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Geological, Soil and Rock Mass Evaluation for Proposed Hydroelectric Power Plant at Sennar Dam, Sudan

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Abstract: A feasibility study by using geological, geotechnical and geophysical investigations (VES and seismic refraction) have been carried out for construction a new hydroelectric power plant at Sennar Dam situated at Sennar State, 350 km south of Khartoum (the capital of Sudan). As a consequence of the completions of the development projects and increasing demand for more energy due to rising population, a recommendation have made to construct a new hydroelectric power plant in the proposed site. Sennar Dam is a masonry gravity dam sits on teschenite-gabbro rock foundation across the Blue Nile, 45 m in height and over 3 km in length. For this study, the depth of soil and rocks, thickness, geological discontinuities, boundaries and geotechnical properties were determined. The drilled boreholes data has revealed shallow depths of soil. The laboratory test of soil samples showed intermediate geotechnical properties. The study suggests that the Proposed Hydroelectric Power (PHP) plant can be constructed directly on the slightly weathered or fresh teschenite-gabbro bedrock to a depth of not less than 10 m.

Key words: Sennar dam, Blue Nile, proposed hydroelectric power (PHP) plant

INTRODUCTION

The Blue Nile River (Arabic = Bahr Azraq) its 1529 km long. The chief head stream of the Nile, rising in Lake Tana in Ethiopia, at an altitude of 1800 m. It flows generally south from the Lake Tana region, then west across Ethiopia, northwest into Sudan. In Khartoum, the Blue Nile merges with the White Nile to form the Nile proper. The flow of the Blue Nile reach is maximum volume in the rainy season (from June to September), when it supplies about two thirds of the proper.

Sennar Dam it is a masonry gravity dam, constructed in the 1925. It sits on the Blue Nile, 45 m in height and over 3 km in length. It is situated at Sennar State about 350 km south of Khartoum (Fig. 1). The total area of the lake resulted from the dam construction is 140-160 km with maximum depth averaging to 26 ms. Up to 60% of the country's agriculture production is dependent upon it is water especially when the water level of the Blue Nile is low. The resulted reservoir provides irrigation water to the Gezira and Manageil canals, which irrigate the Gezira and Manageil agricultural schemes and remains fundamental to the Sudanese economy. It also provides water way for navigation, water for domestic use and industry and to generate hydroelectric power.

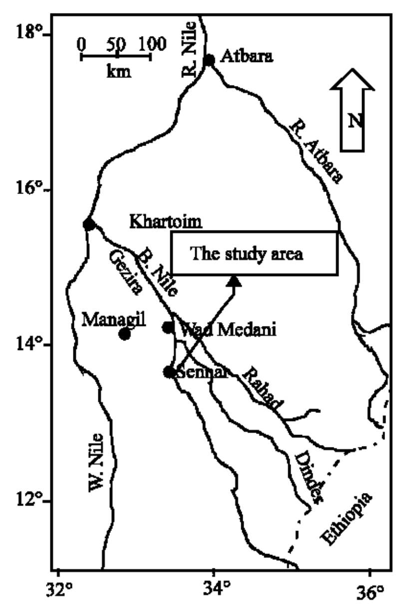

Fig. 1: Location map of the study area

Hydroelectric power is an important source of energy in Sudan. The Roseries and Sennar dams on The Blue Nile provided 80% of the Sudan's electricity. This percentage

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has fallen while energy demand has increased rapidly and strongly as development projects were completed and became operational and the population of the capital increased dramatically. Therefore, recommendations have been made to construct a new hydroelectric power plant at Sennar Dam site, on the eastern bank of the Blue Nile.

This study sets out the engineering geological and geophysical investigations carried out to evaluate the soil and rock mass conditions with emphasis on the teschenite-gabbro rock at the Proposed Hydroelectric Power (PHP) so as to assess the suitability of the site. The data derived are mainly from geological fieldwork and geophysical investigation (vertical electrical sounding and seismic refraction), drilling and laboratory testing of soil and rock samples.

