Permeability Characteristics of the Foundation Materials of Gurara Dam, North Central Nigeria

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ABSTRACT
A comparison of refraction seismic velocities, electrical resistivity and in-situ permeability values were used in this study to evaluate the relationship between permeability values and geophysical parameters in the basement rocks in Gurara Dam area, Kaduna State, North Central Nigeria. Seismic refraction shootings, borehole drilling and rock coring enhanced the interpretations of the geo-electrical studies. The presence of low resistivity values (200-700 Ω-m) on the electrical resistivity soundings coincided with low velocity transmission of seismic waves (500-1,500 m/sec.) in the saprolite. The results of drilling, coring and water testing, show that the basement rock is fresh and moderately permeable. The Lugeon values from the water pressure tests performed in boreholes show local variations of the generally moderate overall permeability. The permeability values in the basement rock fractures which lie between the depths of 20 and 40m vary between 35 and 1,620 x 10^{-7} m/s, meaning that the rocks require cement grouting for structural foundation works at these depths. The permeability values of rocks between 40 and 60m vary between 2.67 and 94.8 x10^{-7} m/sec.
This study has established the relationship between low seismic velocity and low electrical resistivity and high permeability in the basement rock. Permeability increases down the profile in the up thrown side of the dam axis until where the fractures close up at depths, while it decreases downwards at the down thrown side. These areas need extra care in the construction stages, if the dam foundation is not to be “threatened”.
Key words; Permeability, saprolite, fresh rock, grouting.

INTRODUCTION

One of the most important parameter for seepage analysis of a dam and its foundation is permeability, therefore its prediction and distribution for the material of dam body and foundation is one of the critical aspects of dam projects [1]. As important as this parameter is, it is the most spatially variable most uncertain and hence least predictable transport properties of porous media [2]. It is required for estimating the quantity of underground seepage under various hydraulic conditions. It also helps in making stability analyses especially of earth dams. Various empirical models have been proposed to infer permeability from well log – data based on calculations of porosity, water saturation, capillary pressure and formation resistivity factor. It is estimated via correlations among other rock petro-physical properties. In many cases, there may exist deterministic relationships among these properties, but such correlations usually are empirically derived for a given formation in a given area. They are also statistical in nature and therefore cannot be applied to general cases [3]. Rock permeability has not been easy to determine in Nigeria partly because of the cost and non-availability of the equipment. If however, it is determined, the empirical relationship between the determined value and the geological and geophysical data taken in the same area need to be verified. This paper investigates permeability characteristics of the foundation materials (Basement complex rocks and its overburden) via Lugeon test and Le franc Permeability tests respectively**.** It also correlates it with different geophysical empirical methods of determining permeability. This is with a view to determine the cost effective methods of foundation material permeability in dam site investigations.

GEOLOGICAL SETTING

The area under consideration is in sheet 166 (Kachia SW) and is bounded by latitudes 9^0 30’ and 9^0 45’N and longitudes 7^0 30’ and 7^0 45’E. It falls within the area covered by the crystalline rocks of the Pre-Cambrian basement complex of Nigeria, which witnessed the thermo-tectonic event of the late Proterozoic to early Palaeozoic [3, 4]. (Fig. 1) shows map of Nigeria indicating the position of the study area which is part of the ancient African crystalline shield which evolved through the Archean (≥2,500 million years) thermo-tectonic events [5].

The western and eastern abutment features are composed of augen gneiss while the central intervening lowland is granite gneiss. Figure 2 shows lithological and structural features of the study area. The granite gneiss on the western side is said to have been produced by the deformation of the old gneiss [6].

