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ANALYSIS OF RISK FACTORS IN THE MEASUREMENT OF PHYSICAL PROPERTIES OF SOILS

Abstract. The determination of the physical properties of soil is the basis for the successful design and construction of engineering projects. These properties directly influence the behaviour of the soil under various loads, which determines the stability and safety of building structures. To date, the main challenges in this field are the high degree of uncertainty and the risk of errors in laboratory testing. This study presents an experimental study of the physical properties of soil and provides a discussion on the probabilities of error and inaccuracy risks for each of the methods presented. The risk analysis approach was used for the evaluation. The approach focused on quantifying the errors in the measurements and the soil test method. The results showed that all methods of testing the physical properties of soil require a high degree of accuracy and adherence to standards, but the soil compaction test is a more complex process that requires special care and rigour in the procedures.

Keywords: soil test, risk, analyses, physical properties, accuracy.

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Introduction. Determining the particle size distribution of soil is an important step in geotechnical investigations that helps to understand the characteristics of the soil [1]. Particle size distribution shows the size distribution of soil particles and helps to determine its basic mechanical and physical properties. Soil grains that are similar in size and properties are grouped into groups called particle size fractions.

Various methods of investigation are used today [2-3]. These include sieve, hydrometric, liquid and soil plasticity tests, which are the most common and effective. Each of these methods helps to determine the particle size distribution as well as other key characteristics such as flowability, plasticity and compaction ability.

Thus, in [4] conducted studies on the evaluation of present and past methods of pedotransfer functions PTF and soil water retention curve based on soil texture, bulk density, porosity and other related factors. In addition, the performance and limitations of various general semi-physical models proposed and developed by Arya and Paris, Haverkamp and Parlange, the Modified Kovács model by Aubertin et al., Chang and Cheng, the Modified Kovács model by Arya and Paris, Haverkamp and Parlange are evaluated. In a study by authors [5] presented a new approach and developed a standalone machine learning based GUI application for predicting hydraulic conductivity (K), maximum dry density (MDD) and optimum moisture content (OMC) of lateritic soils based on parameters including specific gravity, liquid limit, plasticity index, linear shrinkage and fines content.

The compacted dry density of gravelly soils containing particles that are too large for ordinary laboratory compaction tests is usually estimated by measuring the dry density of the base sample obtained by removing over-sized particles then correcting the measured value by the Walker-Holtz Equation. Authors were proposed efficient compaction method for gravelly soils containing oversized particles that controls the degree of saturation and the compaction energy [6].

In other works, the wet-sieving method was used for separation water-stable aggregates. Five soils (black soil, light chernozem soil, fluvo-aquic soil, sierozem soil, and loess soil) were used with different calcium carbonate ($CaCO_3$) contents as the target materials. The results showed that Excess Ca^{2+} can be converted into various forms of Ca by occupying SOC binding sites on the surface of soil particles with silt and clay particles [7].

Thus, the diversity of studies is related to the need for a thorough approach to determining the granulometric composition of soil. Risk management in soil particle size distribution testing is an important part of ensuring the accuracy and reliability of results, as various errors and uncertainties can occur during the testing process. Risks associated with method selection, equipment, analytical conditions, and sample preparation can have a significant impact on the final results. For example, errors in hydrometer calibration or loss of material during sieve washing can lead to significant errors in determining soil composition, which in turn can affect design and construction decisions.

The impact of risks in the context of particle size analysis is the possible misrepresentation of soil characteristics, which is critical for assessments of soil strength, permeability, and other geotechnical properties. Even small deviations can lead to incorrect conclusions about soil quality and, as a consequence, to erroneous design decisions. This study will present the results of the investigation of soil properties and the quality control features of each process.

