly bedded (60-200 mm) to thickly bedded (600 mm- 2 m) outcrops. The sedimentary structures are well seen in most of the studied outcrops include: planar; cross and trough cross bedding, load cast, horizontal lamination and graded bedding.

Several outcrops of basalts cutting the Omdurman Formation near Omdurman city and penetrated in boreholes in the Nubian Formation at considerable depths between Jebel Aulia and Khartoum has been described by Farah *et al.* (2000). The age of these basalts is probably of Tertiary-Oligocene.

The Quaternary to recent deposits encountered in the study area and it is surrounding include wind blown sands, Qoz sand and fixed dunes, White Nile alluvium and wadi deposits.

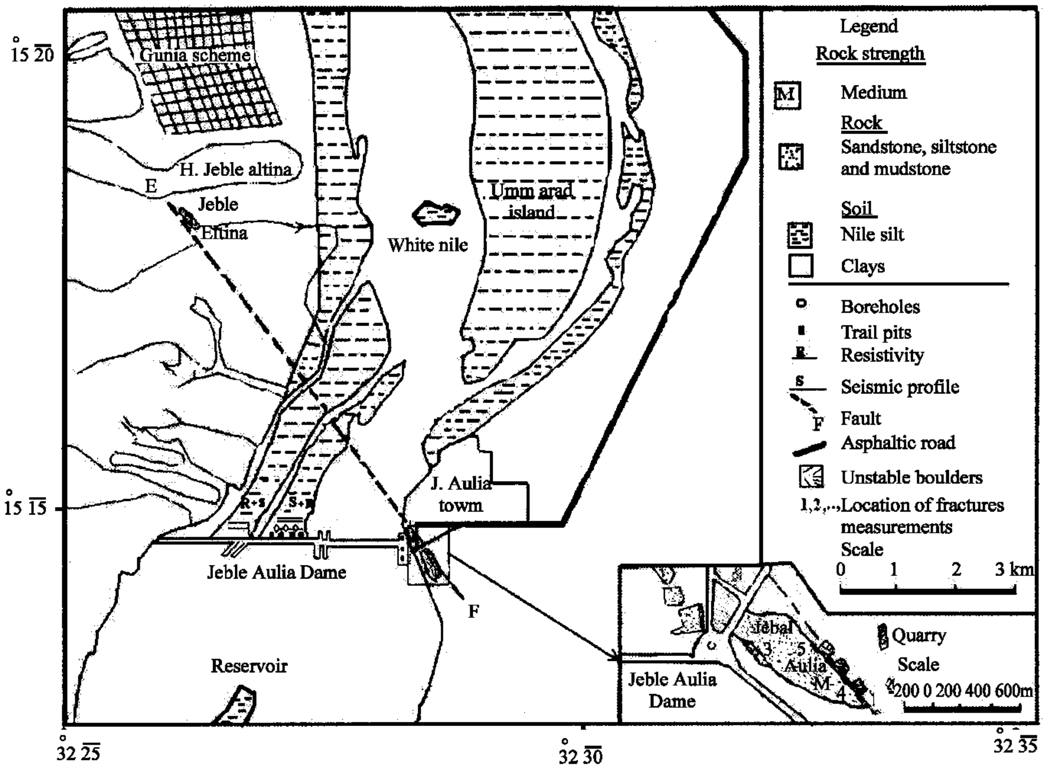

Fig. 3: Simplified engineering geological map of Jebel Aulia NHPP site

The most western part of Jebel Aulia is covered by extensive eolian sands. It presents in the form of sand sheets or fixed sand dunes (Qoz deposits of Pleistocene age), particularly, Qoz Abu Dulu, 40 km west of Omdurman. It is a well developed sand dune in the Tertiary (Whiteman, 1971).

