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SOIL TESTING IN WEATHERED VOLCANIC SOILS

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АНОТАЦІЯ: Мета статті – проаналізувати методики випробувань грунтів, що використовуються для матеріалів, які містять повністю вивітрений базальт та агломерати, в контексті республіки Маврикій. Описана генезис створення матеріалів, виходячи з процесу вивітрювання вулканічного базальту, а також прийняті принципи оцінки структури та міцності вивітрених матеріалів на площадці та в лабораторних умовах. Наведено результати лабораторних та польових випробувань.

АННОТАЦИЯ: Цель статьи - проанализировать методики испытания грунтов, которые применяются для материалов, содержащих полностью выветренный базальт и агломераты, в контексте республики Маврикий. Описаны генезис образования материалов исходя из процесса выветривания вулканического базальта, а также принятые принципы оценки структуры и прочности выветренных материалов на площадке и в лабораторных условиях. Приведены результаты лабораторных и полевых испытаний.

ABSTRACT: This paper aims at analyzing the soil testing methodologies practiced on residual materials comprising highly to completely weathered basalt and agglomerates in the context of Mauritius Republic. The genetics and geological history of the founding material resulting from weathering process of volcanic basalt and also the principles adopted to assess the consistencies and strengths of the encountered weathered material on site and laboratory conditions have been carefully described. Typical results of laboratory and field tests are presented.

KEY WORDS: soil testing, weathering process, volcanic basalt, agglomerates.

INTRODUCTION

Geotechnical investigations are performed with an aim to have an insight of the characteristics of bearing soils such as the physical and mechanical properties of materials that exist underneath a building site. Geotechnical testing is vast in its own context and may start from a walk around on the surface of the delineated area and go as far as geophysical testing (non-destructive testing) to direct access of the bearing soil at various depths. Commonly soil testing may be realised by opening of trial pits, drilling of boreholes, laboratory investigation and in-situ testing.

Trial pits are much like one would expect, that is, a pit is dug either manually or with an excavator to the depth desired in order to reveal the sub-surface conditions. The profile of the trial pit walls are logged and the preliminary classification parameters and consistency of the underlying strata are assessed.

Drilling provides the opportunity to physically remove the soil or rock core samples for testing and inspection. The cores provide the advantage of physically seeing and visually assessing the actual materials, but for certain types of soils, the very act of boring can disturb the soil conditions and the samples extracted may not represent what the conditions will actually be for building and supporting structures. Generally, soil or rock samples from various depths of drilling are taken to a laboratory for further investigation.

In-situ, that is, in the actual location or on site, testing methods include penetration tests such as Standard Penetration Tests (SPT), which penetrate via drilling, and various Cone Penetration Tests, which penetrate via direct penetration of cones. These tests measure the physical and mechanical properties of the subsurface soil directly, without removal of cores. This provides the advantages of generating a more accurate reflection of conditions underground as well as avoiding the necessity of sending samples out for laboratory testing. In situ testing also includes plate load bearing tests, sand replacement, percolation tests among others – also meant to assess the actual nature of the prevailing materials.

The most important in soil testing campaign is to identify the right test for the right situation and for the right geology prevailing on site. Soil testing methodology will vary in function of various parameters, likewise - equipment, normative regulations, working pressure underneath foundations and most importantly - varies with the type of soil being investigated. The types of soils encountered depend on numerous factors namely: genetics of the soil, geographical position, nature of weathering and also age of the formation. So when all these variables are put together, it becomes quite complicated to select the appropriate method to obtain reliable soil parameters for assessment of bearing properties of the strata under investigation.

This paper presents the methods of soil investigation applicable to weathered volcanic basalt in the context of Mauritius. An analysis of various soil testing methods have been made and it has been shown that laboratory investigation carried out by extraction of undisturbed samples from boreholes by drilling, transportation, manipulation prior and during installation in experimental apparatus may induce a significant degree of disturbance to the original sample and results thereof may not be reliable for further exploitation. The original nature of the soil under study and its components do not always conform to the ideal requirements for laboratory testing.