The geology of the dam area and its vicinity is mainly comprised of the Precambrian Basement Complex. It crops out in the West and Southwest of Sennar town (Bashir *et al*., 1993). The Basement Complex overlained unconformably by the Nubian Formation, in south Sennar it overlained unconformably by Elatshan Formation (Hussein, 2004). The Nubian Formation includes: conglomeratic sandstone, sandstones with different cementing materials, non-laminated compact and very hard mudstone occasionally dissected by three sets of joints. Most of the Nubian Formation rocks are characterized by distinctive various colours.

The teschenite-gabbro is discovered during the excavations and borings of Sennar Dam (Fig. 2). It is of two types of textures: the fine-grained carries abundant olivine and titan-augite while the coarse-grained type is poor in olivine and richer in analcite, ilmenite and microcline. Quartz is found in both types of rocks. The teschenite-gabbro is intruded in the Nubian Formation therefore, it is post Nubian and it is probably Tertiary in age. The rock is overlain by the dam.

The Tertiary pisolitic ferricrete occurs North of Sennar Dam on saprolite teschenite-gabbro (Schwarz *et al*., 1989). On top of the ferricrete, a layer of sedimentary ironstone and calcite gravel occurs. On other localities, it is overlain by younger smectite black cotton soil.

Elatshan Formation mainly formed of clay, sand and gravel. This Formation lies unconformably on both: the Basement Complex and the Nubian Formation. It is probably Tertiary to Pleistocene in age.

Elgezeira Formation lies unconformably on either the Nubian Formation or directly on the Basement Complex. It is the same age of Elatshan Formation.

The black cotton soil covers a vast area. Silts are observed along the banks of the Blue Nile. Slope-wash deposits are observed in the eastern bank, down stream just a few meters from the dam.

The Blue Nile region revealed series of major faults, grabens and hosts on regional scale. These faults were occurred due to the tectonic movements and they are Post Nubian in age (Hussein, 2004).

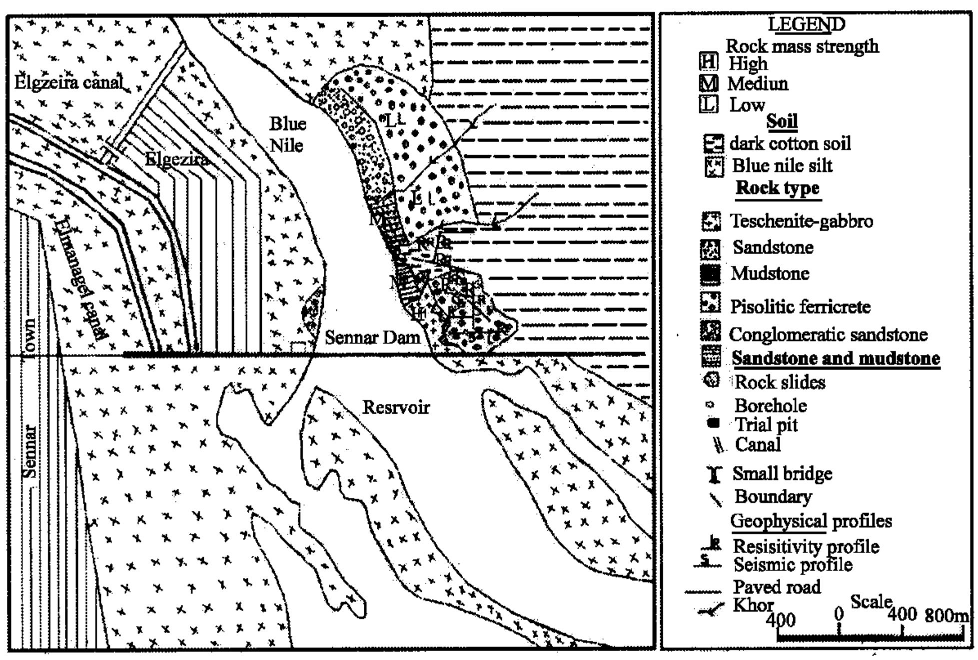

Fig. 2: Simplified engineering geological map of Sennar PHP site

MATERIALS AND METHODS

The fieldwork programme included a preliminary visit to Sennar Dam, eastern bank, down stream of the Blue Nile, followed by several visits in which, detailed geological and geophysical investigations were carried out. During the fieldwork 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; differentiate between the weathered and fresh teschenite-gabbro rock.