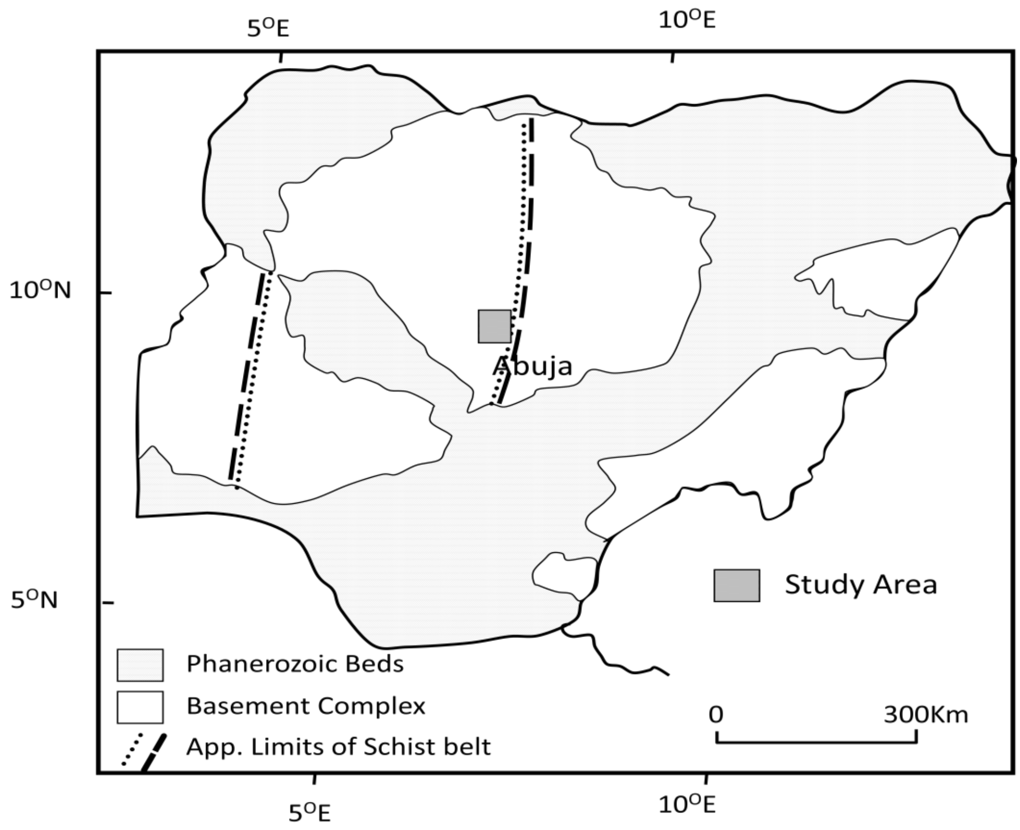


Fig 1. Map of Nigeria showing location of the study area

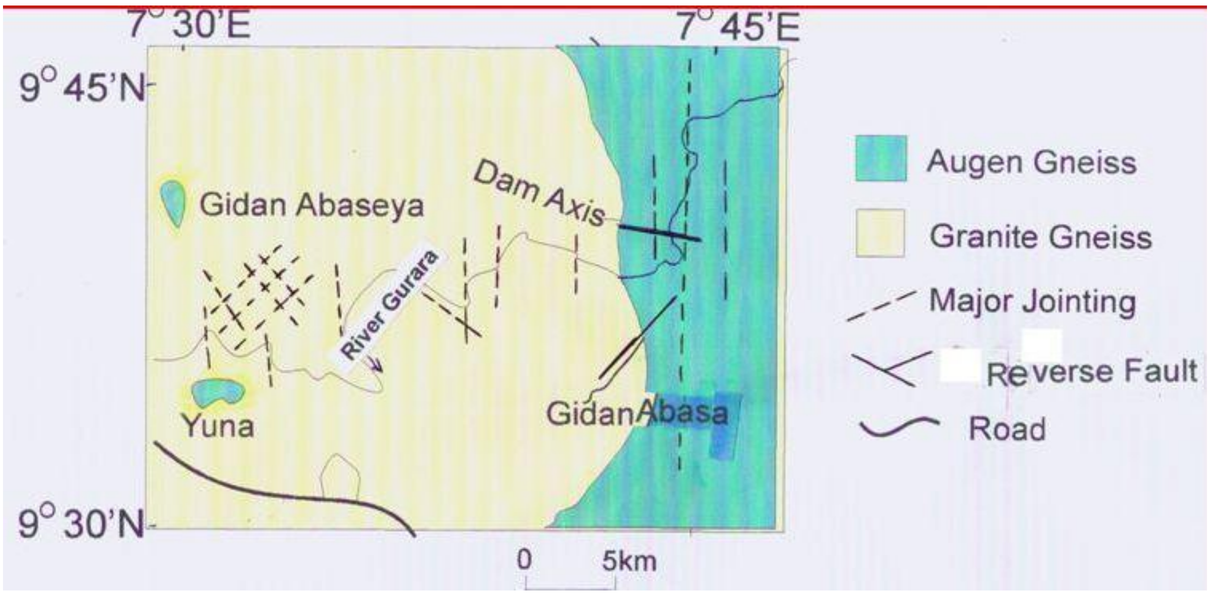


Fig . 2. A lithological and structural map of Gurara Dam Area (After olashehinde, 1990)

Two major rock types occur within the Gurara Dam area up to one kilometer north and south of the dam axis. They are the granite gneiss in the lower grounds and the porphyroblastic gneiss which is referred to as augen gneiss. Four zones of deep depressions or fractures in the bedrock were unraveled. They are located, from the western abutment,

(i) Between 300 and 650 m
(ii) Between 750 and 900 m
(iii) Between 1100 and 1350 m
(iv) Between 2200 and 2700 m (on the eastern flank).

The overburden is, on the average, 3 to 10m thick but reaches 20 to 40 m, in the depressions or fractures. The perennial nature of Gurara River appears to suggest credence to the view that the fractures have healed at relatively shallow depths. The Gurara River flows North-South in the study area which indicates structural control. Vertical movements of the rocks have most probably occurred around the proposed dam axis. The rocks on the east bank of River Gurara have been down thrown and partly covered by thick alluvial and weathered in-situ rock debris. The vegetation is markedly different from the West Bank, [7] also confirmed that the East bank is down thrown compared to West bank.