SITE GEOLOGY AND ORIGIN OF THE FORMATION

General geology

The island of Mauritius is of volcanic origin and formed by several series of volcanic activities. It consists of undulating central uplands, rising to a maximum elevation of about 600m in the south and with a mean elevation of the order of 400m, surrounded by mountain ranges and plains, forming a bowl with chipped rims, filled with layers of young formations, the excess of which has flowed away (Jenny H., 1994; Carte Géologique de Maurice, 1996). Outside are the plains, which were deposited as lava flows. These flows are the products of small volcanoes situated on the wide low median ridge running across the island from south-west to north-east. The much eroded relicts of the rim of the bowl protrude above these younger volcanics as a discontinuous ring of mountain ranges with rugged peaks. The mountain ranges surrounding the central plateau have an asymmetrical profile.

Four volcanic series are considered in the formation of the island: emergence, older volcanic series, intermediate or early volcanic series and younger volcanic series or late volcanic series (Proag V. 1995; Les aquifers de Maurice, 1999).

Intermediate and more recent series of volcanic eruptions from several small emissions of volcanic rocks distributed over the whole island cover the ancient central volcanic plateau and the deeply eroded valleys heading towards the sea. Most of the island is now covered with intermediate and late lava flows which have in general a gradual dipping towards the sea from the interior. Isolated remnants of the ancient series occur in the highest peak of the island.

The lava flows consist of a sequence of massive basalt strata and volcanic breccia. Volcanic tuff layers occur in between the lava flows.

Old Volcanic series

The older volcanic series are essentially made up of basic rocks, most of which are extrusive. These basic extrusive are mainly represented by flows of olivine basalt which are in general fine grained dark rocks, but in some places also show coarse grained facies with quite large phenocrysts of olivine and of pyroxenes of relatively high density. The basaltic flows are generally unvesiculated and massive. However, the rare vesicles are very often infilled with deposits of secondary zeolites, calcites and aragonite. Iron pyrite crystals up to 2 mm and larger are common in some places. The flows in some places alternate with beds of agglomerate and subordinate tuffs and the thicknesses of these layers may vary up to more than 30 m. In general these layers are homogeneous and some weathered zone up to 0.6 m thick are frequently found overlying the agglomerate.

Intermediate Volcanic series

From the Geological Map of Mauritius, basaltic deposits from the Intermediate Volcanic Series, emitted some 1.7 to 3.5 million years ago have been altered by weathering heterogeneously. Their character varies from place to place, but on the whole they are made up of fine-grained rocks, grey to black in colour. The very compact types are rather rare, and are in general porous and often vesicular. They are fissured and the cavities are filled with yellowish/cream coloured clayey material.

Late Volcanic series

Doleritic basaltic deposits from the late Volcanic Series (late lavas) are characterized by uniform doleritic facies. The lavas show little variation in composition; they are nepheline basalt and their potassium content is remarkably low for alkali olivine basalts. They are often porous and vesicular and show many cracks and fissures, but they are also sometimes compact. Scoriaceous textures are common and the major openings are mostly in these scoriaceous zones between the flows and lava tunnels are not rare. The late volcanic lavas are well known for their very high permeability.

Founding material

The identification and description (logging) of soil and rock strata, deposited as results the weathering of volcanic basalt (Goodary et al. 2012, 2014), are currently carried out following recommendations of British Standards (BS 5930, 1999) – Code of Practice for Site Investigations. Foundation materials encountered during logging of profiles depends on the degree of weathering of the parent material and are classified as – slightly, moderately, highly and completely weathered basalt or agglomerate as shown in Table 1 (Byrne G., and Berry A.D., 2008).

Table 1

Rock mass weathering

Descriptive term	Fracture condition	Surface characteristics
Fresh Basalt	Closed	Unchanged
Slightly weathered Basalt	Discoloured and may contain thin filling	Partial discoloration/not friable
Moderately weathered Basalt	Discoloured and may contain thin filling	Partial to complete discoloration/not friable
Highly weathered Basalt	Discoloured and may contain thin to medium thick filling	Friable
Completely weathered Basalt	---	Resembles soil

A scale of strength of rock material, based on the indicative uniaxial compressive strength, as per BS 5930, is used to classify the rock mass according to its strength (Fookes P. G., 1971) and is shown in

