Comparison of results from tests on sandy materials from mine tailing dams: permeability feat. grain size

Jovan Br. Papić
Ss. Cyril and Methodius University, Faculty of Civil Engineering, Skopje, R. North Macedonia, papic@gf.ukim.edu.mk

Saška Velkovska
Granit AD, Skopje, R. North Macedonia, velkovskasaska@gmail.com

ABSTRACT: The monitoring and control of mine tailings in the Republic of North Macedonia is regularly organized on an annual level and covers many aspects: geotechnical and surveying field observations, field explorations, sampling materials, laboratory tests etc. There are several active and closed tailing dams in the country, among which few are above populated area and in seismic prone area, due to which are under constant monitoring. Among the rest, for them it is obligatory to perform field and laboratory tests in order to determine the physical and mechanical properties of the tailing sand. In this process, many typical geotehnical tests are conducted, which gives possibility to compare the achieved results. As a part of an extended research, satisfactory amount of such data was obtained, giving a base for combining the results between them. Thus, they were applied for finding the types and range of application of the relations between results from field and laboratory tests available in literature for natural soils. Moreover, they were used as opportunity for establishing new ones, not only between laboratory and field tests, but also including between different laboratory tests. The paper aims to present some of them, particularly the ones for the permeability.

Keywords: tailing dams; monitoring; geotechnical tests; relations; permeability

1. Introduction

Tailing dams are complex structures used for direct discharges and collection of raw metal mineral material pulp. These facilities are built for the purpose of water capture, capture of reagents used for degradation of ore minerals and some of the ore residues that remain in the flotation processing of minerals. As such, they should always – both during design, exploitation and after closing – be treated with great seriousness because the world experience has shown that the consequences of inadequate design and treatment can be catastrophic. Due to this, beside being instrumented and monitored, their material properties should be regularly checked by conducting field and laboratory tests.

There are several tailing dams in the Rep. of North Macedonia (RNM) with tremendous heights, positioned above populated area and in seismic prone area, thus asking for obligatory monitoring and control. Practicing of field and laboratory tests is a must, but prefers mutual relation, both among field and laboratory tests, as well as either among field or among laboratory tests separately, offering advances as reducing costs, speeding up the process and keeping the quality. Many directions are given in literature, but mostly for natural soils, particular materials or locations. However, absence of such co-relations for sand from tailing dams is notable. Having in mind the importance of these dams, as well as their environmental and human impact, large and complex research was realized on tailing dams in the country, in order to recommend some of the relations. The paper gives short overview of these findings, and focuses on establishing co-relations between common geotechnical laboratory tests: grain size distribution and permeability.

2. Methodology of investigation

The monitoring and control of active mine tailings in RNM is regularly organized on annual level and covers many aspects: surveying observations, field explorations, laboratory tests etc. In this process, the Chair of Geotechnics at the Faculty of Civil Engineering in Skopje is often in charge for testing materials for determining their physical and mechanical properties. In the last period, large geotechnical programs were realized at active tailing dams. Beside covering various tests being made on tailings sand to prove its properties needed for further numerical analyses, they also served the opportunity the data obtained with site investigations to be co-related with the one obtained via laboratory tests on the same material. Namely, finding the correlation through which the site investigation results can be presented as laboratory results or through other field tests perspective has always been challenging [1], while efforts are sometimes done in relating the different laboratory tests between them. In this study, a digest on the work in this area has been made, through correlation of results from standard penetration test (SPT), cone penetration test (CPT) and from laboratory tests such as sieve and water permeability on properly taken samples.

In order to complete the site works, a drilling of four boreholes with total length of 184 m was performed on a tailing dam. SPT was performed all along their depth, while CPT was realized at particular depths, except at fifth location where it was 34 m long (Fig. 1). During the SPT, samples were taken in a proper manner and transported to the geotechnical laboratory for testings. Their main purpose was to classify them and to assist in determining its physical and mechanical properties.

3. Overview of conducted laboratory tests

The samples were delivered in the laboratory for geotechnics, where many control tests were performed: sieving, oedometer, direct shear, triaxial, water permeability etc. For part of them, they were prepared and embedded with the unit weight calculated from the field tests.

In the paper, only the results from the grain size distribution and permeability tests will be commented, while interested reader can find more for the rest in [2] and [3].

Namely, having in mind the size of the grains, their distribution was determined with sieving, while respecting the size of the facilities and performed site investigations, more than 130 samples were tested. Results from them announce that sand fraction dominates with about 90 %, after what there is silt portion of 10 %, while locally gravel components can be met. However, on certain very large depths there are quantities of silt up to 20-25%, on which locations ground water exists. It was notable that on depths where there is flow water, the presence of silt is always expressed with two digits in the grain size distribution: this can be commented as part of certain sufosion.

