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Ultimate Bearing Capacity of Teschenite-Gabbro and Sandstone Rocks Foundation from Sennar Proposed Hydroelectric Power Plant, Sennar Dam, Sudan

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Abstract: This study has been devoted to calculate the ultimate bearing capacity of teschenite-gabbro and sandstone rock foundation situated at Sennar Proposed Hydroelectric Power (PHP) site, at Sennar Dam, eastern bank, down stream, 350 km south of Khartoum. For this study, Terzaghi and Meyerhof equations were used, geological fieldwork and geophysical investigations, geotechnical properties, elastic moduli, hydraulic conductivity, Rock Quality Designation (RQD) were determined and drilling and laboratory testing of rock samples were carried out. The estimated values of the ultimate bearing capacity of the teschenite-gabbro to depth of 10 m are 2578 kN m^{-2} and 2417 kN m^{-2} according to Terzaghi and Meyerhof equations, respectively. The ultimate bearing capacity of the sandstone to the same depth are 1090 KN m^{-2} and 1096 KN m^{-2}, corresponding to Terzaghi and Meyerhof equations, respectively. Up to about D = B Meyerhof is not greatly different from Terzaghi value, the difference is more pronounced at larger D/B ratios. The values of Terzaghi and Meyerhof showed slight difference in bearing capacity values, this is due to D< B. The results of the dynamic elastic moduli, physical and mechanical properties of the slightly weathered or fresh teschenite-gabbro and sandstone reviled intermediate to good geotechnical properties therefore, the study suggests that the foundation of the PHP plant can be erected directly on the slightly weathered or fresh teschenite-gabbro bedrock down to a depth not less than 10 m.

Key words: Foundation, terzaghi and meyerhof equations, ultimate bearing capacity, Proposed Hydroelectric Power (PHP) plant

INTRODUCTION

The foundation is that part of structure, which services to transmit the construction load to the ground, but in a larger sense it includes the soil and rock below. It located at shallow depth if the component of soil is suitable for sustaining it. However, if the upper strata are too weak, the loads are transferred to more suitable strata at greater depth. It should be placed at an adequate depth to prevent frost damage, volume change, undermining and/or damage from future constructions near by. The design of foundation, however, is completely depend on the nature of the ground underlying the construction site. Determine of ground condition is essentially a geological problem leading to selection of the type of foundation as a matter of the engineering judgment.

Ground conditions at a construction site may be classified as one of three general types according to foundation design possibilities (Leggat and Hatheway, 1988). The bedrock may lie at the ground surface or so close to the surface that the building may be founded directly upon it; the bedrock may occur at depth below the ground surface which makes possible the direct transfer of the construction loads by the foundation; the nearest rock stratum may be so far below the surface that the construction will have to be founded upon the unconsolidated sediments/soil overlying the bedrock.

Generally, for the light constructions, the depth of foundation at which the investigations are carried is limited, whereas for heavier construction it's commonly necessary to explore the entire depth of soil covering the rock and even penetrate into the bedrock. The subsurface data such as bearing capacity, physical properties and rock strength, dynamic elastic moduli, depths and degree of weathering of bedrock are essential to the construction design.

This study has been conducted at Sennar Dam. The dam sits on the Blue Nile and it is situated at Sennar State about 350 km south of Khartoum. The main aim of the present study, is to calculate the bearing capacity of the teschenite-gabbro and sandstone rocks situated at the Proposed Hydroelectric Power (PHP) site so as to help in

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the preliminary design and/or site evaluation purposes. The data derived are mainly from geological fieldwork and geophysical investigations, drilling and laboratory testing of rock samples.

Geological conditions of the PHP site: The geology of Sennar Dam area is mainly comprised of the Precambrian Basement Complex, overlained unconformably by the Nubian Formation. The later includes: Conglomeratic sandstone, sandstones and mudstone. The sandstone is characterized by various types of cementing materials, fine to medium-grained size; abundant quartz; plagioclase and rare muscovite. It cemented by iron-oxides and hydroxides, silica, kaolinite and carbonate.

The teschenite-gabbro is discovered during the excavations and borings of Sennar Dam. It characterized by fine-grained texture, presence of plagioclase, quartz and abundant olivine and titan-augite. It is intruded in the Nubian Formation and overlain by the dam.

The tertiary pisolitic ferricrete occurs on saprolite teschenite-gabbro. 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.

The superficial deposits in the study area include the black cotton soil which extends to cover 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).