Drilling and excavation of pits were carried out. Cable percussion and auger drilling are used. In case of hard rocks, core boring NX size is performed. During drilling and excavations, samples were collected for laboratory tests, nature of the underlying soils and rocks, depths of weathering, bedding and structures are observed and studied. Soil samples were collected during the drilling and excavations of pits. Disturbed samples were taken every 0.5 m, while undisturbed samples were taken with a sampler tube 100 mm in diameter and 500 mm in length when necessary.

The laboratory tests are carried out in order to determine the physical and mechanical properties of the soil and teschenite-gabbro rock core samples using British Standard laboratory techniques (BS, 1981, 1990). The tests on soil include: water content (w%), specific gravity (γ_s), particle-size distribution, Liquid Limit (LL), Plastic Limit (PL), consolidation tests and shear strength. On the other hand, the rock core samples tests include: specific gravity (ρ_S), bulk density (ρ_a), porosity (n), Uniaxial Compressive Strength (UCS) and point load strength.

RESULTS AND DISCUSSION

Trial pits and boreholes: Four trial pits were excavated at the PHP site. Their sizes are 2×1.5 m and depth of 2 m. The pits helped in the visual inspection of the in situ soil condition, observation of water seepage, collection of soil samples and assessing the stability of excavation.

Three boreholes (from west to east BS_1, BS_2 and BS_3, respectively) were drilled at the eastern bank, down stream of the Blue 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 4.30, 0.30 and 1.20 m, respectively. The soil is generally made up of artificial fill, Nile silt and pisolitic ferricrete. The latter appears in BS_1 and BS_2 only. The teschenite-gabbro underlying this soil is fine to medium-grained, medium to highly weathered and fresh strong to very strong. The degree of weathering decreases with increasing of depth. The drilling sealed at depths of 18, 25 and 25 m, respectively. Based on aquifer and wells, production tests data; the initial level of water in the drilled boreholes at the proposed PHP site was 3.5 m.

Rock quality: Rock mass quality is an important geological factor for design, assessing foundation support and construction of hydraulic project. There have been notable attempts for accurate rock mass quality classification, which not only evaluate the properties of rock masses and rock engineering geological properties in the hydraulic project site, but also judge the range of utilization rock masses around the project and determine the reasonable excavation depth of the hydro project foundation (Lashkaripour and Ghafoori, 2002).

The average quality of the rock mass (Deer *et al*., 1967) has been used to evaluate the condition of the teschenite-gabbro rock at the proposed site. The RQD (Rock Quality Designation) was 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 teschenite-gabbro were determined and an assessment made of their weathering state. On the basis of the weathering classification, changes in RQD values for each weathering degree were determined (Fig. 3). It can be seen that only 14% of the teschenite-gabbro have excellent, 16% good, 25% fair, 13% poor and 32% very poor rock quality.

The teschenite-gabbro showed three grades of rock conditions I, II and IV, which corresponded to fresh, slightly and highly weathered (Table 1), respectively. According to the RQD classification, these grades coincide with excellent, fair and poor rock quality. Generally, the values of the RQD increase with increasing of depth unless other conditions may disturb this situation. This result is similar to that obtained by Gurocak and Kilic (2005). The main agent responsible for

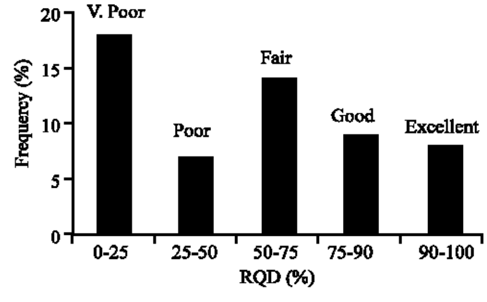

Fig. 3: Percentage distribution of RQD values of teschenite-gabbro in Sennar PHP site