Different fault sets have affected the sediments of the Upper Omdurman Formation and it is very clear in Merkhyiat Member. Faults trending E-W and N-S exist in the north and northeast of Khartoum. Another major fault trending NW occur west of Jebel Aulia Dam. Other NW trending faults are observed cutting the Nubian Formation near Jebel Aulia Dam (Fig. 3). These faults can be traced to Jebel Eltina and Jebel Honeik (both occur northwest of Jebel Aulia) west of the White Nile and towards the east across the White Nile into El Gezeira. The down thrown side of the main fault is more than one Kilometer to the northeast of Jebel Aulia Dam (Farwa, 1978). North west of Jebel Aulia dam, a set of parallel faults trending in the same direction as that of Jebel Aulia are also observed. Most of the affected rocks are characterized by silicification, brecciation, slickenside surfaces and ferruginization. The faults are probably resulted from post-Nubian tectonic movements.

MATERIALS AND METHODS

The fieldwork programme included several visits to the Jebel Aulia NHPP site, western bank, down stream and it is vicinity. During the fieldwork, detailed geological and geophysical investigations were carried out, topographic and geological maps, aerial photos and satellite images were studied and evaluated. This provided the basis for the geophysical surveys (Vertical Electrical Sounding (VES) and seismic refraction profiling). The geophysical work aimed at determining the thickness of the geological units and to differentiate between the weathered and fresh sandstones. Drilling and excavation of pits were carried out. During drilling core boring NX size is performed, samples were collected for laboratory tests, nature of the underlying soils and rocks, depths of weathering, bedding and structures are observed and studied. Thin sections are made from core samples.

A number of laboratory tests were carried out on the sandstone cores, including specific gravity (ñs), bulk density (ñ$_{a}$), porosity (n), Uniaxial Compressive Strength (UCS) and point load strength, generally following the recommendation of the British Standard laboratory techniques (BS, 1981). The strength of the sandstones with different degrees of weathering was determined using uniaxial compressive strength and point load strength.

RESULTS AND DISCUSSION

Trial pits and boreholes: Four trial pits (TJ_1, TJ_2, TJ_3 and TJ_4, respectively) were excavated at the NHPP site (Fig. 3). Their sizes are 2×.5 m and depth of 2 m. The pits helped in the visual inspection of the in situ soil condition, observation of water seepage and assessing the stability of excavation.

Three boreholes (from east to west BJ_1, BJ_2 and BJ_3, respectively) were drilled at the western bank, down stream of the White Nile. The distance between every two adjacent boreholes is about 60 m and they are parallel to the dam axis. The thickness of the soils was 6.7, 8 and 9.3 m, respectively. The soil is generally made up of artificial fill and remnant of the building materials which has been accumulated during the construction of the dam, underlain by dark clay, dark grey sandy silty clay, grey sandy silt and gravel clayed sand. The soil is underlain by sandstones occasionally coated by lenses of mudstone and siltstone. The sandstones are porous, highly permeable, weathered, moderately strong, very thinly bedded and with variable grain-sizes, cementing materials and colours. The degree of weathering decreases with increasing of depth. The drilling sealed at depths of 20.20, 25 and 24.75 m, respectively.

The subsurface units revealed from the drilling consist of fining upward sequences. The cycles are more or less well developed than that of the outcropping sediments. They are moderately sorted, fine-grained sandstones, siltstone with subordinate mudstone. The bedding of sandstones is alternating with finely laminated siltstones and mudstones. Horizontal to low-angle bedding sandstone is noticed in individual units.

Fractures analysis: Bellahsen *et al*. (2006) defined fractures as "parting planes along which there has been little or no displacement". In engineering these fractures may represent possible sites for surface of sliding, potential leakage channels or untrusted sites in construction projects.

The sandstones of Jebel Aulia out crop has been affected by ruptures, which lead to the formation of fractures. They occur in sets more or less parallel and regularly spaced, sometime their spacing varies from narrow to wide (Deere, 1963). Several sets are observed running in different directions resulting in blocky structure are recorded. Some of them are horizontal and others are vertical. The distances between fractures are varied; they range between 40-100 cm and their width ranges between few millimeters to few centimeters. Some of them are long and the rest are short running in 2 sets and crossing each other and their lengths do not exceed 10 m. The spacing between the two sets is about 10 cm and their width ranges between a few millimeters to 2c m. Most of the studied fractures are described as tight, partly open or clear visible cavities and filled. Their set frequency increases with proximity to the fault plane. This description is similar to that given by (ISRM, 1981). In tight fractures the rupture is quite apparent with the naked eye, though the walls of the fractures are brought together to such an extent that it becomes impossible to see the cavity along the rupture. Blind and refilled fractures by mud are not uncommon.