Table 2

Strength description of rock material

Term	Field description	Compressive strength (MPa)
Very weak	Gravel lumps can be crushed between finger and thumb.	< 1.25
Weak	Gravel lumps can be broken by heavy hand pressure.	1.25 to 5
Moderately weak	Only corners can be broken off with heavy hand pressure.	5 to 12.5
Moderately strong	Held in hand, rock can be broken by hammer blows	12.5 to 50
Strong	On a solid surface, rock can be broken by hammer blows	50 to 100
Very strong	Rock chipped by heavy hammer blows.	100 to 200
Extremely strong	Rock rings on hammer blows.	>200

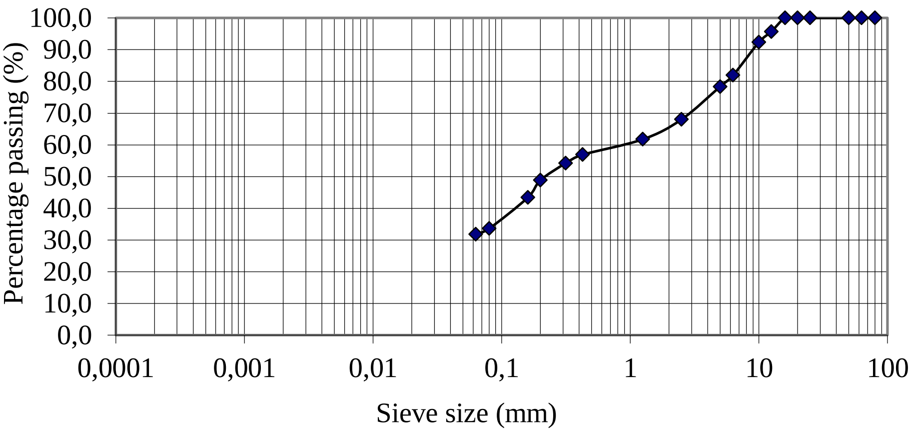
The soil mass is then identified and classified as sand, silt and clay or a combination of all coexisting components (Little A., L., 1969). Its physical state is determined by the principles listed below.

Table 3

Soil strength description for cohesive/fine soils

Consistency	Identification
Very soft	Easily moulded by fingers
Soft	Easily penetrated with thumb
Firm	Indent by thumb/moulded with strong pressure
Stiff	Indent by thumb
Very Stiff	Penetrated by thumbnail
Hard	Penetration by thumbnail difficult

Soils, hosting foundations, are normally end results of weathering process which occurred in the original parent basalt over millions of years and these are most likely gravels and cobbles in a matrix silty clay or sand (Fookes P. G., 1997). A typical particle size distribution curve for the type of soil under study is shown in Fig. 1.



Clay: 0-0.002mm Silt: 0.002-0.063mm Sand: 0.063-2.0mm
Gravel: 2.0-60.0mm Cobbles: >60mm

Fig. 1. Typical granulometric curve of a completely weathered basalt

From fig. 1, it can be seen that for a typical soil encountered, and from the various components present, the material may thus be classified as a gravelly silt/sand (Vargas M., 1974). However the sample contains 30 percent fines comprising silt and clay particles which also enables its appellation as gravelly silty clay. This is evidenced by the typical drilled core sample shown in Figure 2. In the figure, the plastified segments show depths at which Standard Penetration tests were carried out.

Fig. 2. Drilled coring in volcanic weathered basalt

Generally, the founding material underlies an organic top soil layer – as it can be seen between 0 to 0.55 m in Figure 2. It is obvious that the presence of gravels make it difficult to extract undisturbed cylindrical samples for further laboratory investigation (Jennings J. E. et al, 1973). However, occasionally it becomes possible to retrieve undisturbed samples during site investigation, which are despatched to appropriate competent laboratories for testing. As a matter of fact, tests namely: one dimensional consolidation oedometer test, direct/triaxial tests, permeability, unconsolidated unconfined test and also classification and compaction tests are performed on the sample, among others. During site investigation the most popular in-situ tests realised are mainly plate load bearing test and dynamic standard penetration test.

This paper aims at comparing some selective methodologies currently adopted on the island, along with an analysis of the various test results obtained.

SOIL TESTING

The cost of an adequate investigation is very low in comparison to the budget put aside for a whole project. The consequences of not providing sufficient, accurate and reliable geotechnical data may have a significant effect on a project and can lead to delays and extra funding during construction. Consequently, a proper soil investigation campaign prior to start of construction is unavoidable.