MATERIALS AND METHODS

The geotechnical studies were conducted in two stages: Field and laboratory work. During the fieldwork; several visits to Sennar Dam, eastern bank, down stream of the Blue Nile were carried out. Detailed geological and geophysical investigations were executed. The geophysical work aimed at to differentiate between weathered and fresh teschenite-gabbro and to calculate the elastic dynamic moduli of the teschenite-gabbro and the sandstone rocks. The fieldwork also included the examination of the cores from the three boreholes drilled at Sennar PHP site. The Rock Quality Designation (RQD) values of the two rocks were determined and the assessment made of their weathering state according to their depths.

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, the hydraulic conductivity is evaluated and nature of the underlying rocks; depths of weathering; bedding and structures are observed and studied. Samples obtained from drilled boreholes have been examined petrographically. The laboratory tests were carried out on rock core samples to define porosity (n), specific gravity (ρ_S), bulk density (ρ_a), Uniaxial Compressive Strength (UCS) and point load strength.

RESULTS AND DISCUSSION

Porosity, specific gravity and bulk density: The unweathered teschenite-gabbro having virtually no pores, or very little primary porosity. Weathering progress outward from fractures, caused to increase in porosity. The number of the microfractures, caused to increase as weathering increases. The unweathered and slightly weathered teschenite-gabbro has very low porosity, equal to 1.96% and those pores that are present are mainly microfractures. Significant development of pores was observed in highly weathered teschenite-gabbro, it reached to 6.27%. Despite an increase in porosity in the completely weathered teschenite-gabbro, the petrographic examination showed very little conversion of feldspar to clay minerals. An increase in porosity was caused by an increase in the number and openness of microfractures by action of hydrolysis.

In the sandstone samples studied, porosity is a relic of deposition (primary porosity) or develops due to the weathering of the rock (secondary porosity). In the unweathered sandstone pore shapes are often ellipsoidal and spherical although pores have also developed by fracturing. Chemical and physical process create voids (pores and microfractures), or deposit new minerals, especially clay within voids. Moderately and highly weathered sandstones are open textured, weakly bonded, microfractured and iron stained. In the completely weathered sandstone, fractures could not be identified but some microfractures remain unfilled and other decomposition products. They contain a small amount of clay cement. There is a progressive increase in porosity and microfracture frequency with increasing weathering. The porosity of the sandstone ranges between 3.75 and 4.23%.

The specific gravity of the teschenite-gabbro and sandstone were determined by applying the Pycnometer method. The specific gravity of the weathered and fresh teschenite-gabbro is 2.45 and 3.10 g cm^{-3}, respectively while for the sandstone is 2.4 and 2.6 g cm^{-3}, respectively.

The minimum and maximum values of the bulk density of the teschenite-gabbro are 2.40 and 3.04 g cm^{-3}, respectively while for the sandstone is 2.3 2.49 g cm^{-3}, respectively.

Generally, the specific gravity and bulk density increase with depth while porosity decreases with depth. The porosity of the weathered teschenite-gabbro can be described as medium while for the fresh teschenite-gabbro and sandstone can be interpreted as low.

Hydraulic conductivity: Todd and Larry (2005) defined the hydraulic conductivity as" the capacity of the material for transmitting water under hydraulic head, or the ease of flow of water through the material". Accordingly, the hydraulic conductivity of the boreholes at the PHP 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 tests performed in the three boreholes to evaluate the hydraulic conductivity materials was 8×10^{-7} m/sec. This value is interpreted as very low hydraulic conductivity (Lee *et al*., 2005) with no significant vertical variation in the water level and impossible seepage occurrence on the foundation. The low value of the hydraulic conductivity may be attributed to the low porosity of the fresh teschenite-gabbro and the cementing materials of the sandstone.

Rock Quality Designation (RQD): The teschenite-gabbro of the PHP site is fine-grained, carries plagioclase, quartz and abundant olivine and titan-augite. The RQD was obtained so as to locate the zones in the two rocks that are highly to be of low quality due to the high degree of weathering or jointing (Deer *et al*., 1967). The RQD values of the teschenite–gabbro and sandstone 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. 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 (Eldin, 2000). On the other hand, the sandstone showed only 10% have excellent, 25% good, 15% fair and 25% correspond to poor and very poor rock quality, respectively (Fig. 1).