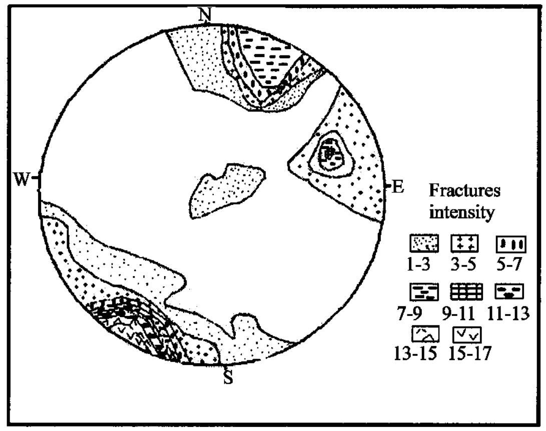

Fig. 4: Lambert equal-area contour diagram of fractures intensity of Jebel Aulia NHPP site

A total of 160 measurements of fractures strikes and dips are plotted on a single diagram, with the aim of establishing predominant orientation of the fractures. Three graphical methods are used in this research: the Lambert and Schmidt Equal-area diagrams and rose diagram. The first showed a general trend of NE-SW but, the dominant orientation of the strikes and dips are N30E and 220 W, respectively (Fig. 4). Schmidt net diagram (Fig. 5) showed the azimuth of dip of the two contagious fractures systems from Jebel Aulia. The arc of the big circles represents the intersection of the surface of fractures and the lower hemisphere. The diameter of the diagram connecting the end-points of the arc will then be the line of strike of the fractures. The rose diagram (Fig. 6) showed the dominant orientation of the fractures striking N30E but, the general trend is NE.

The fracture analysis of Jebel Aulia gives a general trend of NE-SW. According to Mikhailov (1987) "the break fractures are always perpendicular to the maximum tensile normal stress" therefore, the acting force of Jebel

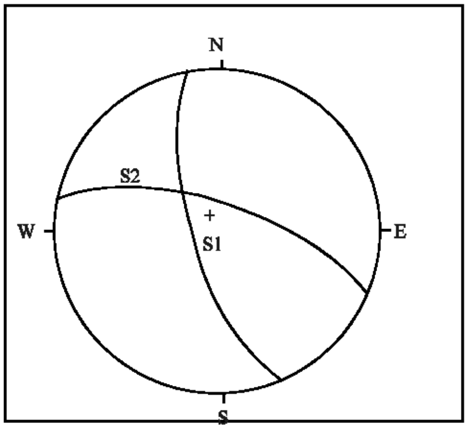

Fig. 5: Schmidt net projection of fractures, Jebel Aulia NHPP site. S1: Fractures system No. 1, S2: Fractures system No. 2

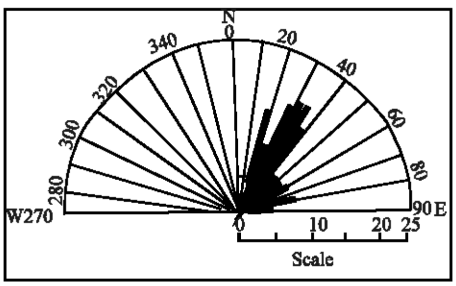

Fig. 6: Rose diagram showing the dominant strike direction of fractures, Jebel Aulia NHPP site

Aulia would be perpendicular to the direction of the fractures i.e NW-SE that is coinciding with the trend of Jebel Aulia post Nubian fault. Therefore, the fractures of Jebel Aulia are probably tectonic in origin and were formed due to the effect of Jebel Aulia fault (Ez Eldin, 2000).

