Proceedings of the 7th World Congress on Civil, Structural, and Environmental Engineering (CSEE'22)
~~Lisbon, Portugal~~ Virtual Conference – April 10 – 12, 2022
Paper No. ICGRE 101
DOI: 10.11159/icgre22.101

Features of Engineering Geological Investigations in Regions Underlain by Deposits of Volcanic Origin

Rajeshwar Goodary[1], Viacheslav Iegupov[2], Yeshvin Goodary[3]
[1]Université des Mascareignes
Avenue de la Concorde, Roches Brunes, Rose Hill, Mauritius
rgoodary@udm.ac.mu
[2] Kharkiv National University of Civil Engineering and Architecture
40 Sumska Street, 61002, Kharkiv, Ukraine
slavaegu@gmail.com
[3]McGill University, 845 Sherbrooke St W, Montreal, Quebec H3A 0G4, Canada
yeshvin.goodary@mail.mcgill.ca

Abstract **-** Soils of volcanic origin in the fields of Geotechnical Engineering and Engineering Geology are rarely encountered as compared to other global residual soils. As such, research on the behavior of weathered soils of volcanic origin is almost inexistent and in literature these deposits are treated same as conventional residual soils, complying to existing standards which are applicable in respective developed countries. This paper gives an inventory of volcanic basaltic deposits and the soil testing methodologies practiced on residual materials derived from weathered basalt and agglomerates occurring in Mauritius Republic, which is an island of volcanic origin located in the Indian Ocean, and where currently soil testing is carried out in compliance with the British Standard BS 1377. Some comparisons have been made with existing standards of another regions, particularly those prevailing in the Eastern European Countries. 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 overviewed. Laboratory tests, like consolidation and triaxial tests, performed on undisturbed samples of volcanic residual soils may not always be appropriate for this particular family of soils due to the gravelly nature and degree of disturbance during extraction of the latter. Somehow adapted site investigation methods, namely standard penetration tests and plate load bearing tests yield tangible information which are coherent with prevailing site conditions, deemed reliable for design purposes and may be recommended for weathered soils of volcanic origin encountered on the island and possibly for countries underlain by similar deposits.

Keywords**:** Residual soil, weathered basalt, degree of weathering, Standard Penetration Test, Plate Load Bearing Test.

1. Introduction

Site investigations in Geotechnical Engineering are carried out with an aim to assess the bearing properties of soils and as such their classification, physical and mechanical properties of materials prevailing on a building site are determined. Geotechnical investigation, in its own context, is vast and may start from a visual examination of the formation overlying the delineated area and go as far as non-destructive geophysical testing to direct access of the bearing soil at various depths. Soil testing may be commonly realised by drilling of boreholes, digging of trial pits, extraction of disturbed and undisturbed laboratory and other in-situ testing.

Coring or drilling provides the opportunity to physically remove the soil or rock core samples for testing and inspection [1]. The cores provide the advantage of physically seeing and visually assessing the actual materials, but for certain types of soils, particularly for gravelly ones, the process of boring can disturb the soil conditions and the samples extracted may not represent the actual conditions for formations underlying buildings and supporting structures. Soil or rock samples from various depths of drilling are eventually transported to the laboratory for further investigation [2, 3, 4). 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 is logged and the preliminary classification parameters and consistency of the underlying strata are assessed.

In-situ testing methods include penetration tests such as Standard Penetration Tests (SPT), which consist of direct access to the soil at desired depth, and various Cone Penetration Tests, which are realised by direct penetration of cones [5, 6]. The physical and mechanical properties of the subsurface are measured directly on site, without extraction of cores. On site testing provides the advantages of generating more accurate data related to ground conditions underneath and as well as avoiding the hassle of sending samples out for laboratory testing. Plate load bearing tests [6], sand replacement, percolation tests among others are also often used to assess the actual nature of the prevailing ground conditions. However, the main objective in soil testing campaign is to identify and recommend the right tests for the right purpose considering the actual site geology. The testing methodology may vary with the purpose of the investigation, expected soil parameters, equipment, normative regulations, working pressure underneath foundations and most importantly will have to comply with the family 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 [7].