Table 1: Weathering classification (British standard code of practice for site investigation, BS 5930: 1981)

Term	Description	Grade
Fresh	No visible sign of rock weathering; perhaps some slight discolouration on major discontinuity surfaces.	I
Slightly weathered	Discolouration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering.	II
Moderately weathered	Less than the half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a discontinuous framework or as core stone.	III
Highly weathered	More than the half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a discontinuous framework or as core stone.	IV
Completely weathered	All rock material is decomposed and /or disintegrated to soil. The original mass structure is still largely intact.	V
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.	VI

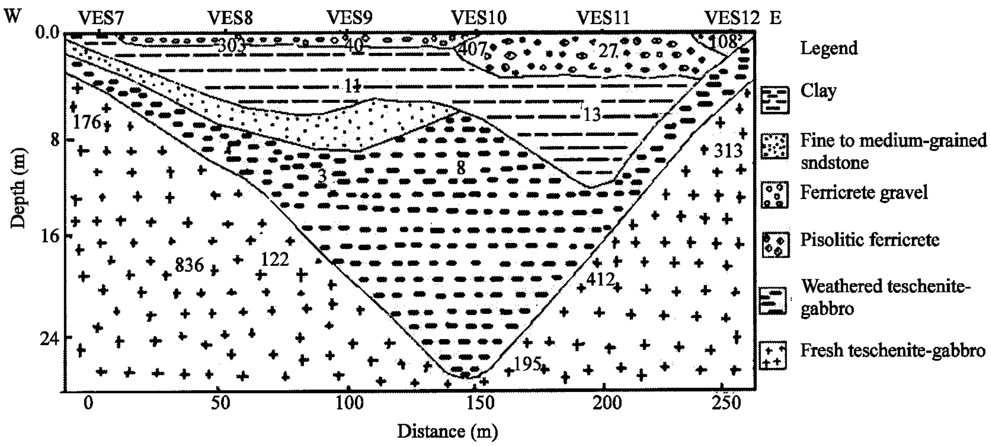

Fig. 4: Geoelectric section trending E-W, Sennar PHP site

this weathering is probably from the action of water, which percolates through the overlying porous and fractured sedimentary rocks.

Geoeletric cross sections: Figure 4 is east wast 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 ferricrete gravel/or pisolitic ferricrete, underlain by clays/or weathered teschenite-gabbro. There is a layer of sandstone, it is situated below the clay layer and overlain the weathered teschenite-gabbro. It extends to the middle of the section. The whole are underlain by fresh teschenite-gabbro.

The resistivity of the units overlying the fresh teschenite-gabbro ranges between 4-77 ohm-m and seismic velocities range between 300-3600 m sec^{-1}. The resistivity of the weathered teschenite-gabbro is less than 4 ohm-m and it is average seismic velocities range between 2365-2692 m sec^{-1} while the fresh teschenite-gabbro is more than 176 ohm-m and it is average seismic velocities range between 4751- 7900 m sec^{-1}. The depth to the fresh teschenite-gabbro is about 3 m and it is restricted to the ends of the section below VES_1 and VES_{12}, respectively. The maximum depth attained is about 26 m (below VES_{10}). There are two steep boundaries, which seem to control the structure of the teschenite-gabbro and the overlying units (Ez Eldin, 2000). The thickness of the geological units can be calculated from (Fig. 4).

Depth to bedrock contour map for the PHP site has been drawn. The calculated shallow depth is about 10 m and the maximum depth does not exceed 50 m (Fig. 5). The sediments overlying the fresh teschenite-gabbro include weathered teschenite-gabbro, ferricrete and ferricrete gravel and clays. The steep gradients on the contour map are probably indicating steep boundaries.