MATERIALS AND METHODS

Detailed geological mapping of the entire area including detailed logging of the borehole cuttings and pits were carried out. Geophysical investigations and in-situ permeability tests of the foundation soil and rocks were carried out. The geophysical investigations carried out were of three types: Vertical Electrical Sounding (VES), Horizontal Electrical Profiling (HEP) and Seismic Profiling. The composite geophysical method employed in this study helps to ensure no strata either horizontal or inclined is missed out. This consisted of 31 electrical soundings and 336 short electrical profiling carried out on 21 lines, while seismic profiling cumulated 43 spreads of 110 m length each.

Most efforts of permeability determinations have been laboratory results. However in-situ determination tests have to be considered in geotechnical studies [8]. Lugeon in situ permeability test method was used in the bedrock in order to confirm its apparent natural water tightness. This test gives a measure of the passage of water under pressure by in-situ rock. It comprises the measurement of the volume of water that can escape from an uncased section of borehole in a given time under a given pressure. Plug seals were inserted about 3-5m from the bottom of each borehole drilled in rock. Water under pressure was pumped into the holes through inlet pipes which passed through the seals to the bottom of the holes at varying pressures (i.e. 2, 5, 10, 5, 2 atmospheres) . Most classical solutions for pumping test data are based on the assumption that the aquifers are homogeneous and isotropic, and that the flow is governed by Darcy’s law. This test was used in boreholes to determine the permeability of the different strata encountered in the hole. A screen of about 3-5m was inserted at the depth to be tested or at the bottom of the hole. Water was pumped into the hole at a pressure of 10 kg/cm^2 (9806 kN/ m^2) through the steel-cased hole. The water level was maintained in the boreholes and the rate of in-flow of water was measured to determine the permeability of the rock at that depth. The “pumping-out” test is more reliable in in-situ field determination of permeability coefficient up to 45m depth, but it is handicapped in that it cannot determine the permeability at different depths. That was why the Lugeon(pump in test) method was used for this study. The result of the test is usually expressed in “Lugeon” units. A rock is said to have a permeability of 1 Lugeon if, under a head above groundwater level of 100m, a 1m length of borehole accepts 1 litre of water per minute at a specified pressure of 10kg/ m^2.

Le franc Permeability Test was carried out in the Soil and Saprolite region using the principles of the variable head method and the Constant Head Water Test. In both methods the entire hole was steel cased and the zone to be tested was exposed at the bottom of the hole, say, 2 meters. The casing was filled with water and the rate at which the water level dropped in the casing was noted. The permeability (K) of the medium was calculated from the formula: -

$$\mathbf{K} = \frac{Q}{\pi(\mathbf{h_1} - \mathbf{h_2})} . \ln \frac{R1}{R2}$$

where: R= radius of casing

h_1 and h_2 are the pressure heads at times t_1 and t_2 (mins.)

Water from a stand pipe flows through the soil . Initial head difference h_1 at time

$t = 0$ is recorded and water is allowed to flow through the soil sample such that the final head difference at time $t = t_1$ is h_2.

The rate of flow of water through the sample at any time t can be given by

$$\mathbf{q} = \boldsymbol{K}\frac{\mathbf{h}}{\mathbf{L}}.\mathbf{A} = -\mathbf{a}.\ \boldsymbol{\delta}\mathbf{h}/\boldsymbol{\delta}\mathbf{t}$$

where q = rate of flow,

a = cross sectional area of the standpipe.

A = cross sectional area of the soil sample.

Integration of the left of the equation above with limits of time from zero to any time t and the right side with limits of head difference from h_1 to h_2 gives

$$\mathbf{t} = \frac{\mathrm{aL}}{\mathbf{At}}.\ln\frac{\mathbf{h_1}}{\mathbf{h_2}}$$

The permeability tests carried out were 86 (Lugeon), 35 Constant Head and 149 Falling Head tests. The permeability of the overburden and weathered materials (le franc) is measured in meters per second while the permeability of the rocks is measured in lugeon units. Nine (9) boreholes were considered on the left or eastern bank of river Gurara along the dam axis. These are: DL-7, DL-3, DL-5, LEP-5 (left exploratory pit), DL-2, DL-4, DL-6, DL-1 and DL-8. On the right or western bank of the river Gurara, the twelve boreholes considered are DR-10, REP-5 (right exploratory pit), DR-11, DR-12, DR-6, REP-12, DR-18, DR-16, DR-9 , DR-17, DR-13, and DR- 7.

The following relationships were considered:

- Relationship between seismic velocity and apparent resistivity
- Relationship between rock permeability and apparent resistivity, and
- Relationship between rock permeability and seismic velocity.

Empirical relationships were also considered.

RESULTS AND DISCUSSION

GEOLOGICAL STUDIES

The results of the geological studies indicate that the Upper Gurara river area is intensely fractured. This fracturing is usually accompanied by deep weathering which will in turn leads to seepage under a dam structure. It also results in weakening of the bearing capacity and shear strength of the crystalline basement rock thereby endangering the stability of heavy structures built on such formations (Ojo et al, 1990). The overburden is, on the average, of 3 to 10 m thick but reaches 20 to 40 m, in the depressions or fractures. These depressions are longitudinal and parallel to the river course, thus aligning with the NE to NE-SW regional trend of tectonic fracturing reported in (Odeyemi, 1976).