The purpose of this paper is to provide a brief reflection on the methods of soil investigation applicable to weathered volcanic basalt in the context of Mauritius. Testing methods have been proposed and it has been shown that laboratory investigation carried out by extraction of undisturbed samples from drilling, may not be appropriate for volcanic residual soils because of high percentage of gravels. On the hand, transportation, manipulation prior and during installation in testing equipment may induce a significant degree of disturbance to the original sample and experimental results may not be reliable for design purposes. The gravelly nature of the soil (as an end product of weathered basalt) under investigation and its components may not comply with the ideal requirements for laboratory tests performed on undisturbed soil samples [8].

2. Brief historical geology of the island

The island of Mauritius is entirely of volcanic origin with exception of some small territories of beaches, coral reefs and local alluvial formations [9, 10, 11]. It is the end result of four major volcanic activities as follows:

1. Emergence of the Island;
2. Older Volcanic Series;
3. Intermediate or Early Volcanic Series;
4. Younger volcanic or Late volcanic series.

Period of the Island Emergence

During the late Miocene, 10 – 6.7 million years ago, the first volcanic emissions acted as a rift eruptive fissure. This process is characterized by a marine phreatomagmatic, with large amount of water. The brecciated series or basic series consisted of volcanic products such as tuff, boulders and breccia flows. The island foundation is an accumulation of pillow-lava – lava that has solidified as rounded masses, characteristic of eruption under water. The accumulation of tuffs and breccia products was acted upon by ocean waves which disintegrated the lavas as they rose up. The lava flows separated by volcanic ash layers lie on top of these initial formations. In the period between 7.8 and 6.8 million years ago these massifs were the eroded remnants of a single, large, shield volcano built above sea level by the extrusion of lavas.

The Older Volcanic Series (Old Lavas)

The second phase of activity continued from 6.2 to 5 million years ago and the island acquired a round shield. The volcano that appeared was a huge dome with a diameter of 40 km and a height of about 900 m, with gentle slopes (5 °). In this series of lavas, basalts prevailed the flows of which sometimes reached a thickness of 50 - 100 m. In the volcanic structure, a system of isolated cracks began to develop. The top of the elongated shield crumbled, forming a caldera with a diameter of 24 km. More differentiated lavas were erupted about 5.5 million years ago. The rift weakened and began to show mainly hydrothermal activity.

The Intermediate Series (Early Lavas)

A relatively quiet period lasting for a duration of 1.5 million years, giving rise to intense erosion. But between 3.5 to 1.9 million years ago, the bottom of the caldera and secondary depressions was filled up with volcanic flows of eventual series of eruptions. During that period activities were relatively intense especially in the south western part of the island. At the late Pliocene (about 3.5 million years ago), volcanic activity resumed, giving rise to a younger volcanic series of basalts. These eruptions continued intermittently until recently. Volcanism had a completely different character than before - during the formation of the shield volcano. Eruptions came from relatively small craters. Although younger volcanic lavas are very widespread, their total volume is relatively small compared to older ones. Early lavas were extruded extruded from about 3.5 to 2.0 million years ago.

The Younger Volcanic Series (Late Lavas)

The intermediate phase ended about 1.9 million years ago, followed by a rest period lasting for more than 1.2 million years. The renewed eruptions in the Quaternary period, 700 thousand to 25 thousand years from now, are reported to be the latest volcanic events on the island. Eruptions associated with the reactivation of a secondary rift, came from 26 craters with Hawaiian-type basalt flows of thickness 0.2 to 2 m sometimes reaching 5 m. Empty tunnels are not rare in the lava horizons, very often interconnected.

The very deep weathering of the older series led to the formation of clay materials, which contributed to the filling of cracks in rock masses over the past 6.8 million years.