Petrographic study: Thin sections of the sandstones are made from rock samples collected from the drilled boreholes, at the NHPP site are studied petrographically in order to know their mineral composition and degree of weathering. The studied sandstones are mainly composed of quartz, rock fragments and little feldspar (less than 5%) and micas. Accordingly, these sandstones can be classified as greywacke or quartz wacke based on Pettijohn's definition (Pettijohn *et al*., 1987). The sandstones reported by Ulusay *et al*. (1994) are similar to the Cretaceous sandstones mentioned in this article but have a greater content of feldspar (about 5-15%).The petrographic study leads to the following facts:

- Quartz is the main constituent mineral in the sandstones. The other constituents include muscovite, feldspar (K-feldspar and plagioclase) and opaque minerals.
- Most of the examined quartz was highly fractured but quartz intergrowth and quartz sutured boundaries are rarely found.
- A few sandstone can be regarded as texturally and mineralogically immature due to the presences of clays, feldspar and lithic fragments.
- The presences of highly altered feldspars and mudstones are reflected in the morphological appearances of the sandstones. This is probably responsible for the low strength of this rock.
- The increase of the subangular and the subrounded quartz grains in the sandstones has reduced the strength value.
- The iron cemented sandstones is harder and stronger than the kaolinitic and manganese cemented sandstones.

Hydraulic conductivity: Hydraulic conductivity of the sandstones at the NHPP site is an important parameter may affect seepage through the foundation stability. In future, a foundation material of sufficient low hydraulic conductivity is required for long-term sustainability. The average hydraulic conductivity test performed in the three boreholes to evaluate the hydraulic conductivity of the sandstones was found to be 3×10^{-3} m sec^{-1}. This value is interpreted as high hydraulic conductivity (Lee *et al*., 2005) with no significant vertical variation in the water level and seepage occurrence on the foundation. Based on aquifer and wells production tests data, the initial level of water in the drilled boreholes at the proposed NHPP site was 0.5 m during February.

Degree of weathering: Weathering and subsequent alteration processes affect rocks by changing their physical, chemical, mineralogical, petrographical and mechanical properties. Although these changes are important inputs for project designs, especially in engineering geology and civil engineering, their complex nature in rocks makes evaluation difficult for non-specialists. Rock masses are grouped into two derivative categories, unaltered and altered. Rock material change occurs by physical disintegration, chemical decomposition and biological activity. Rock materials are affected by supergene and hypogene processes (Delvigne, 1998), so that weathering and alteration features develop on the surface and in deep zones of rocks. The effect of weathering generally decreases with depth and is partly controlled by atmospheric conditions

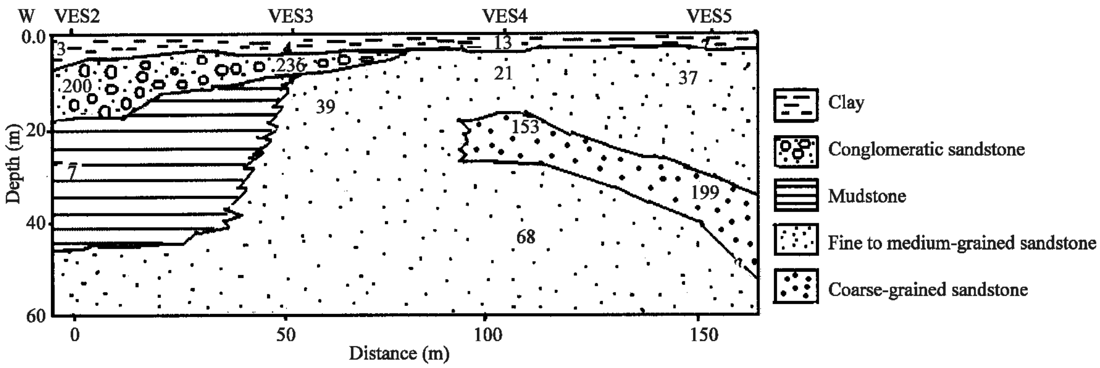

Fig. 7: East-west geoelectric section, Jebel Aulia NHPP site

and ground water. Chemical alteration is enhanced by water. The main difference between weathering and alteration is the formation of a new product by alteration (Krauskopf, 1979).

The development of weathering and alteration in the NHPP sandstones occurs through changes in physical properties of the rocks. The style and rate of weathering is controlled by porosity and permeability of the sandstones at the NHPP site, which governs the ease with which water can enter and the weathering products be removed. Porosity and permeability are in turn controlled by grain packing and the amount of space between grains as well as sandstones structures of various kinds. The sandstones at the surface is in a continuous state of decay while those in subsurface decompose by solution of elements in water, which enter through discontinuities, bedding and cross-bedding. The weathered zone may be deep if the discontinuity continues to great depth.