Lugeon Values across the Dam Axis

Lugeon values are higher on the west than on the east of river Gurara. This is expected because the west is upthrown and the east is downthrown with thicker overburden. The displacement is about 10meters. There is also a cyclic variation in the lugeon values as illustrated by fig ------The deep boreholes are mostly located in the fractures. Figure ---- illustrates the actual depth of boreholes and the array of boreholes along the Gurara Dam axis representing some of the boreholes in which le franc and lugeon tests had been performed. It has been established by the field tests that permeability increases down the profile at the fractured zone in the basement rocks but reduces as the fractures close with depth. The middle portions of the boreholes represents the fractured areas with higher permeability than in the upper and lower zones. The figure shows the permeability at different depths in some of the boreholes along Gurara dam axis. Figure 4.10 shows the variation of lugeon values from west to east along the dam axis. It is observed that permeability is higher in the upthrown side than in the downthrown eastern side in the basement rocks.

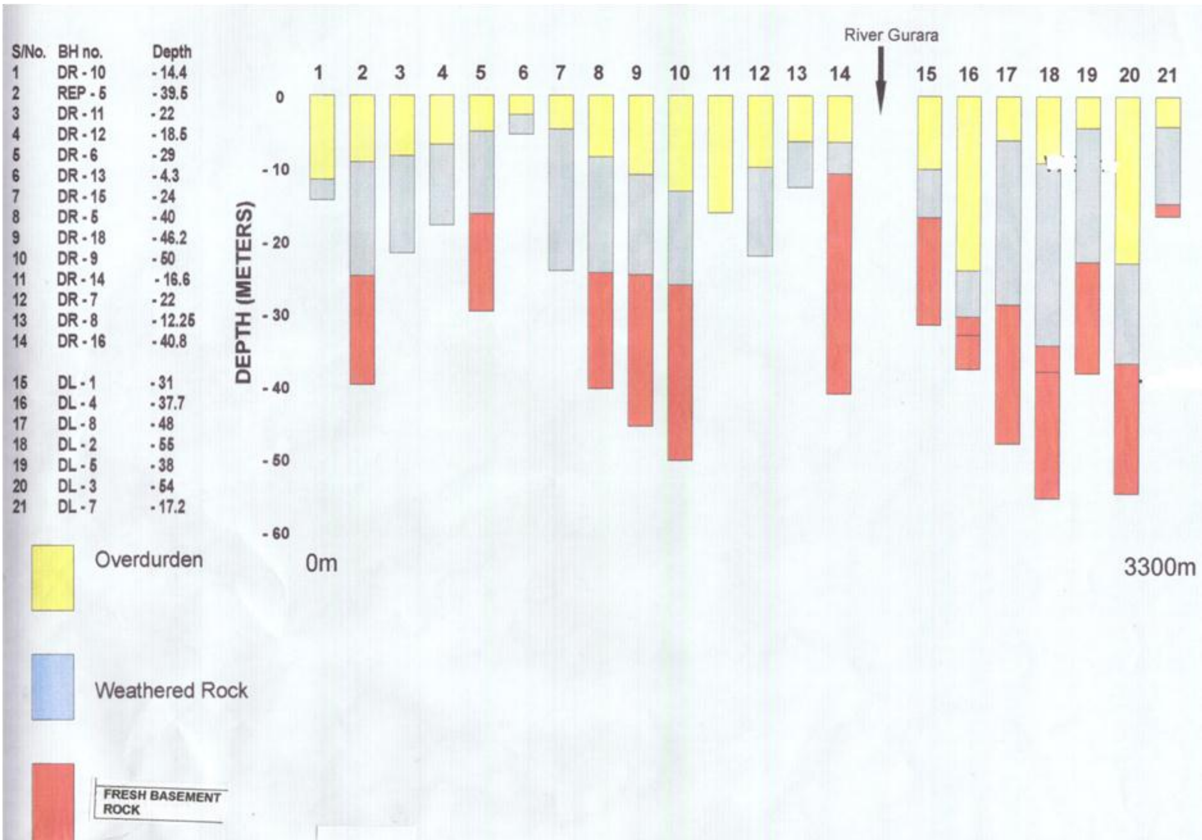


FIG. 4.9 : Gurara Dam Axis Boreholes Lithologic Logs.

permeability is higher in the rocks in the upthrown side than in the downthrown side.

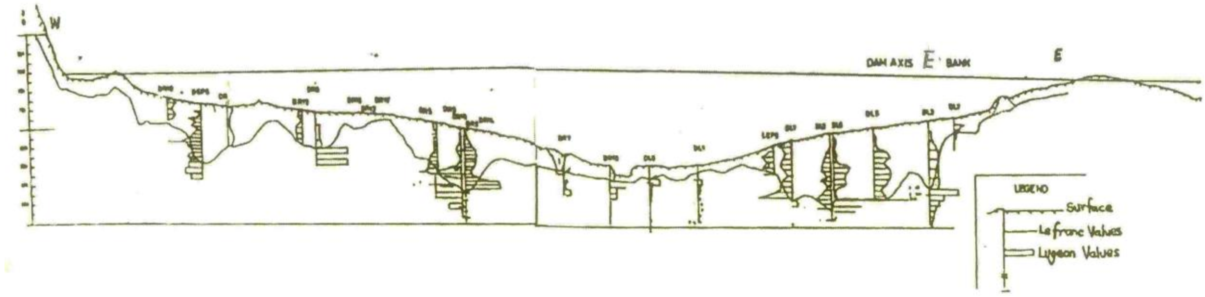


FIG. 2. ILLUSTRATIVE DIAGRAM FOR PERMEABILITY TESTS ACROSS GURARA DAM AXIS.