For the purpose of determining the vertical permeability of these materials, samples were placed in cylinders with diameter D=103,6 mm and height H=118,8 mm. Since it was dealed with kind of sands, they were exposed on constant pressures of 100-200 kPa, depending upon the depth where the sample was taken. As expected, with the permeability test on these materials, high values of the water permeability coefficient were obtained, since the values were in the range $k=2*10^{-5}÷1,02*10^{-3}$ m/s. However, the low values are very rare, thus the average permeability coefficient is $3,2*10^{-4}$ m/s. More details about their relation with the relative density and porosity are given in [3].

4. Comparison of site and laboratory results

4.1. General

In order to complete the task, it was needed to ascertain the existing co-relations in form of equations, charts and tables in the literature, where results from field and laboratory tests would be overlaid and will show their effectiveness. Thus, the data usually gained in laboratory conditions could be obtained with minimal performance of field investigations, i.e. rational utilization of tests will apply. This would save time and reduce the costs, while the results would be within the required accuracy.

So, with the data from SPT, information on mechanical properties of the material (density, angle of friction etc.) are achieved, following instructions given in literature, e.g. [1] and [4]. The positive element in this test is that the obtained material is used for further laboratory investigations in order to get the same and other properties. Information on the mechanical properties are also got with CPT, but usually there are no samples [5].

4.2. Defining soil type

One of the main purposes of the CPT is to define the strata, although further quality obtaining of soils' mechanical properties is also possible. According to the procedure, during the test, values of cone resistance q_t and shaft friction f_s are measured. Usually, the cone resistance q_t is greater in sands and smaller in clays, while the coefficient of friction ($R_f=f_s/q_t$) is low in sands and high in clays [4].

Typical results from CPT performed in the tailing dam is shown in Fig. 1 (test at fifth location), while below it, Fig. 2 presents typical grain size distribution curve of materials found in the monitored tailing dam.

In interpreting the results from the CPT, recommendations given by [5-6] were followed. Thus, for determining the type of material, both normalised and non-normalised charts are used: they are shown in Fig. 3. The results from CPT in this tailing sand, applied on these charts, fit very well with results from the appropriate laboratory grain size distribution tests: zones 5÷6, i.e. sand to silty sand. This way, it proves that data from these diagrams related to material type in tailing dam can be obtained with great accuracy.

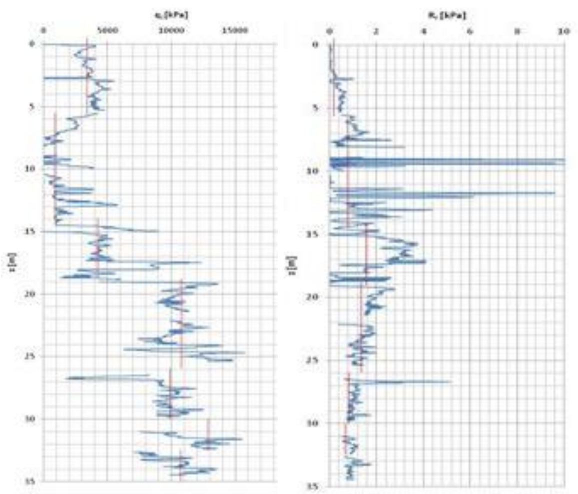

Figure 1. Typical results for q_c and R_f from CPT in the tailing dam

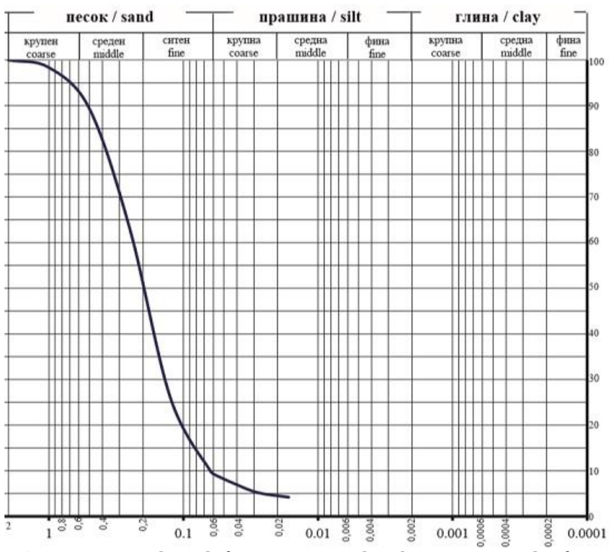

Figure 2. Typical result from grain size distribution on samples from the tailing dam