Soil tests

Particle-size distribution: Particle size distribution and the hydrometer tests were carried out. It is seen that for the full sieved soil the fine grains (< 0.063 mm) decrease while the coarse grains (> 0.063 mm) increase with increasing depth, this is due to the presences of the weathered sandstone source rock. The uniformity

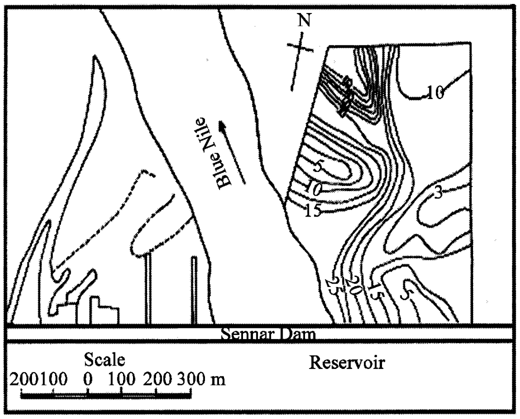

Fig. 5: Depth to bedrock contour map of Sennar PHP site.

coefficients indicated that, the proposed site is characterized by a range between well-graded and poorly graded soil (Fig. 6).

Water content: The water content of a soil is defined by Joyce (1982) as the weight of water contained in the pore space of a soil expressed as a percentage of the dry weight or it's the ratio of the quantity of water removed from the wet soil in the course of drying at 105°C up to constant mass value and to dry soil mass; then:

$$W\ (\%) = \frac{m_w}{m_s} \times 100$$

Where:
w (%) = Water content,
m_w = Mass of the water removed by drying at 105°C (g),
m_s = Dry soil mass (g).

The maximum value of the water content is 59.5% and the minimum is 34%, respectively.

Specific gravity: The specific gravity is the ratio of the solid weight to the volume of the solid material excluding all pores. It calculated using the following equation:

$$\gamma_S = \frac{(M_2 - M_1)}{(M_4 - M_1) - (M_3 - M_2)} = \frac{MS}{VS}$$

Where:
γ_s = Specific gravity of the soil (g cm^{-3}),
M_1 = Mass of the bottle (g),
M_2 = Mass of the bottle + soil (g),
M_3 = Mass of the bottle + soil + water (g),
M_4 = Mass of bottle + water (g),
M_s = Weight of the solid part in soil mass (g),
V_s = Volume of solid part in the soil mass (cm^3).

The maximum value is 2.88 g cm^{-3} and the minimum is 2.63 g cm^{-3} of the soil increase with depth for depths less than 6 m. According to Telford *et al*. (2004), the results of the specific gravity lie above the range given to the soil. The high values can be attributed to the weathering of iron content source rock such as pisolitic ferricrete.

Atterberg limits: Atterberg limits or consistency limits are characterized by plastic and liquid limits and plasticity index. The liquid limit represents the minimum water content at which soil particles flow under their own weight and the plastic limit is the minimum water content at which a soil is molded without breaking. These limits control the consistency of the soils as wetting conditions change. Atterberg limits have a very extensive use in geotechnical engineering for identification, description and usually used for the determination of water content of soils.

The liquid limit showed maximum value of 109 % and minimum value of 53.1%. The other values are situated between the two extremities. The plastic limit test results showed 37.3 and 22.6% for the maximum and minimum values, respectively. Generally, the liquid and plastic limits decrease with depth. Based on the their test results, the soil can be classified in terms of plasticity according to the IAEG (1981) as low to moderate plastic and high to extremely high plastic.

The plasticity of the soil can be classified as inorganic clay of intermediate to high plasticity index. A more reliable relation between the swell potential and the plasticity index can be established. According to the definition of the clay activity (Coduto, 2004), the soil is characterized by medium to low potential expansiveness (Fig. 7). The clay activity equation is shown as:

$$\text{Activity} = \frac{\text{Plasticity index}}{\text{Clay fraction}}$$

(particle size < 0.002 mm)

The coefficient of volume compressibility and consolidation showed medium compressibility when saturated with water while the uncoslidated undrained triaxial test results are interpreted as soft clays. The cohesion (C) decreases as water content increases.