Fig 2 illustrates the variation in permeability in the boreholes which were tested. This Illustrative diagram shows that permeability decreases downwards in the basement rocks at the purportedly downthrown side, while it increases downwards at the up thrown side, to the level where the fractures close up at depths. The middle portions of the boreholes represents the fractured areas with higher permeability than in the upper and lower zones. Figure 5 shows the variation of lugeon values from west to east along the dam axis.

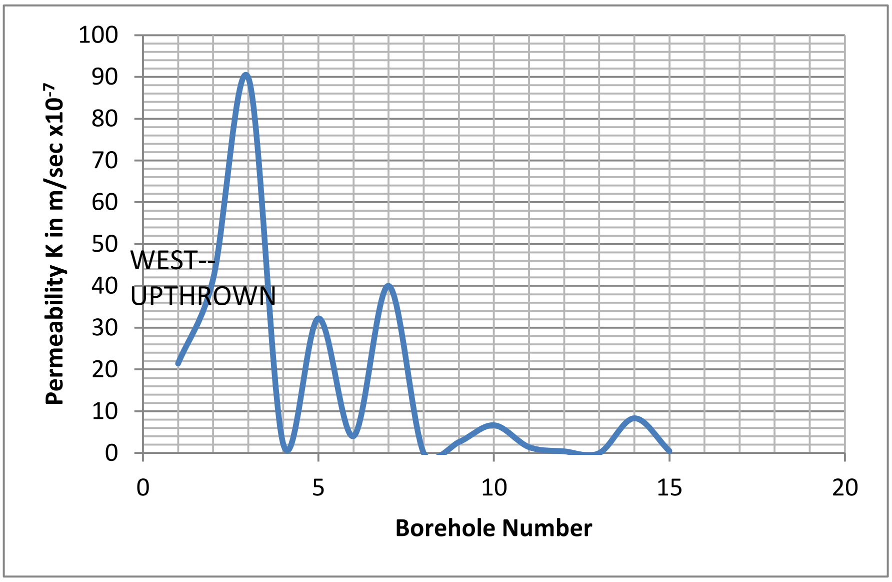


Fig 5. Variations in Lugeon (permeability) Values from West to East Along Gurara Dam Axis.

SUMMARY OF THE CORRELATION BERWEEN THE BOREHOLE LOGGINGS, ELECTRICAL RESISTIVITY SURVEYS ,

THE SEISMIC REFRACTION SHOOTINGS AND THE IN SITU PERMEABILITY TESTS

From the detailed logging of the borehole cuttings and pits, three soil units were identified above the fresh basement rock. The seismic, electrical and permeability properties of these soil units and the basement rock are presented in table ----- This result was gotten by correlating the borehole loggings with the all results gotten from Electrical resistivity surveys , the seismic refraction shootings and the in situ permeability tests

Layer Number	Description	Electrical Resistivity (Ohms-m)	Seismic Velocity (m/s)	Permeability K(m/s)	Thickness of Layer (m)
1.	The Upper Fringe of soils (clay with predominant kaolinite), Upper Ferralitic Layer.	200-3,000	400-600	$1x10^{-7} – 1x10^{-6}$	0-1
2.	The Ferralitic Latosols (silty, sandy residual soil).	600-2,500	500-1,200	$2.5x10^{-6}$	1-6
3.	The Upper Fringe of highly weathered and fragmented bedrock.	1,200-2,500	1,500-2000	$1x10^{-5}$	6-40
4.	Granite-gneiss Basement Rock.	3,500-5,000	2,500-4,500	$1x10^{-7}$	∞

table --- characteristics of the geological formations in gurara dam area.

ZONES OF FRACTURE AS DETECTED BY THE SEISMIC AND RESISTIVITY STUDIES.