Weathering of the sandstones at the NHPP site consists largely of attack on the cement and removal of support of the sand grains. The cementing material may be removed or altered. The clay matrix and sandstones weather by breakdown and eluviations of clay. Iron oxides cements tend to hydrate to hydroxides and there is often migration of iron within the sandstones to form concretions or other accumulation is also observed. The petrographic study indicated that there is mineral alteration occurred to the plagioclase and K-feldspar. The alterations are attributed to the action of the penetrating water through fractures, bedding planes and porosity of the rock. Generally, the degree of weathering decreases with increasing of depth.

Rock Quality Designation (RQD): The average quality of the rock mass (Deere *et al.*, 1967) has been used to evaluate the condition of the sandstones at the NHPP site. It is defined as ''the percentage of intact core pieces longer than 100 mm in the total length of core''. The RQD is an easy and quick measurement as only certain core pieces (longer than 10 cm) are included. The RQD (Rock Quality Designation), TCR (Total Core Recovery) and other indices are obtained so as to locate the zones in the rock that are highly to be of low quality due to the high degree of weathering or jointing. The (RQD) values of the sandstones were determined and an assessment made of their weathering state. On the basis of weathering classification, changes in RQD and TCR values for each weathering degree were determined. It can be seen that only 10% of the sandstone have excellent, 26.3% good, 15.8% fair, 21.1% poor and 26.3% very poor rock qualities, respectively. The TCR only 5.3% of the sandstone have excellent, 52.6.3% good, 36.8% fair and 15.3% poor rock qualities, respectively.

The bedrock at the NHPP site showed three grades of rock weathering namely: High, moderate and slightly weathered. They corresponded to grade IV, III and II, respectively. Generally, the values of the RQD and TCR increase with increasing of depth unless other conditions may disturb this sequence.

Geoelectric cross sections: Figure 7 is east-west trending selected geophysical subsurface cross section, along the drilled boreholes. The section has been drawn depending on the available drilling and the geophysical data (not shown here). It composed of five geological units: a top layer of mostly continuous, thin, low resistivity intercalated silt and clay layers. A thick layer of conglomeratic sandstone underlain the surface layer, decreases in thickness and extend from west to east and end at the mid of the section. A third layer of mudstone underlain the conglomeratic sandstone and confined to the third of the section. The whole are underlained by fine to medium-grained sandstone. Inclined layer of coarse-grained sandstone is located within the layer of the fine to medium sandstone. It located below VES_4 and VES_5.

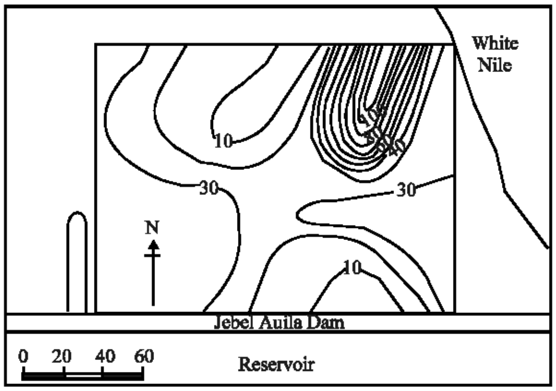

Fig. 8: Depth to bedrock contour map at Jebel Aulia NHPP site

The resistivity of the top layer ranges between 2-13 ohm-m and seismic velocities ranges from 315-417 m sec^{-1}. The resistivity of the mudstone is less than 7 ohm-m and it is average velocities range between 2107-2627 m sec^{-1} while the whole sandstone (conglomeratic, fine to medium and coarse-grained sandstone) are characterized by range of (200-236 ohm-m), (21-68 ohm-m) and (153-199 ohm-m), respectively. The average velocities of the sandstone layers range between 3577-4287 m sec^{-1}. The depth to the fine to medium sandstone is about 2.5 m and it is located below VES_4 and VES_5, respectively. The maximum depth attained is about 10 m (below VES_3). The presence of the inclined coarse-grained sandstone layer seems to control the overlying units between VES_4 and VES_5.