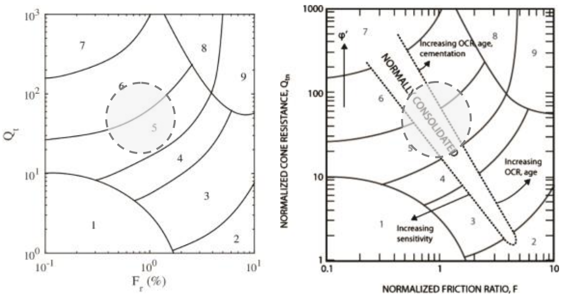

Figure 3. Non-normalized (left) and normalized (right) soil behavior type chart [6]: discontinued line is for the zone of tested material

4.3. Correlations for determination of hydraulic conductivity

An approximate estimate of soil hydraulic conductivity or water permeability, *k*, can be made from the soil type assessment using the normalized and non-normalized tables for prognozing the type of soil materials [6]. They are textual representation of the charts described and successfully used above.

Below is Table 1 which gives their extracts based on the results from the conducted CPT at the analyzed tailing dam. Although they are approximate, these can serve as a very good guidance to the range in which the permeability values of the tested material can be. So, in this particular case, the permeability obtained via laboratory tests was $k=2x10^{-5}÷1x10^{-3}$ m/s, which is almost the same as proposed in Table 1 for sands. This evidence gives support to its application at sand materials from tailing dams.

Table 1 Estimated soil permeability based on CPT/SPT chart by [6]

Type	Material description	Permeability k (m/s)	Soil Behavior Type index Ic	$[(q_c/p_a)]/N_{60}$
5	Sand mixture	$1x10^{-7} ÷ 1x10^{-5}$	2.05 < Ic < 2.60	3.0
6	Sand	$1x10^{-5} ÷ 1x10^{-3}$	1.31 < Ic < 2.05	5.0
7	Dense sand to gravelly sand	$1x10^{-3} ÷ 1$	Ic < 1.31	6.0

5. Comparison of results from laboratory tests

Furthermore, an attempt was made to corelate the permeability coefficient with certain diameters of the particles in the grain distribution curve. Namely, there are several available and in practice often used expressions for such calculation [1], but most of them are for natural soils, which is valid also for the above exposed as well.

In order to contribute to their extension, simplification and application for tailing sands, an approach with using already existing data from the grain size distribution was applied. Namely, the aim was to use typical data already present in other calculations and obtained through other common classification tests. Such examples are those implemented in determination of coeficient of uniformity C_u or curvature C_z, necessary for determination of the type of the coarse grained materials. As it is known, they consume values of diameters of particles present in amount of 10 %, 30 % and 60 % in the material, obtained during the sieve test and drawing the grain size distribution curve. Only one single additional value was added to these, i.e. the one for 90 %. They are arranged according to the given in Eq. (1):

$$k = \frac{d_{10}}{d_{30}} \frac{d_{60}}{d_{90}} \frac{1}{500 \div 1000} \qquad (1)$$

where *k* – permeability coefficient [m/s], while d_{nn} – diameter of particle present in the tested material with “nn” percents [mm].

The comparison between values obtained from laboratory permeability tests on sand from the tailing dam and from calculations with Eq. (1) is shown in detail in Table 2. As it could be seen, in vast majority of the 20 presented compares, which is in accordance with the number of performed laboratory tests for determination of permeability of the tailing sand, there is very good agreement between tested and calculated permeability coefficient. Evenmore, in certain ocassions the Eq. (1) gives results exactly the same as determined via laboratory tests. The exclusions are registered at only three samples where either very high or very low coefficients were found: the tests for these samples were not repeated.

Having in mind that these are initial analyses and that the research is performed in stages, in order to confirm these findings it is planned to continue with the tests and checks. It will use both sand from tailing dam as well as modelled samples, where some fractions will be removed. This will lead to increasing of the data base and would allow to determine the validity of the expression and its application domain, acceptability of values 500 or 1000, maybe even in function of quantity of material (silt, sand), depth, testing pressure etc.

However, at the moment, it can be concluded that the presented relation gives firm relation between particle diameters and permeability coeffient for this kind of materials and, as such, can be used for preliminary estimations of sand‘s permeability at, at least, this tailing dam.