S/N	STATION (m)	SEISMIC VELOCITY (m/s)	RESISTIVITY (Ohm-m)	BOREHOLES DRILLED AT STATION	MAXIMUM PERMEABILITY AT THE STATION. K (m/s)
1.	300	2,500-2,600 (sm- 03)	3,500 (ED-01, ED-02)	REP 5	46.118 $x10^{-6}$
2.	600	4,500 (sm-06)	3,000 (ED-03)	DR-12, DR-06	$6.06x10^{-6}$ 107.152 $x10^{-6}$
3.	1,200-1,300	1,300-3,400 (sm-11) (sm-12)	(ED-07) 1,018	DR-5, DR-9, DR-15, DR-18, REP-12	2.532 $x10^{-6}$ 116.774 $x10^{-6}$ $1.87x10^{-5}$
4.	2,300-2,400	2,700 (sm-21)	2,500 ED-12	DL-2, DL-8, DL-4	49.538 $x10^{-6}$ 111.22 $x10^{-6}$ 9.99 $x10^{-6}$
5.	2,670	1,500-1,800 (sm-24)	2,500 ED-13, ED-14	DL-3 DL-5	178.702 $x10^{-6}$ $1.62x10^{-4}$

Relationship between Permeability and Geophysical Parameters

Geophysical parameters give reliable information on the permeability of the different litho-types. From the present study, it has been found that where the resistivity values are low (100-400) Ω-m or where the transmittal velocity is low (400-500) m/sec., the permeability is usually high because of the low density of the materials. Loose materials like sandy gravel and weathered rock give moderate electrical resistivity and transmittal velocity of about 300-1000 Ω-m and 500-1,500 m/sec. respectively [9]. Such materials are also moderately permeable. In summary, the higher the density and dryness of a rock type the higher the electrical resistivity and transmittal velocity with corresponding low permeability.

Geo-electrical and Seismic Measurement Results.

The results from electrical resistivity studies revealed mostly three geo-electric layers viz:

i. The top soil layer with thickness of up to 10 metres and resistivity values ranging between 100 and 400 Ω-m ;
ii. An intermediate weathered rock layer of about 5 metres and resistivity values of between 300 and 1,000 Ω-m ;
iii. And lastly, the hard basement complex rock of infinite depth and resistivity of 3, 5000 Ω-m and above.

The range of velocities of the upper fringe of soils is 400-500 m/sec. and resistivity values of 200-3,000 Ω-m. The ferralitic latosols and the top layer of the silty, sandy residual soil have transmission velocity of 500-1200 m/sec. and resistivity values of 60-2500 Ω-m respectively. The upper fringe of the highly weathered and fragmented bedrock is of velocity 1500-2000m/sec. and resistivity of 1200-2500 Ω-m. The range of velocity values of the underlying sound bedrock is 2500-4500m/sec. and resistivity values of 3500-5000 Ω-m . The resistivity of the upper ferralitic layer has a medium range of values of 300-1000 Ω-m. From all the identification tests that were performed in the foundation of the dam and the potential borrow area the upper ferralitic sub unit can be classified as clayey material with medium plasticity. Its range of permeability values is $1x10^{-7}$ to $1x10^{-6}$m/sec. This clayey part contributes to a large extent, to the natural water tightness of the overburden. The texture of the intermediate soil unit becomes more consolidated with depth but more variable when moving down to the underlying weathered gneissic bedrock. The range of permeability of this unit is between $8x10^{-6}$ and $1x10^{-6}$ m/sec. with a low coefficient of variation. This is true across the dam area. The available results of investigations indicate that the contact between the soil overburden and the underlying bedrock is very thin. However in the boreholes that were logged, especially in the four depression zones, (DR-18, DL-2, REP-5, and DL -3), a lower layer of coarse-grained sandy and gravely layer was encountered just above the surface of the bedrock. For instance, in borehole DR 9, a 5 meter thick layer described as greyish silty sand with weathered rock material was drilled from 28.0 to 33.5m. Also in borehole DL2, a 3 meter thick layer of coarse grained material was encountered just on top of the bedrock. The relative permeability value measured in these layers proved to be high, in the range of $1x10^{-5}$ m/sec. but concentrated in the lower and deep sections of the soil sequence. The intermediate soil unit can be considered as a slightly permeable foundation with an average value of $2.5x10^{-6}$m/sec.

The intermediate soil unit can be considered as a slightly permeable foundation with an average value of $2.5x10^{-6}$ m/sec. The lower coarse grained layer within the soil sequence is the only adverse permeable horizon to the natural water tightness of the dam foundation. This can be sealed by grouting works such as extensive thin wall through the total thickness of the soil to bedrock or jet-grouting. Another alternative is a water tight blanket of compacted latosol upstream of the dam.

Similar findings for the seismic refraction measurements were obtained. The first layer velocity is about 400-500m/sec., the second layer velocity is about 500 to 1,500m/sec., while the basement rocks have a velocity of about 3,500m/sec. and above. There is in general, some correlation between the electrical resistivity of the various rock types and their susceptibility to chemical weathering [10]. This may have some relationship with the temperature of formation of the constituent minerals and consequently the permeability of the rocks. The gneisses are characterized by lineations which constitute planes of weaknesses and consequently show relatively lower resistivity and weather more readily. Hence gneisses are often overlain by a very thick weathered material. It may be observed that granite has higher resistivity than the gneisses and so less permeable.

Empirical Relationship between Permeability and Geophysical Parameters.