The importance of obtaining adequate and reliable information and design mechanical data relevant to the subsurface conditions at a sufficiently early phase is vital when considering the choice and design of an economical and technically sound foundation. In quest of such information, a complete geotechnical investigation comprising the following is necessary: planning of the investigation, execution of fieldwork and management of laboratory testing and finally interpretation and reporting.

The soil investigation campaign aims to obtain the following parameters (Shootenko L. N. and Goodary, 1988, 1989): description of the soil profile, consistency of the soil profile, in situ tests – dynamic cone penetration tests, drained and undrained shear strengths from undisturbed samples, compressibility characteristics from plate load test and one dimensional consolidation, location of ground water level from piezometers installed in boreholes and index properties of the encountered strata from laboratory testing on bulk samples (Raj J. K., 1994). Physical and index properties of weathered volcanic basalt are generally found to be coherent with conventional soils as these are normally performed on selected samples with specified particle size, that is sand, silt and clay particles (BS 1377, Part 2). As regards the laboratory testing on undisturbed samples - a special attention is required as results show deviations from expected values and are not often coherent with information gathered during site investigation. For the purpose of this analysis, the one dimensional consolidation test has been set as an example.

LABORATORY TESTING

One dimensional consolidation test

This method covers the determination of the magnitude and rate of the consolidation of a saturated specimen of soil in the form of a disc with specified diameter and height, confined laterally, subjected to vertical axial pressures and allowed to drain freely from the top and bottom surfaces (BS 1377, Part 5). The method is concerned mainly with the primary consolidation phase, but it can also be used to determine secondary compression characteristics. Data obtained from this type of consolidation test, if carried out on undisturbed samples of good quality, enable the amount of settlement under a structure to be estimated. Values of the coefficient of consolidation can also be calculated from which an indication of the theoretical rate of settlement can be derived. The very important aspect of the results is that the initial portion of the compression curve must indicate the virginity of the undisturbed sample, that is, its ability to resist the early phase of loading – indicating that the sample is familiar to such loadings and theoretically shall not react to it. This will prove the intactness of the sample and will be representative to the natural deposit on site.

For the purpose of this study, a typical one dimensional consolidation experiment with sample diameter 50 mm and height 20 mm is being considered. The material inside the consolidation ring is classified as highly to completely weathered basalt – possible residual basalt and was sampled from the north western part of the island.

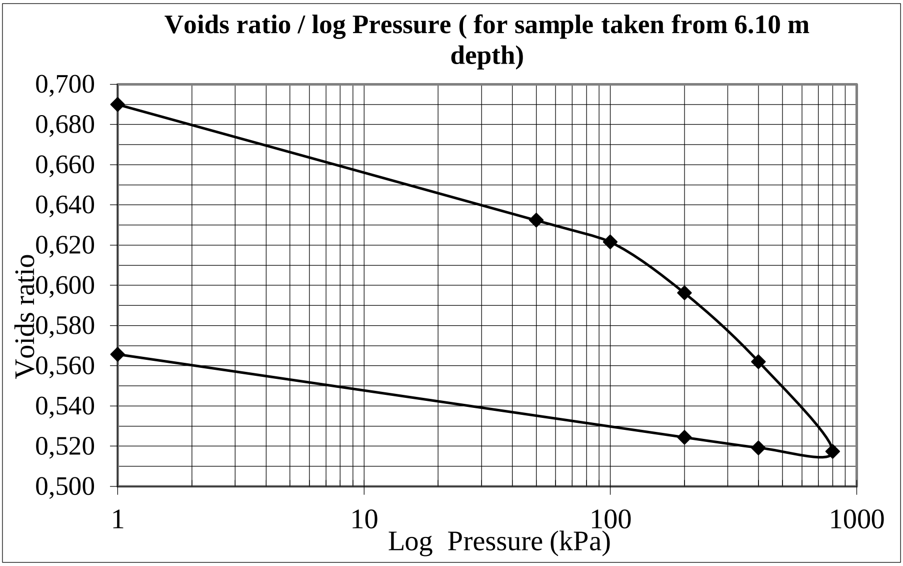


Fig. 3. Typical laboratory compression curve for weathered basalt

An analysis of the compression curve shows that the soil started to react at the very early stage of loading, which is not conform to the real case. The soil has been sampled from a depth of 6.10 m, meaning that solely the overburden pressure p kPa should be equal to

$$p = h\rho g = 6.1 x 1.6 x 10 = 97.6 \text{ kPa (rounded to 100 kPa)},$$

where h is the depth, ρ – soil bulk density and g – gravity.