Materials and methods. The investigations were conducted in the “ENU-Lab” laboratory of L.N. Gumilyov Eurasian National University, Republic of Kazakhstan. The experiment’s technical process consisted of the following main procedures for soil:

- Sieve analysis;
- Sedimentation analysis (hydrometer test);
- Compaction test analysis;
- Atterberg limits analysis (Liquid and plastic limit tests);

Determination of particle size distribution of soils by sedimentation analysis method. During the study, a soil sample was filled into a 1000 cm^3 container and mixed with distilled water. The water suspension was shaken with a stirrer for 1 min to a full depth until the sediment was completely agitated from the bottom of the cylinder, no splashing or foaming of the suspension was allowed (Fig. 1).

a) b)

Fig. 1. Preparation of the mixture: a) soil during mixing; b) soil after mixing

Hydrogen peroxide 6% was used to separate the soil particles into their individual components (Fig. 2). An hydrometer placed in this liquid allowed measuring the density of the suspension, which in turn allows calculating the content of fine particles in the sample [8].

a) b)

Fig. 2. Test process: a) soil before the hydrometer measurement; b) during the measurement process with hydrometer

After that, the hydrometer value was measured at 1 min, 2 min, 5 min, 15 min, 30 min, 60 min, 240 min, 1440 min from the end of shaking the suspension for a day.

The temperature of the suspension was controlled by measuring the temperature with an error of up to 0.5°C during the first 5 min (before the beginning of the experiment) and then after each measurement of the suspension density with hydrometer.

Determination of particle size distribution (grain size distribution) of soil sample by sieve method (wet method). The wet method for determining the grain size distribution is based on the use of water to separate soil particles by their size. The main purpose of the wet method is the separation of soil particles with the help of water, which contributes to the effective separation of larger particles from smaller ones [9].

The soil sample in the flask was transferred to pre-mounted sieves with mesh diameters of 5 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.16 mm, 0.063 mm. The sieves were placed them from the sump in order of increasing mesh size. Water gradually washed the soil through the sieves, separating it into fractions based on particle size. Particles of larger fractions were retained on the upper sieves, while smaller particles passed through the sieves and settled (Fig. 3).


a)

b)

c)

d)

Fig. 3. Soil fractions remaining on the sieves after washing: a) size 0.5 mm, b) size 0.25 mm, c) size 0.16 mm, d) size 0.063 mm.

Soil fractions retained on the sieves were transferred to bins, weighed and then dried in an oven at (105±2)°C. In contrast to the dry method, the wet method eliminates errors that can occur when particles aggregate, e.g. clay or dust particles tend to stick together as a result of interaction with water, preventing accurate size determination. The wet method allows for a more accurate separation of particles into fractions.

Determination of soil moisture content by the constant mass drying method. The drying to constant mass method is based on evaporating moisture from the soil at a temperature of about 105-110°C and measuring the change in mass of the sample before and after drying. A soil sample for moisture determination was collected with a mass of 15-30 g, then placed in a pre-dried, weighed, and numbered bunker. When taking a sample from the disturbed sample, the soil was thoroughly mixed to ensure that the moisture was distributed evenly throughout the sample. The soil samples in the bax were weighed and the baxes were placed in a heated desiccator. The soil was dried overnight to constant weight at (105±2)°C.

From the desiccator, the soil was cooled to room temperature in an desiccator to avoid absorption of moisture from the air. After cooling, the mass of the sample was measured again on an analytical balance to obtain its dry mass.

Soil moisture content was determined by the equation:

$$w = \frac{m_1 - m_0}{m_0 - m} \times 100\% \quad (1)$$

where: m_1 – mass of wet soil with the brix, g; m_0 – mass of dried soil with the brix, g; m– mass of empty brix, g.

Method for determining the soil compaction factor. The method for determining the soil compaction factor aims to evaluate the load bearing capacity of the soil and to determine the optimum conditions for construction. The compaction ratio is an indication of how effectively the soil can be compacted to improve its strength and stability. This indicator is necessary to develop recommendations for the choice of foundation type as well as to predict the behaviour of the soil under load.

A 3 kg soil sample was placed in a cylindrical mould with a volume of 947.39 cm^2, which was divided into several layers. Distilled water was added to the soil in an amount of 3% of the total mass of the soil under study. Each layer of soil was subjected to compaction using a falling weight in 3 series of 25 blows. After the compacted soil sample was weighed and the density at water saturation of 3% of the total mass of the soil was calculated (Fig. 4).