3. Bearing Material

The logging of soil and rock strata, deposited as results the weathering of volcanic basalt [12, 13] are currently carried out following recommendations of British Standards BS 5930, 1999. Founding materials encountered during description of profiles depends on the degree of weathering of the parent volcanic material and are classified as slightly, moderately, highly and completely weathered basalt or agglomerate [14,15]. The consistency of the disperse soil is furthermore classified as sand, silt and clay or a combination of these components [16]. The consistency is then determined by the principles listed below.

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

The above methodology has been compared with standards prevailing in Ukraine, where the method of classification of soils in engineering and geological surveys for construction purposes is the DSTU B.V.2.1-2-96 in compliance with GOST 25-100-2011 [17, 18, 19] standards which are also applicable to former soviet states, and which were developed by leading design and survey organizations. Recently, a comparison study of the Ukrainian and other interstate (7 countries of former USSR) regulations on soil classification and an analysis of their strengths and weaknesses have been done [20]. Recommendations for inclusion in new regulations, a number of soil characteristics, which are not in the existing standards are given [21] and compared with similar European and American regulations [21, 22]. The physical state (consistency) of cohesive clay soils according to GOST 25-100 (and similar standards of the EU countries) is determined quantitatively in accordance with the name of the soil and the plasticity index.

The classification of the cohesive clay soil, depending on the plasticity index, is determined as follows.

Soil	**Plasticity Index I_P, %**
Sandy loam	$1 \leq I_P \leq 7$
Loam	$7 < I_P \leq 17$
Clay	$I_P > 17$

The plasticity Index, Ip %, is a quantitative characteristic of the plastic properties of the soil and is determined (using Atterberg limits) by the formula: $I_P = w_l - w_P$, where w_l is the liquid limit, % and w_P - plastic limit, % (GOST 5180).

Further classification is done using the consistency value, I_L as shown below:

Soil	**Consistency**
Sandy loam:	
- solid	$I_L < 0$
- plastic	$0 \leq I_L \leq 1$
- fluid	$I_L > 1$
Loams and clays:	
- solid	$I_L < 0$
- semi-solid	$0 \leq I_L \leq 0.25$
- stiff plastic	$0.25 < I_L \leq 0.50$
- soft plastic	$0.50 < I_L \leq 0.75$
- fluid plastic	$0.75 < I_L \leq 1$
- fluid	$I_L > 1$

Index I_L is an indicator of the state (consistency) of clay soils and is determined from $I_L = (w - w_P) / I_P$, where w is the natural moisture content of the soil, %.

Soils, hosting foundations, in the present case study, 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 [7]. A typical particle size distribution curve for the type of soil under study is shown in Figure 1.

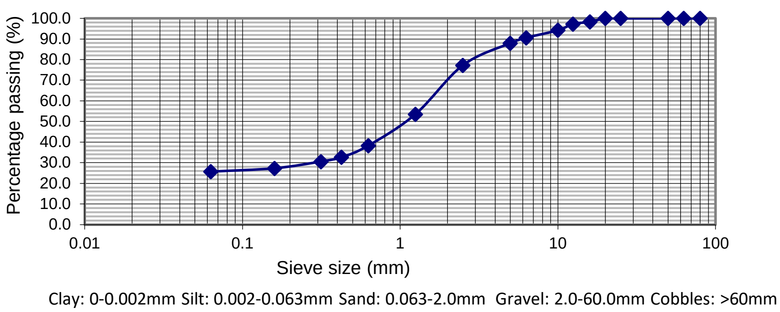

Figure 1: Typical granulometric curve of a completely weathered basalt.

From figure 1, it can be seen that for a typical soil encountered, and from the various components present, the material may be classified as a gravelly silt/sand [3]. However, the sample contains 28 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 plastic segment shows depth at which Standard Penetration tests were carried out.

Figure 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 0.40 m in Figure 2. It is obvious that the presence of gravels makes it difficult to extract undisturbed cylindrical samples for further laboratory investigation [15]. 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, mechanical tests namely: one dimensional consolidation oedometer test, direct/triaxial shear tests, permeability, unconsolidated unconfined tests are carried out on undisturbed samples and classification and compaction tests are performed on bulk sample. 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.