Table 2 Comparison of permeability coefficient k obtained in the laboratory and permeability coefficient k calculated according to Eq. (1)

Borehole	Depth [m]	Silt [%]	Sand [%]	d_{10} [mm]	d_{30} [mm]	d_{60} [mm]	d_{90} [mm]	Tested k [m/s]	Calculated k [m/s] with Eq. (1)
D – 1	1-2	25,5	73,6	0.016	0.091	0.207	0.42	0.00012	0.00009 ÷ 0.00017
	6-7	6,4	93,3	0.105	0.182	0.279	0.48	0.00017	0.00033 ÷ 0.00067
	12-13	9,1	90,9	0.066	0.131	0.237	0.51	0.00010	0.00023 ÷ 0.00005
	17-18	19,3	80,6	0.025	0.093	0.185	0.34	0.00003	0.00015 ÷ 0.00029
	19-20	7,3	92,7	0.072	0.144	0.239	0.41	0.00023	0.00029 ÷ 0.00058

D – 2	8-9	11,6	88,2	0.057	0.147	0.253	0.49	0.00016	0.0002 ÷ 0.0004
	15-16	10,4	89,6	0.062	0.136	0.233	0.44	0.00018	0.00024 ÷ 0.00048
	17-18	6,2	93,8	0.074	0.131	0.219	0.40	0.00062	0.00031 ÷ 0.00062
	19-20	5,3	94,7	0.081	0.151	0.239	0.41	0.00058	0.00031 ÷ 0.00063
	25-26	3,6	96,4	0.087	0.150	0.226	0.399	0.00033	0.00033 ÷ 0.00066
D – 3	2-3	11,3	88,7	0.051	0.111	0.199	0.37	0.00023	0.00025 ÷ 0.00049
	17-18	9,7	90,1	0.064	0.121	0.217	0.41	0.00023	0.00028 ÷ 0.00056
	19-20	9,9	90,1	0.063	0.137	0.215	0.38	0.00016	0.00026 ÷ 0.00052
	24-25	4,1	95,9	0.086	0.151	0.232	0.41	0.00102	0.00032 ÷ 0.00064
	25-26	4,1	94,6	0.086	0.153	0.234	0.41	0.00083	0.00032 ÷ 0.00064
D – 4	2-3	7,2	92,8	0.072	0.139	0.271	0.49	0.00010	0.00029 ÷0.00057
	3-4	9,5	90,5	0.065	0.141	0.256	0.48	0.00076	0.00025 ÷ 0.00049
	4-5	7,1	92,9	0.072	0.135	0.230	0.44	0.00047	0.00028 ÷ 0.00056
	5-6	9,7	90,3	0.064	0.139	0.262	0.47	0.00011	0.00026 ÷ 0.00051
	7-8	9,5	90,5	0.064	0.094	0.178	0.44	0.00002	0.00028 ÷ 0.00055

6. Conclusions

The purpose of this paper was to give review of the existing correlations between field, particularly SPT and CPT, and laboratory tests from the tailing sand point of view, more specifically – relating the permeability. Namely, there are many tables, charts and expressions in the literature, but mainly for natural soils: with this research it was found that some of them are fitting to be used for tailing sands.

Moreover, an attempt was made to establish corelations between common laboratory tests, e.g. sieve and permeability. So, for the case of tested tailing sand, it was concluded that:

- charts and tables proposed by Robertson [5-6] can be used for defining the type of material and its permeability from CPT;
- the presented Eq. (1) for corelating diameters and permeability [3] gives firm relation.

In future, during next monitoring and control study on tailing dams of this type, it is suggested to take into consideration and re-examine the above given recommendations, both with field and laboratory tests, including also modelled samples, in order to confirm or improve their functionality. Moreover, further researches can also focus on the validity domain of the presented expression, check the application of either 500 or 1000, taking into consideration the quantity of participating fractions in the material (silt, sand), depth, testing pressure etc. These will all surely be beneficial both for researchers, designers and investors.

7. Acknowledgements

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8. References

[1] Das, B.M. "Fundamentals of Geotechnical Engineering", 3rd Edition, 2007.

[2] Velkovska S., Papic J. Br., "Applicability of relations between results from field and laboratory tests on sands from tailing dams", XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, 1-6.09.2019.

[3] Velkovska S., "Корелации помеѓу резултати од теренски и лабораториски геотехнички испитувања на хидројаловишен песок" ("Corelations between results from field and laboratory geotechnical tests on sands from tailing dams"), master thesis, Ss. Cyril and Methodius University, Faculty of Civil Engineering – Skopje, R. North Macedonia, 2019. (in Macedonian)

[4] Monnet, J., "In Situ Tests in Geotechnical Engineering", 2015.

[5] Robertson, P.K., Cabal, K.L. "Guide to Cone Penetration Testing for Geotechnical Engineering", 6th Edition, 2014.

[6] Robertson, P.K. "Evaluation of Flow Liquefaction and Liquefied Strength Using the Cone Penetration Test, Journal of Geotechnical and Geoenvironmental Engineering", ASCE, June 2010.