Fig. 4. Soil compaction test

The density of wet soil was determined by the equation:

$$\rho_t = \frac{m_2 - m_1}{V} \quad (2)$$

where m_1 – mass of wet sample, g; V – sample volume,cm^3.

The density of dry soil is determined by the equation:

$$\rho_d = \frac{p_t}{1 + \frac{W}{100}} \quad (3)$$

where: p_t– moist soil density, g/cm^3; W – humidity, %.

Determination of the lower plasticity limit - soil moisture at the rolling boundary. The lower plasticity limit is understood as the minimum water content in the soil at which it retains plastic properties, i.e. the ability to deform without fracture when an external force is applied. This limit characterises the degree of moisture content at which the soil begins to lose its ability to plastic deformation and becomes brittle. During the research a sample of air-dry soil weighing 100 g was sifted through a sieve with a 0.5 mm hole and ground in a mortar with a pestle with a rubber tip (Fig. 5). The soil sample was moistened with distilled water to a thick dough. The rolling boundary was determined by rolling the soil dough into the wire by hand. It is considered that the rolling limit is reached when the soil flagellum with a diameter of 3 mm starts to break up into pieces of 3-10 mm in length.

a) b)

Fig. 5 The process of rolling the soil into flagella: a) at the rolling boundary; b) after drying in an oven

The ground dough was rolled on glass until fine cracks appeared in the 3 mm diameter bundle and it began to disintegrate into individual pieces. The pieces were then collected in bins to be weighed and dried in an oven for 24 hours and then re-weighed again.

Soil moisture content at the rolling boundary Wp was determined by the equation:

$$W = \frac{m_1 - m_0}{m_0 - m} \cdot 100\%, \quad (4)$$

where m – mass of an empty bucket with a lid; m_1 – mass of the bucket with wet soil at the rolling boundary; m_0 – mass of the bunker with dried soil.

The probability and impact-based risk assessment method was used to assess the risks associated with the soil particle size distribution tests conducted. This method allowed to systematise and quantify the risks that may arise during testing. It is based on two main criteria:

1. Likelihood is the probability that a particular risk or error could occur during a trial. It is scored on a scale of 0 to 1, where 0 means no probability at all and 1 means that the event is guaranteed to occur.
2. Impact is the extent to which risks affect the final outcome of the trial, i.e., the accuracy and validity of the data. Impact was also rated on a scale of 1 to 5, where 1 means negligible impact and 5 means catastrophic. Those risks that have a major impact on the outcome were rated at 4-5. While other less critical risks had a low impact of 2-3.

Research results and discussion. Readings of the hydrometer lowered into the flask with soil are given in Table 1.

The masses of soil fractions are presented in Figure 6. Depending on the percentage of these fractions, the soil classification was subsequently determined. Each fraction affects the soil's ability to retain water and interact with external loads, which is important to consider when designing construction projects.

Table 1

Performance in the hydrometer test

Hydrometer reading, mm	Soil holding time, min	t, °C
1 min	1009	21
2 min	1008.5	21
5 min	1005	21
15 min	1025	21
30 min	999.5	21
60 min	998.5	21
240 min	998.5	21
1440min	998.5	21

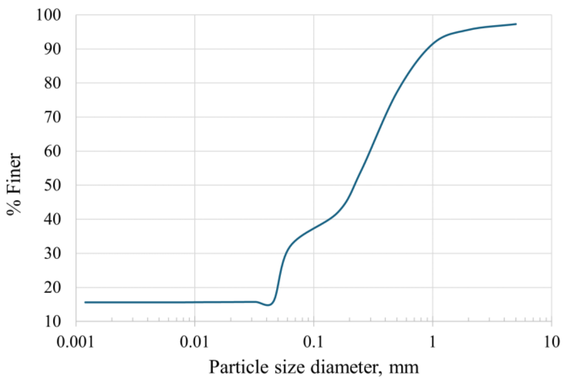

Fig. 6. Particle size distribution curve

The results of soil moisture determination by drying to constant weight method are presented in Table 2. The soil sample was classified as poorly graded sand with fine frictions (Table 3).