4. Testing

A comprehensive soil investigation cost is relatively low as compared to the budget allocated for a whole project. The absence of reliable geotechnical data may have significant incidence on a project, leading to delays and extra funding during construction. Consequently, a proper soil investigation campaign prior to start of construction is mandatory.

The importance of obtaining adequate and reliable information and design mechanical data relevant to the subsurface conditions at an 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. Soil investigation campaign aims at obtaining the following parameters [23, 24]: logging and consistency of the soil profile, in situ tests – most commonly plate load bearing and standard penetration tests, drained/undrained shear strengths and consolidation tests from undisturbed samples, location of ground water level from piezometers. Index and compaction properties of the encountered strata are obtained from laboratory testing on bulk samples. Physical and index properties of weathered volcanic basalt are generally found to be coherent with conventional soils as these are normally performed on samples with specified particle size (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 often not coherent with information gathered during site investigation.

As shown in a series of field and laboratory studies performed on weathered basalts, laboratory tests, particularly, one dimensional consolidation test, may not give reliable results on the mechanical properties of these soils [25]. The reason for this might be the presence of induced voids inside the consolidation cell. These voids are those visible on the surface between the wall of the sample and the metal ring, cracks and also internal artificial voids introduced during sampling and manipulation. At the same time, the sample should fit tightly in the ring, which is almost impossible to ensure due to the presence of gravels in the soil. It is clear that the consolidation parameters obtained from such samples may not reflect the real prevailing conditions. Obviously, such samples may also not reveal convincing results in other experiments, such as shear tests and triaxial compression tests. Consequently, the use of in-situ testing is deemed reliable for weathered volcanic soils.

4.1 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 [5, 26]. 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 (BS 1377, Part 9) in order to be coherent with the norms for which the plate load testing equipment has been designed.

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 the present case study, settlement Sp (mm) of the plate with diameter Bp = 450 mm, corresponding to a settlement of 25 mm of the above-mentioned base is deduced. As such Sp = (S x Bp) /B = (25 x 0.399)/2 = 4.9875 mm, a value which has been achieved at mean pressure value of 470 kPa.

This allows to conclude that for a usual allowable settlement of 25 mm, the value of the allowable bearing capacity is in the range of 300 kPa (assuming a factor of safety of between 1.5 and 2), a value which corresponds to a rather very stiff soil consistency and which is in agreement with site conditions as per available logs of borehole cores and trial pits.

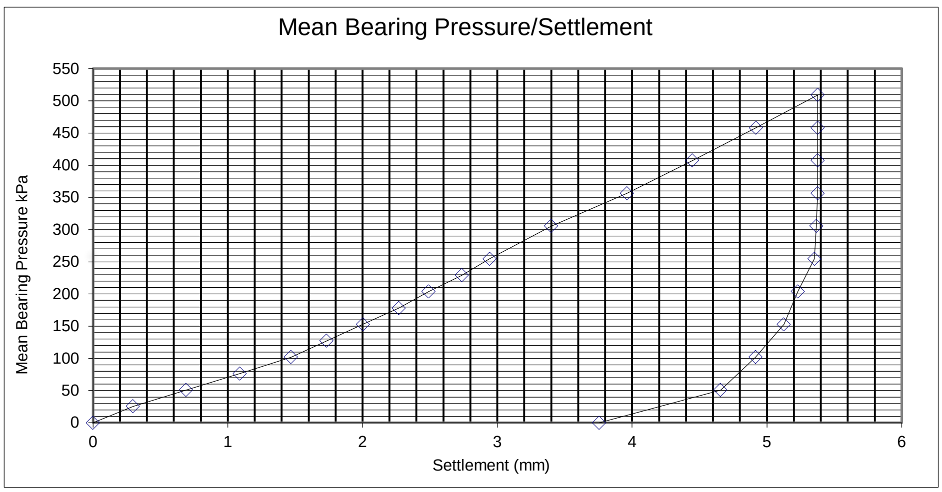

Figure 3: Typical Plate load bearing test result in weathered basalt.