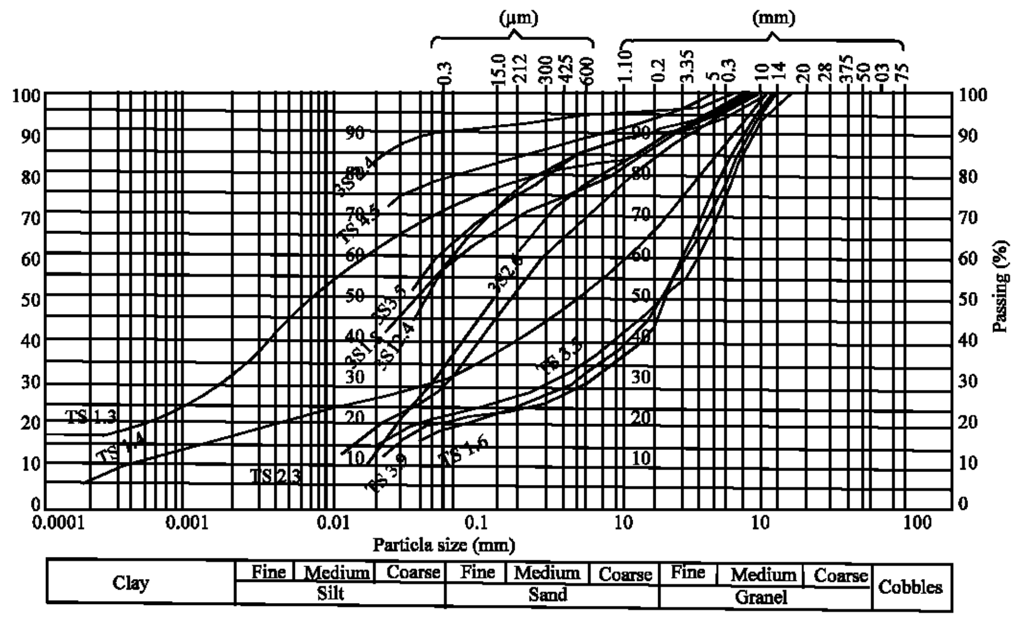

Fig. 6: Cumulative particle-size distribution of soil samples from Sennar PHP site

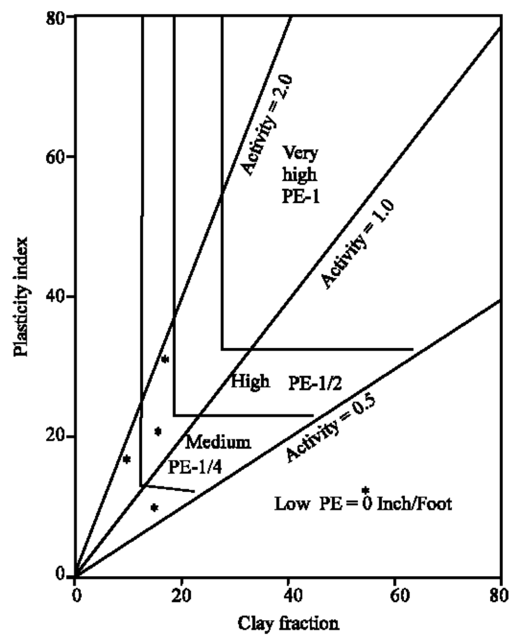

Fig. 7: Potential expansiveness of the soil from Sennar proposed PHP site

Rock tests

Specific gravity: The true specific gravity of the teschenite-gabbro was determined by applying the Pycnometer method. The specific gravity of the weathered and fresh teschenite-gabbro is 2.55 and 3.08 g cm^{-3}, respectively. The low values are attributed to the weathering effect and the alteration of the rock. The high values of the fresh rock are due to the high iron content.