Table 2

Results of soil moisture determination by the method of drying to constant weight

No. of bux	m, g	m_1, g	m_0, g	w, %	w_{aver}, %
4	5.17	20.38	20.18	1.332	1.297
6	5.2	17.3	17.14	1.34	
19	10.09	24.21	24.04	1.218	

Table 3

Physical characteristics of soil

Soil characteristic	Value
Specific gravity, g/cm^3	2.538
Maximum dry density, g/cm^3	2.031
Optimum water content, %	10.194
Sand sized fraction (75µm-2mm), %	60.794
Silt sized fraction (5-75µm), %	19.193
Clay sized fraction (<5µm), %	15.607
Liquid limit, LL, %	23.251
Plastic limit, PL, %	1.190
Plasticity Index, PI, %	22.061

The results on risk assessment according to the conducted research methods are presented in Table 4 and Figure 7.

Table 4

Risks assessment

Method	Risks	Likelihood	Impact
Hydrometer Method	1. Error in selecting the suspension concentration	0.5	3
	2. Incorrect calibration of the hydrometer	0.5	3
	3. Inability to analyze large fractions	0.5	3
	4. Errors due to imperfections in the method	0.4	3
	5. Instability of temperature conditions	0.3	2
	6. Contamination of the hydrometer		
Sieving Method (Wet)	1. Loss of particles during washing	0.8	3
	2. Inability to separate fractions with similar sizes	0.8	3
	3. Errors due to moisture	0.6	3
	4. Sample heterogeneity	0.6	3
Drying to Constant Mass Method	1. Overheating of the sample	0.2	2
	2. Temperature instability	0.2	2
	3. Inability to account for hygroscopic moisture	0.4	3
	4. Insufficient drying time	0.2	2
Compaction Coefficient Method	1. Inability to control moisture accurately	0.6	4
	2. Error during the compaction procedure	0.6	4
	3. Sample non-uniformity	0.6	4
	4. Temperature and humidity fluctuations	0.6	4
Lower Plasticity Limit Method	1. Errors in determining the rolling boundary	0.5	3
	2. Sample heterogeneity	0.5	3
	3. Inability to control moisture accurately	0.5	3
	4. Temperature and humidity fluctuations	0.5	3

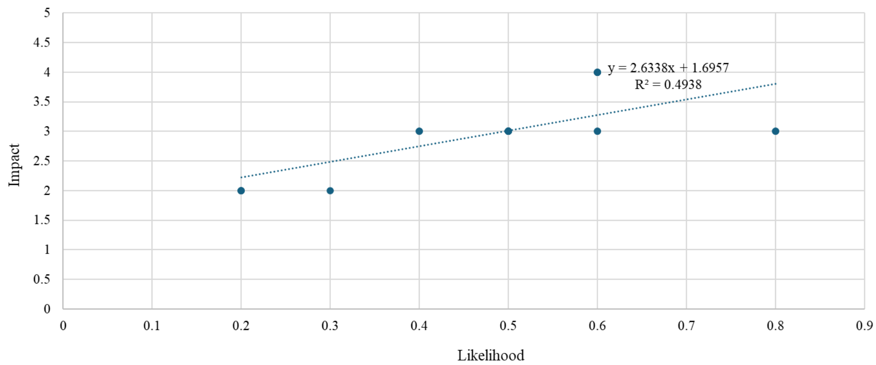

Fig. 7. Risk spread diagram

The scatter diagram with probability and influence showed that with each increase of the reduced probabilities by 1 the influence value increases by 3 units, and the calculated coefficient of determination shows a moderate degree of strength of the reduced model.

Conclusion. The particle size distribution of soil plays a crucial role in determining its construction and performance characteristics such as strength, permeability and compressibility. Its accurate study helps to predict the behaviour of the soil under the influence of external factors, which is important for the development of safe construction solutions. Errors in determining particle size distribution can lead to incorrect estimates of soil characteristics and increased risks during construction.

The conclusions of the study are as follows:

1. Various methods are used to accurately assess the particle size distribution of soil, including sieve analysis, hydrometer analysis, and liquid and plastic limit studies. Each of these methods provides detailed information on the soil's partial composition, compressibility, and water absorption capacity. The combined use of these methods provides a more accurate and comprehensive understanding of soil characteristics.