Depth to bedrock contour map for the NHPP site has been drawn. The calculated shallow depth is about 10 m and the maximum depth does not exceed 100 m (Fig. 8). The sediment overlying the sandstone includes the White Nile silt and clay. The steep gradients on the contour map are probably indicating steep boundaries.

Rock tests

Specific gravity: The true specific gravity of the sandstone was determined by applying the Pycnometer method. The specific gravity of the sandstone ranges from 2.36-3.16 g cm^{-3} and the average value is 2.70 g cm^{-3}. The low values are attributed to the weathering effect and the alteration of the rock. The high values are due to the silicified and ferruginiated sandstones.

$$\tilde{n}_S = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} = \frac{M_S}{V_S}$$

Where:

ñs = Specific gravity of rock (g cm^{-3}).
M_1 = Mass of the bottle (g).
M_2 = Mass of the bottle + the rock powder (g).
M_3 = Mass of the bottle + the rock powder + water (g).
M_4 = Mass of the bottle + water (g).
M_s = Weight of the solid part in rock mass (g).
V_s = Volume of the solid part in the solid mass (cm^3).

Bulk density: The bulk density of the sandstone was calculated by using the formula:

$$\tilde{n}_a = \frac{m_s}{V}$$

Where:

m_s = Mass of rock specimens (g).
V = Total volume (cm^3).

The minimum and maximum values of the bulk density are 2.31 and 2.7g cm^{-3}, respectively. The average bulk density is 2.48 g cm^{-3}. The low values are due to the high porosity, high degree of weathering and presence of kaolinitic and carbonaceous cementing materials.

Porosity: The porosity (n) of a rock is a measure of the interstitial nature of the rock and is expressed quantitatively as percentage of the total volume of rock occupied by the interstices. It is a parameter used in engineering geology and many hydrogeological and geophysical calculations. Porosity governs strength, deformability and hydraulic conductivity and it has been highlighted as an important parameter in safety calculations considering radioactive waste storage in the bedrock (Johansson, 2000). This usually refers to pores in sedimentary rocks but also in soil. However, although microfractures may constitute a large part of the pores there is also a contribution from intragranular pores in secondary minerals and fluid inclusions. In addition dissolution of minerals may produce voids, e.g. by quartz dissolution (Petersson, 2002). In this research, the porosity was calculated by using the following formula:

$$n = \frac{(\tilde{n}_s - \tilde{n}_a)}{\tilde{n}_s} \times 100\%$$

Where:

n = Porosity expressed in percentage.
$\tilde{n}_s$ = Specific gravity.
$\tilde{n}_a$ = Apparent density (bulk density).

The porosity of the sandstones from the NHPP site ranges between 2.12-14.50% and the average porosity is 7.88%. According to Anon (1990), the sandstones porosity can be interpreted as medium to low porosity.

The reduction of the porosity has occurred due to the effect of the cementing materials. Generally, the specific gravity and bulk density increase with depth and porosity decreases with depth.

Uniaxial Compressive Strength (UCS): The Uniaxial Compressive Strength (UCS) test describes the strength properties of rocks unless affected by the factors which have been stated by Atewell and Farmer (1979). The UCS of the sandstones from Jebel Aulia NHPP site, range between 4.08-28.82 MPa with average strength of 15.14 MPa. Majorities of the sandstones are moderately strong (18.65-28.82 MPa) while the other is weak to moderately weak (4.08-7.12 MPa). Weak and moderately weak and moderately strong sandstones are distributed commonly in both Ummbada and Merkhyiat members. Moreover, the UCS of sandstones coincide with stratigraphic level. The variation in the UCS of Jebel Aulia NHPP site sandstones appeared to be related to the nature of the grain packing, type of grain contact, cementing material, mineral composition, texture and degree of weathering. As the quartz content of Jebel Aulia sandstone increases the UCS will increase, this result confirms the result obtained by Chen and Hu (2003). Also the strength of the sandstones decline as the clay lenses, degree of weathering and porosity increases. The cement content and textural interlocking of the quartz grains was considered more important in terms of strength. It noticed that, as the amount of cement increases, the strength also increase. The silicified and ferruginated sandstones are stronger than the kaolinitic sandstones. The low strength of the sandstones corresponds to grade IV while the medium to high strength correspond to grade III and II, respectively.