Bulk density: The bulk density of the teschenite-gabbro was calculated by using the formula:

$$\rho_a = \frac{m_s}{V}$$

Where:

m_s = The mass of rock specimens (g),

V = The total volume (cm^3).

The minimum and maximum values of the bulk density are 2.39 and 3.02 g cm^{-3}, respectively.

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. The porosity was calculated using the following formula:

$$n = \frac{(\rho_s - \rho_a)}{\rho_s} \times 100\%$$

Where:
n = The porosity expressed in percentage,
ρ_s = The specific gravity,
ρ_a = The apparent density (bulk density).

The porosity range between 6.27% for the weathered teschenite-gabbro and 1.95% for the fresh teschenite-gabbro, respectively. 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 many factors such as porosity and density, mineralogy, water content, texture… etc.. The interpretation of the teschenite-gabbro strength is based on the scale of the UCS given by Joyce (1982).

The teschenite-gabbro gave maximum value of 116 MPa and minimum value of 27.2 MPa. The strength of the teschenite-gabbro can be interpreted as strong to very strong. The high values are probably due to the low or negligible porosity, fine texture and decreasing of weathering with depth.

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 a standard thickness of 50 mm. The test result of the teschenite-gabbro showed, maximum value of 14.2 MPa and minimum value of 5.6 MPa, respectively. Generally, the UCS and point load strength test results increase with increasing depth.

The values of the specific gravity, bulk density and porosity of the pisolitic ferricrete from the same site gave values of 3.22, 2.31 g cm^{-3} and 28.26%, respectively. The relative higher values of the specific gravity and porosity are attributed to the iron content and to the etched and irregular shape of the quartz grains, respectively. The porosity of this rock can be described as large.

CONCLUSIONS

The teschenite-gabbro underlying the soil is fine to medium-grained, medium to highly weathered, fresh and strong to very strong. The degree of weathering decreases with increasing depth while the RQD values increases with increasing depth. Only 14% of the teschenite-gabbro have excellent, 16% good, 25 fair, 13% poor and 32% very poor rock quality. The teschenite-gabbro showed three grades of rock conditions I, II and IV, which corresponded to fresh, slightly and highly weathered.

For the full sieved soil, the fine grains decrease while the coarse grains increase with increasing depth, this is due to the presence of the weathered sandstone source rock. The uniformity coefficient indicated that, the PHP site characterized by a range between well and poorly graded soils.

The specific gravity of the soil increase with depth, for depth less than 6.0 m. The high values can be attributed to the weathering of the pisolitic ferricrete.

The liquid and plastic limits decrease with depth. The soil of the PHP site can be classified as low to moderate plastic and high to extremely high plastic with medium to low potential expansiveness and soft clays with medium compressibility. The cohesion (C) decreases as water content increases.

The *in situ* test such as Standard Penetration Test (SPT) is highly needed to evaluate the physical properties of the soil *in situ*.

The laboratory tests on teschenite-gabbro reveal that, the fresh and slightly weathered are characterized by low porosity, high values of bulk density and specific gravity; these are attributed to the high iron content while the highly weathered teschenite-gabbro is comparatively characterized by low bulk density and specific gravity and rather high porosity. Generally, the specific gravity and bulk density increase with depth while porosity decreases with depth.

The high values of the UCS of the teshenite-gabbro are probably due to the low or negligible porosity, fine texture and decreasing of weathering with depth. The UCS and point load strength tests results increase with depth.

It noticed that the values of the UCS, point load test, specific gravity and bulk density increase with increasing of depth, while the porosity decreases with increasing of depth. This can be attributed to the decreasing of weathering with depth. This confirms the result obtained by Shalabi *et al.* (2007).

The specific gravity and porosity of the pisolitic ferricrete are relatively high, this probably due to the iron content and the etched and irregular shape of the quartz grains, respectively.

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 proposed site reveal shallow depths of soil. The laboratory tests of soil samples showed intermediate geotechnical properties. Accordingly, the foundation can be erected directly on the slightly weathered or fresh teshenite-gabbro bedrock down to a depth not less than 10 m.

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