This implies that the soil sample should not react for the logarithm pressure value of 2 (logarithm of 100) which is not the case in the actual example. Contrary to the above said, void ratio e decreases from 0.69 to 0.68 which is quite significant, implying that the sample has settled, which should not be the case. It is to be noted that no surcharge added to the soil overburden pressure has been considered.

Discussion: The reason behind this anomaly is the existence of induced voids inside the consolidation cell. These voids might be residing at the extremities of the sample, between the sample wall and the metal ring, or within cracks or any other disturbance which might have given place to some amount of artificial voids. Theoretically, the sample should have fitted tightly inside the ring which might not be possible due to the coarse components within the soil structure. It is clear that the original state of the material is compromised and consolidation parameters obtained from such samples will far not reflect the natural site conditions. It is now obvious that such samples will eventually not yield conclusive results in other experiments, likewise direct shear test or even triaxial compressive strength tests. Hence recourse to in situ testing is an ultimate option.

IN SITU TESTING

Plate Load Bearing test

The plate load bearing test is usually carried out to determine the compressibility and bearing capacity of soils (Meyerhoff G. G., 1963; Mohammed S., 2013). The test is convenient and provides a direct method of obtaining these parameters. It is often used in soils which cannot be sampled with good quality sample or cannot be retrieved. In its simplest form, the plate load test comprises a rigid plate placed on the surface of the soil to be tested. The load is provided by a hydraulic jack, using a lorry to obtain the reaction. The plates used must be rigid and generally vary in diameter from 305 to 1200 mm. The procedure for the above test has been worked out by the author with the collaboration of local consultants. The methodology was adopted to suit the local soil conditions and characteristics and was not altered much from prevailing standards (Terzaghi K. and Peck R. B., 1967; BS 1377 Part 9) in order to be coherent with the norms for which the plate load testing equipment has been designed. The following steps were adopted for the testing procedure:

- Apply load to produce deflection between 0.25 mm and 0.51 mm.
- Record and release load.
- Apply ½ seating load (seating load is the load required to produce deflection between 0.25 mm and 0.51 mm).
- Allow dial needles to come to rest.
- Set dial needles to zero.
- Apply load to produce 25 kPa above ½ seating load. This will depend on plate diameter, for d = 305 mm, pressure = 34 kPa.
- Allow action of load to continue until rate of deflection of not more than 0,03 mm/min has been maintained for three consecutive minutes.
- Record load and deflection readings for applied load increment.
- Reload by applying 50, 100, 200, 300, 400, 500 kPa … (if reaction load allows) and repeat steps above. The values of applied pressures will depend on plate diameter.
- Unload in reverse sequence and release the load to load at which dial gages were set to zero.

Fig. 4 below illustrates results of plate load test carried out in the same family of soils as previously, that is, in weathered basalt.

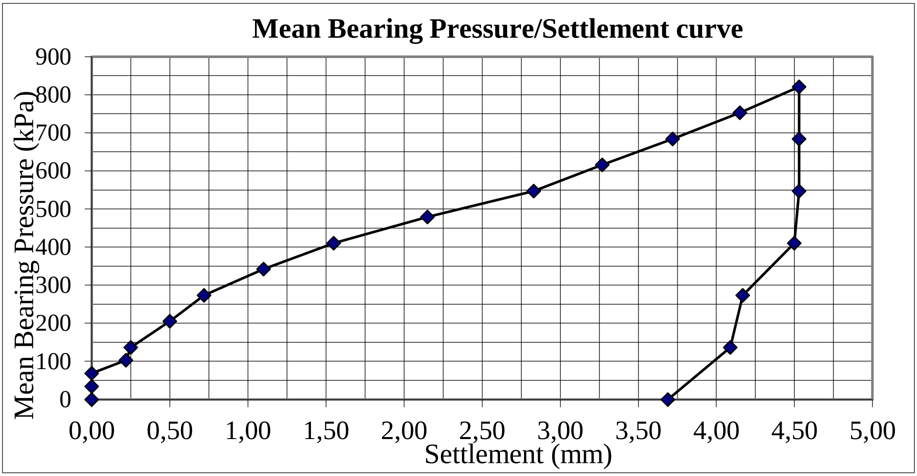


Fig. 4. Plate load bearing test result in weathered basalt

Assessment of ultimate bearing capacity

The value of q_{ult} for a proposed foundation is generally determined from a corresponding value of allowable settlement S of the foundation. A value for permissible settlement of 25 mm is being assumed for a presumed base of size 2 m x 2 m.