Point load strength test: Point load strength used as an index test for the strength classification of rock material. Because of the size dependence of the test results are corrected to standard thickness of 50 mm. The test result of the Jebel Aulia NHPP site sandstones showed, maximum value of 6.31 MPa £¬minimum value of 0.14 MPa and the average value is 2.11 MPa, respectively. Generally, the UCS and point load strength test results increase with increasing of depth.

CONCLUSION

The fine, medium and coarse-grained sandstone are cemented mainly by silica, kaolin, iron oxides, manganese oxides and calcium carbonate. Quartz is the main constituent mineral in the sandstone. The other constituents include muscovite, feldspar and opaque minerals. A few sandstone can be regarded as texturally and mineralogically immature due to the presences of clays, feldspar and lithic fragments. The presences of highly altered feldspars and mudstones are reflected in the morphological appearances of the sandstone, this is probably responsible for the low strength of this rock.

The studied sandstones are mainly composed of quartz and rock fragments and have little feldspar (less than 5%) and mica accordingly, these sandstones can be classified as greywacke or quartz wacke.

The subsurface units revealed from the drilling consist of fining upward sequences. The cycles are more or less well developed than that of the outcropping sediments. They are moderately sorted, fine-grained sandstone, siltstone with subordinate mudstone. The bedding of sandstone is alternating with finely laminated siltstones and mudstones. Horizontal to low-angle bedding sandstone is noticed in individual units. The sedimentary structures are well seen in most of the studied outcrops include: planar; cross and trough cross bedding, load cast, horizontal lamination and graded bedding.

The low resistivity values observed at the upper horizon at Jebel Aulia NHPP site correspond to clays and sandy clay, while the high resistivity values correspond to sandstone and gravels.

The fracture analysis of Jebel Aulia sandstone gives a general trend of NE-SW. The acting force would be perpendicular to the direction of the fractures i.e NW-SE that is coinciding with the trend of Jebel Aulia post Nubian fault. Therefore, the fractures of Jebel Aulia sandstone are probably tectonic in origin and were formed due to the effect of Jebel Aulia fault.

Only 10% of the sandstone have excellent, 26.3% good, 15.8% fair, 21.1% poor and 26.3% very poor rock qualities, respectively. The TCR only 5.3% of the sandstone have excellent, 52.6.3% good, 36.8% fair and 15.3% poor rock qualities, respectively. The bedrock at the NHPP site showed three grades of rock weathering namely: high, moderate and slightly weathered. They corresponded to grade IV, III and II, respectively.

The variation in the UCS of Jebel Aulia NHPP site sandstones appeared to be related to the nature of the grain packing, type of grain contact, cementing material, porosity, mineral composition, texture and degree of weathering. As the quartz content of Jebel Aulia sandstone increases the UCS will increase, this result confirms the result obtained by Chen *et al*. (2003). Also the strength of the sandstone decline as the clay lenses, degree of weathering and porosity increases.

Porosity governed strength, deformability and hydraulic conductivity of the sandstone at Jebel Aulia

NHPP site. The ranges of the sandstone porosity can be interpreted as medium to low porosity. The reduction of the porosity has occurred due to the effect of the cementing materials. The hydraulic conductivity of the sandstone was found to be 3×10^{-3} m/sec. This value is interpreted as high hydraulic conductivity. Generally, the specific gravity and bulk density increase with depth and porosity decreases with depth.

Vertical Electrical Sounding (VES) and seismic refraction surveys were combined to outline the geoengineering investigations. The correlation between the geological information and the geophysical data has extensively extended the horizontal extent of the boreholes data. Both geophysical methods identified the weathered rock: their boundaries and thickness of the layers.

The drilled boreholes at the NHPP site reveal shallow depths of soil. The depth to the fine to medium-grained sandstone varies from about 2.5-10m. Accordingly, the foundation can be erected directly on the sandstone bedrock down to a depth not less than 10 m.

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