<u>*Standard Penetration Test (SPT)*</u>

For the above site, Standard Penetration Tests (SPT) were conducted at various depths as per BS 1377, both in cohesive and granular/gravelly soils [26]. 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 1 below.

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.

Classification tests: Low cost laboratory tests on bulk samples to determine soil indices I_L and I_P, mentioned in paragraph 3 above, were carried out to control the validity of the in-situ testing results using the GOST 25-100 standard. The purpose of the laboratory tests was to check the coherence of the above in-situ results with an independent standard, other than the one used on the island.

Classification tests performed in laboratory, on bulk samples, revealed natural moisture content w = 34%, w_l=48% and w_p = 43.6%.

From the above relationships $I_L < 0$ and I_P = 4.4% which allows the encountered soil to be classified as solid sandy loam which is also in agreement with figures visible in the particle distribution curve in Fig 1. These values are coherent with results of in-situ testing.

Table 1: 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
1.15	24	150 - 300	75 - 150	Very stiff
2.30	22	150 - 300	75 - 150	Very stiff
3.50	29	150 - 300	75 - 150	Very stiff
5.15	22	150 - 300	75 - 150	Very stiff

5. Conclusions

This study concerns the methodology of soil testing, applicable to tropical soils of volcanic origin at various stages of weathering - from strong to completely weathered basalt and agglomerates. Based on the analysis of experimental results, the following conclusions can be drawn:

1. The geology and genetic origin of the site in the case study shows that it is located on an island of volcanic origin, formed as a result of three consecutive series of volcanic eruptions, leaving deposits of older, intermediate and younger volcanic series at various stages of weathering ranging from strong to completely weathered (laterite) basalt, each of which has its own characteristic geotechnical properties.

2. Weathered basalt of volcanic origin requires a special approach in the assessment of their geotechnical parameters, because they may not comply with traditional test methodology, especially laboratory tests performed on undisturbed samples extruded from weathered volcanic soils often give unreliable results for reasons stipulated in paragraph 4.

3. It is found that the plate load bearing test (PLT) is suitable for the type of soil under investigation, and a case study is discussed. Results confirm the consistency to be coherent with the actual prevailing conditions on the site. For this case study, the value of the allowable bearing capacity is in the range of 300 kPa, corresponding to a very rigid soil texture, which is in agreement with actual conditions and coherent with the drill cores and trial pits logs.

4. Results of standard penetration tests (SPT) are in good correlation with those obtained from the plate load bearing tests performed. SPT results show that the soil is of very rigid consistency, and is coherent with the PLT results. The consistency obtained from the above in-situ testing was again confirmed by control laboratory classification tests using the soil index properties, I_P and I_L, in compliance with standards prevailing in Ukraine.

5. It is proposed that field testing should be privileged for engineering surveys of sites underlain by weathered basalt, as standard laboratory geotechnical tests performed on undisturbed samples of weathered volcanic soils may not yield conclusive results due to their gravelly nature.

6. Laboratory testing on undisturbed samples may be undertaken for individual cases where it is possible to take sufficient number of undisturbed samples without any fault, and such locations are deemed limited.

References

[1] British Standards Institution BS 5930. 1999. Code of practice for site investigations, 190 p.

[2] British Standards Institution BS1377-9. 1990. Methods of Tests for Soils for Civil Engineering Purposes. Part 9. In-situ tests.

[3] British Standards Institution BS1377-2. 1990. Methods of Tests for Soils for Civil Engineering Purposes. Part 2. Classification tests.

[4] British Standards Institution BS1377-5. 1990. Methods of Tests for Soils for Civil Engineering Purposes. Part 5. Compressibility, permeability and durability tests.

[5] Mohammed S., 2013. Evaluation of allowable bearing capacity of soil by plate bearing test. Basrah Journal of Engineering Science, p101 – 111.

[6] Byrne G., Berry A. D., 2008. A guide to Geotechnical Engineering in Southern Africa, 4th Edition, Franki.