2. In sieve analysis there is a risk of misinterpretation of particle sizes, which can lead to misinterpretation of the particle size distribution. In hydrometer analysis, errors can occur due to improper sample preparation or errors in solution density measurements. Errors in liquid limit and plastic limit analyses can distort the yield and plasticity of the soil, which affects the predicted behaviour of the soil in service.

3. The study showed that the soil may contain impurities that affect its physical properties. Precise analysis of the particle size distribution allowed to determine that the investigated soil belongs to a certain type taking into account the presence of different fractions and impurities. The soil sample was classified as poorly graded sand with fine frictions.

4. The use of scatter plots allowed us to visualise the risk analysis of each survey method, which may lead to measurement errors. The use of scatter diagrams opens up opportunities for more accurate interpretation and optimisation of investigation methods, minimising potential errors and improving the quality of geotechnical investigations.The greatest influence on the indicators of determination of physical properties of soil affects the accuracy and elimination of errors when carrying out tests on the Compaction Coefficient Method, where the probability of errors can reach a critical value, where the impact was 80%, and the probability was 60%.

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ТОПЫРАҚТЫҢ ФИЗИКАЛЫҚ ҚАСИЕТТЕРІН ӨЛШЕУ КЕЗІНДЕГІ ТӘУЕКЕЛ ФАКТОРЛАРЫН ТАЛДАУ

Аңдатпа. Топырақтың физикалық қасиеттерін анықтау инженерлік нысандарды сәтті жобалау мен салудың негізі болып табылады. Бұл қасиеттер әртүрлі жүктемелердегі топырақтың сипаттамасына тікелей әсер етеді, бұл құрылыс құрылымдарының тұрақтылығы мен қауіпсіздігін анықтайды. Бүгінгі таңда бұл саладағы негізгі проблемалар – бұл белгісіздіктің жоғары деңгейі және зертханалық зерттеулер кезінде қателіктер қаупі. Бұл жұмыс топырақтың физикалық қасиеттерін эксперименттік зерттеуді ұсынады және ұсынылған әдістердің әрқайсысы үшін қателіктер ықтималдығы мен дәлсіздік тәуекелдерін талқылайды. Бағалау үшін тәуекелдерді талдауға негізделген тәсіл қолданылды. Тәсіл өлшеу қателіктерін және топырақты сынау әдісін сандық бағалауға бағытталған. Нәтижелер топырақтың физикалық қасиеттерін анықтауға арналған барлық сынақ әдістері жоғары дәлдікті және стандарттарды сақтауды қажет ететіндігін көрсетті, бірақ топырақты тығыздау сынағы процедуралардың ерекше күтімі мен қатаңдығын қажет ететін күрделі процесс болып табылады.

Тірек сөздер: топырақты сынау, қауіптілік, талдау, физикалық қасиеттері, дәлдігі.

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АНАЛИЗ ФАКТОРОВ РИСКА ПРИ ИССЛЕДОВАНИИ ФИЗИЧЕСКИХ СВОЙСТВ ГРУНТА

Аннотация. Определение физических свойств грунта является основой для успешного проектирования и строительства инженерных объектов. Эти свойства напрямую влияют на поведение грунта при различных нагрузках, что определяет устойчивость и безопасность строительных конструкций. На сегодняшний день основными проблемами в этой области являются высокая степень неопределенности и риск ошибок при проведении лабораторных испытаний. В данной работе представлено экспериментальное исследование физических свойств грунта и приведено обсуждение вероятности ошибок и рисков неточности для каждого из представленных методов. Для оценки использовался подход, основанный на анализе рисков. Подход был направлен на количественную оценку погрешностей измерений и метода испытания грунта. Результаты показали, что все методы испытания по определению физических свойств грунта требуют высокой степени точности и соблюдения стандартов, однако испытание на уплотнение грунта – более сложный процесс, требующий особой тщательности и строгости процедур.

Ключевые слова: испытание грунта, риск, анализ, физические свойства, точность.