In this situation, settlement S_p (mm) of the plate (B_p of diameter 305 mm) corresponding to a settlement of 25 mm of the above mentioned base will be deduced. As such $S_p = (S \times B_p) / B = (25 \times 0.305)/2 = 3.81$ mm, a value which has been achieved at mean pressure value of 700 kPa.

This allows to conclude that for an assumed allowable settlement of 25 mm, the value of the allowable bearing capacity is in the range of 233 kPa (assuming a factor of safety of 3), a value which corresponds to a very stiff soil consistency and is in agreement with site conditions as per available logs of borehole cores and trial pits.

Standard Penetration Test (SPT)

For the above site, Standard Penetration Tests (SPT) were conducted at various depths as per BS 1377, both in cohesive and granular/gravelly soils (Meyerhof G. G., 1956). The test was carried by using a thick walled sample tube, the outside diameter of which is 50 mm. This is driven into the ground at the bottom of the borehole by blows from a standard weight of 63.5 kg falling through a standard height of 760 mm. The number of blows required to drive the sampler at each 150 mm increment of a total of 450 mm penetration was recorded. The blow count for the first 150 mm increment was discarded and the sum of the blow counts for the second and third increments were recorded as the SPT 'N' value. Results of Standard Penetration Tests carried out in boreholes at different levels are shown in Table 4 below.

Table 4

Standard Penetration tests results in highly to completely weathered basalt

SPT level (m)	SPT N value	Estimated UCS, kPa (Jennings et al, 1973)	Estimated shear strength Cu, kPa	Consistency
1.00	44	150 - 300	75 - 150	Very stiff
1.50	34	150 - 300	75 - 150	Very stiff
3.500	31	150 - 300	75 - 150	Very stiff
8.15	26	150 - 300	75 - 150	Very stiff

Standard penetration tests results reveal soil of a very stiff consistency which is once again in agreement with plate load test results and trail pits and borehole logs.

CONCLUSIONS

This study concerns the various soil testing methodologies implemented to tropical weathered soils at various stages of weathering – ranging from highly to completely basalt and agglomerates. Based on analysis and experimental results, the following can be concluded:

1. Desk study of the geology and genetical origin of the site under consideration shows that the island, of volcanic origin, has been formed by three consecutive volcanic eruptions giving deposits of the older, intermediate and younger volcanic series which have weathered variously to yield slightly, moderately and highly to completely weathered basalt (residual basalt) each exhibiting its own characteristic geotechnical properties.
2. It has been shown that soil testing in weathered basalt of volcanic origin demands a special approach in the assessment of their geotechnical parameters as these soils may not submit themselves to conventional methods of soil testing, particularly in what laboratory testing is concerned.
3. Laboratory testing results on undisturbed samples of weathered volcanic soils often yield unreliable results. Likewise, the one dimensional consolidation test gives results typical to disturbed samples. The reason behind this anomaly is the existence of induced voids inside the consolidation cell. These

voids might be residing at the extremities of the sample, between the soil sample wall and the metal ring or within cracks or any other disturbance which might have given place to some amount of artificial voids.

4. Plate load bearing test has been found to be appropriate for the type of soil under consideration and case study of a typical test has been discussed. Results prove the coherence with actual prevailing site conditions. For the given case study with an assumed permissible settlement of 25 mm, the value of the allowable bearing capacity is found to be in the range of 233 kPa (assuming a safety factor of 3), a value which corresponds to a very stiff soil consistency and which is in agreement with site conditions as per available logs of borehole cores and trial pits.

5. Standard penetration tests performed have also shown very good correlation with plate load bearing test results. For the given case study, test results reveal soil of a very stiff consistency which is once again in agreement with plate load test results and trail pits and borehole logs.

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