[7] Fookes P. G., 1997. Tropical Residual Soils. A Geological Society engineering group working party revised report. London. The Geological Society.
[8] Fookes P. G., Dearclan W.R., Franklin I.A., 1971. Some engineering aspects of rock weathering. Quarterly Journal of engineering Geology 4. P 139 – 185.
[9] Giorgi L. and Borchiellini S., 1999, Les aquifères de l'Ile Maurice (Map).
[10] Carte Géologique et Hydrogéologique, 1996. République de Maurice.
[11] Proag, V. (1995), The geology and water resources of Mauritius, analysis, Mahatma Gandhi Institute
[12] Goodary R, Lecomte-Nana G. L, Petit C., Smith D., 2012. Investigation of the strength development in cement - stabilised soils of volcanic origin. Construction and Building Materials 2012; 28: 592-598.
[13] Goodary R, Horpibulsuk S., Lecomte-Nana G. L., Beeharry R., Ramlogun R., 2014. Effect of Fly Ash on Strength and Compressibility of Dark Magnesium Clay. Advances in Civil Engineering for Sustainable Development. 27-29 Aug 2014.
[14] Jenny H., 1994. Factors of soil formation. Dover publications.
[15] Jennings J. E. Brink A. B., Williams A.A., 1973. Revised guide to soil profiling for civil engineering purposes in southern Africa. South African Inst. Civil Eng. P 13 – 15.
[16] Little A. L., 1969. The engineering classification of residual soils. Proc. Seventh International Conference on soil mechanics and foundation engineering. Mexico City. Vol. 1. p 1 – 10.
[17] DSTU B.V.2.1-2-96. Soils. Classification. - Kyiv: State Committee of Ukraine for Urban Development and Architecture, 1997. - 32 p.
[18] Soil science. Textbook. / Ed. Acad. E. M. Sergeev. - Moscow: 1983. – 392 p.
[19] Interstate standard GOST 25100-2011 "Soils. Classification". - Moscow: Standard form, 2013. -- 38 p.
[20] Iegupov V. Yu. Recommendations for improving the current state standard of Ukraine (DSTU B.V. 2. 1-2-96) "Soils. Classification" taking into account the latest interstate standards / V. Yu. Iegupov, I.V. Khrapatova // Collection of scientific works [Y. Kondratyuk Poltava National Technical University]. Series: Industry Engineering, Construction. - 2015. ¬ Issue 2, pp. 112-117.
[21] ASTM D 2487-2000. Standard Test Method for Classification of Soils for Engineering Purposes. https://www.astm.org/DATABASE.CART/HISTORICAL/D2487-00.htm.
[22] ISO 14688-2:2004). Geotechnical investigation and testing – Identification and classification of soil – Part 2: Classification principles and quantification of descriptive characteristics. https://www.iso.org/obp/ui/#iso:std:iso:14688:-2:ed-1:v1:en.
[23] Iegupov V., Goodary R., Goodary Y. Georisks and Sustainability Resource of the Mascarene Islands Territories to External Impacts. Proceedings of the 6 th International Conference On Civil Structural and Transportation Engineering (ICCSTE'21) Niagara Falls, Canada Virtual Conference – May 17-19, 2021. DOI: 10.11159/iccste21.151/ISBN: 978-1-927877-84-5 | ISSN: 2369-3002.
[24] Shootenko, L.N. and Goodary, R. 1988. A Statistical Analysis of Physical and Mechanical Properties of Lateritic Soils. Quality Amelioration in Urban Construction, Kharkov.
[25] Goodary R. Soil Testing in Weathered Volcanic Basalt**.** Proceedings:Ninth All-Ukrainian scientific-technical conference "Soil mechanics, geotechnics and foundation engineering":October 3 – 7, 2016: 312-325. Dnipro, Ukraine.
[26] Meyerhof G. G., -1956. Penetration tests and bearing capacity of cohesionless soils. Fourth International Conference on Soil Mechanics and Foundation Engg. ASCE, Volume 82, proc. Paper 866.