An empirical relationship between permeability and geophysical parameters were plotted as in figures below;

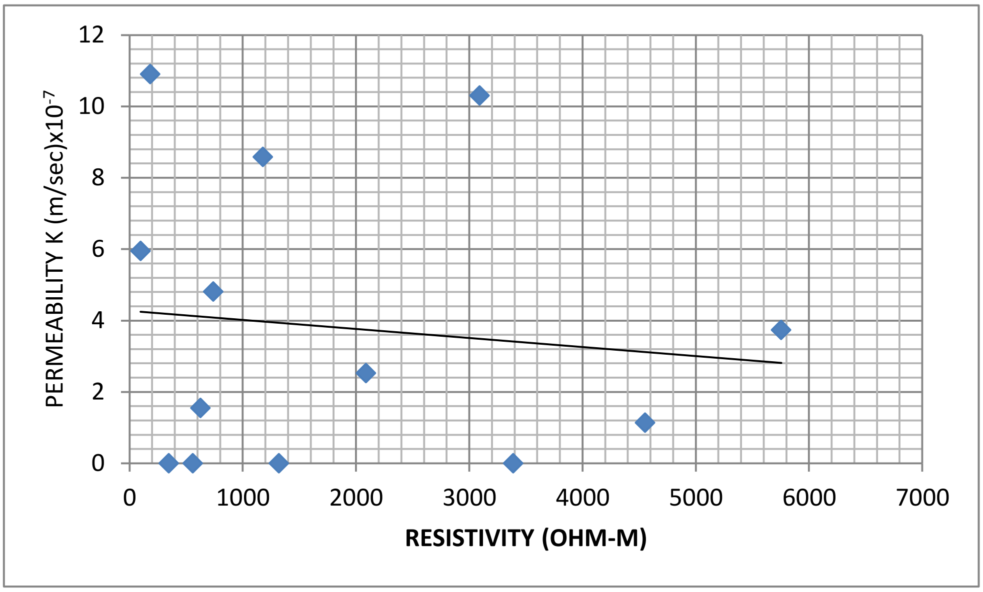
a. permeability versus electrical resistivity both in the overburden and basement rocks (Fig. 5.1a and 5.1b); and the relationship is **a = K.ℓ;** The constant **a = $1x10^{-10}$ Ω-m^2/sec.** in the overburden and **a= $6.25x10^{-12}$ Ω-m^2/sec.** in the basement rock; where **K = rock permeability in m^3/sec., a is the derived constant, and is ℓ the apparent resistivity of the formation in (Ω-m).**

b. Seismic velocity versus electrical resistivity both in the overburden and basement rocks from the data collected on the field in Gurara area and ; the resultant regression line gave a slope of **b= $9.4x10^{-2}$ mhosec.** for the overburden, and **b= 1.125x 10^{-3} mhosec. -** for the basement rocks; **b = V/ ℓ where V is seismic velocity; b is the derived constant** (slope of the regression line) and **ℓ is the apparent resistivity** of the formation**.**

c. **Permeability versus seismic velocity** in the overburden as well as in the basement rocks. The relationship is c **= KV; where c = $9.4x10^{-10}$m^2/sec^2 ,** in the overburden, and