The teschenite-gabbro showed three grades of rock conditions I, II and IV, which correspond to fresh, slightly and highly weathered, respectively. According to the RQD classification, these grades coincide with excellent, good and poor rock quality. Also the sandstone showed three grades of rock conditions II, III and IV, which correspond to slightly, moderately and highly weathered, respectively. According to the RQD classification, these grades coincide with good, fair and poor rock quality. Generally, the values of the RQD increase with increasing of depth unless other conditions disturb this situation (Gurocak and Kilic, 2005).

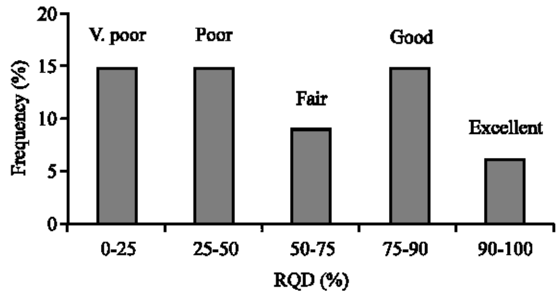

Fig. 1: Percentage distribution of RQD values of sandstone in Sennar PHP site

The petrographic study indicated that these zones showed altered plagioclase and olivine. The alteration zones are confined to grade IV. The main causes for this weathering is probably from the action of chemical weathering which may be enhanced by the percolated through the overlying porous and fractured sedimentary rocks.

Unconfined Compressive Strength (UCS) and point load strength: The Unconfined Compressive Strength (UCS) describes the strength properties of rocks unless affected by many factors such as porosity and density, mineralogy, water content, etc. The point load strength used as 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 Unconfined Compressive Strength (UCS) and point load strength of teschenite-gabbro decreases from over 118 and 15.2 MPa at depths greater than 10 m to around 29.2 and 5.8 MPa closer to rock head, respectively. Therefore, strength of the teschenite-gabbro can be interpreted as very strong to strong.

Unconfined Compressive Strength (UCS) and point load strength of the sandstone also decreases from over 28.82 and 6.31 Mpa at depths greater than 10 m to around 4.08 and 0.14 MPa closer to rock head, respectively. Hence, the strength of the sandstone can be interpreted as moderately strong to weak. Generally, the UCS and point load strength test results increase with increasing depth. This can be attributed to the decrease of weathering and porosity with depth and increase of specific gravity and bulk density with depth.

Table 1: Elastic properties of teschenite-gabbro and sandstone rocks from Sennar PHP site

Rock type	Velocity m/sec V_p	V_s	Poission's Ratio (σ)	Young's Modulus (E) Mpa	Lame's constant (λ)	Shear Modulus (μ) MPa	Bulk Modulus (K) MPa
Fresh teschenite-gabbro	5481.2	3457.0	0.4 (σ >1/3)	12742.8	1592.9	5603.6	3685.9
Weathered teschenite-gabbro	2367.3	1543.7	0.4 (σ >1/3)	1485.7	1552.7	625.2	421
Sandstone	3846.8	2590.7	0.4 (σ >1/3)	4128.2	516.1	1815.4	1164.3

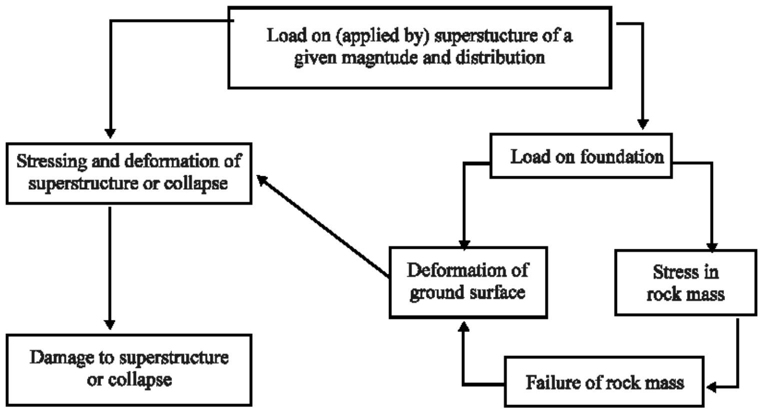

Fig. 2: Simplified rock-structure interaction flow chart for foundation instability

Elastic properties of the teschenite-gabbro and sandstone: Kabsonnova (1989) defined elasticity as " the property of rocks to change in shape and size and frequently in volume due to external forces, then recover the original configuration completely or partially after the forces have been removed and their action has not exceed the elastic limit". The change in size and shape of a rock (deformation) results from the mutual displacement of its constant elements.