4.29 x10^{-10}m^2/sec^2 in the basement rock**.**

The Slope of regression line is 0.0909×10^{-10}



Slope of the Regression line 2.02×10^{-10}

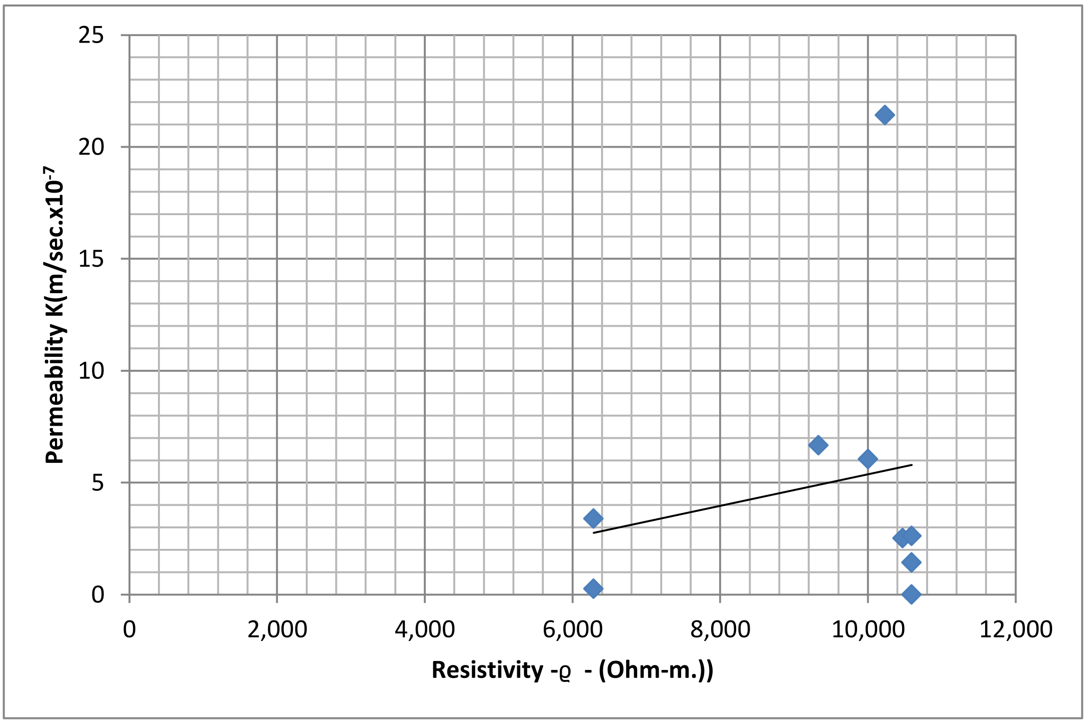


Fig Permeability , K versus ℓ in the Basement rocks

Permeability were also plotted with electrical resistivity against the borehole locations along the river Gurara dam axis (Fig. 5.4c and 5.4d). The behaviour of the curves show that permeability rises where resistivity falls (and vice versa) in the overburden whereas the two tend to follow one another in a sub-parallel form, in the basement rock especially in the upthrown western side of the river Gurara.

CONCLUSION AND RECOMENDATIONS

This study shows the relationship between geophysical and permeability parameters in a part of the basement complex terrain of Nigeria. The study has proved that geophysical parameters can successfully be used along with geological information to replace costly and time consuming geotechnical studies such as rock permeability determinations. It is usual to establish the fact that permeability in the underground decreases downwards due to natural compaction and diagenesis because of the pressure of the overburden. This study has also revealed that permeability in the basement rocks increases with depth at the up thrown side of the fracture while it reduces with depth at the down thrown side to the bottom of the fracture. The picture that emanates from the above studies is a system of north-south fractures coinciding with places of low resistivity and seismic velocity and low permeability at the up thrown side of the fractures and corresponding high permeability at the down thrown side of the fractures. Where there are deep fractures in the basement rocks in Gurara Dam area, rock permeability values which have been determined by the Lugeon tests have increased with depth, but progressively reduce as the fractures close up at greater depths. The permeability of the basement rocks in Gurara dam area vary generally between 2.67 and $1{,}620 \times 10^{-7}$ m/s. Water boreholes will give appreciable yields while foundations of structures will require cement grouting to forestall underground seepage and eventual collapse of the dam.

REFERENCES

[1] Ali, A. M and Mehdi, P., 2005. Uncertainty in Karkheh Dam Foundation Permeability. 73rd Annual Meeting of ICOLD Tehran, IRAN Paper No.: 080-S3

[3] Racz, A. J., Fisher, A. T., Schmidt, C. M., Lockwood, B. S., Los Huertos, M., Spatial and temporal infiltration dynamics during managed aquifer recharge, *Ground Water*, doi: 10.1111/j.1745-6584.2011.00875.x, 2011.

[4] Oyawoye, M.O., 1972. The Basement Complex of Nigeria. In TFJ, Dessauvagie & A. J. Whitman (Ed.) African Geology. Dept. of Geology, University of Ibadan, Nigeria. Pp. 67-99.

[5]Oyawoye, M.O., 1967. The Petrology of a Potassic Syenite and its Associated Biotite Pyroxenite at Shaki, Western Nigeria: Contributions to Mineralogy and Petrology, 16, pp.115-138.

[6] McCurry, P. C., 1976. The Geology of the Precambrian to Lower Palaeozoic Rocks of Northern Nigeria – a Review, -In: Kogbe, C.A. (ed.): Geology of Nigeria. Elizabethan Pub. Co., Lagos, pp. 15-40.

[7]Annor, A. E, Olasehinde, P.I. and Pal, P.C., 1990. Basement Fracture Patterns in the Control of Water Channels - An Example from Central Nigeria; Journal of Mining and Geology Vol. 26 No.1: pp. 5-11.

[8] Olasehinde, P. I., and Awojobi, M. O., 2004. Geological and Geophysical Evidences of a North-South Fracture System East and West of Gurara River in Central Nigeria. Water Resources – Journal of the N.A.H., Vol. 15, November, 2004. (pp. 33-37).

[9] Kenney, T. C., Lau, D., and Ofoegbu, G. I., 1984. "Permeability of Compacted Granular Materials," ,Canadian Geotechnical Journal, Vol.21, No. 4, pp. 726-729.

[2] Torskaya, T., Jin, G., and Torres-Verd´ın, C., Pore-Level Analysis of the Relationship Between Porosity, Irreducible Water Saturation, and Permeability of Clastic Rocks. Society of Petroleum Engineers (SPE) Annual Technical Conference and Exhibition held in Anaheim, California, U.S.A., 11-14 November 2007.

[10] Olayinka, A. I. and Olayiwola, M. A. , 2001. Integrated Use of Geoelectrical Imaging and Hydrochemical Methods in Delineating Limits of Polluted Surface and Groundwater at a Landfill Site in Ibadan Area, Southwestern Nigeria. Journal of Mining and Geology, Vol. 37, pp 53-68.

Olasehinde, P. I. and Annor, A. E., 1990. An Approach to Spectra Interpretation of Aeromagnetic Maps with Special References to Fractures – Example from Central Nigeria. Paper presented at the 26th A.G.M. of Nig. Min. and Geosciences Society, Kaduna, 4th-8th March, 1990.