Dynamic elastic moduli like Poission's ratio (σ), Young's modulus (E), Lame's constant (λ), Shear modulus (μ) and Bulk modulus (K) of the foundation rock of the PHP site have determined by calculating V_p and V_s velocities of the teschenite-gabbro and sandstone rocks with their corresponding densities by seismic refraction with a dynamite as source (Table 1).

Poission's ratio plays an undeniably important role in the elastic deformation of rocks and rock masses subjected to static or dynamic stress; it is utilized in rock engineering problems associated with the deformation of rocks. Furthermore, its effects emerge in a wide variety of rock engineering applications. Therefore, information of Poission's ratio can be beneficial for rock engineering.

The values of Poission's ratio for many materials are close to the initial recommendation of 1/4 by Poisson's or 1/3 by Wertheim; the theoretical value for an isotropic material is between -1 and 1/2. These lower and upper limits exist due to the fact that Young's (E), shear (μ) and bulk (K) moduli of a material must be positive. For isotropic rocks, therefore, the value of Poission's ratio is practically between 0 and 0.5. In fact, the range bounded by the values of 0.05 and 0.45 covers most rocks.

The results of Poission's ratio obtained from the weathered and fresh teschenite-gabbro and sandstone gave similar values, it may be due to the low porosity of the rocks. Although, the porosity of the two rocks material will play a role on the value of Poission's ratio; however, the geometry (size and shape), orientation, distribution and connecting of pores are expected to complicate the influence. The Poisson's ratio values of the fresh and weathered teschenite-gabbro and sandstone of the PHP site all showed 0.4 (Table 1). The value can be interpreted as high according to the suggested classification stated by Gercek (2006). Since the values of Poission's ratio are approaching to 0.5, the materials may easily undergo shear deformation but resist volumetric deformation and become incompressible (Lakes, 1987). For such materials, shear modulus is much less than bulk modulus (Gercek, 2006).

Bearing capacity: The bearing capacity of a rock, often termed its stability, is the ability of the rock to carry a load without failure. The load-carrying capacity of rocks varies not only with its strength but also with the magnitude and distribution of the load (Fig. 2).

Computation of bearing capacity of the two rocks: Assumed angle of internal friction and cohesion from triaxial tests are used to calculate the bearing capacity factors of the teschenite-gabbro and sandstone.

According to Stagg and Zienkiewicz (1968) the bearing capacity factors of the hard rocks can be expressed approximately by:

N_q = $\tan^6 (45 + \phi/2)$.
N_c = $5\tan^4 (45 + \phi/2)$.
N_γ = $N_q + 1$.
ϕ = Internal friction angle.

The factors are substituted in bearing capacity equations of Terzaghi and Meyerhof to calculate the ultimate bearing capacity of the teschenite-gabbro and sandstone. The ultimate bearing capacity is defined as "the average load per unit area required to produce failure by rupture of a supporting soil or rock mass". The calculation has been carried out according to the available data and the geoengineering properties of the rocks at the PHP site. The following assumptions and limitations apply to this computation methodology:

- The vertical load would be applied by a rectangular footing of 20×60 m to the bedrock of the PHP site.
- Angle of internal friction (ϕ) = 34°
- Cohesion (C) equal to 1500 kN m^{-2} for the slightly weathered teschenite-gabbro and value of 150 kN m^{-2} for the sandstone.
- Depth (D_f) = 10 m.

Terzaghi bearing capacity equation: Terzaghi (1943) proposed one of the early sets of bearing capacity equations. He derived them from slightly modified bearing capacity theory developed by Prandtl (1920). The equations were intended for shallow foundation. The ultimate bearing capacity of a rectangular foundation is expressed by the following equation:

$$q_{ult} = C N_c S_c + \gamma D_f N_q S_q + 0.5\gamma B N_\gamma S_\gamma$$

Where:

N_γ, N_c and N_q = Are bearing capacity factors that are functions of the angle of internal friction. In this study, Stagg and Zienkiewicz (1968) bearing capacity factors of hard rocks are used.
C = Rock cohesion.
B = Foundation width.
S_γ, S_q and S_c = Shape factors,

For:	Strip	Round	Square
S_c =	1.0	1.3	1.3
S_γ =	1.0	0.6	0.8

D_f = Depth of foundation.
γ = Unit weight.

Table 2: Shape, depth and inclination factors of Meyerhof bearing capacity equation

Factors	Value	For
Shape	$S_c = 1+0.2K_pB/L$	Any ϕ
	$S_q = S_\gamma = 1+0.1K_pB/L$	$\phi > 10$
	$S_q = S\gamma = 1$	$\phi = 0$
Depth	$d_c = 1+0.2\sqrt{K_pD/B}$	Any ϕ
	$d_q = d\gamma = 1+0.1\sqrt{K_pD/B}$	$\phi > 10$
	$d_q = d_\gamma = 1 \quad \phi$	$\phi = 0$
Inclination	$i_c = i_q = (1-\theta/90)^2$	Any ϕ
	$i_\gamma = (1-\theta/\phi)^2$	$\phi > 10$
	$i_\gamma = 0$	$\phi = 0$

Table 3: Ultimate bearing capacity of teschenite-gabbro and sandstone

Rock name	qult = σ_u/SF = σ_u/10 kN/m^2	Bearing capacity values Terzaghi equation	Meyerhofequation
		- qult = kN/m^2	- qult = kN/m^2
Slightly weathered teschenite-gabbro	2700-6300	2578	2417
Sandstone	2900	1090	1096

Meyerhof bearing capacity equations: Meyerhof (1951 and 1963) proposed a bearing capacity equation, similar to that of Terzaghi but included shape factors (S_c, S_q and S_γ), depth factors (d_c, d_q and d_γ) and inclination factors (i_c, i_q and i_γ). The equations of these factors are shown in (Table 2).

$$q_{ult} = C N_c S_c d_c + \gamma D_f N_q S_q d_q + 0.5\gamma B N_\gamma S_\gamma d_\gamma$$

The above two bearing capacity equations are used to calculate the ultimate bearing capacity of the teschenite-gabbro and sandstone.

Geological conditions, rock type and Rock Quality Designation (RQD) are significant parameters used in the ultimate bearing capacity calculation. Bowles (2003) mentioned that "it's common to use large safety factor in rock capacity. The safety factor should be somewhat dependent on the RQD. They are commonly in the range from 6-10 with small values of RQD less than about 0.75 unless RQD used to reduce the ultimate bearing capacity". Accordingly, the ultimate bearing capacity is reduced using the below formula and the result is shown in Table 3.

$$q_{ult} = q_{ult} (RQD)^2$$

The allowable rock bearing pressure in the present work is taken as 1/10 of the unconfined compression strength (σ_u) obtained from intact rock samples.

The estimated values of the ultimate bearing capacity of the teschenite-gabbro and sandstone (at depth of 10 m) using Terzaghi and Meyerhof equations are found to be 2578 and 2417 kN m^{-2} and 1090 and 1096 kN/m^{-2}, respectively. Also the strength test carried on the slightly weathered sandstone gave reliable results. The few fracture, pore spaces and bedding planes of the sandstone may enhance the permeability of the rock, increase the degree of weathering and decrease the strength and the bearing capacity of the rock with time. The fresh teschenite-gabbro is overlain by weathered one. The rock test carried on the highly weathered teschenite-gabbro showed very weak strength and low geotechnical properties.

CONCLUSION

The ultimate bearing capacity is an important design consideration for hydro structures, roads, bridges and other engineering structures particularly when large rock masses are the foundation material (Merifield *et al*., 2006). With the exception of some very soft rocks and heavily jointed media, the majority of rock masses provide an excellent foundation material.

The estimated value of the ultimate bearing capacity of the teschenite-gabbro to a depth of 10m are 2578 and 2417 kN m^{-2} according to Terzaghi and Meyerhof equations, respectively. The bearing capacity of the sandstone at the PHP site to a depth of 10m showed two values: 1090 and 1096 KN m^{-2}, corresponding to Terzaghi and Meyerhof equations, respectively.

The power plants can be constructed on hard and as far as possible impermeable beds at suitable site topographically permeating the best exploitation and maintenance of the hydroelectric head. These characters are available at the investigated sites.

Up to about D = B Meyerhof is not greatly different from the Terzaghi value. The difference is more pronounced at larger D/B ratios.

The ultimate bearing capacity values of teschenite-gabbro and sandstone obtained from Terzaghi and Meyerhof equations showed slight difference, this is due to $D<B$.

The dynamic elastic moduli, physical and mechanical properties of the slightly weathered or fresh teschenite-gabbro and sandstone reviled intermediate to good geotechnical properties therefore, the foundation can be erected directly on the slightly weathered or fresh teschenite-gabbro bedrock down to a depth not less than 10 m.

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